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Tors in Central European Mountains – are they indicators of past environments?

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Abstract. Tors represent one of the most characteristic landforms in the uplands and mountains of Central Europe, including the Sudetes, Czech-Moravian Highlands, Šumava/Bayerischer Wald, Fichtelgebirge or Harz. These features occur in a range of lithologies, although granites and gneisses are particularly prone to tor formation. Various models of tor formation and development have been presented, and for each model the tors were thought to have evolved under specific environmental conditions. The two most common theories emphasised their progressive emergence from pre-Quaternary weathering mantles in a two-stage scenario, and their development across slopes under periglacial conditions in a one-stage scenario. More recently, tors have been analysed in relation to ice sheet extent, the selectivity of glacial erosion, and the preservation of landforms under ice. In this paper we describe tor distribution across Central Europe along with hypotheses relating to their formation and development, arguing that specific evolutionary histories are not supported by unequivocal evidence and that the scenarios presented were invariably model-driven. Several examples from the Sudetes are presented to demonstrate that tor morphology is strongly controlled by lithology and structure. The juxtaposition of tors of different types is not necessarily evidence that they differ in their mode of origin or age. Pathways of tor remodelling and degradation under subaerial conditions are identified and it is argued that processes of tor formation and development are ongoing. Thus, tors are not reliable indicators of past environments, because they are considerably influenced by both geological factors, such as lithology and structure, and geomorphological factors such as hillslope setting.

Key words:
tors,
deep weathering,
periglacial processes,
glacial erosion,
rock control,
surface degradation,
Bohemian Massif,
Central Europe

Introduction

The importance of landforms as indicators of landscape change is undoubted. Every landform is a product of geomorphic processes, but only some can be unequivocally interpreted in a process-form framework. Those landforms that are notoriously difficult to interpret but nevertheless attractive as potential indicators include exposed masses of solid rock known as tors. The setting, shape, and morphology of tors and related residual features have been used as indicators of palaeo-environments in mid-latitude mountains since the 1950s, following Linton's seminal paper on the two-stage model of tor formation (Linton 1955), subsequent debate with protagonists of a one-stage model (e.g. King 1958; Palmer and Neilson 1962), and early studies focused on periglacial landforms in the uplands of Central Europe (e.g. Czudek 1964; Demek 1964a). Although much of the interest in the significance of tors dates back to the 1960s and 1970s, they are still an important topic for research, especially in the upland landscapes of central and northern Europe, where studies tend to focus on the persistence of tors under glacial conditions (André 2004; Darmody et al. 2008; Hall and Migoń 2010). However, since landforms such as tors and related residual features are built of massive bedrock, any interpretation requires a proper consideration of structural and lithological factors before their palaeo-environmental significance can be assessed.

Different concepts of tor formation and development were born independently in Britain (e.g. Linton 1955; Palmer and Radley 1961) and Germany (e.g. Meinecke 1957; Wilhelmy 1958) and then applied in other landscapes of Europe. Studies carried out in the Bohemian Massif by Czech, Polish and German geomorphologists contributed to a better understanding of the tor phenomenon, and these continue to be widely cited in regional studies (Jahn 1962; Martini 1969; Bartošíková 1973; Jahn 1974). However, other advances in tor research have been made in the last few decades, partly validate older opinions but also shed new light on some contentious issues such as structural and lithological controls, the selectivity of glacial erosion, the preservation of landforms under ice, and patterns of tor degradation. Consequently, the aim of this paper is to provide an updated review of tor research, including a comparison of opinions regarding the formation and development of tors in the uplands and mountains of Central Europe. An important part of this study is a discussion of the remodelling and degradation pathways of tors – an important issue rarely addressed in tor research. Most of the observational material presented here comes from the Sudetes, but supporting evidence is also incorporated from other mountain ranges in Austria, Czechia and Germany.

Tors and related landforms: terminology

Widespread use of the term "tor" in the geomorphological literature can be traced back to D. Linton and his seminal paper from 1955. Linton borrowed it from the Welsh word *twr* or the Latin word *turris*, which both mean "tower" (Selby 1972). The definition of tor proposed by Linton (1955, p. 476) focuses on the genesis of the form, which he described as "a residual mass of bare bedrock rising conspicuously above its surroundings from a basal rock platform […] it is isolated by steep free-faces on all sides and is the result of differential weathering of joint blocks, and mass slope wasting". In addition, Linton used and specified two others terms for tors, highlighting their position and shape: stack and buttress. The former denotes a distinct rock mass rising from the slope or top surface, and the latter term denotes a residual rising from a valley side and separated from the slope surface by only two or three steps (Linton 1955). Another definition of tor was presented by Pullan (1959), who did not argue for a specific model of tor development, highlighting instead the various processes involved in bedrock degradation and removal of regolith. He considered tors as upstanding rock forms "formed by the differential weathering of a rock bed and the removal of the debris by mass movement". Tors were also considered equivalents of "boulder inselbergs" (Gerrard 1988), e.g. singular, isolated residual forms whose heights range from 3 to 50 metres (Selby 1972). Larger scale rock landforms often co-occurring and akin to tors are "inselbergs" and "monadnocks", both of which are morphologically considered to be a bedrock-built hill. Inselbergs are sharply protruding from the surface as products of scarp retreat or varied differential structurally-controlled subsurface weathering (Twidale and Vidal Romani 2005), whereas monadnocks are residual remnants of long-term erosion (Goudie et al. 1994; Migoń 2004). A morphologically different landform that is non-compliant with the tor criteria is the "crag". A crag is considered to be an irregular, asymmetric rock outcrop of elongated shape without distinct edges, and often surmounting ridges.

This terminology is mainly derived from research of granite landscapes and is only used in the context of granite landforms. However, in this paper, the author uses the term "tor" in its wider meaning, which includes rock forms of different lithology.

Early studies of tors contributed to the emergence of different views about their formation and development. The most popular, and highly influential, was the two-stage theory outlined by Linton (1955). In this model, rock mass was subsurface chemically weathered in conducive conditions. The chemical weathering of the bedrock was followed by stripping of the decayed material simultaneously exposing solid unweathered parts of granite, which are then known as the tor. In response, an alternative one-stage evolution concept was presented by King (1958), in which the simultaneous nature of degradation and stripping were stressed. He considered that summit tors are remnants of old pediplains, whilst tors located below the summit reflect more recent selective weathering (King 1958). This one-stage theory was then adopted to explain slope rock forms developed under periglacial conditions (Palmer and Radley 1961). In subsequent years, evidence both for deep weathering and excavation from saprolite and for superficial rock breakdown in presumably cold environmental conditions was presented. Consequently, tors came to be regarded as examples of equifinality, i.e. landforms that may form through the operation of various processes (Cunningham 1965; Migoń 2006). However, this rationale obscures the fact that very different landforms have been designated as "tors" in the published literature.

Linton (1955, p 470) defined tors as features "as big as a house" and emphasised that they should rise above the surrounding regolith-covered surface from all sides. This is a requirement not met by the majority of frost-riven cliffs, which may be simple rock steps, commonly only 2–3 m high, and thus much less than the height of a house, interrupting an otherwise planar slope surface. Martini (1969) cautiously used the term "tor-like features" to emphasise the periglacial origin of rock forms protruding asymmetrically from a slope. Likewise, apparently irregular piles of boulders, typical for granites and often >5 m high, do not strictly follow the definition given by Linton as they have no steep faces, although Thomas (1965, p. 64) stated that tors are indeed "groups of spheroidally weathered boulders, rooted in bedrock". But a range of transitional landforms may exist, e.g. those projecting out of a slope with three steep sides. Hence, defining a sharp boundary between tors and rock cliffs is probably not feasible. Some Czech researchers distinguish between tors, castle koppies, and frost-riven cliffs on the basis of the following morphological characteristics and the presumed mode of origin (Bajer et al. 2014):

- Tor – an isolated rock outcrop of rather minor dimensions, smaller than a castle koppie, rising above the surroundings from all sides. Its height surpasses its length. A two-stage origin is envisaged.
- Castle koppie – a laterally extensive rock outcrop, bounded by steep sides, often cut into smaller compartments by joint-aligned clefts. Height does not exceed length. A one- or two-stage model may apply.
- Frost-riven cliff – a bedrock step across a slope, steep or even overhanging, typically a few metres high and formed through joint-controlled frost shattering of rock.

Areas of tor occurrence

Overview: general relief and geology

The part of the Central European Highlands considered in this paper incorporates a range of uplands in the Bohemian Massif and the isolated massif of Harz (Fig. 1). The Bohemian Massif is a vast basement block with a rhomboidal shape, surrounded by sedimentary rock terrain at lower elevations (Reicherter et al. 2008). To the west and to the north, the sedimentary rocks exposed at the surface are of Mesozoic age whereas, to the northeast, basement rocks disappear beneath the sediments of Neogene and Quaternary age. To the southeast and to the southwest, belts of Cenozoic molasse deposits separate the Bohemian Massif from the younger orogenic chains of the Carpathians and the Alps. The Bohemian Massif is highly diversified in terms of relief and geology. It comprises low- to medium-altitude terrain in its central part, mostly coincident with the outcrop area of Cretaceous shallow marine deposits, and higher terrain along all four sides of the block. However, elevations and the style of relief vary considerably, from more than 1,000 m a.s.l. along extensive tracts in the northeast (the Sudetes) and southwest (Bohemian Forest) to gently undulating topography at 600–800 m a.s.l. in the southeast (the Czech-Moravian Highlands). These uplands, characterised in more detail in the following subsections, are predominantly built of crystalline igneous and metamorphic rocks, mainly post-orogenic granites, gneisses, and schists whose ages span from the late Proterozoic to the Carboniferous. Among less widespread lithologies are quartzites, amphibolites and syenites, which also give rise to tors. Finally, Carboniferous and Permian clastic deposits have survived in Variscan intramontane basins and these occasionally also form crags. A thorough presentation of Cenozoic environmental change in the Bohemian Massif is beyond the scope of this paper, but various proxies allow us to infer a generally warm and humid climate until the Miocene, gradual climate deterioration towards the end of the Neogene, and alternating cool and temperate episodes in the Quaternary (Mosbrugger et al. 2005). During the cold stages of the Pleistocene, the Bohemian Massif and Harz remained in the periglacial zone, with permafrost, but glaciation was restricted to the low-lying northern forelands and the most elevated parts of the Sudetes and the Bohemian Forest, where local cirque glaciers developed.

The Sudetes

The Sudetes form the northeastern marginal area of the Bohemian Massif and represent the highest of the four outer elevations. Mount Śnieżka in the Western Sudetes rises to 1,603 m a.s.l., whereas the floors of the intramontane basins typically lie at 300–400 m a.s.l. The treeline is located at c. 1,250–1,300 m a.s.l. and, therefore, the most elevated parts are open terrain typified by marginal periglacial environments (Křížek et al. 2010). The Sudetes are c. 300 km long, striking NW–SE, and up to 80 km wide (Fig. 2). This range comprises a large number of smaller morphological units and it genetically represents a horst and graben topography of Neogene-to-Quaternary age superimposed on a rock-controlled denudational landscape whose protracted geomorphic history can be traced back to the beginning of the Cenozoic (Migoń 2011). One characteristic feature of many of the uplifted blocks is that they have surfaces of low relief in wa-

Fig. 1. Map of Central Europe indicating the areas described in the text. 1 – location of tors of the Waldviertel region (Figs 3 and 4)

tershed settings, and these are interpreted as former base-level plains. They give way to moderately steep slopes and valley sides connecting to the basin floors. The most common lithologies are gneisses, granites, and mica schists, although large tracts in the central and eastern part of the range are built of sedimentary rocks. Tors and related residual features occupy various geomorphic settings – from basin floors in the foreland to the summit plains at >1,400 m a.s.l. (Jahn 1962, 1974; Czudek 1964; Demek 1964a). They can be found in almost every lithology but tend to be particularly common in granites (Jahn 1962; Štěpančíková and Rowberry 2008; Migoń 2016), greenschists (Martini 1969; Michniewicz 2016) and gabbros (Placek 2007), although instances of the two latter rock types are rather localised. Less frequently they occur in gneisses (Czudek 1964; Sobczyk 2005) and only sporadically in volcanic rocks (Migoń et al. 2002).

The Czech-Moravian Highlands

The Czech-Moravian Highlands form a wide tract of upland relief, more than 180 km long, connecting the Eastern Sudetes with the eastern tip of the Bohemian Forest in Lower Austria. In the southeast, a clear but rather low escarpment represents the sharp transition to the Carpathian Foredeep. It is incised by a series of fluvial valleys with steep, locally rocky slopes (Kirchner 2016a). By contrast, the decrease in altitude to the northwest is gradual and the basement disappears under a sedimentary cover of Cretaceous age. The most elevated parts of the Czech-Moravian Highlands exceed 800 m a.s.l. (Javornice – 837 m; Žďárské vrchy – 836 m) but elevations of between 500 and 600 m a.s.l. are more common, and slopes are gentle – rarely exceeding 15°. The entire area has been interpreted as an etchplain, i.e. a basal weathering surface, exposed as thick weathering mantles were eroded away in the Neogene (Czudek and Demek 1970).

Fig. 2. Map of the Polish and Czech Sudetes. 1 – tors of the Okole massif (Fig. 9), 2 – the Staróścińskie Skały tor group (Figs 5 and 7) and Skalny Most tor (Fig. 8A), 3 – the Paciorki tor group (Fig. 8B).

Except for the easternmost part north of Brno, characterised by Devonian limestones and Carboniferous greywackes, the geology of the Czech-Moravian Highlands is rather monotonous, dominated by extensive gneissic terrains and Variscan granite intrusions (Early Carboniferous). Tors are scattered across the region, although they tend to cluster in specific areas, such as in the central part of Žďárské vrchy (Kirchner 2016b) and in the vicinity of Dyje Canyon (Kirchner 2016a), both built mainly of gneiss, or in the highlands of Nova Bystřice (Votýpka 1964; Věžnik 1982) and western Waldviertel in Austria (Migoń et al. 2017), developed across Variscan granites. These tors occupy various topographic settings from summit convexities to steep valley sides.

The Bohemian Forest

The southwestern borderland of the Bohemian Massif comprises an elevated block of basement rocks, mainly pre-Variscan gneiss and Variscan granites (Early Carboniferous), which begins in Lower Austria and stretches to the northwest along the Czech–German border towards the western margin of the Eger Graben. This region is referred to as the Bohemian Forest but it can be subdivided into several smaller units such as Novohradské hory/Weinsberger Wald, Šumava/Bayerischer Wald, and Český les/Oberpfälzer Wald (Fig. 1). Further to the north, at the intersection between the Bohemian Forest and the Ore Mountains, the block-faulted massif of Fichtelgebirge is located. The Bohemian Forest is more than 250 km long and up to 50 km wide, with the most elevated central part (Grosser Arber – 1,457 m a.s.l.), and large tracts of terrain above 1,000 m a.s.l.. A remarkable geomorphic feature of Šumava is the presence of an extensive low relief surface (~670 km^2) at high elevations, interpreted as a remnant post-Variscan planation surface (Mentlík 2016). The highest peaks rise above this surface in broad domal forms so that slopes in the central part of the area are of relatively low inclination. In the Pleistocene, local glaciation developed at about ten localities but, apart from cirque formation, the erosional effects of the glaciers were rather minor. Tors are common in the Bohemian Forest and Fichtelgebirge, especially in granites (Votýpka 1971, 1975; Rypl et al. 2014; Mentlík 2016), where they may even form clusters large enough to be termed “rock cities”, e.g. at Luisenburg in Fichtelgebirge (Wilhelmy 1958; Lagally et al. 2012). However, gneisses hereabouts also support tors, especially on steeper slopes, while quartzite is another common tor-forming rock (Lagally et al. 2012).

The Ore Mountains

The more-than-130-km-long Ore Mountains (*Erzgebirge* in German, *Krušné hory* in Czech) constitute the northwestern borderland of the Bohemian Massif and extend along the Czech–German border up to the Labe/Elbe gorge in the east. Their gross morphology is defined by two characteristic features: (a) an overall cross-sectional asymmetry, with a gentle slope towards the NW and a steep slope towards the SE, the latter being a tectonic fault-generated escarpment; (b) an extensive surface of low relief along the water divide, at approximately 900 m a.s.l. (Vilímek and Raška 2016). The highest peaks (Klínovec – 1,244 m, Fichtelberg – 1,214 m) rise gently above this broad surface. The Ore Mountains owe their present-day elevation to late-Neogene-to-Quaternary uplift, concurrent with vigorous fluvial dissection. As with the Bohemian Forest, the Ore Mountains are built mainly of gneissic complexes and phyllite series, later intruded by granite plutons. The gneisses and granites give rise most readily to tors, while quartzites are also important for tor-forming processes.

The central part of the Bohemian Massif

The central part of the Bohemian Massif, although much less elevated than its outer uplands and mountain ranges, includes areas abounding with tors. Among them are the Brdy Highlands to the southwest of Prague, where impressive crags and cliffs have formed in hard Cambrian conglomerates (Žák 2016), and the granite massif of Sedmihoří west of Plzeň (Votýpka 1974). For gently undulating granite landscapes, which are numerous in the region, clusters of huge granite boulders, including rocking stones, are fairly typical (Motyčková et al. 2012).

Harz

Harz is an isolated, uplifted block that rises above the Mesozoic sedimentary tableland in central northern Germany (Fig. 1). It displays an overall asymmetry, with its northern slopes steeper than its southern ones. The Harz block is about 80 km long and up to 30 km wide, built mostly of Devonian-Carboniferous metasediments, and intruded by Carboniferous granites. The latter are exposed in the most elevated part of Harz (Brocken – 1,142 m) and support numerous tors, including some of impressive dimensions. In the German literature, the granite tors of Harz were cited as the model examples of these forms and examination of the relationships between the tors and local weathering mantles led to the formulation of a two-stage model of tor development (Meinecke 1957; Wilhelmy 1958) that partly differed from the contemporaneous proposal by Linton (1955). Wilhelmy (1958) presented a three-stage model of tor development referencing Linton's theory, but supplemented it with a stage of weathering under surficial conditions.

Views on the formation and development of tors in Central Europe

Deep weathering and stripping

Deep chemical weathering is now considered a universal phenomenon, in principle unrelated to lithology and climatic conditions, although climate – especially temperature and precipitation – certainly controls the rates of weathering (Taylor and Eggleton 2001; Migoń 2013; Pope 2013). Nevertheless, the internal structure of a deep weathering mantle varies and, in igneous rocks in particular, considerable diversity exists in terms of weathering grade and horizon thickness (e.g. Thomas 1966; Hall 1986; Lageat et al. 2001; Migoń and Thomas 2002). The depth of chemical weathering, typically from several to several dozen metres, varies considerably for different parts of the world (Ollier 2010). Non-uniform profiles consist of weathering mantle and unweathered fragments of bedrock that – after the degradation of weathered debris – present various residual landforms, e.g. inselbergs, tors and boulders. It was often assumed that exposed blocky compartments building tors would have rounded shapes (e.g. Thomas 1965), occasionally named "woolsacks" and "pillows" (Linton 1955).

In the Sudetes, deep weathering is particularly evident within granite landscapes, where both very thick clay-rich saprolites and thinner, but still >10-m-thick, mantles of grus have been documented (Franz 1969; Migoń 1996, 1999; Kajdas et al. 2017). In numerous localities, there is a clear separation of the weathered rock mass into almost fresh boulders, known as "corestones", and thoroughly disintegrated granite. The two-stage theory of tor evolution was first considered by Jahn (1962) and this paper became an important reference article for future research in this region. He described the main morphological features of granite tors from the Karkonosze Mountains and adjacent Jelenia Góra Basin, presenting their presumed origin and age. The period of subsurface weathering was ascribed to the pre-Quaternary times and the depth of the weathering was assumed to be 20–30 metres, estimated on the basis of the height of the highest tors in the region. The second phase, during which the weathered material was removed, was proposed to have occurred in the Pleistocene, under periglacial conditions. Jahn (1962) maintained that exhumation of tors proceeded upwards with the youngest tors situated in the upper parts of slopes and on ridges. Furthermore, certain morphological differences between tors were emphasised and explained by the petrographic and structural diversity of the granite, most especially the influence that joint systems exerted on tor morphology, although little supporting evidence was presented. Finally, Jahn (1962) modified (expanded, in fact) the concept of Linton, by considering the influence exerted by the periglacial climate and post-exposure surface conditions on tor development. Accordingly, it was suggested that the excavation of tors intensified during the last glaciation and that forms exposed much earlier had been rounded due to rainwater–rock interactions (Jahn 1962). Thus, he did not assume that all rounded boulders were corestones formed in the subsurface. A decade later, Jahn (1974) slightly changed his view, highlighting the subsurface stage of tor formation and minimising the importance of development at the surface.

Tors as products of deep weathering are also known from the Žulovská pahorkatina region, part of the Sudetic Foreland, located at the foot of the Sudetes. This granitic terrain is characterised by the presence of residual hills, mainly low domes and inselbergs with heights of up to >100 m, interpreted as elements of an exposed basal weathering surface or etchplain (Czudek et al. 1964; Demek 1976; Ivan 1983). However, smaller residual hills also occur that broadly conform to the definition of tor offered by Linton, their rounded shapes and the absence of angular debris being presented as evidence for a two-stage origin (Štěpančíková and Rowberry 2008). The age of the granitic terrain of the Sudetes and Sudetic Foreland comprising bornhardts, tors and various weathering products is conceptualised as pre-Quaternary (Palaeogene to Pliocene) and Early Quaternary (Migoń 1993, 1996). Generally, chemical weathering is related to humid and warm environments, but its efficacy in cold climate conditions is also noted by some authors (Rea et al. 1996; Munroe et al. 2007).

Beyond the Sudetes, the origin of certain tors in the Czech-Moravian Highlands, especially those assuming a castle koppie morphology, have also been explained in terms of deep and selective weathering (Demek 1964a). The process of subsurface chemical weathering, termed rock rotting, was believed to cause rounded forms (woolsack shapes). However, Demek also pointed out that observations of exposed weathering profiles indicate irregular and selective rock rotting in which weathered materials, corestones and solid rock could all be present in one horizon. Furthermore, he emphasised the influence that the type of climate could exert on the dominant formative process, believing that the role of mechanical versus chemical weathering in tor development is climate-dependent and that the morphology of the residual landforms would depend on the climatic conditions under which they formed, even within the same geological settings (Demek 1964b). Because watershed ridges, summits and the upper parts of slopes represent the most frequent locations for castle koppies, structural and lithological features were considered to exert major control (Demek 1964a).

However, in the Czech-Moravian Highlands it is typical for tors and castle koppies to give disappointingly few clues as to their origin. This is the case in the Žďárské vrchy Highland, where impressive residual rock formations built of coarse gneiss are abundant (Bajer et al. 2014; Kirchner 2016a). Some of them exceed 20 m in height and are nearly 100 m in length, rising from the surrounding slope surfaces on all sides, thus fulfilling the definition of a tor. It is uncertain, though, as to whether they formed according to the two-stage model, as no corroborating evidence (e.g. outcrops of deeply weathered material) is available. In contrast, the distinctive angular shapes and the spatial association with blockfields and blockstreams, considered as a diagnostic cold-climate geomorphic phenomenon, suggest a periglacial origin. A similar problem is faced when trying to interpret the large granite tors in the most elevated parts of the Bohemian Forest, such as Gratzener Bergland in Austria, Šumava in Czechia and Fichtelgebirge in Germany (Votýpka 1979; Huber 1999; Lagally et al. 2012). The origin of tors in subdued upland terrains appears to be clearer, as exemplified by rock outcrops in the Waldviertel of Lower Austria (Huber 1999; Michniewicz et al. 2015; Migoń et al. 2018). Firstly, bedrock outcrops tend to be piles or clusters of rounded boulders with specific microforms that indicate subsurface weathering (flared slopes) rather than angular castellated forms or cliffs (Fig. 3). A flared slope is a longitudinal hollow on the rock wall that has often developed along scarp foot zones as a result of chemical weathering of the rock surface. This minor form indicates the past water table level and vertical line of the regolith (Twidale and Vidal Romani 2005).

Secondly, they rarely coexist with angular blockfields, so there is no circumstantial evidence for their periglacial origin. Thirdly, at some localities it is possible to observe tors emerging from weathered granite that has turned into grus (Fig. 4). Thus, the two-stage model is more likely to apply here.

Tors and slope development in periglacial climates

The one-stage model of tor formation in cold conditions presented by Palmer and Radley (1961) found many followers in the Bohemian Massif, particularly Czechia and Poland. Demek (1964a) present-

Fig. 3. Many tors in the Waldviertel region of Austria are characterised by rounded shapes and the presence of flared slopes (red arrows), interpreted as evidence for emergence from the weathering mantle

Fig. 4. Fuchstein Tor near Blockheide in Waldviertel, partially exposed from the weathered grus

ed a model of slope development in a periglacial climate for granite terrains, highlighting diagnostic elements of slope morphology and characteristic medium-scale landforms. For a hypothetical slope – a flat or gently inclined (i.e. <5°) altiplanation terraces separated either vertical bedrock steps (referred to as frost-riven cliffs) or debris-covered steeper slope segments. The long-term development of such stepped slopes was thought to be accomplished by joint-controlled breakdown of frost-riven cliffs and gradual backwearing of the rock wall. Loose material derived as a result of mechanical degradation of the cliffs is removed by way of gelifluction across the altiplanation terraces. If gravitational movements do not work efficiently enough, the weathered material accumulates at the foot of the cliff, forming talus. This model, later repeated in Czudek and Demek (1972) and more recently by Czudek (2005), was linked with cold-climate conditions of the Pleistocene and the presence of an active layer of permafrost, whereas climatic amelioration at the beginning of the Holocene impeded the cliffs and the production of talus, thereby preserving a periglacial landscape. This concept was then used to explain numerous site-specific situations across the Bohemian Massif, with cliffs and angular talus sought and presented as unequivocal evidence for a one-stage theory of tor evolution. Examples may be forwarded from Czechia (Czudek 1964; Votýpka 1971, 1976; Věžnik 1982; Vítek 1975; 2000; Štěpančíková and Rowberry 2008), Poland (Martini 1967, 1979; Żurawek and Migoń 1999; Migoń et al. 2002), Austria (Chábera and Huber 1999) and Germany (Präger 1987). In some studies the occurrence of cliffs was apparently thought to be random, while in others more specific controls were sought. Thus, Czudek (1964) highlighted the role of resistant quartzites on the formation of mid-slope steps, and Martini (1979) concurred with this assertion when describing rock cliffs from the Śnieżnik Massif. Furthermore, it was noted that the inclination of the planar discontinuities exerts a dominant influence on the shape of greenstone tors, which often take the form of asymmetric crags (Martini 1969).

Of particular interest are attempts to decipher the long-term development of large residual tors, i.e. castle koppies, in watershed positions in the Czech-Moravian Highlands, as they were intended to reconcile two contrasting evolutionary models (Demek 1964b). The size and setting of these large residual features suggests a protracted history that would go back to the Palaeogene. However, these residuals bear obvious signs of mechanical weathering that most probably occurred under dry and cold climate conditions, such as angular shapes, widened fractures, dislodged and fractured loose rock blocks, talus-filled clefts, etc. In addition, blocky talus and impressive blockstreams occur in the vicinity of some large tors, which clearly represent the source for this blocky material (e.g. Kirchner 2016b). Thus, a view was presented that these large tors may have been excavated from long-since removed deep weathering profiles during pre-Quaternary times, but subsequently they have been reshaped by surface processes, particularly active in the periglacial realm. The extent of this remodelling may have been so severe locally that detailed morphological features are no longer inherited from the distant past. This may be the case for the large castellated tors on the summits of Nebelstein and Mandlstein in Gratzener Bergland. The latter is crowned by an exposed granite ridge of nearly 95 m long and 17 m high, dissected by deep clefts, and surrounded by extensive blocky talus (Chábera and Huber 1999; Michniewicz et al. 2015). Nevertheless, there are also localities within the Bohemian Massif where various types of residual landforms coexist. One such area is the hilly landscape of Königshainer Berge near Görlitz in easternmost Germany, where both solitary castle koppies, castle koppies associated with widespread blocky talus, and bedrock cliffs with surrounding blockfields have been described (Migoń and Paczos 2007).

Other evolutionary pathways

Neither antecedent deep weathering nor periglacial conditions have been explicitly invoked for sandstone tors present in sandstone tablelands. The extremely diverse sandstone geomorphology of the Bohemian Massif has been the subject of numerous studies and reports (Vítek 1981a; Cílek et al. 2007; Adamovíč et al. 2010). It is clear that solid rock outcrops that fulfil the descriptive criteria for a tor are merely one variant of residual landform in sandstones. In addition, their relationships to other types of sandstone relief may vary too. Thus, Walczak (1963) considered “mushroom-like” tors as transitional products of ongoing dissection of minor interfluves in the escarpment zone along a grid-like joint pattern, but landforms of similar shapes and sizes (up to 10 m high) may also testify to the advanced degradation of “rock cities”, i.e. parts of plateaux dissected into labyrinths of narrow corridors separating adjacent rock blocks (Migoń et al. 2017; Duszyński and Migoń 2018). Finally, isolated tors may develop from rock spurs at plateau edges and cuesta rims through sustained retreat of joint-controlled rock faces (Pilous 1992; Migoń and Placek 2007). The multidimensional evolution of sandstone landscapes may cause the tors development.

A rare case is provided by isolated formations that have been separated from the slope by landsliding. In general, the geology of the Bohemian Massif and the dominance of basement rocks do not favour sliding processes but they have been documented in specific locations conditioned by structural detachment and translation of rock walls and towers, e.g. on the trachyandesite ridge of Rogowiec in the Middle Sudetes (Kasprzak et al. 2016). Steep valley sides ubiquitous in gorges and V-shaped incisions throughout the Bohemian Massif abound in rock outcrops that may reach imposing heights of 40–50 m (e.g. Kirchner 2016a). They are distinctively asymmetric, joined to the slope in the top part and outlined by vertical rock faces on the remaining three sides. They occur as solitary bedrock spurs or form continuous lines of crags overlooking rivers. Mechanically strong rocks such as granite, gneiss, quartzite and amphibolite are typical crag-forming lithologies, whereas the joint pattern controls the details of spur shapes. Rock outcrops built of this group are apparently linked with intense fluvial incision in response to the Neogene-Quaternary uplift and concurrent slope evolution.

The Scandinavian ice sheet versus tor presence and morphology

The Scandinavian ice sheet reached the parallel latitude of 51° N in Germany and 50° N in Poland during the Elster glaciation. The ice mass encroached into the Sudetic interior at least once during the Saalian (200–300 ka) glaciation (Badura and Przybylski 1998) covering the basins and slopes up to 500–550 m a.s.l. Tors have been used occasionally to assist in the identification of the horizontal and vertical extent of the Scandinavian ice sheet in Central Europe. These studies were based on an assumption that the movement of ice would have destroyed, or at least significantly remodelled, upstanding tor features. One of the early studies of this kind was that of Jahn (1952), who re-evaluated rounded granite outcrops, formerly likened to roche moutonnées, in the Jelenia Góra Basin in the Western Sudetes. He concluded that they are structurally controlled, rather than having been reshaped by ice flow, although some may indeed have been smoothed and polished. Later, the presence of tors was considered to indicate that a given ridge or hilltop had not been glaciated and acted as a nunatak (Szczepankiewicz 1958; Martini 1969). Żurawek and Migoń (1999) observed a characteristic spatial pattern of gabbro tor distribution on Mt. Ślęża – a 500-m-high inselberg in the Sudetic Foreland. Tors of up to 15 m high are ubiquitous above elevations of 550 m a.s.l., whereas they are nearly absent below this altitude. Building upon the previous findings of Szczepankiewicz (1958) and considering the distribution of periglacial features such as blockfields and terraces, they claimed to have identified a Mid-Pleistocene trimline and suggested that tors were useful indicators to delimit the former ice surface. An analogous vertical differentiation of basaltic slopes in the Western Sudetes was described by Migoń et al. (2002).

The problem of glacial trimlines was subsequently addressed in the Izerskie Mountains and the degree of weathering, i.e. decreasing rock strength, was examined in tors and related residual features along a vertical profile across the northern escarpment of the massif (Traczyk and Engel 2006; Černá 2011). Glacial sediments left no doubt that the footslope was covered by ice up to heights of c. 480 m a.s.l. (Nývlt 2003) but there were few clues as to the maximum vertical extent of the ice and the erosional power of the ice in the marginal zone. Differences in rock strength determined by Schmidt hammer correspond with the diversity of tor morphology. While those on slopes assume the shapes of towers and castle koppies, those on footslopes are subdued, rounded and apparently devoid of superstructures. This observation could also be applied in other marginal parts of the Sudetes and more elevated sections of the Sudetic Foreland. It was demonstrated that the effects of glacial erosion upon tors increased with the distance from the ice sheet margin, while tors survived in the marginal glacial zone, thus casting doubt on the usefulness of tors as indicators of nunataks (Hall and Migoń 2010). Even more telling in this respect are angular granite tors of up to 12 m high at very low elevations, i.e. 300–400 m a.s.l., in the Königshainer Berge, where the thickness of ice was at least 200 m. Studies from areas of Scandinavia and Scotland describe a series of examples of tors that have persisted and been modified under ice sheets on the basis of the presence of pre-Quaternary long-term weathering forms and sediments, glacial sediments – tills and erratics – lying on rock surfaces, a shortage of summit blocks, etc. (André 2004; Darmody et al. 2008; Hall et al. 2012). However, no signs of glacial remodelling as described from Scandinavia and Scotland have been recognised on any of more than a dozen tors (Migoń and Paczos 2007).

Non-environmental factors: geological controls and pathways of degradation

Towards a better understanding of rock control on tor morphology

The role of geological setting as a factor that could account for the morphology of residual rock landforms has been mentioned by many authors but, in comparison with the influence of climate and process, its importance is generally considered to be rather minor. Rare exceptions include the presentation of granite tors in the Karkonosze as landforms whose shapes are clearly controlled by the orthogonal joint pattern (Berg 1927; Bartošíková 1973) and of sandstone mushroom-like tors (“hoodoos”, a term nonethless rarely used in European literature) in which the variable density of the horizontal bedding was identified as a control with wide caps built of massive sandstone and narrow stems comprising thinly-bedded sandstone (Walczak 1963; Vítek 1981b). In a more recent study of a group of such sandstone tors in the central part of the Sudetes, it was demonstrated, using a series of Schmidt hammer tests, that the massive caps are consistently associated with higher mechanical strength than the narrow stems (Migoń and Placek 2007).

A detailed study of an extensive group of granite tors in the Western Sudetes, known as Starościńskie Skały, provided further insights into the role of joints. This group is built from coarse granite cut through by 1- to 2-m-thick aplite veins. It represents a “rock city” with a varied, hierarchical morphology along its length of 180 m (Michniewicz et al. 2016; Kasprzak et al. 2017) and comprises two morphologically distinct parts. The southern part includes a half-dome hill with a series of isolated pinnacles and towers in the summit section (Fig. 5), whereas the second part is composed of a narrow ridge with angular towers and steps separated by blocky talus. The morphology of the former clearly reflects a concentric pattern of steeply dipping (>40°) sheeting joints, which account for the convex shape of the dome. However, it is further crossed by zones of vertical fractures, prone to selective weathering, which come to form avenues, clefts and ravines dissecting the dome. Granular disintegration of coarse-grained granite leads to the rounding of block edges. The morphology of the northern section is determined by an orthogonal system of joints, more densely spaced than the southern one, while sheeting joints are absent. These differences in the joint patterns are reflected by the dissimilar appearance of different parts of the “rock city”.

Whereas the southern part may be likened to a large dome or hemispherical tor excavated from the weathered mantle, the northern part represents a type of relief that in the Bohemian Massif is typically explained by mechanical disintegration under periglacial conditions (Fig. 6). However, given that both parts are adjacent to one another and at the same altitude, any idea that they may have different ages and histories seems inconceivable. Structural controls dictate diverse pathways for the morphological development of the “rock city”. The dome disintegrates on a grain-by-grain basis and these fine products of rock breakdown are transported downslope, especially along the steeply inclined clefts. Hence, little residual material is present, suggesting the stability of rock forms and limited degradation. In contrast, the northern part breaks down on a block-by-block basis and these mechanical weathering products – blockfields and angular debris – are present next to rock towers and on terrain steps, without the possibility of being transported further downslope under contemporary conditions (Michniewicz et al. 2016).


Fig 5. Sheeting joints (red dashed lines) and the convex rock slope in the half dome at Starościńskie Skały

The role of lithology is illustrated by tors comprising more than one rock type. In certain parts of the Karkonosze-Izera granite massif, aplite veins inside granite bodies are common and may be exposed within a singular tor. Aplite, as a fine-grained rock, is mechanically strong and more resistant to weathering than the host porphyritic granite. Rock forms with an aplite core often represent imposing landforms, apparently characterised by surface stability (Fig. 7). In contrast, aplite is usually densely jointed and, therefore, aplite intrusions break down easily and tend to form clefts infilled by rock debris (Fig. 8). Another example in which discontinuities control the development of rock forms is offered by Okole ridge in the Kaczawskie Mountains, also in the Western Sudetes, where there are tens of tors of differing morphologies. It is mainly built of Early Palaeozoic greenstones (metamorphosed basalt lavas) that locally show distinctive pillow lava structures formed in underwater conditions. Thus, geologically and morphologically, this area shows striking similarities to the region described by Martini (1969), who used greenstone tors to illustrate the role of periglacial slope processes in tor formation. The greenstones of Okole ridge are structurally complex. The original lava pillows were stretched and flattened during transformation of the basalt to greenstone during the Variscan Orogeny (Early Palaeozoic) so irregular tabular shapes are present. In other cases, the pillows are missing and the greenstone exhibits a distinct platy appearance, akin to stratification. Dips of these layered formations are variable but a NW–NNW dip dominates. The strike of the greenstone belt follows a WNW–ESE direction. These ancient structures are cross-cut by younger generations of joint sets which trend in an approximately

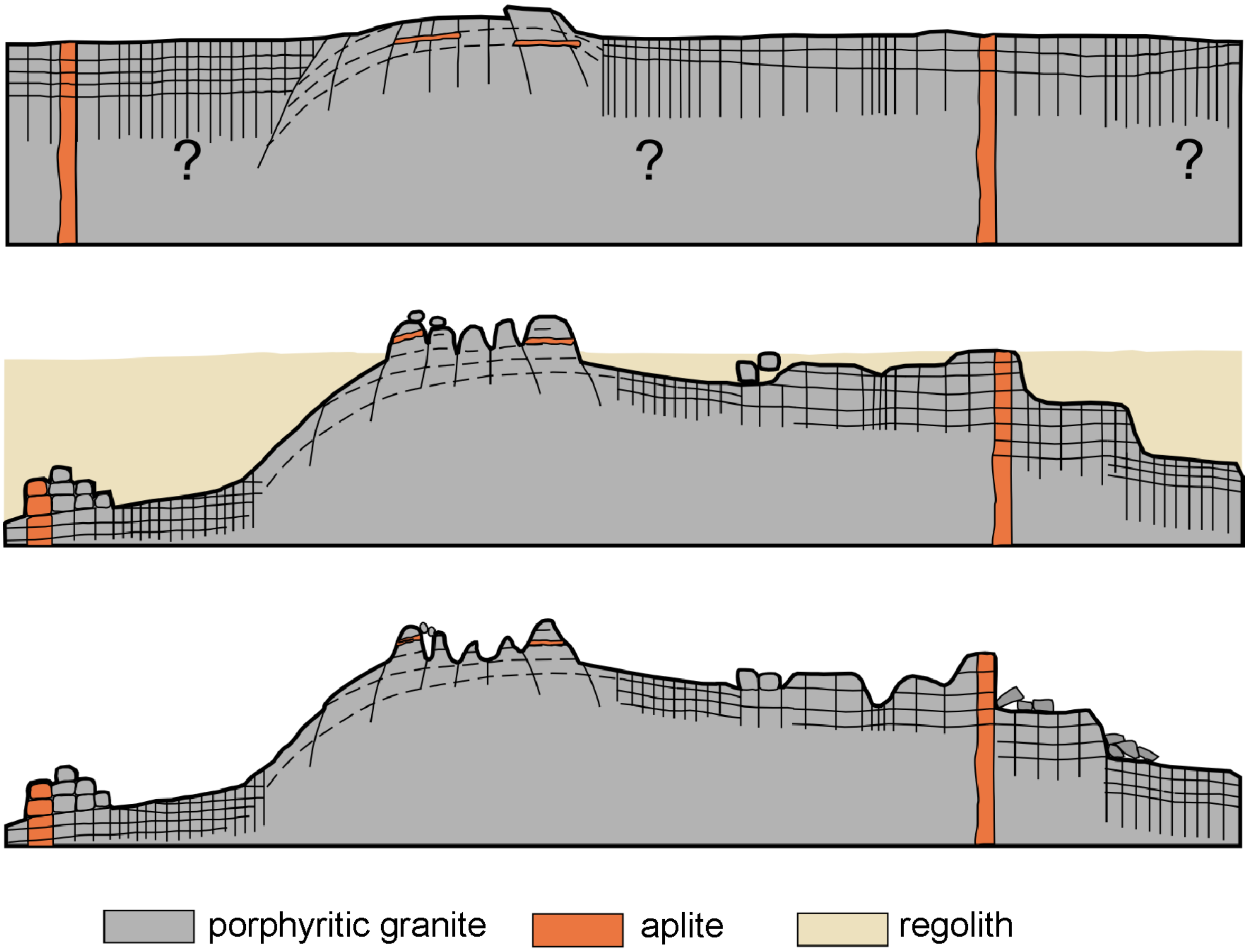
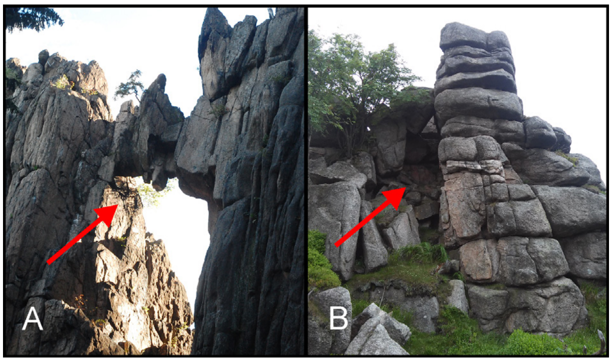


Fig. 6. An evolutionary model for the group of tors at Starościńskie Skały, Rudawy Janowickie, Western Sudetes. Differences in joints system are visible in tor morphology – the left part of the tor group is more resistant, while the right part has been severely degraded.



↑Fig. 8. Examples of tor degradation along densely jointed aplite veins in the West Sudetes. A – Skalny Most tor in Rudawy Janowickie, B – Paciorki tor group in the Karkonosze Mountains. The red arrows indicate vein remnants inside granite bodies.

←Fig. 7. Krzywa Tor in the group of tors at Starościńskie Skały, Rudawy Janowickie, Western Sudetes. The red arrow indicates aplite veins cross-cutting granite

38–45° direction. Structural control on greenstone tor morphology is threefold. Tors are preferentially associated with the SW-facing slope, i.e. one that truncates layering. As many as 30 individual tors protrude from this slope, whereas only nine are present in the broadly concordant NE-facing slope. They also differ in shape and size as tors on the NE slope have heights of 2–4.5 m, while tors on the SW slope reach 7–8 m (max. 12 m). Those on the SW slope emerge as tall steps and cliffs, also overhanging, and are typified by sharp, angular edges and associated with angular talus, supplied by fragments detached along open subvertical joints (Fig. 9). By contrast, those on the opposite slope are lower and more subdued. The most extensive and massive are tors built of the least metamorphosed rocks, in which the pillow lava structures are still partially preserved. Thus, the geomorphological characteristics of Okole ridge, including morphological tor diversity and distribution, mainly reflects structural predisposition. It is indisputable that during the Pleistocene this ridge was located in the periglacial zone, even in the immediate vicinity of the Scandinavian ice sheet (Badura and Przybylski 1998), but so too were other ridges in the vicinity where tors are scarce. In the Eastern Sudetes the issue of rock control was examined by Štěpančíková and Rowberry (2008), who analysed a suite of mid-slope rock steps in the Rychlebské Mountains so far uncritically referred to as frost-riven cliffs. They demonstrated a preferential association with more resistant lithologies as well as clear joint control on the morphology of the rock face in the majority of cases.

Fig. 9. Angular rock forms of Okole ridge in the Kaczawskie Mountains, Western Sudetes, reflecting the internal structure of pillow lava. Enlarged picture presents another example of greenstone pillows. The tors here occur preferentially on one side of the ridge.

Transformation and degradation of tors

Examination of the literature relating to tors in the Bohemian Massif indicates that research has generally focused on those processes responsible for tor formation, which is usually based on circumstantial evidence. Once formed, their morphology has tended to be regarded as stable, at least implicitly. In fact, such an assumption was necessary in order to use tor forms as palaeo-environmental indicators. Changes attributed to the Holocene period were those associated with the development of surface microrelief such as weathering pits on granite tors (Jahn 1962; Czudek et al. 1964; Michniewicz et al. 2016) and honeycombs and tafoni on sandstone tors (Vítek 1981a). Nevertheless, we can observe abundant evidence of degradation of tors under surface conditions (Figs 10 and 11), which is difficult to date but clearly attests to ongoing tor decay. The patterns of tor degradation are dependent on the structural conditions of bedrock, mainly the orientation and the density of discontinuities. The former dictates the preferential direction of breakdown whereas the latter controls the size of the detached rock fragments, which may vary from large blocks with dimensions in the order of metres to small pieces of rock with dimensions in the order of centimetres. The mechanisms are divided into two groups – those leading to mechanical weakening (Fig. 10) and disintegration processes (Fig. 11). Due to mechanical stresses, the rock mass weakens, joints open and, if this process occurs on a slope, the slow outward movement of a rock column may ultimately lead to its catastrophic collapse. The resultant angular talus may not relate in any way to an often assumed periglacial environment. Other processes are falls and lifting of rock blocks as a result of tree throws. Downslope sliding is an enigmatic process and it is not clear whether this occurs suddenly or gradually. Other processes such as blocky and granular disintegration, basal undercutting and cleft weathering proceed at low rates.

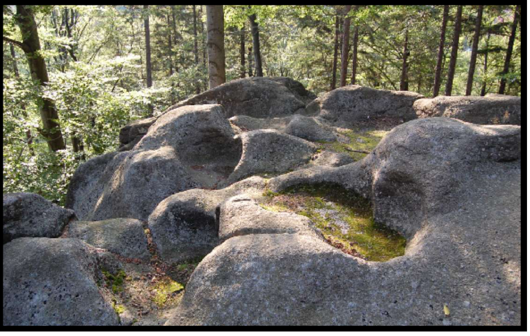
Process	Description	Example and geomorphic evidence
Tree-throw induced detachment	Applies to overgrown tors, with tree roots penetrating into joint surfaces. Episodes of strong wind may lead to tree throw, whereby rock blocks are lifted up along with the root plate.	
Preferential cleft weathering	Non-catastrophic disintegration of more densely fractured zones within a tor, followed by removal of fine particles. Common for sandstone tors evolving from rock spurs and escarpments.	
Basal undercutting	Enhanced, but nevertheless slow weathering at the base, aided by capillary rise, elevated moisture content and/or lithological differences. More common in sedimentary rocks.	
Granular disintegration	Ongoing grain-by-grain breakdown followed by formation of sandy-gravelly veneer (on flat surfaces) or fall (on steep surfaces). This process does not leave clear depositional evidence.	
Weathering pit and tafoni development	Growth of pits and pans on vertical and horizontal surfaces, reduction in horizontal dimension and surface lowering. Positive feedback mechanism applies.	

Fig. 10. Patterns of tor degradation – preparatory processes

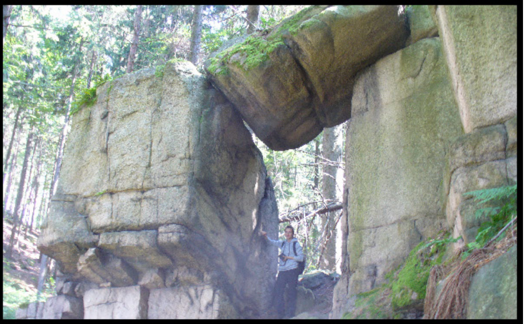
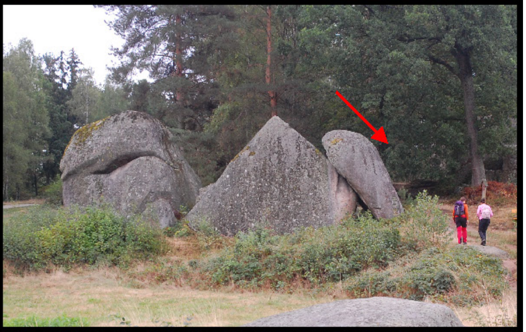
Process	Description	Example and geomorphic evidence
Cleft opening/ tilting	Gravity-driven slow outward movement of a marginal rock column	
Toppling	Final stage of the above – collapse of the rock column due to loss of lateral support	
Sliding	Movement of a single boulder along an underlying planar, sloping rock surface	
Fall	Detachment of a rock block from the vertical tor face, followed by free fall in the air. Leads to the development of allochthonous talus.	
In situ blocky disintegration	Breakdown and loss of stability of a jointed mass inside an otherwise massive tor. Juxtaposition with more massive compartments prevents from free fall	

Fig. 11. Patterns of tor degradation – disintegration processes

Concluding remarks

The formation and development of tors has been considered in the context of two dominant models representing one-stage and two-stage processes. Initial studies on this subject were presented in the late 1950s and 1960s but, subsequently, these two models started to be accepted rather uncritically – the documentation of tor phenomena gained precedence over detailed research and theory testing. In the 21st century, a revival of interest in tors has taken place, with more explicit considerations of geological controls and the exploration of new hypotheses such as the relationship between tors and selective glacial erosion. In the past, numerous studies attempted to link tor morphology with the specific environmental conditions under which tor-forming processes occurred. This approach relied on somewhat rudimentary observations that rarely considered lithology and structure in sufficient detail and largely ignored any modifications to tor morphology caused by weathering and mass movements. Nonetheless, notes of caution were occasionally expressed and the wider geomorphic context was not always treated as an important piece of information that could help to elucidate reasons for the formation of tors and related residual features. Lithology and structure appear to be crucial variables to explain asymmetric slope tors and cliff sections across slopes, commonly referred to as “frost-riven cliffs”. It is proposed that “cliffs” or “crags” are more adequate, non-genetic terms to describe such mid-slope residual landforms, since a genetic association with frost weathering cannot always be unequivocally demonstrated. The origin of these forms is predisposed by the presence of zones in which the vertical inclination of bedrock discontinuities or their dip into the slope allow for efficient mechanical breakdown, and this may occur under contemporary conditions. Also predisposed to the formation of rock steps are convex slope breaks that develop as a result of local lithological variability. Likewise, classic angular castle koppies do not have to be associated only with mechanical weathering in cold and dry climates of the Pleistocene but are better viewed as landforms whose shapes reflect the pervasive influence of fine-grained rock structure and regular jointing, which is able to account for the detachment of sharp-edged rock blocks. Tors in the uplands and mountains of Central Europe, often located in forests and overgrown, should not be considered as entirely relict, inherited landforms from the Pleistocene or even earlier. Evidence suggests that their remodelling and degradation are ongoing despite the fact that tangible evidence for their decay, i.e. talus, block-filled clefts and weathering pits, is very difficult to date. Pathways of tor development and degradation appear to be much better constrained than the temporal aspect of these processes. Therefore, at least in the Central European context, tors represent poor palaeo-environmental indicators. They are perhaps better thought of as continuously evolving rock-controlled landforms, with a multitude of specific, but not necessarily climate-dependent, processes involved in their development.

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