22 Kraków-Częstochowa Upland—Monadnocks and Relic Caves in the Karst Landscape

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Abstract

The Kraków-Częstochowa Upland is the largest carbonate karst area in Poland and belongs to the largest in Central Europe. It is built of limestones with a thickness of over 250 m. They were deposited in a relatively shallow sea as a carbonate ramp on the northern shelf of the Tethys Ocean in the Late Jurassic. Limestone facies differentiation associated with carbonate buildups and related variable resistance to erosion and karstification contributed to the geomorphic diversity within the region. Karst relief is an essential component of the landscape of the Kraków-Częstochowa Upland. Limestone rocky hills, monadnocks, and tors are residual forms that dominate in the surface relief. Numerous cave relics, including hypogenic ones, occur within these landforms. The rocky valleys and gorges, including the picturesque Prądnik Valley, cut the southern part of the Upland. The northern part was the only area of the Upland covered by the Pleistocene ice sheet, and the rocky hills and monadnocks were transformed by glacial erosion into asymmetric roche moutonnées. In the areas mantled by till and loess, covered karst developed. Although the origin and age of karst and caves are still discussed, the Late Cretaceous marine recession and the Holocene mark the general temporal constraints for the development of karst landforms in the Kraków-Częstochowa Upland. The karst landscape attracted humans to settle in this region since the Palaeolithic. Numerous archaeological sites in caves, rock shelters, and ruins of medieval castles testify to the rich cultural heritage of the region, underpinned by geodiversity.

Keywords

Karst landforms · Monadnocks · Tors · Caves · Kraków-Częstochowa Upland

22.1 Introduction

The Kraków-Częstochowa Upland represents a unique geomorphological region in southern Poland, located in the western, highest part of the upland belt in the northern foreland of the Western Carpathians. The area presented in this chapter is the most homogeneous and interesting part of the region and includes the Częstochowa Upland and the Ojców Plateau (Fig. 22.1; Solon et al. 2018). Sawicki (1920) called this region 'Kras' (Karst)—a name reflecting the karst nature and its similarity to karst areas in central and southern Europe. Other names are also used for the uplands located between the cities of Kraków in the south and Częstochowa in the north—the Kraków Upland, the Kraków-Częstochowa Jura, the Polish Jura or just the Jura.

The northern part of the Kraków-Częstochowa Upland is formed by a meridional belt of the Częstochowa Upland (Fig. 22.1). The varied surface of the area rises to an altitude of 300–450 m asl and reaches its maximum height of 515.6 m asl in Podzamcze near the town of Ogrodzieniec. The southern segment of the region, the Ojców Plateau, reaching the mean altitude of 450–480 m asl, with the highest elevation at 512 m asl, has more uniform relief. The plateau passes southward to the area characterized by the presence of numerous faults, horsts and grabens, constituting the Krzeszowice Trench and the Wisła valley. The latitudinal lowering of the Biała Przemsza valley creates the transition zone between two main parts of the Kraków-Częstochowa Upland. Less pronounced latitudinal structures (e.g. Pilica or Biała grabens) dissect the Częstochowa Upland, dividing it into smaller microregions.

Covering an area of almost 2000 km^2, the Kraków-Częstochowa Upland belongs to the most significant

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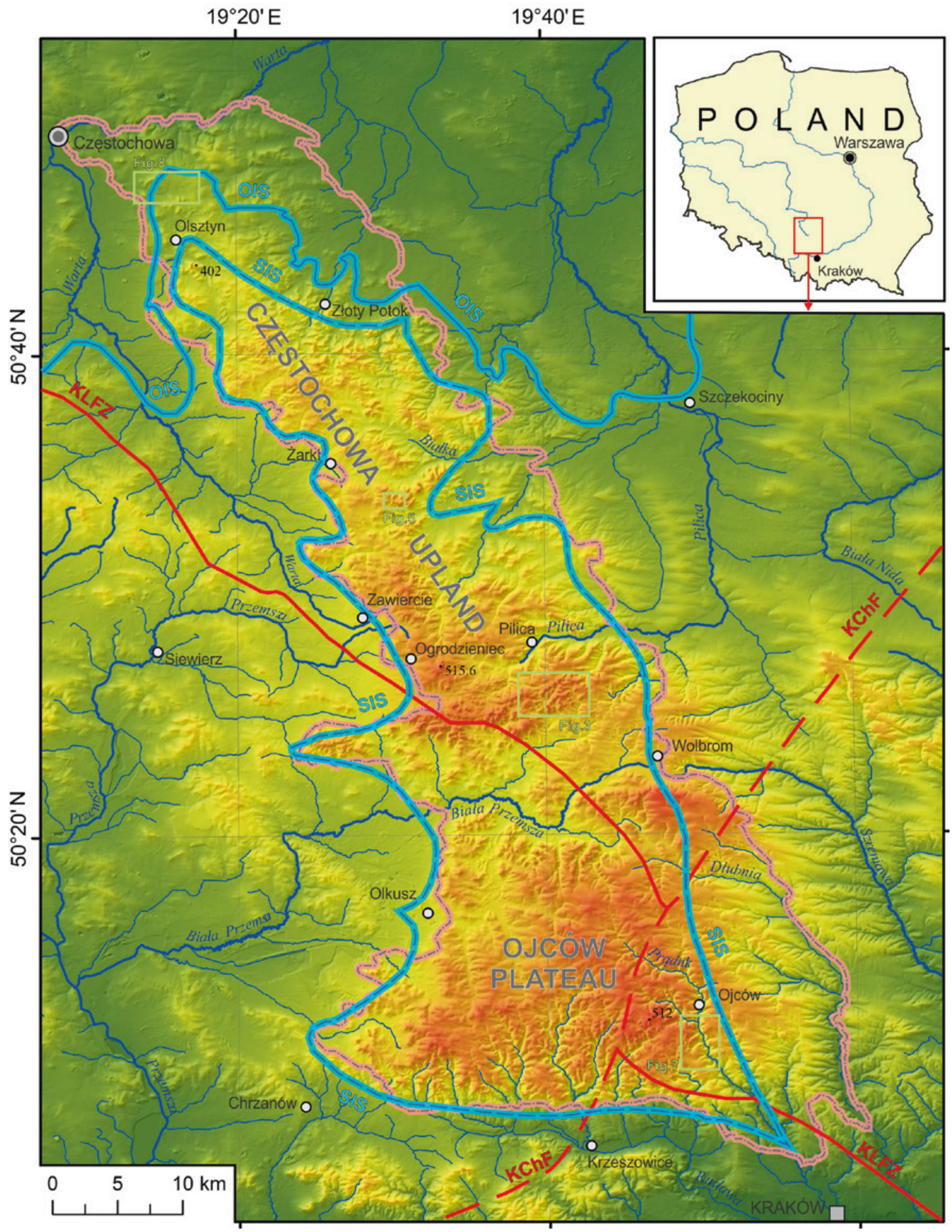


Fig. 22.1 Location of the Kraków-Częstochowa Upland (boundaries as dashed-and-dotted line on pink background; after Solon et al. 2018). KLFZ—Kraków-Lubliniec fault zone and KChF—Krzeszowice-Charsznica fault (after Buła et al. 2002); SIS—the maximal extent of the Sanian I glaciation; and OIS—the maximal extent of the Odranian glaciation (after Lewandowski 2011)

areas of carbonate karst in Central Europe (Tyc 2004). Following views presented by Gilewska (1964), Głazek et al. (1972), Głazek (1989), the region has been regarded in geomorphological and karst literature mainly as an example of fossil or relict karst (palaeokarst) and, more recently, also as a part of an important region (Silesian-Kraków) of hypogene karst and caves (Gradziński and Tyc 2017).

22.2 Geological Setting

Upper Jurassic limestones play a dominant role in the geological structure of the Kraków-Częstochowa Upland. On the surface, they reveal themselves in the form of picturesque rocky hills, monadnocks, and isolated limestone tors, otherwise being present under the cover of younger sediments, mainly of Quaternary age. These limestones occur as a long belt of outcrops stretching from Kraków in the south towards Częstochowa. Structurally, the area belongs to a larger geological region known as the Kraków-Silesian Homocline.

Upper Jurassic limestones form a complex with a thickness of over 250 m, deposited in a relatively shallow sea, on the northern shelf of the Tethys Ocean, as a carbonate ramp (Matyszkiewicz 1997; Matyszkiewicz et al. 2006a; Krajewski and Matyszkiewicz 2009). They mainly represent the Oxfordian, locally early Kimmeridgian stage of the Jurassic. Traditionally, three main facies are distinguished within the limestone succession—massive and nodular limestones (so-called rocky limestone), thick-bedded limestones, usually with cherts, and thin-bedded (platy) limestones. The former are distinctly diversified and represent both small bioherms developed within platy and marly limestones as well as large carbonate buildups that pass laterally to bedded limestones (Dżułyński 1952; Matyszkiewicz 1997; Matyszkiewicz et al. 2006a, b; Krajewski and Matyszkiewicz 2009). Compact and resistant bioherms are associated with lithified but less resistant granular sediments—turbidities, debrites or even debris of submarine landslides (Matyszkiewicz et al. 2006a; Krajewski and Matyszkiewicz 2009). An extensive carbonate platform developed in the vicinity of villages of Smoleń and Strzegowa in the southern part of the Częstochowa Upland, which, punctuated by clusters of rocky hills and monadnocks is still clearly visible in the relief of this area (Matyszkiewicz et al. 2006a). Facies differentiation of the Upper Jurassic limestones and related differential resistance to erosion contributed to the geomorphic diversity within the region.

The tectonic settings of the Palaeozoic basement of the Kraków-Częstochowa Upland control the formation and spatial distribution of Upper Jurassic carbonate buildups and platforms. The prominent Kraków-Lubliniec fault zone (KLFZ) crossing the upland (Fig. 22.1) is responsible, among others, for the occurrence of Palaeozoic magmatic intrusions in its basement, detected by drillings (e.g. Jędrys et al. 2004; Matyszkiewicz et al. 2006b). The major carbonate build-ups and the carbonate platform near Smoleń and Strzegowa are located above these intrusive bodies. Most of the main systems of joints and faults are related to the KLFZ. The latter is of the nature of overpass structures, among them positive flower structures, related to the displacements in the basement along the KLFZ (Żaba 1994, 1999). These structural conditions were favourable for the ascending fluids, and presumably, low-temperature hydrothermal processes were especially present in the northeastern and eastern margin of the KLFZ (Żaba 1999; Pulina et al. 2002, 2005; Żaba and Tyc 2007; Tyc 2009a; Matyszkiewicz et al. 2015; Gradziński and Tyc 2017). Lithological differentiation of the Upper Jurassic limestones and complex tectonic settings of the Kraków-Częstochowa Upland were among the factors affecting the evolution of karst and caves.

The geomorphological landscapes of Poland north of the Sudetes and the Carpathians were, to a large extent, shaped by the Pleistocene glaciations. The Kraków-Częstochowa Upland is one of the exceptions, as in the Pleistocene it was never entirely covered by the ice sheet. This view was formulated by Łoziński (1912) and developed by Różycki (1960), who proposed the term 'Jurassic Glacial Oasis' for the most probable concave nunatak in this region. Różycki (1960) based his statement mainly on the absence of erratics in the sedimentary cover of this region. The central area of the upland, elevated 150–200 m above the surrounding terrains, is considered either not to be covered by inland ice or perhaps only local ice streams penetrated its peripheries during the maximum extent of the Sanian I (Elsterian, MIS 12) glaciation (Lewandowski 2011) (Fig. 22.1). A consequence of the concave nunatak during this glaciation, in the Częstochowa Upland especially, is the presence of a sandy glacifluvial cover, preserved in most of the topographic depressions. Some of these sands were later reworked by aeolian processes. The Odranian (Saalian) glaciation reached only the northern part of the Częstochowa Upland (Fig. 22.1). The subsequent ice-sheet advances during the Warthanian (Late Saalian) and the Weichselian did not reach the upland, but left a record of intense periglacial processes, both in the sedimentary cover and the landscape. It includes debris and loess covers, patterned grounds in the upper layer of thin-bedded limestones, and clusters of rock blocks at the foot of tors resulting from lateral retreat of rock walls due to frost weathering and rock fall (e.g. Tyc 1997, 2009a; Alexandrowicz and Alexandrowicz 2003; Pawelec 2008; Lewandowski 2011).

22.3 Karst Relief

22.3.1 Surface Landforms

The Kraków-Częstochowa Upland has a very diverse landscape, the significant element of which is karst relief. However, 'classical' karst landforms such as solution dolines and karrenfields do not occur in the region. Instead, the characteristic landforms are rocky hills, monadnocks and isolated limestone tors appearing both on the plateaus and valley sides. In the northern part of the upland, within the range of the Pleistocene ice sheet, the shapes of rocky hills and monadnocks were modified by glacial erosion.

Fig. 22.2 Landscape with the rocky hills near Olsztyn town in the north part of the Kraków-Częstochowa Upland (photograph by A. Tyc)

Fig. 22.3 Monadnocks in the highest part of the Ojców Plateau near the village of Jerzmanowice; in the foreground, spongy structures of micro-relief on the top surface of the Łysa Skała Hill (photograph by A. Tyc)

Moreover, in the areas mantled by Pleistocene glacial sediments and loess, covered karst has developed.

22.3.1.1 Rocky Hills, Monadnocks, and Limestone Tors

The surface of the Kraków-Częstochowa Upland is generally flat, becoming undulated in places. Such gentle relief is characteristic of plateaus built mainly of bedded limestones. This image is contrasted with rocky hills and monadnocks built mainly of massive and nodular limestones. The former are large limestone hills that stand out in regional relief. Representative, non-forested hills of this type occur near the town of Olsztyn in the northern part of the Częstochowa Upland (Fig. 22.2). In turn, monadnocks are residual forms of lower rank, built of more resistant massive facies of Upper Jurassic limestone. A separate group of rock relief of the Kraków-Częstochowa Upland are minor, isolated rocks—limestone tors. However, rocky hills and monadnocks are characteristic of the plateaus, so tors occur both in the top parts and slopes of the limestone hills and on slopes of valleys.

These rock landforms are not evenly distributed in the area of the Kraków-Częstochowa Upland. Rocky hills and monadnocks form clusters, the spatial pattern of which refers to the distribution of the above-mentioned carbonate

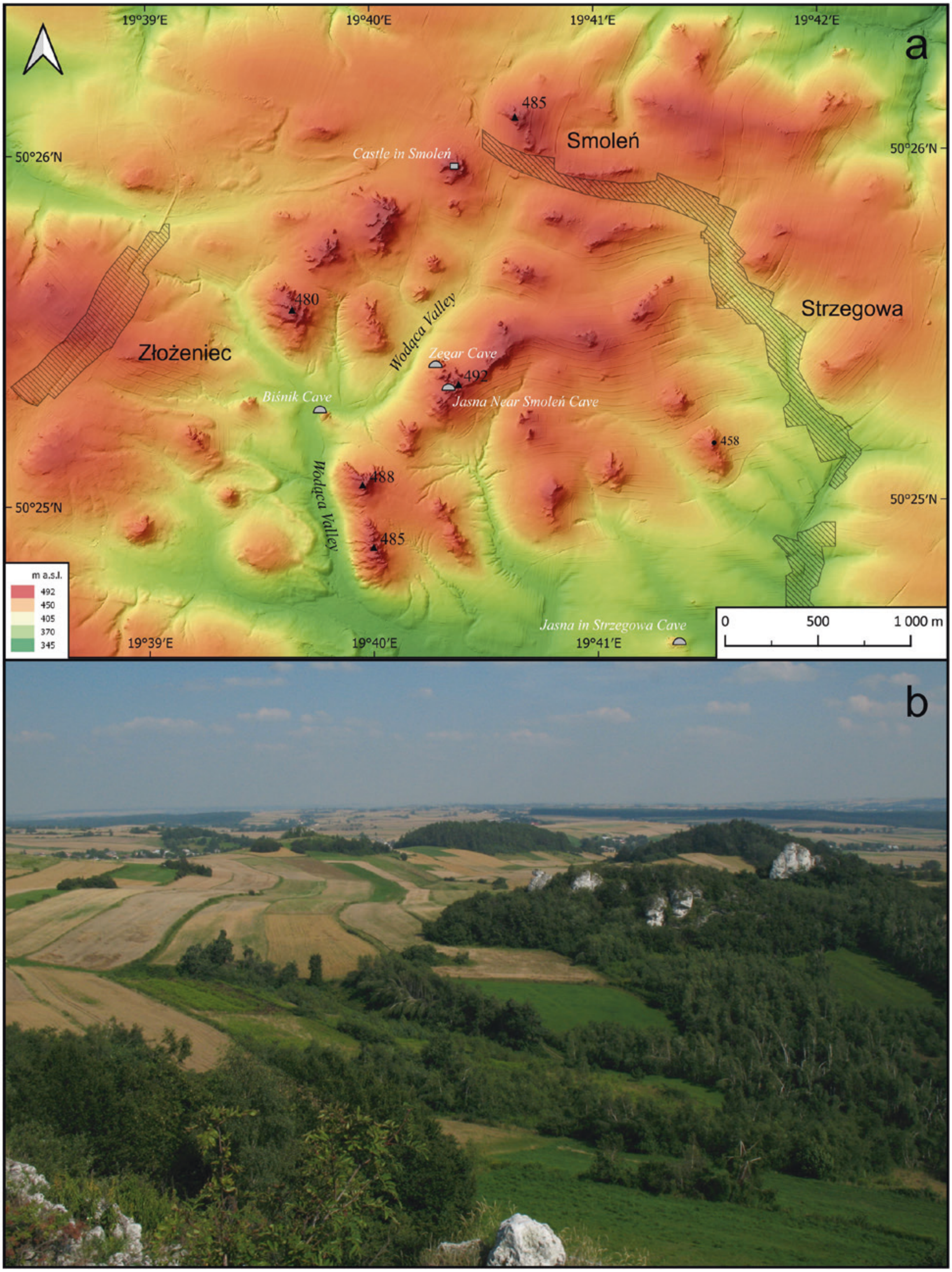


Fig. 22.4 Relief of the carbonate platform near the villages of Smoleń and Strzegowa, with rocky hills and monadnocks, and dry valleys (location on Fig. 22.1). **a** Digital terrain model. **b** Panoramic view of the landscape (photograph by A. Tyc)

Fig. 22.5 Monadnocks and limestone tors of the so-called 'rock city' in Podzamcze village near Ogrodzieniec (photograph by A. Tyc)

buildups (see Matyszkiewicz et al. 2006b). The largest ggregation of such features on the Ojców Plateau lies next to the village of Jerzmanowice, to the west of the Prądnik Valley (Figs. 22.1 and 22.3). The largest monadnocks in this area reach up to 20–30 m high, 100–150 m long, and almost 25 m wide (covering a surface of over 2500 m^2), but most of them are much lower and smaller, up to 50 m long and 20 m wide, covering an area of 700–1000 m^2 (Alexandrowicz and Alexandrowicz 2003). Rocky hills and monadnocks of the Częstochowa Upland are much more numerous and extensive than those on the Ojców Plateau (Figs. 22.4, 22.5 and 22.6). In the village Podzamcze near Ogrodzieniec and on the Zborów Hill next to the village of Podlesice, massive hills are topped with complex rock landforms. They form picturesque landscapes called 'rock cities' or 'rock towns' (Figs. 22.5 and 22.6). These groups include specific minor features such as walls, towers or spires up to 25–30 m high, and the perimeter of the rock groups ranges from several dozen to several hundred metres.

The size of monadnocks depends significantly on the size and shape of carbonate build-ups. Forms developed on extensive and deep-rooted massive limestone bases are more extensive and stable. On the other hand, flat-rooted carbonate build-ups and small bioherms give small rocky forms, which are susceptible to mechanical disintegration (Alexandrowicz and Alexandrowicz 2003).

Relief of rocky hills and monadnocks is determined mainly by the original features of Upper Jurassic limestones and their significant facies differentiation. The presence of joints, primarily vertical and widened by karst or gravitational processes, is essential. Along these joints, individual tors and crags are isolated. The pattern and density of jointing are essential for the shape of rock relief. A crucial structural factor influencing the morphological evolution of monadnocks is the system of fissures and faults developed in several tectonic phases in the Neogene (e.g. Żaba and Tyc 2007). Monadnock morphology is also influenced by differential resistance of the limestones to chemical and mechanical weathering. An essential factor, in this case, is the presence of detrital, grained limestones among the massive and nodular variants. In addition, there are places where discontinuities within massive limestone are observed. They can be interpreted as a record of breaks in bioherm growth.

Moreover, relict caves have been preserved within monadnocks and isolated limestone tors of the Kraków-Częstochowa Upland (Tyc 2005, 2009a, b; Fig. 22.7). The recent relief of monadnocks reflects mainly structural elements of the Upper Jurassic carbonate massif. However, stages of the early development of underground karst (speleogenetic stages) are related to the same structural conditions. Considering the fact that the part of the karst system which developed in bedded limestones became almost destroyed by denudation and erosion, monadnocks and limestone tors are the only elements in the region where relics of early stages of speleogenesis were preserved (Tyc 2005, 2009a, b). In some cases, the walls of monadnocks and tors are relics of cave walls, and they became remodelled by superficial corrosion and mechanical weathering. Relief of the cliffs of many monadnocks shows that their gravitational decay takes place along the walls of these relict caves (Fig. 22.7a).

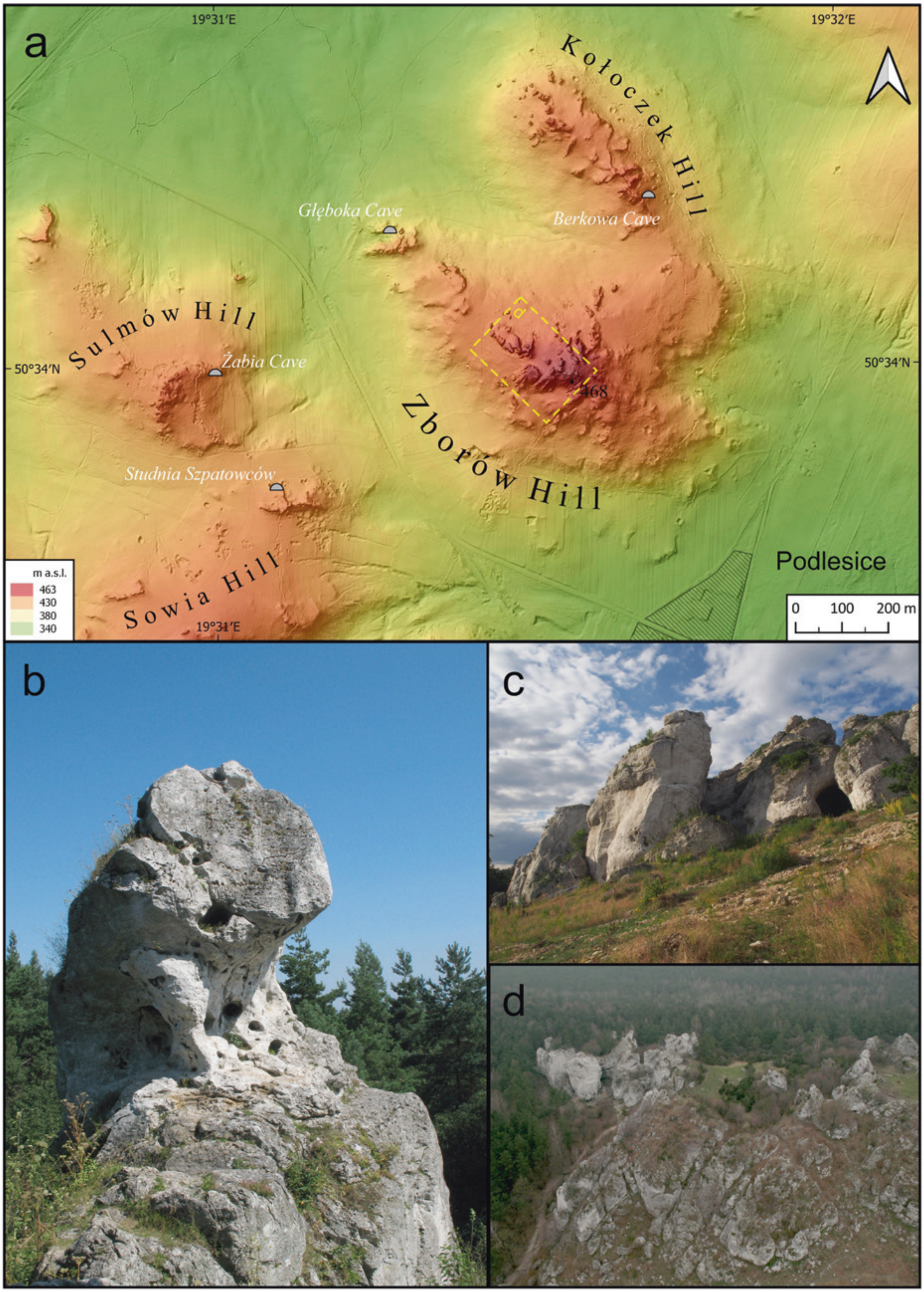


Fig. 22.6 Karst landform with monadnocks, tors, and caves of the rocky hills next to the village of Podlesice (location on Fig. 22.1). **a** Digital terrain model. **b** Limestone tor of Sowa with relics of a cave. **c** Monadnocks on the top of the Zborów Hill with the rock shelter of Kazamar. **d** General view of the highest part of the Zborów Hill (photographs by A. Tyc)

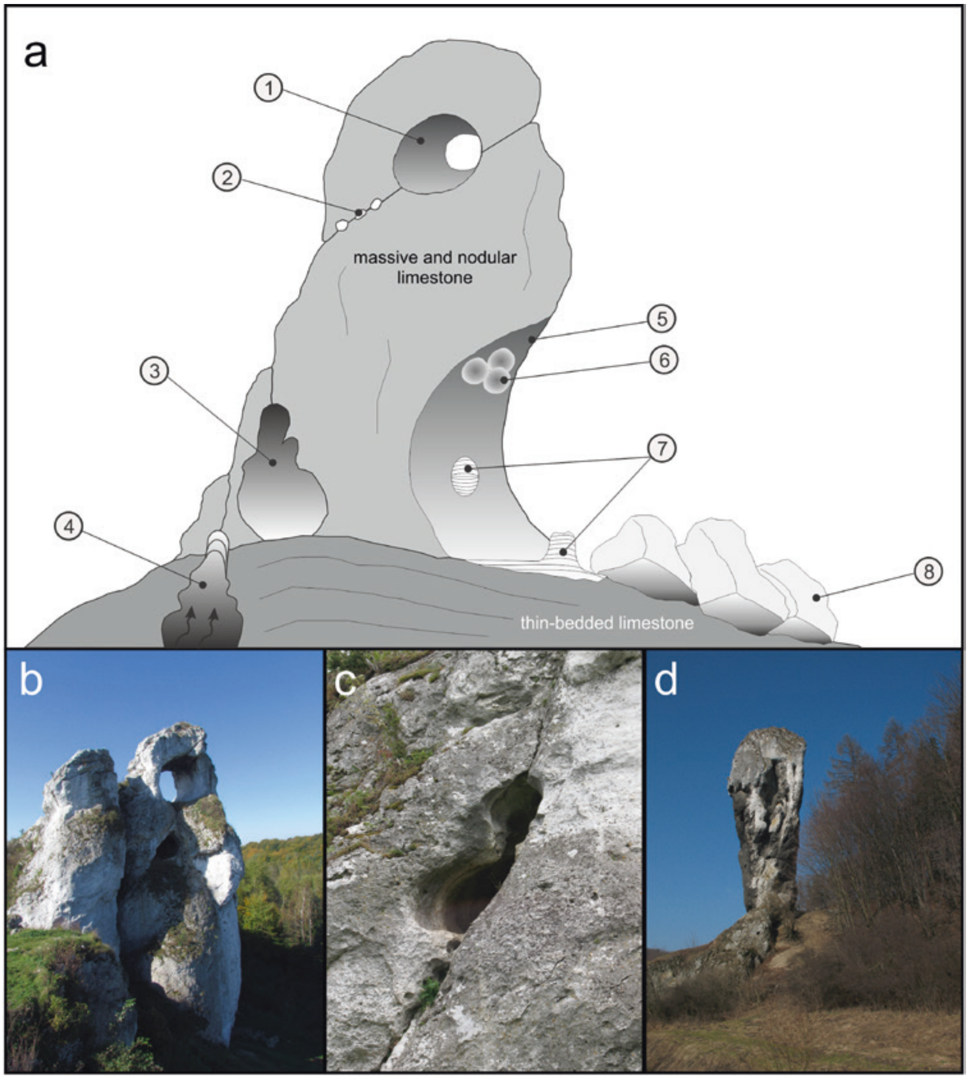


Fig. 22.7 Relics of caves in the relief of monadnocks of the Kraków-Częstochowa Upland. **a** Model of the monadnock with relics of caves (after Tyc 2009b, modified). 1—rock window—relic hemispherical cave chamber, 2—small anastomosis channels related to lithological discontinuity, 3—small relic cave conduit, 4—relic cave with rising half-tubes, 5—overhang being relic cave wall, 6—hemispherical cupolas and niches on the overhanging rock wall, 7—relics of cave clastic sediments and speleothems, 8—rock blocks derived from breakdown of former cave roof. **b** Monadnock with rock window—Okiennik Wielki (Great Window) near the village of Skarżyce. **c** Relics of phreatic tube developed along a joint in massive limestone visible on the wall of a monadnock. **d** Maczuga Herkulesa (Hercules Club)—rocky form (tor) isolated from the slopes of the Prądnik Valley (photographs **b**–**d** by A. Tyc)

To the north and northeast of Olsztyn, rocky hills and monadnocks were reshaped in the Pleistocene by glacial erosion (Fig. 22.1). They were transformed into asymmetric *roche moutonnées*, with gentle proximal (NE) and steep distal (SW) rock slopes. Różycki and Lamparski (1982) linked the remodelling of monadnocks near Olsztyn with the maximum extent of the Odranian glaciation. According to the latest study by Lewandowski (2011), they should be rather associated with the previous Sanian I glaciation.

The rock walls of monadnocks and limestone tors have a very diverse micro-relief. It includes various superficial weathering forms: (1) pock-marked structures—a dense network of shallow, trough-shaped depressions with an oval or round outline, 0.3–3.0 cm in diameter and up to 2.5 cm deep; (2) spongy structures—consisting of irregularly shaped depressions with diameters over 3 cm, short narrow grooves, up to 15 cm long, shallow vertical channels up to 20 cm long, and small nodules; (3) kamenitzas—solution pans, elliptical and isolated depressions, lacking an outlet and with a nearly flat bottom (Otęska-Budzyn 1987). Spongy structures are the most characteristic and frequent features of micro-relief on the monadnocks in the Kraków-Częstochowa Upland. They strictly respond to the structure of limestone building a monadnock (Fig. 22.3). Pock-marked structures occur on inclined wall surfaces. In contrast, spongy structures and kamenitzas are present on more gentle top surfaces of monadnocks and tors. The structurally-conditioned micro-relief of monadnocks and tors of the upland is characterized by the lack of classic hydraulically-controlled karrens such as rills and runnels.

The origin of monadnocks within the landscape of the Kraków-Częstochowa Upland has been discussed since the early 1950s. The karst origin of these rocky forms was formulated by Klimaszewski (1958). According to his concept, the rock landforms standing out from the gentle surface of the Upland are 'mogotes'. The proposed term refers to the tower karst known from tropical and subtropical karst areas in the Caribbean. Using the term 'mogote', Klimaszewski referred to the shape of rock forms and tower karst landscape rather than its origin. The concept of Klimaszewski

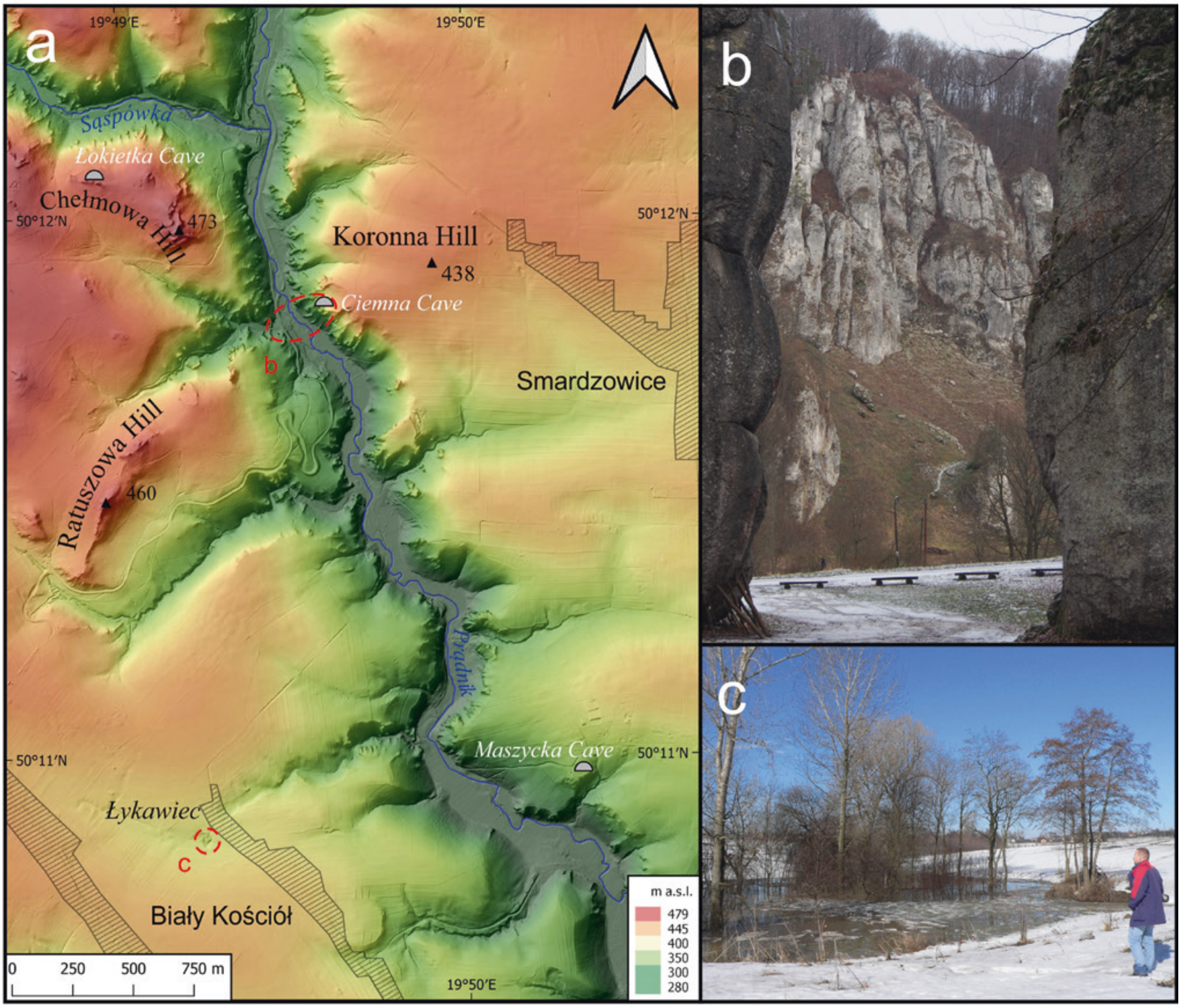


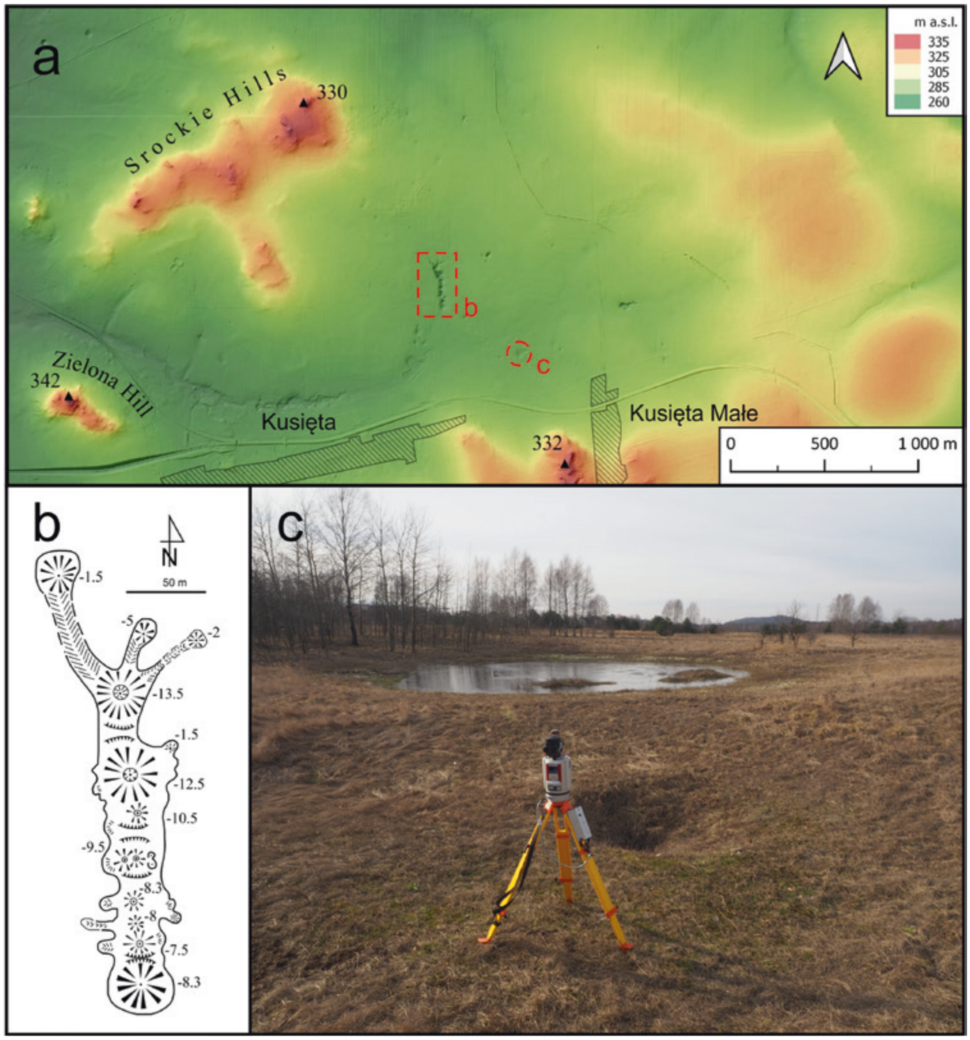
Fig. 22.8 Relief of the central part of the Prądnik Valley (location on Fig. 22.1). **a** Digital terrain model. **b** Brama Krakowska (Kraków Gate) in the foreground and rock walls of the Prądnik Valley—the Rękawica (Glove) Tor in the massif of the Koronna (Crown) Hill in the background (photograph by A. Tyc). **c** Swallow hole Łykawiec during intense snow melting in 2006 (photograph by R. Jach)

(1958) was developed by Polichtówna (1962), Pokorny (1963). The last of the cited authors proposed a schematic profile of the 'mogote' for the area of the Ojców Plateau. This scheme has been reproduced in the literature for decades. However, despite accepting Klimaszewski's view on 'mogotes', Pokorny (1963) envisaged that these are residual forms developed in more resistant rocks than present in the surroundings, and hence, they are monadnocks. The conceptual model of the origin of rocky hills and monadnocks could have been developed after Dżułyński's (1952) publication on the facies differentiation of Upper Jurassic limestones and the origin of rocky limestones (massive and nodular ones). This concept was supported by Szaflarski (1955), who made the first detailed overview and description of monadnocks of the Kraków-Częstochowa Upland. Szaflarski (1955) and Pokorny (1963) considered these forms polycyclic and polygenic. They argued that their relief depends not only on climatic conditions, karst processes and time, but also on their structural features.

22.3.1.2 Rocky Valleys and Gorges

Beside the vast plateaus, punctuated with rocky hills and monadnocks, a characteristic feature of the Kraków-Częstochowa Upland is the presence of deep valleys cutting through the complex of Upper Jurassic limestones. These valleys begin on the plateau as trough-shaped depressions and continue in the form of narrow ravines and then deep rocky gorges with steep slopes, on which limestone tors occur. The upper parts of the valleys are buried by Quaternary sediments.

Fig. 22.9 Covered karst to the north of the village of Kusięta (location on Fig. 22.1). **a** Digital terrain model. **b** Complex of suffosion dolines called Koziniec (after Nowak 1993). **c** Shallow suffosion doline filled temporarily with water, small dropout doline in the foreground (photograph by A. Tyc)



The most characteristic and picturesque forms of rocky valleys and gorges are found in the southern part of the Ojców Plateau. The Prądnik Valley is among them, being the most extensive such valley in the entire region (Figs. 22.1 and 22.8a). Tributary valleys of the major river valleys in the plateau are rock gorges without permanent water flow (see tributary gorges of the Prądnik Valley in Fig. 22.8a). Localized, short, and narrow valley reaches (rock gates) are among the characteristic relief elements in the valleys of the Ojców Plateau (Dżułyński et al. 1966; Gradziński et al. 2008). They are often developed in places where a tributary gorge joins the main valley. The most spectacular example is the Brama Krakowska (Kraków Gate) in the Prądnik Valley near Ojców (Fig. 22.8b). Rocky features on the slopes of the Prądnik Valley and side valleys determine the unique landscape of this area. Many rock landforms reach a height of several dozen metres and extend over hundreds of metres, e.g. the rock walls of the Koronna (Crown) Hill (Fig. 22.8b). Maczuga Herkulesa (Hercules's Club), isolated from the slopes, is one of the most spectacular and picturesque rocky forms (Fig. 22.7d). Valleys typical of the Częstochowa Upland are deep and dry, often with rocky upper parts of slopes. They occur in the upper reaches of river valleys draining the upland area. The Wodąca Valley near the villages of Smoleń and Strzegowa is a classic example of dry valleys in this region (Fig. 22.4a).

Rocky valleys and gorges drain the karst massifs and play a crucial geomorphological role as local base levels. Permanent and temporary karst springs are located in these valleys. In the dry valleys of the Częstochowa Upland springs are located in their distal reaches (e.g. at the mouth of the Wodąca Valley, Fig. 22.4a). On the other hand, in the valleys and gorges cutting through the southern part of the Ojców Plateau, springs occur in many places at the bottom of the valley. The karst drainage system, unique at the scale of the whole region, is the underground flow from the semi-blind valley of Łykawiec on the plateau to the spring in the bottom of the Prądnik Valley (Fig. 22.8a, c). Łykawiec is a swallow hole (ponor) developed in loess-like sediments covering this part of the Ojców Plateau, located at a horizontal distance of ca. 1 km from the spring located at the base of rock slopes in the Prądnik Valley. The elevation difference between the swallow hole and spring is ca. 90 m (Gradziński et al. 2008).

22.3.1.3 Covered Karst—Dropout and Suffosion Dolines

Karst areas in Poland that were glaciated in the Pleistocene host characteristic landforms of covered karst. These phenomena are limited to areas with karst in the subsurface zone, and at the same time, where the cover of glacial sediments, clays, and sands (preferably inter-layered) is sufficiently thick, reaching several to several dozen metres. The main manifestations of covered karst are dolines (sinkholes) (Veress 2016; De Waele and Gutiérez 2022). They are mainly dropout dolines developed due to collapses of cover sediments into the cavity developed within karstified bedrock, and suffosion dolines developed due to wash of cover deposits into fissures and voids in a bedrock. In areas with a higher proportion of cohesive sediments (loam and silt layers) above karstified bedrock, dropout dolines develop. On the other hand, in non-cohesive sediments (sands or sandy clay), suffosion processes dominate in the development of shallow depressions. An important factor determining the development of doline forms at the surface is the location of groundwater level below the top layer of karstified rocks.

Favourable conditions for the development of covered karst landforms occur in the northern part of the Kraków-Częstochowa Upland. Discontinuous cover of glacial deposits from at least one glaciation appears to the north and northeast of the town of Olsztyn (Figs. 22.1 and 22.9). Both dropout and suffosion processes dominate the latter and contribute to the development of covered karst relief in this region. The area in the vicinity of the village of Kusięta is particularly interesting (Fig. 22.9a). The groundwater level in the massif built of Upper Jurassic limestones occurs here at a depth of 25–55, 15–30 m below the top layer of limestones. The density of suffosion and dropout dolines in Kusięta is up to 15 forms per 1 km^2 (Nowak 1993; Tyc 2009a). The most interesting example of covered karst in the Kraków-Częstochowa Upland is the complex of 16 suffosion dolines called Koziniec (Fig. 22.9a, b). The complex is 300 m long and 40 m wide. Two dolines are more than 12 m deep, whereas others are shallower. Most dolines have swallow holes at the bottom, active after heavy rains or intense snow melting (Tyc 2009a). Dropout dolines are also developing in the southern and eastern parts of the Kraków-Częstochowa Upland, where karstified limestones are covered with loess or loess-like sediments.

22.3.2 Caves

Karst landforms of the Kraków-Częstochowa Upland include numerous caves. They are distributed unevenly throughout the area. Their occurrence and origin are conditioned mainly by their location in relation to the main structural elements—major faults and the distribution of carbonate build-ups. Despite the presence of Upper Jurassic limestones in the whole upland area, most of ca. 1600 caves and rock shelters in this region lie to the northeast and east of the KLFZ. In the southwestern part of the Kraków-Częstochowa, on the opposite side of the KLFZ, there are only non-karst caves of crevice and fissure types. Moreover, numerous rock shelters within the monadnocks result from frost weathering. They developed actively in the cold and humid conditions of the Pleistocene and continue to enlarge under contemporary environmental conditions.

The karst caves of the Kraków-Częstochowa Upland are generally small. The majority is not more than 40 m long, and most caves have depths up to several metres only. The longest caves are just over 1 km (Nietoperzowa-Zygmunta Cave System—1047 m; and Wierna Cave—1027 m). The deepest one, Studnisko Cave, has a depth of 77.5 m. Their entrances are on the slopes of limestone hills and, in some cases, even in the top parts of the monadnocks. In the case of valleys cutting through the Ojców Plateau or dry valleys of the Częstochowa Upland, cave entrances are located on their slopes. The occurrence of karst caves is related to the massive limestone facies, and their morphology is strongly controlled by the internal lithological diversity and jointing. Their development occurred via gradual widening of pre-existing joints. Most often, the direction of cave passages is related to the directions of such joints. Considering only the karst caves, the majority consists of isolated chambers integrated later into a larger cave along the joint system (Fig. 22.10). The shape of individual chambers is usually hemispherical or elliptical. The largest chamber in the Ciemna Cave (Prądnik Valley in the Ojców Plateau; Fig. 22.8a) is elongated, 88 m long and 23 m wide, with an average height of 8 m (counting from the surface of the bottom sediments).

Most of the karst caves of the Kraków-Częstochowa Upland are relics of the phreatic drainage system within the Upper Jurassic carbonate massifs. The abundance of phreatic-rising morphology of caves in the whole region is one of the manifestations of ascending water circulation in confined conditions, presumably in the presence of elevated temperature (Rudnicki 1978; Głazek and Szynkiewicz 1980; Tyc 2009b; Gradziński et al. 2011; Gradziński and Tyc 2017). One of the most spectacular examples of a cave, the origin of which Rudnicki (1978) linked to the thermal convection process, is the Berkowa Cave in the village of Podlesice (see Fig. 22.6 for location). The cave has an original morphology, with its walls composed of hemispherical niches forming complex grape-like structures. Evidence of convection and rising water in confined conditions can be found in many caves in the region. High cupolas (up to 2–3 m in diameter and up to a few metres high), dead-end chimneys, rising wall channels, and half-tubes are

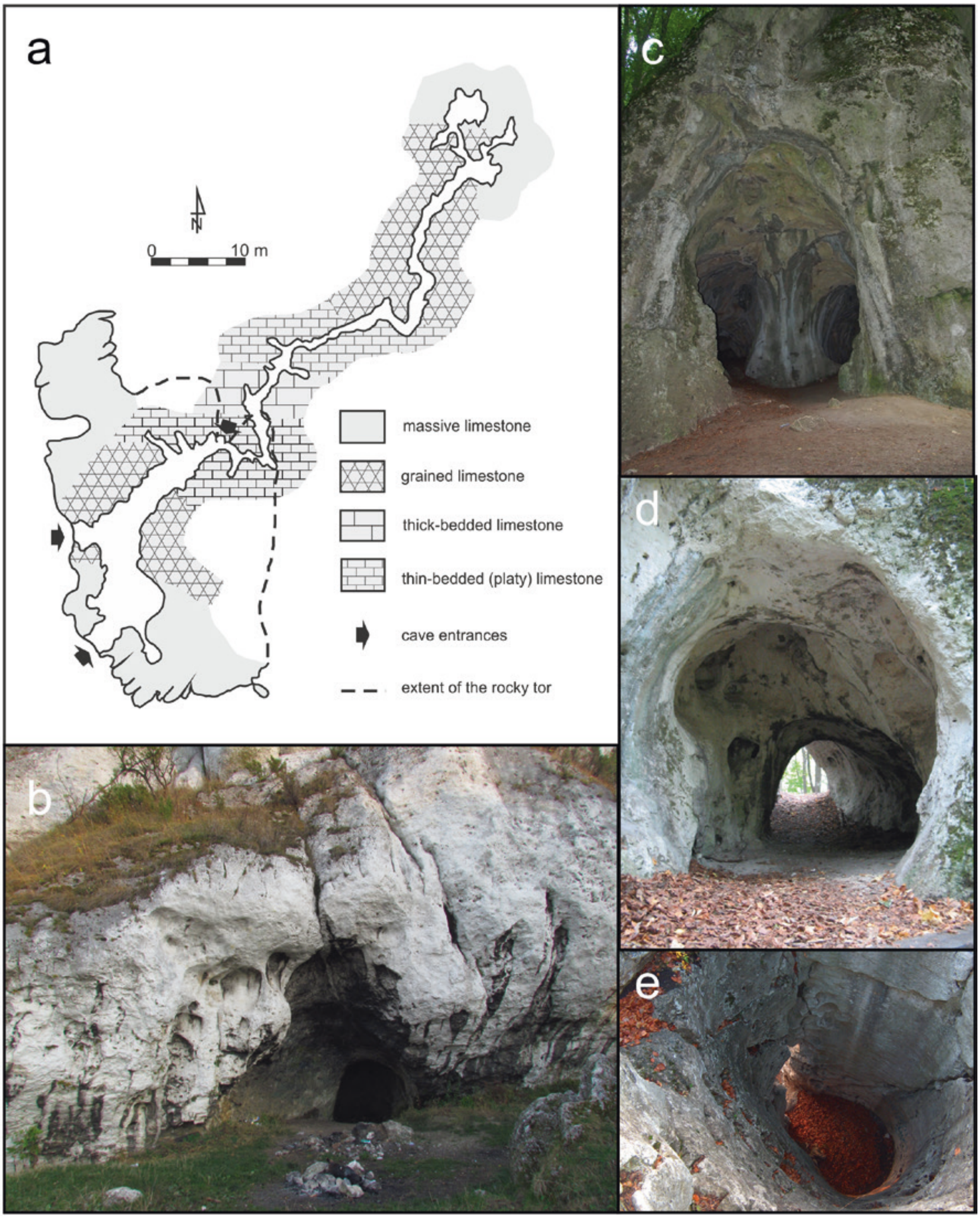


Fig. 22.10 Examples of caves in the Kraków-Częstochowa Upland. **a** Cave morphology versus facies differentiation of Upper Jurassic limestones—W Straszykowej Górze Cave (after Tyc 2009a, modified). **b** Entrance of the Towarna Cave at the foothill of the Duża Towarna Hill near the town of Olsztyn. **c** Entrance chamber of the Ostrężnicka Cave in the village of Złoty Potok—cave rocky relief was modified by mechanical weathering due to frost action. **d** Tunel w Górze Smoleń Cave near the village of Smoleń—cupolas and other cave relief transformed by superficial chemical and mechanical weathering. **e** Studnia w Amfiteatrze in the Sokole Hills near the town of Olsztyn—relic shaft, which was in the past infilled with residual clays and moulding sands (photographs by A. Tyc)

probably traces of the hypogene stage of speleogenesis. Morphological evidence indicates the ascending stage in cave evolution, but is still insufficient to confirm its hypogene nature. Additional evidence of the hypogene stage in the speleogenesis in the Kraków-Częstochowa Upland comes from calcite spar occurrence in caves. Calcite crystalized underwater in phreatic conditions, presumably under slightly elevated temperatures, was found in caves of the Sokola Hill near Olsztyn (Gradziński et al. 2011). Calcite veins and spar were quite common in caves in the northern

Fig. 22.11 Kettle-shaped doline with overhanging sides—an example of an unroofed hypogenic cave (Zborów Hill in the village of Podlesice) (photograph by A. Tyc)

part of the region, but most were mined in the late nineteenth and early twentieth centuries (Tyc 2009a).

Relics of hypogene caves morphology are present among forms preserved on monadnocks and tors. Interesting geomorphological features are kettle-shaped dolines, which can be regarded as unroofed hypogene caves (Fig. 22.11).

It should be emphasized, however, that in the Pleistocene the morphology of caves was modified by other geological and geomorphological processes, e.g. condensation corrosion within cupolas on the cave ceiling, corrosion on the contact with infilling sediments, and gelivation (Fig. 22.10). Almost all karst caves of the Kraków-Częstochowa Upland are filled or partly filled with fine-grained sediments and debris (Madeyska and Cyrek 2002; Krajcarz et al. 2014, 2016).

22.4 Evolution of Karst Landforms

The origin and age of karst of the Kraków-Częstochowa Upland are still a subject of discussion and require further research. The non-uniform Neogene uplift of different parts of this region impedes the interpretation of karst development. The upland forms the western part of the Meta-Carpathian Ridge in the foreland of the overthrust Carpathians (Lewandowski 1993). This uneven uplift, much more significant in the south, means that in the recent relief of the Ojców Plateau there may be relics of different stages of karstification than in the more northerly Częstochowa Upland. The Late Cretaceous marine recession and the Holocene constrain the general time frame for karst development in the Kraków-Częstochowa Upland. The extent of the Cretaceous sedimentary cover and the rate of its subsequent removal were essential for the evolution of karst in different parts of the upland. Hence, several stages can be distinguished in the nearly 70 million years of karst development and landform evolution.

- ***Stage I—Paleogene and Lower Miocene***
  Paleogene to Lower Miocene timespan is the oldest and the most controversial stage of karstification. The Paleogene denudation affected vast areas of Central Europe and took place in subtropical climate conditions. This long terrestrial period has been associated with intensive development of karst, which is recorded in numerous palaeokarst forms (e.g. Gradziński 1962; Gilewska 1964; Głazek and Szynkiewicz 1980; Głazek 1989; Felisiak 1992). The most significant hypogene event recorded in the phreatic stage of cave evolution occurred in the Paleogene, most probably up to Eocene. The ascending groundwater circulation within the Upper Jurassic limestones was active before the removal of the confining Cretaceous marls (Głazek and Szynkiewicz 1980; Gradziński and Tyc 2017). Relics of the hypogene karst of this stage have been preserved in the relief of the Częstochowa Upland (e.g. in the vicinity of Podlesice and Olsztyn).

  After the removal of the Cretaceous sedimentary cover in the Paleogene, intense chemical weathering and early development of residual surface forms (monadnocks) took place (e.g. Pokorny 1963; Gilewska 1964; Felisiak 1992). One of the effects of this stage of denudation are the so-called moulding sands. These are sediments most probably redeposited to karst depressions and shafts from sandy Cretaceous deposits present in the proximity of the deposition area (Gradziński 2004). Relics of these sediments have been preserved in the fossil surface karst forms and caves of the Częstochowa Upland.

- ***Stage II—Miocene***
  The Miocene witnessed the main phase of tectonic development of the Carpathian foreland. Most likely, this stage can be linked with the formation of joints and fissures essential for the development of caves in the subsequent phases. Latitudinal tectonic grabens dividing the Kraków-Częstochowa Upland into smaller segments were also formed at that time, and faults of the KLFZ were reactivated.
- ***Stage III—Pliocene and Early Pleistocene***
  This stage of karst evolution can be associated with the uplift of the Meta-Carpathian Swell. As a result of significant lowering of the erosion base due to the Late Miocene and Pliocene uplift, the pre-existing caves were exhumed and distinct vadose entrenchments developed. Many caves, especially in the Częstochowa Upland, were subsequently filled with sequences of bone-bearing sediments from the Lower Pliocene to Early Pleistocene (e.g. Głazek 1989). Monadnocks were isolated and reshaped in this stage. The layout of the current network of valleys has formed, including the main geomorphic features of rocky valleys and gorges (Alexandrowicz and Alexandrowicz 2003).
- ***Stage IV—Middle and Late Pleistocene***
  Since the Kraków-Częstochowa Upland was only marginally covered by the ice sheet, the Pleistocene stage of karst development involves mainly periglacial processes. Mechanical weathering during multiple Pleistocene glaciations intensified and partial burial of the entire region by glacial, glacifluvial, and periglacial (loess) sediments occurred. Over the remains of red and reddish-brown allochthonous Pliocene and Early Pleistocene sediments, thick series of Middle and Late Pleistocene deposits were deposited in caves (Głazek 1989; Madeyska and Cyrek 2002; Krajcarz et al. 2014). Speleothems were formed in more humid periods. Mechanical weathering and gravitational processes caused the retreat of monadnock walls and accumulation of rock debris and blocks at their base. In the periglacial environment of the Late Pleistocene, a specific epikarst zone with debris mantles and patterned ground developed (Tyc 1997).
- ***Stage V—Holocene***
  The present-day development of karst landform is associated with the exhumation of relief from beneath clastic sediments of Pleistocene age. Within the range of glacial deposits and loess varieties, processes related to covered karst are developing. The walls of monadnocks and tors continue to be modelled by weathering, giving rise to specific micro-relief.

22.5 Geomorphological Landscape and Cultural Heritage

The Kraków-Częstochowa Upland is known for numerous well-studied archaeological sites. Caves and rock shelters with well-exposed and accessible entrances and overhanging rock walls attracted early humans to settle in the upland. Inhabitation of caves in the region from the

Fig. 22.12 Ruins of a medieval castle built on the monadnocks of a vast rock hill in Podzamcze near Ogrodzieniec town (photograph by A. Tyc)

Middle Palaeolithic to historical times has been confirmed (e.g. Cyrek 2009). The earliest relics of human presence have been found in the Biśnik Cave in the Wodąca Valley (Fig. 22.4). The cave and its surroundings were inhabited in the period between the Odranian and Late Weichselian glaciations, i.e. over 250,000 years. At least 18 settlement phases have been distinguished, which can be interpreted as single campsites set up by cave inhabitants (Cyrek et al. 2014). A distinct intensification of Neanderthal settlement, which is characteristic of the whole of Europe, took place in the early Weichselian, with representatives of Middle Palaeolithic—Micoquian, especially Micoquo-Prondnikian, and Mousterian cultures. Caves and rock shelters in the Ojców area in the south (e.g. Koziarnia Cave) can be regarded as more frequently settled basic encampments. At the same time, other ones more to the north were briefly occupied as occasional camps (Cyrek 2009). The second period of intense human settlement in the Kraków-Częstochowa Upland is dated to the Upper Palaeolithic. Aurignacian and Gravetian cultures created by *Homo sapiens* have left their rich testimony in cave settlements of the entire region.

The karst landscape, with rocky hills and monadnocks, was attractive for humans also in the following periods of the Neolithic, Bronze Age, and Middle Ages. In the latter, rocky hills and individual monadnocks were used to construct defensive castles at the former western border of the Polish Kingdom. They formed the entire defensive chain along the main axis of the upland, between Kraków and Olsztyn, the so-called Eagle nests (Fig. 22.12).

The Kraków-Częstochowa Upland has a long tradition in nature conservation in Poland. Protection of karst phenomena dates back to the first half of the twentieth century when projects of nature reserves were created to protect caves and karst landforms in the vicinity of Ojców, Olsztyn, and Złoty Potok. Finally, more than 30 years later, the Ojców National Park was established in 1956, covering the Prądnik Valley. During that time, nature reserves 'Parkowe' next to the village of Złoty Potok, 'Sokole Góry' close to the town of Olsztyn, and 'Góra Zborów' in the vicinity of the village of Podlesice were created. Individual protection as nature monuments and documentary sites was established to protect monadnocks and caves. In the early 1980s, a complex of landscape parks was established, covering substantial areas of the Kraków-Częstochowa Upland.

22.6 Conclusions

The Kraków-Częstochowa Upland has a very diverse landscape with significant karst landforms. The most distinctive landforms of the region are limestone rocky hills, monadnocks, and isolated tors appearing both on the plateaus and within the slopes of hills and valleys. Significant lithological differentiation of the Upper Jurassic limestones and complex tectonic settings have controlled the spatial differentiation and evolution of karst and caves of this region.

Considering the structural settings, different magnitude of Neogene uplift and variable position in respect to the extent of the Pleistocene inland glaciation, karst landforms and landscapes of the Ojców Plateau and the Częstochowa Upland are significantly different. The rocky valleys and gorges, the picturesque Prądnik Valley among them, cut the southern part of the Ojców Plateau. On the other hand, the northern part of the Częstochowa Upland was the only part of the region covered by the Pleistocene glaciation, and the rocky hills and monadnocks were transformed by glacial erosion into asymmetric roche moutonnées. In the areas mantled by glacial deposits and loess covered karst developed.

Although the origin and age of karst and caves are still discussed, the Late Cretaceous marine recession and the Holocene constrain the timespan for the development of karst landforms in the Kraków-Częstochowa Upland. Karst landforms and caves of the Kraków-Częstochowa Upland are polygenetic and multi-stage. Several stages can be distinguished within the nearly 70 million years-long history of karst evolution, with a significant hypogene stage in the early phase of karst development.

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