19 Gravitationally Induced Non-karst Caves in the Polish Outer Carpathians

Włodzimierz Margielewski and Jan Urban

Abstract

The Outer Carpathians, formed of siliciclastic-clayey rocks, abound in non-karst (pseudokarst) caves. In their Polish part, 1646 such caves with a total length of 27,857 m have been recorded up to July 2021. The longest Jaskinia Wiślańska cave reaches 2275 m, whilst 43 caves are longer than 100 m and 31 caves are 15 m deep or more (up to 60 m). Most of them are genetically related to slope gravitational deformations, but there are also caves—principally only several metres long—formed due to non-uniform weathering of sandstone crags. Amongst the gravitationally induced Carpathian caves, several types can be distinguished. In the morphogenetic classification, considering the succession of processes, three types of caves are recognized: initial caves (preceding the main slope failures), subsequent caves (formed during the main slope deformations) and intermediate caves. Regarding the geomechanic criterion also three principal groups are discriminated: dilational caves (formed due to simple tensional fracturing), dilatancy caves (related to a fissure macrodilatancy) and boulder caves (developing within very strongly deformed slopes). Four examples representing various morphogenetic and geomechanic types of caves are described in this chapter. The gravitationally induced caves have been formed since the Late Glacial, when the destruction of slopes started along with permafrost degradation, but have fully developed and transformed during the Holocene, with several periods of intensification connected with climate changes (moistening).

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Keywords

Non-karst caves · Pseudokarst · Gravitational slope deformations · Flysch · Late Glacial · Holocene · Outer Carpathians

19.1 Introduction

Most caves are of karstic origin, but there are regions lacking soluble rocks, which are nevertheless abundant in caves of various non-karstic origin. The Outer Carpathians formed mainly of siliciclastic-clayey rocks are such a region, where 1646 non-karst caves of a total length of 27,857 m were recorded up to July 2021 (Fig. 19.1a). The longest cave, Jaskinia Wiślańska, is 2275 m long (cave position on Fig. 19.1b—4), three other caves are longer than 1 km, and totally 43 caves are longer than 100 m, whilst 31 caves are at least 15 m deep (Klassek and Mleczek 2018; Gądek 2021). The majority of these caves have originated due to gravitational deformations of slopes, whereas a much smaller number has formed due to weathering of sandstone crags and these are principally very short caves, rarely more than 10 m long.

Caves in the Carpathians have been recognized and explored for a long time. The first explorations took place in the nineteenth century, whereas the first descriptions and maps were published in the first half of the twentieth century. A significant increase in the number of explored and documented caves occurred in the 1970s–1980s, when the Bielsko-Biała Speleoclub intensified its activities. Since the beginning of the twenty-first century, exploration was followed by the Beskidy Caving Club (created by amalgamation of the Dębica and Limanowa speleoclubs) as well as the Association for the Cave Conservation "Malinka Group". The number of explored caves increased from several tens in the 1960s to more than six hundred, of the total length higher than 10 km at the beginning of the twenty-first century (Klassek and

P. Migoń and K. Jancewicz (eds.), *Landscapes and Landforms of Poland*,
World Geomorphological Landscapes, https://doi.org/10.1007/978-3-031-45762-3_19

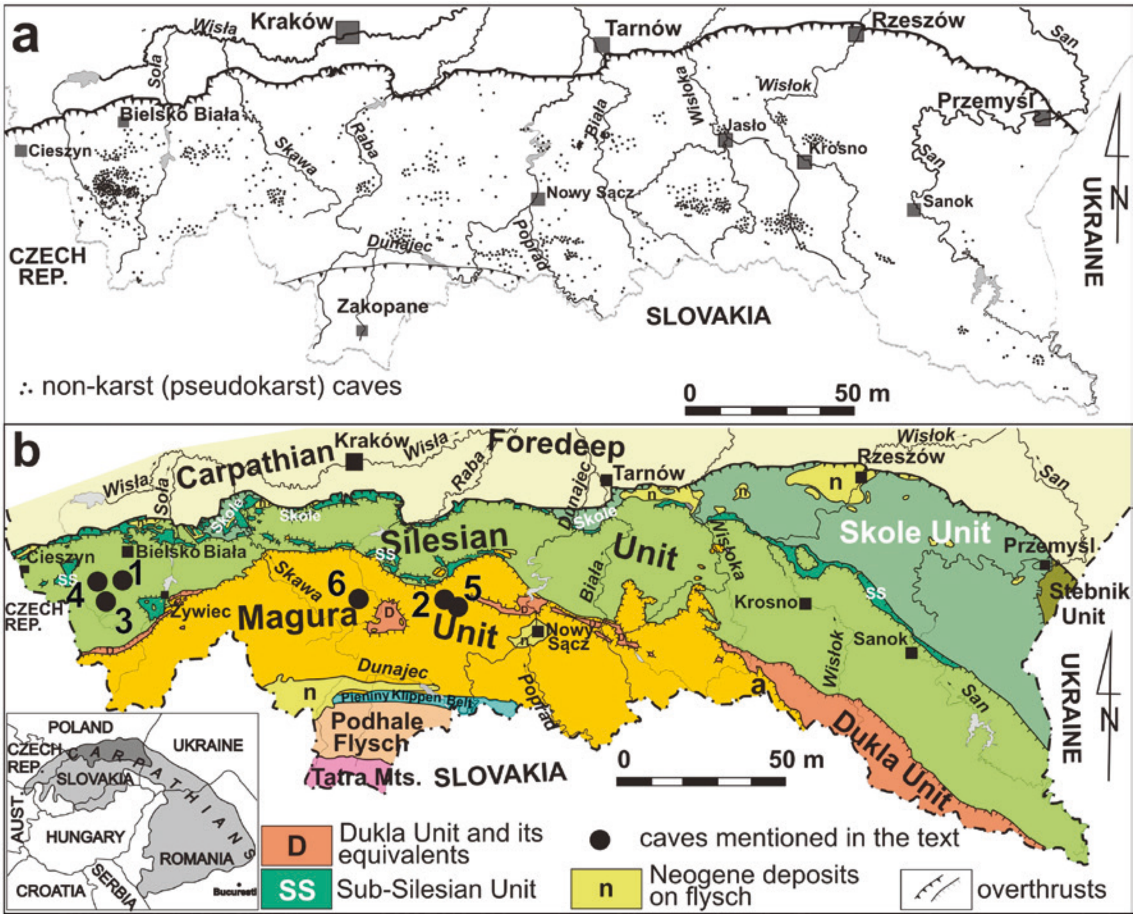


Fig. 19.1 The occurrence of non-karst caves in the Polish Outer Carpathians. **a** Distribution of caves (after Margielewski and Urban 2017). **b** Geological map of the Carpathians (after Żytko et al. 1989), with location of caves mentioned in the text. 1—Jaskinia Malinowska cave, 2—Jaskinia Złotopieńska cave, 3—Jaskinia Miecharska cave, 4—Jaskinia Wiślańska cave, 5—Jaskinia Zbójecka na Łopieniu cave, 6—Zimna Dziura w Szczeblu cave

Mleczek 2008; Urban and Margielewski 2013). At that time also the first scientific studies of these caves were performed and first their genetical descriptions and categorization were proposed (Janiga 1974; Puchejda 1989; Klassek and Mikuszewski 1997). The categorization proposed by Klassek and Mikuszewski (1997), combining many features such as the shape of caves, their spatial situation and selected genetical attributes, was very complex; therefore, the most popular classification of non-karst caves used by Polish speleologists during the first decade of this century was the one proposed by Vítěk (1983) and a similar one by Bella and Gaál 2013.

Executed in the first decade of the twenty-first century, intensive research of non-karst caves in the Polish Carpathians focused on detailed observations of spatial situation of the upslope and downslope cave walls as well as interrelations between subsurface and superficial slope deformations (also using ERT—electrical resistivity tomography), brought about much better understanding of reasons and mechanisms behind the development of these caves. In turn, the analysis of speleothems enabled one to determine the age and environments of cave formation and evolution (Margielewski and Urban 2002, 2003; Margielewski 2006a; Margielewski et al. 2007; Urban et al. 2007, 2015; Pánek et al. 2010). These studies showed that the classification by Vítěk (1983) is not sufficient for unequivocal interpretation of cave types and made possible the elaboration of a new, more adequate cave categorization (Urban and Margielewski 2013; Margielewski and Urban 2017). This chapter aims to describe a very interesting phenomenon of non-karst, gravity-induced caves that commonly occur in mountainous areas formed of siliciclastic-clayey rocks, basing on their recently proposed classification and genetical interpretation.

19.2 Geological and Geomorphological Setting

The Outer Carpathians represent an Alpine orogen formed of the Upper Jurassic–Lower Miocene flysch rocks: sandstone, sandstone–siltstone–claystone, siltstone–claystone and sandstone–conglomerate series, being sediments of deep depositional marine basins. In the Polish Outer Carpathians, such rocks, strongly folded and faulted, form several lithostratigraphic–tectonic units that are thrust upon one another towards the north. Amongst them, the following main units should be mentioned (from the south): Magura Unit, Dukla Unit (and their equivalents), Silesian Unit, Sub-Silesian Unit, Skole Unit and Stebnik Unit (Fig. 19.1b) (Żytko et al. 1989; Lexa et al. 2000).

The Polish Outer Carpathians, in geographical terms comprising the Western Beskidy and Bieszczady (Eastern Beskidy) Mountains and their foothills, are composed of many hill ranges and groups reaching 800–1300 m asl in the mountainous part and standing up to 800 m above river valleys (Starkel 1972). The specific sequence of initially tectonic (compressional–extensional) and then tectonic-gravitational (gravitational collapse) and gravitational processes brought about the present-day morphology of mountain massifs (Jankowski and Margielewski 2021). Since the Late Glacial (uppermost Pleistocene), the steep slopes of the Beskidy and Bieszczady Mountains have been shaped principally by gravitational processes, such as landsliding, toppling and spreading, which have been conditioned by geological structures: tectonic (spatial) positions and lithology of rocks (Margielewski 2006a). These processes have been also responsible for the development of underground discontinuities and cavities (caves being the cavities accessible and recognized by people).

19.3 Classification of Gravity-Induced Caves in the Outer Carpathians

The formation of gravity-induced underground cavities, also voids accessible for people, i.e. caves, consists in opening and widening of discontinuities, principally joints. It is caused by disturbance of slope gravitational equilibrium by loading and relaxation of shear or extensional stresses in rock massifs related to various factors such as rainfall, earthquakes or erosion. Shearing stress is unloaded along potential or existing tectonic discontinuities in rock massifs such as joints and faults, which are opened and widened as extensional cracks (caves) (Fig. 19.2a, b). This process continues until the shearing stress limit is exceeded, and the fragment of a rock massif, for a long time separated by cracks, is gravitationally displaced down the slope within the relatively short time period (Fig. 19.2c). The formation of extensional cracks in the first stage of stress unloading is associated with the phenomenon of dilation (dilatation), i.e. a change in the rock medium volume without changing its shape (Neuendorf et al. 2005; Rustan et al. 2010). During this process, the rock massif gradually increases its volume by the appearance and expansion of fissures (the rock mass "swells"), but there is no destruction (disintegration) of rock masses, e.g. due to shearing processes. There are no brittle deformations transforming the massif in the shearing zone as a result of rock grinding.

During the second stage of gravitational displacements of rock masses along the shearing zone, the other type of voids (caves) is formed, as a result of fissure macrodilatancy (Fig. 19.2a and c, no. 2–4) (Kwaśniewski 1986; Margielewski and Urban 2017). Fissure macrodilatancy comprises an increase in the volume of the rock medium along with the change in its shape, owing to the extensive opening of fractures (Fig. 19.2c, no. 3–4) (Kranz and Scholz 1977; Kwaśniewski 1986, 2007). Dilatancy phenomenon occurs in the zone of rock mass destruction, i.e. in the failure zone formed along the border of a displaced fragment of the massif and bedrock (hence dilation is considered as a "herald" of the destruction of the rock massif—Kwaśniewski 1986). As a result of such disintegration of rock material in the failure zone, its volume increases (the rock mass "swells", also with the participation of fissures/caves—see Fig. 19.2c, no. 3). During this process, the shape of the rock medium is distinctly changed and rocks break down as a result of shearing (Fig. 19.2c, no. 3). Cataclasites, tectonic breccia and tectonic powder (gouge) are usually formed in the failure zone.

Consequently, the categorization of caves originated due to these processes makes sense if it enables for the determination of the interrelations between cave formation and slope evolution, as well as covers the nature and range of rock massif deformation. Therefore, two criteria of classification have been proposed. The first is morphogenetic criterion that determines the relationship between the origin of the cave and the stage of slope evolution. According to this criterion, three cave types are distinguished (Fig. 19.3) (Urban and Margielewski 2013; Margielewski and Urban 2017):

- Initial caves, which develop before the main slope failure, i.e. prior to the typical landslide. They are usually simple passages or bundles of passages formed within slightly deformed slope sections within more advanced slope failures. Most them, but not all, can be identified with crevice-type caves in the classification by Vítěk (1983).
- Subsequent caves formed during the principal phase of slope deformation—landslide development. These caves are situated in the slope sections apparently modified by

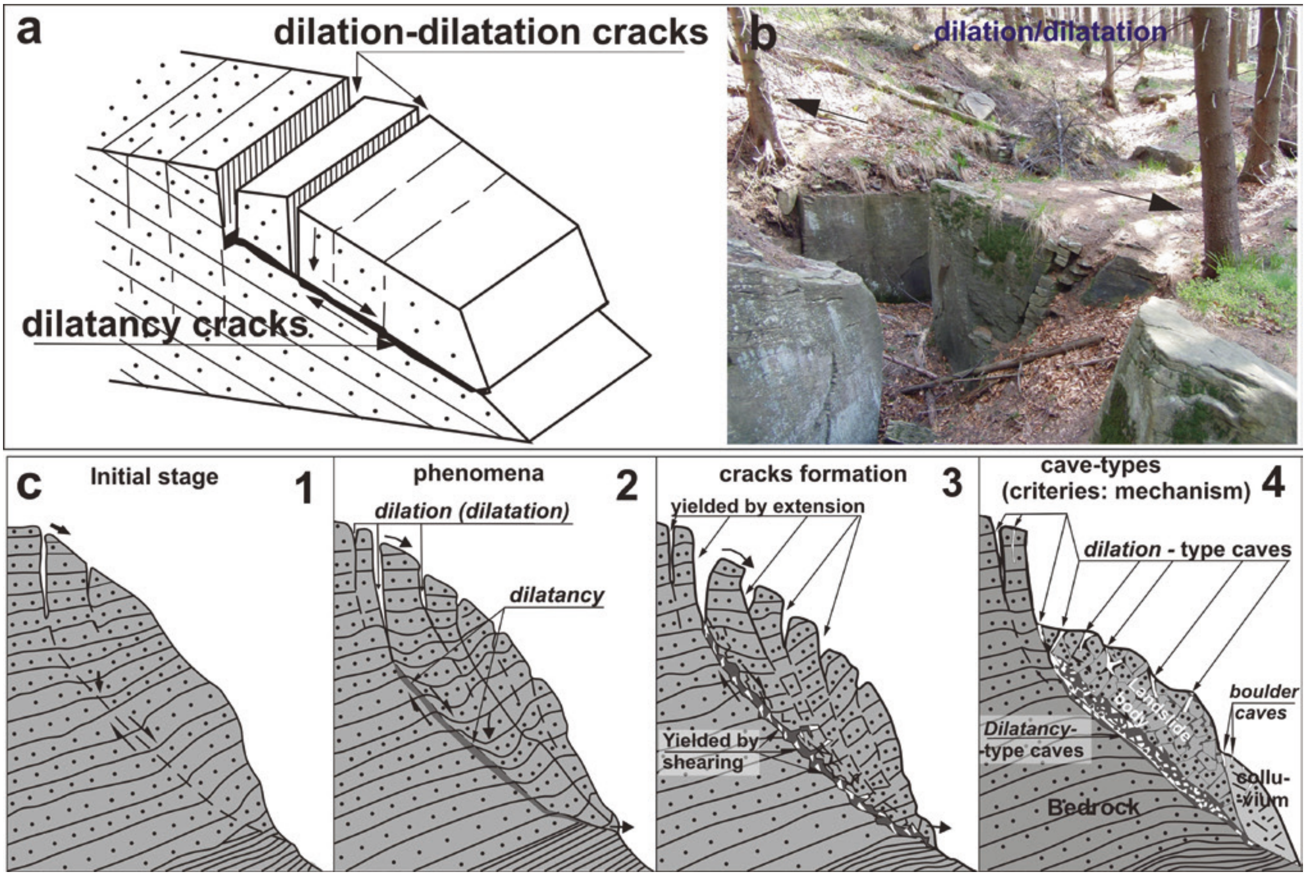
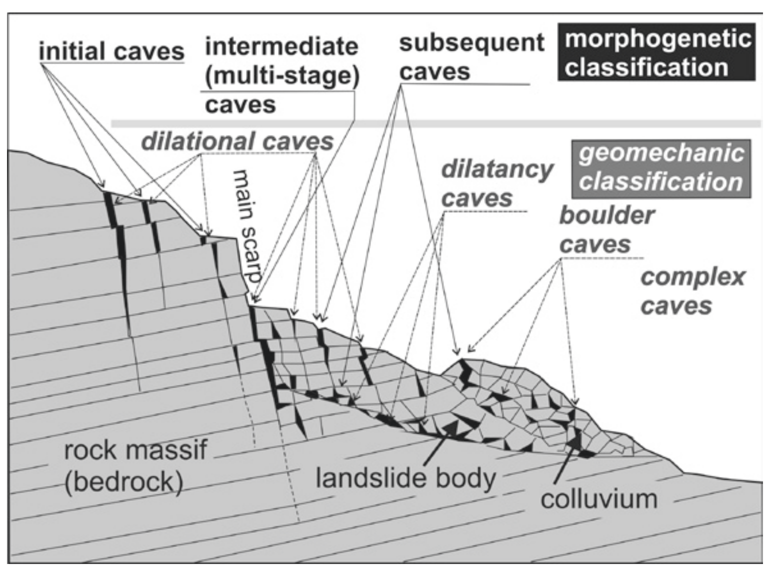


Fig. 19.2 The conceptual model of formation of non-karst caves due to dilation (dilatation) and dilatancy phenomena. **a** Cracks formed owing to dilation and dilatancy phenomena in hypothetical slope. **b** Trenches formed in effect of dilation (sandstones of the Magura Beds, Mt. Wierch nad Kamieniem, Beskid Sądecki Mts.). **c** Stages of cave development due to dilation and dilatancy phenomena (after Margielewski and Urban 2017). Failure zone formation (with fissure macrodilatancy) is preceded by rock flow (Dikau et al. 1996) (see: c 1–2) (photograph b by W. Margielewski)

Fig. 19.3 Conceptual model and proposal of classification of non-karst caves (after Margielewski and Urban 2017)



gravitational movements, within the landslide bodies, and represent usually complex systems of passages but not always very long. In respect to the classification by Víték (1983), most of them belong to the group of talus caves.

- Intermediate (multi-stage) caves, which occur in a zone of the main landslide scarp, and can form during both initial and final stages of slope gravitational evolution. In this first stage, they are initial caves, which are partly destructed (due to the slope failure) and re-modelled during the main movements. They are not very frequent and usually represent bundles of more or less parallel cavities.

According to the second, geomechanic criterion, describing the nature and range of deformations of the rock massif that are genetically connected with the cave formation, also three types of caves are discriminated:

- Dilational caves, formed owing to the process of rock dilation caused due to simple tensional stresses. Most of these caves, but not all, represent initial caves in the morphogenetic classification, so they are simple passages or benches of parallel passages; often crevice-type caves in the classification by Víték (1983).
- Dilatancy caves, developed owing to fissure macrodilatancy (Kwaśniewski 2007) due to more advanced slope failure, produced by shear stress or combination of shear and extensional stresses. They are connected with significant modifications of slope within landslides and often represent networks or maze systems of passages, corresponding in part to caves qualified by Víték (1983) as of the talus type.
- Boulder caves, developed owing to chaotic distribution of large boulders in totally disintegrated rock masses forming landslide colluvia. They can be very irregular, short or forming maze systems if they are longer. In other classifications, they are described as talus caves (Víték 1983) or boulder caves (Bella and Gaál 2011).

19.4 Case Studies of Representative Caves

19.4.1 Jaskinia Malinowska—Initial and Dilational Cave

The Jaskinia Malinowska cave in the Beskid Śląski Mts. (Fig. 19.1b, site 1), 230 m long and up to 19.5 m deep, is one of the earliest explored caves in the Beskidy Mts. and a legendary hiding place of mountainous robbers in the eighteenth century (Klassek and Mleczek 2008). It has been known for a long time because of its location near the ridge of Mt. Malinów, within its southern slope, and the presence of a large entrance comprising a shaft ca. 10 m deep (Fig. 19.4). It is formed in thick- and very thick-bedded sandstones and conglomerates of the Godula Beds of the Silesian Unit. The strata are slightly inclined towards the south and south-west, thus similarly to the slope inclination (Fig. 19.4c) (Margielewski and Urban 2003).

The main part of the cave comprises a system of passages, which represent opened and widened sections of joints that belong to two crossing joint sets (Fig. 19.4a, b, d). The “zigzag system” of such high, straight and narrow passages is particularly regular in the central and western parts of the cave (Fig. 19.4g). Comparison of structures on both upslope and downslope cave walls, as well as the lack of slickensides on their surfaces, indicates that the main movement producing these passages was simple extension, with participation of slight vertical translation (ca. 10–30 cm). Consequently, dilation was the principal process responsible for cave formation (Margielewski and Urban 2003).

The cave formation took place within the slope not deformed by a landslide. However, the cave shape, including the direction of its central section parallel to the slope contours and downslope directions of its western and eastern sections, resembles a ground plan typically followed by the main scarp of a landslide (Fig. 19.4e, f). Therefore, it is interpreted as an extensional feature developed due to stress relaxation along the structural discontinuities of a rock massif antecedent to the main stage of deformation. Such suggestion is confirmed by geoelectrical (ERT) images, showing various zones of relaxation, also inaccessible one in the vicinity of the cave (Margielewski and Urban 2003; Pánek et al. 2010).

The Jaskinia Malinowska cave, protected as nature monument, is now the only cave in the Beskidy Mts. equipped with specific facilities for touristic exploration, namely ladders in the entrance shaft.

19.4.2 Złotopieńska Dziura—Intermediate, Dilational Cave

The Złotopieńska Dziura cave, 105 m long and 10 m deep, is situated in the Beskid Wyspowy Mts. (Fig. 19.1b, site 2). The cave is located in the northern slope of Mt. Łopień, within the long (ca 400 m) and relatively high (up to 20 m) landslide main scarp, called Czartorysk (Fig. 19.5). Within this scarp zone (also upslope but close to it), 12 caves have been found and explored by cavers from the Limanowa Speleoclub since 1995 (Gubała and Kapturkiewicz 2018). The whole landform assemblage is formed in thick-bedded sandstones of the Magura Beds, Magura Unit. The entrance

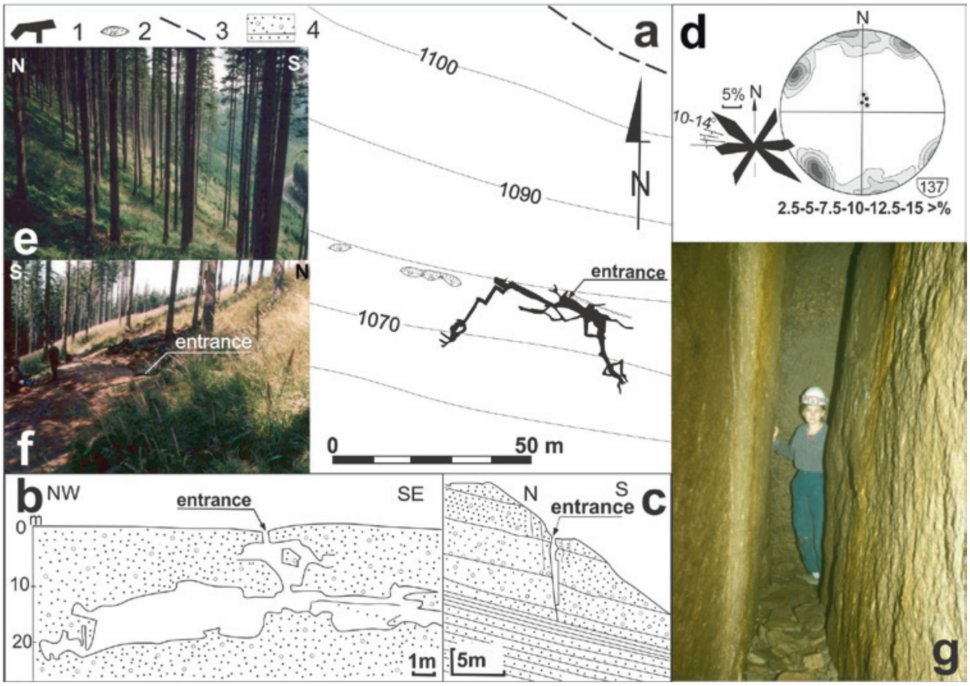


Fig. 19.4 Jaskinia Malinowska cave. **a** Map (cave contours after Rachwaniec and Holek in: Pulina 1997); explanation of symbols: 1—cave galleries, 2—surface depressions, 3—ridge path (touristic trail), 4—sandstones and conglomerates (on cross sections). **b** Longitudinal cross section of the cave (simplified after Ganszer in: Pulina 1997). **c** Conceptual model of transversal cross section of the cave and geological structure (after Margielewski and Urban 2003, modified). **d** Joints and spatial position of strata on the upslope walls in the central and western parts of the cave: joints in rose and contour diagrams—equal area plot, projection of poles in the lower hemisphere, with the number of measurements (137) and contour intervals (5%); bedding plane in the pole point diagram. **e** Slope below the cave entrance. **f** Cave entrance. **g** Passage in the western part of the cave (photographs by W. Margielewski)

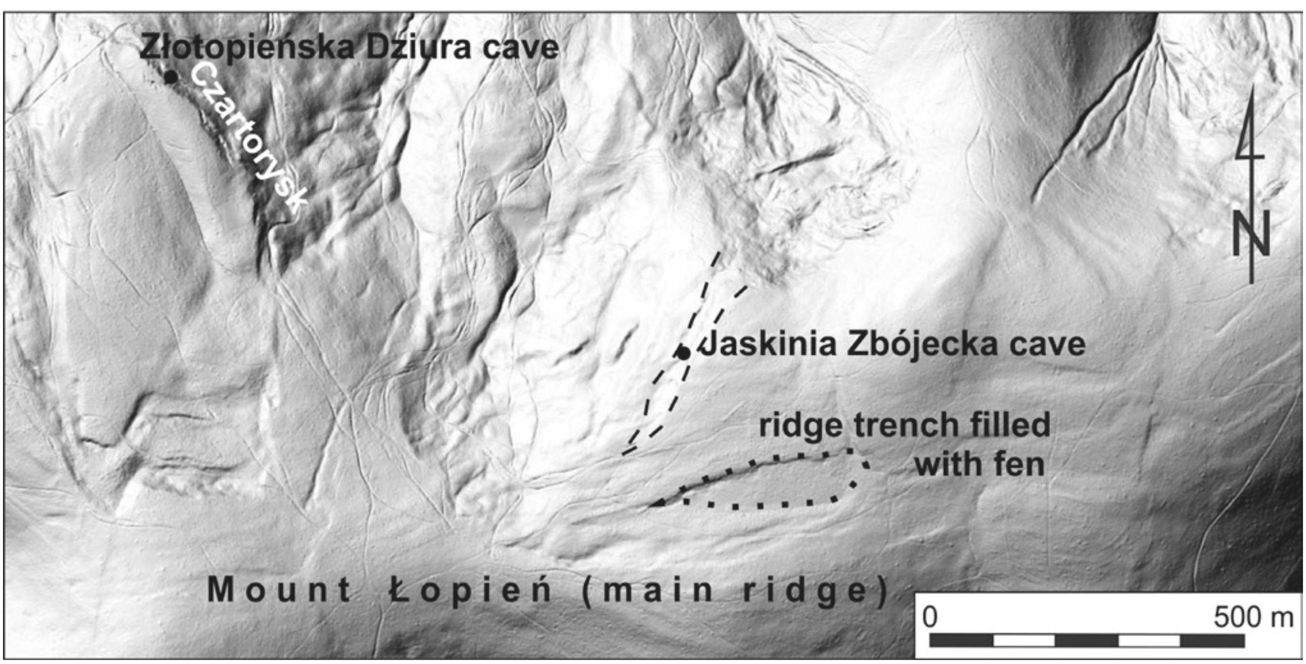


Fig. 19.5 Position of the Jaskinia Złotopieńska cave and the Jaskinia Zbójecka cave in the gravitationally deformed northern slope of Mt. Łopień (on the background of a digital terrain model downloaded from the public domain, www.geoportal.gov.pl)

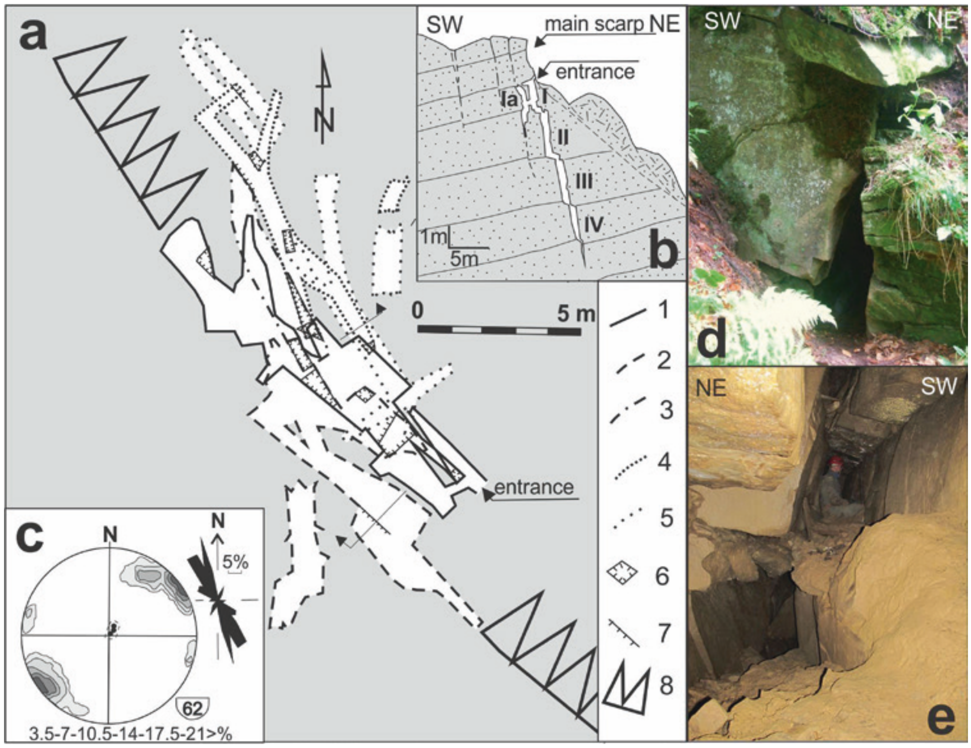


Fig. 19.6 Złotopieńska Dziura cave. **a** Map of cave (after Mleczek in: Pulina 1997); explanation of symbols: 1 to 5—contours of the cave passages (1—level I, 2—level Ia, 3—level II, 4—level III, 5—level IV), 6—cave shaft or chimney, 7—scarp within the cave, 8—landslide main scarp. **b** Conceptual model of transversal cross section of the cave and geological structure (after Margielewski and Urban 2003); **c** Joints and spatial positions of strata of the upslope passage walls in the cave (after Margielewski and Urban 2003); for further explanation see Fig. 19.4. **d** Cave entrance within the main scarp; its shape indicates the share of backward rotation in the cave development. **e** Two levels of passages: lower passage is shifted towards slope dip (photographs by J. Urban)

of the Złotopieńska Dziura cave is situated in the middle part of the vertical scarp, whereas its passages form four levels developed below it, downslope. They are located under one another, but slightly shifted towards the slope dip (Fig. 19.6a, b, d, e). The uppermost level is situated within the more disintegrated part of rock massif, whereas lower levels consist of passages up to 15 m long and 0.4–1.0 m wide, fairly regular in cross section. These passages originated due to the widening of the joints—the same ones which shape principal faces of the main scarp (Fig. 19.6a, c). However, some walls, especially in the deeper levels, are slightly bent (with concave and convex walls), which suggests their formation along joints induced during gravitational and dilational movements (Margielewski and Urban 2003).

The observations of structures on the walls (lack of slickensides, etc.) and their spatial orientation indicate that the main process forming the cave passages was an almost horizontal translation, with backward rotation in the uppermost parts and slight (up to 20 cm) vertical shift downslope. Consequently, it can be postulated that the landslide developed owing to spreading and subsequent massif disintegration into rock packets currently constituting the landslide body and colluvial swell, whereas the Złotopieńska Dziura cave, being part of the main detachment zone and its prolongation into the slope massif, experienced only spreading and hence dilation (Margielewski and Urban 2003).

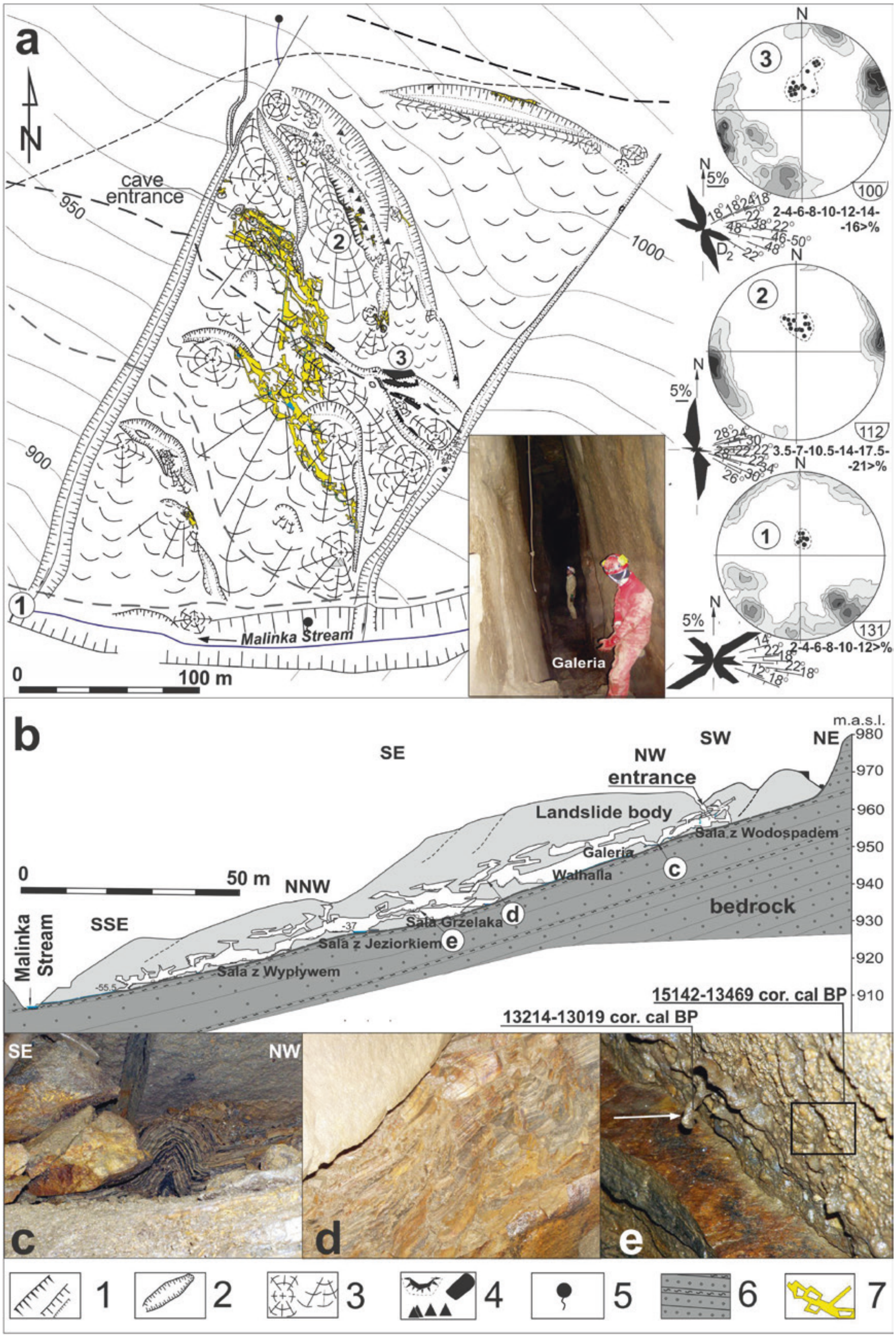
The whole landslide zone of the Czartorysk is protected within the Special Area of Conservation Nature 2000 called Uroczysko Łopień.

19.4.3 Jaskinia Miecharska Cave—Subsequent and Dilatancy Cave

The Jaskinia Miecharska cave is situated in the Beskid Śląski Mts (Fig. 19.1b, site 3) and formed in the Upper Godula Beds (Upper Cretaceous), Silesian Unit, that are composed of thick-bedded sandstones and conglomerates intercalated with shales and thin-bedded sandstones (Burtan 1973).

The cave, 1838 m long, has formed in the northern slope of the Malinka Stream valley (tributary of the Vistula River). The vertical difference between its highest and lowest parts reaches 55 m (Szura and Juroszek 2016). The cave is composed of a maze system of galleries and chambers, 0.5–10 m high and 0.4–8.0 m wide, formed along joints (Fig. 19.7a, b). The central section of the cave comprises a regular network of passages, whilst other parts are composed of irregular caverns developed along highly disintegrated and displaced rock blocks, often rotated horizontally and vertically (Margielewski and Urban 2017).

The cave was formed within the body of large landslide of complex type, developed in a valley side setting. Therefore, the cave represents a subsequent cave in the morphogenetic classification. The cave system formed along the shear (slip) zone of the landslide consequent to the strata dip, ca. 10–12 m below the ground surface (see Fig. 19.7b), due to the opening of cracks along joints, during gravitational displacement, so the cave is of dilatancy type in the geomechanical classification. In the cave tectonic deformations typical for the shear zone have been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cave entrance
950
1000
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Malinka Stream
0
100 m
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b
m.a.s.l.
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Landslide body
Sala z Wodospadem
Galeria
Walhalla
bedrock
NNW
SSE
Malinka Stream
Sala Grzelaka
Sala z Jeziorkiem
Sala z Wypływem
0
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13214-13019 cor. cal BP
SE
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c
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Fig. 19.7 Jaskinia Miecharska cave (after Margielewski and Urban 2017, modified). **a** Map of the landslide with plan view of the cave (marked in yellow colour) and photograph of cave main gallery; joints of rocks outcropping in the landslide (localities 1, 2, 3) area are presented on rose and contour diagrams (for explanation see Fig. 19.4). **b** Longitudinal cross section of the cave and its position along the slip surface of landslide, with location of photographs **c**–**e**. Phenomena related to the cave formation: **c** Shearing fold. **d** Tectonic breccia. **e** Speleothems (helictite) dated by radiocarbon method. Explanation of symbols: 1—scarps, 2—trenches and depressions, 3—landslide body, 4—crags; 5—springs, 6—sandstones and shales on cross section, 7—cave outline (photographs by W. Margielewski)

recognized. They include both plastic (shear folds in claystones) and brittle-type deformations (tectonic breccias) (Fig. 19.7c, d). The geoelectrical survey (ERT) of the landslide recorded other cavities (cave systems) formed due to macro-fissuring process along the shear zone (Pánek et al. 2010), later discovered by cavers.

In the Jaskinia Miecharska cave, various speleothems occur such as carbonate stalactites and unique helicites (up to 4 cm long; Fig. 19.7e), small stalactites (2–4 cm long), and flowstones formed of siliceous–argillaceous mineraloids and organic substance (encrusted by mineraloid material) (Urban et al. 2007, 2015). Radiocarbon datings (regarding a reservoir effect) indicate that the helictites were formed in the Late Glacial (ca. 13.21–13.02 ka corrected cal BP and 15.14–13.47 ka corrected cal BP). The younger carbonate and organic stalactites were dated at ca 8.44–8.37 ka corrected cal BP; 7.51–6.48 ka corrected cal BP; 7.67–7.28 corrected cal. BP) (Margielewski and Urban 2017).

Another example of a dilatancy cave is Jaskinia Wiślańska cave—the longest cave (2275 m) discovered so far in the Polish Beskidy Mts., situated close to the Jaskinia Miecharska cave, in the Beskid Śląski Mts. (Fig. 19.1b, site 4) (Margielewski and Urban 2017).

19.4.4 Jaskinia Zbójecka na Łopieniu—Subsequent, Boulder Cave

The Jaskinia Zbójecka na Łopieniu cave, 433 m long and 20 m deep, is situated in the Beskid Wyspowy Mts (Fig. 19.1b, site 5). It is formed in thick-bedded sandstones of the Magura Beds, Magura Unit, and located within the northern slope of Mt. Łopień, close to its northern culmination (Fig. 19.5). The whole southern part of Mt. Łopień massif is probably significantly deformed by spreading—gravitationally induced extensional movement which broke and detached this part of rock massif from the main ridge. This is evidenced by a ridge depression situated between the southern and northern parts of the massif, which is currently filled by a fen and periodically overflowed (outlined by dotted line on Fig. 19.5). The fen, up to 2.5 m thick, is composed mainly by sedge peat covered by a thin layer of *Sphagnum* peat The datings of organic matter at the bottom of the fen indicate that its accumulation started at ca. 5.8 ka cal BP, at the beginning of the Subboreal phase of the Holocene, so the movements deforming the mountain massif must be of similar or older age than this date (Margielewski 2006b).

The large-scale gravitational deformation of Mt. Łopień rock massif encompassed its highest, relatively flattened and extensive parts, along with the southern culmination. It did not bring about the formation of large and distinct scarps in these parts (which are present in the lower, steeper slopes), but significantly disintegrated the structure of the rock massif, especially in the most deformed zones. This is perfectly visible in the area above the Jaskinia Zbójecka cave and its vicinity. The ground surrounding the main cave entrance is uneven and formed of numerous rock boulders, but it is not very steep and no evident scarp occurs. However, on the digital terrain model, the characteristic zone of SSW–NNE direction can be recognized (outlined by narrow dashed line on Fig. 19.5). It is most likely a tectonic discontinuity significantly deformed due to the gravitational movements. This rock massif failure is evidenced by the nature and shape of the Jaskinia Zbójecka cave, which developed in this zone. The cave is a system composed of several large chambers of very various shapes and sizes, ranging 3–6 m in horizontal plan and 2–10 m in vertical dimensions. These chambers are connected by narrow and very irregular (horizontal, vertical and diagonal) passages that form a very dense, complex labyrinthine network of voids often overlapping one another (Fig. 19.8a–d). This is why the area covering the cave, which is more than 400 m long, is ten times smaller, ranging only 40 m × 15 m. It is not possible to find any predominating or regular direction in the elongation of cavities and their walls related to a regular joint set. However, the elongation of the general cave contours is in accordance with the strike of the tectonic deformation zone visible on the digital terrain model (Figs. 19.5 and 19.8). The formation of such a cave, as a set of large chambers, was possible owing to the formation of very large rock blocks ranging the length of 10 m and more, which were involved in movements of different types, including rotation, translation and their combinations. In this sense, the Jaskinia Zbójecka cave is a boulder-type cave according to the geomechanic criterion, but it is very specific, related to strongly disintegrated landslide body rather than to classic colluvium *sensu* Dikau et al. (1996).

Another interesting geological feature of the Jaskinia Zbójecka cave is non-calcareous stalactites, tooth-like and ribbed sheetings, as well as small calcite coralloids. These last ones were dated by radiocarbon methods at 2.68–2.35 ka corrected cal BP (Margielewski and Urban 2017).

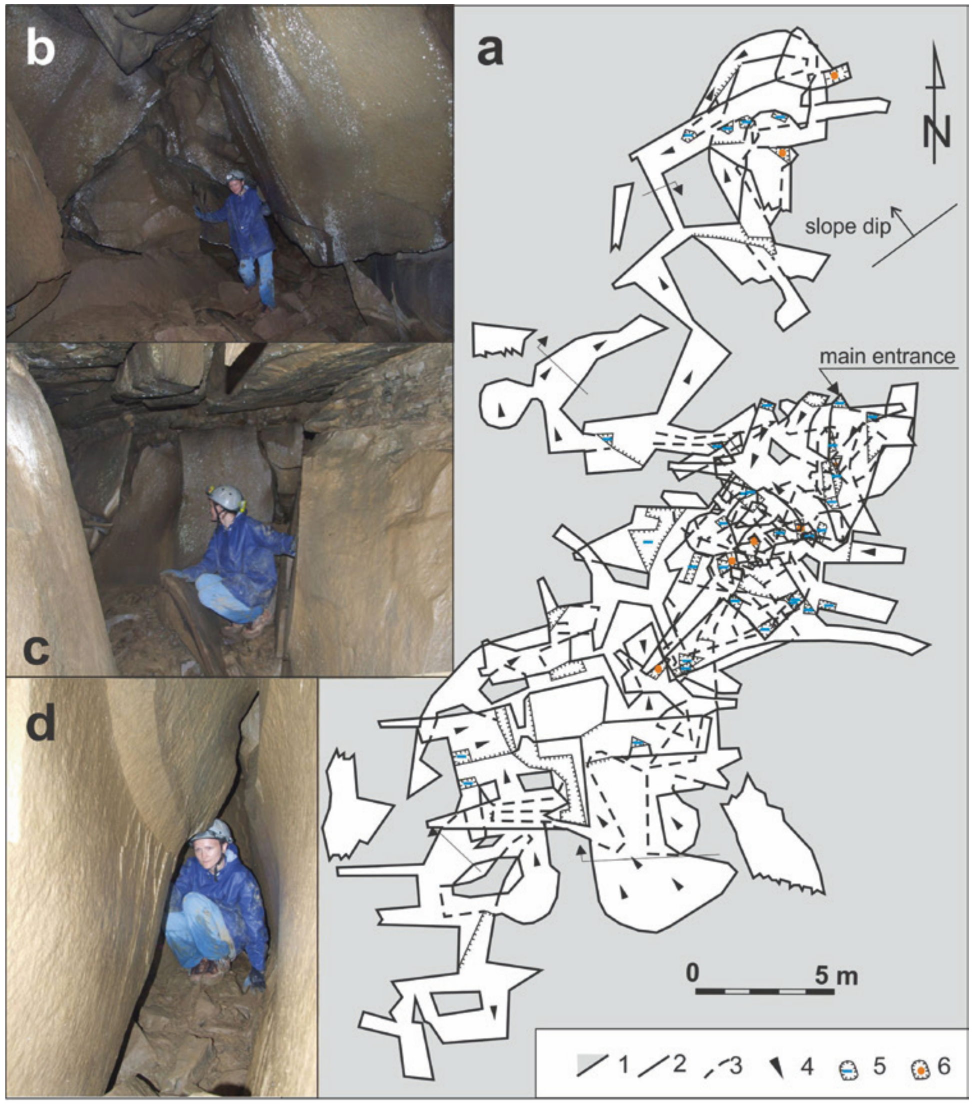

Fig. 19.8 Jaskinia Zbójecka cave. **a** Map (after Mleczek: in Pulina 1997, modified); explanation of symbols: 1—main outline of the cave, 2—contour of passage/chamber of the highest level, 3—contour of passage/chamber overlapped by higher cavities, 4—cave floor inclination, 5—shaft, 6—chimney. **b** Janosik Chamber (4 m long, 3 m wide and up to 10 m high): irregularly situated large boulders (rotated and fallen) form walls and ceiling of this chamber. **c** Rondo Chamber: cavity with relatively regular ceiling related to claystone layer, but with walls formed along irregular, uneven joints induced during the massif disintegration. **d** Łoś Passage: shell-like, concave and convex walls were formed along joints induced during disintegration of the massif, but the hackle marks indicate previous, tectonic stresses recorded in the rock structure (photographs by J. Urban)

The cave has been known for a long time (named also Jaskinia w Łopieniu), which is documented by legends and inscription inside the cave, but its entrance was forgotten in the twentieth century and it was repeatedly explored and documented in 1997–1998 (Gubała and Kapturkiewicz 2018). The cave is the greatest known bat hibernaculum (of mainly *Rhinolophus hipposideros*) amongst the caves of the Polish Outer Carpathians (Gubała and Piksa 2009). It is legally protected as a nature monument and situated within the Special Area of Conservation Nature 2000 called Bagna Łopieńskie.

19.5 The Age and Circumstances of Formation and Evolution of Caves

The development of caves within the mountain slopes of the Outer Carpathians has been connected with the same gravitational rock mass movements which were responsible for slope evolution since the permafrost deterioration in the Late Glacial. Radiocarbon dates of calcareous and organic speleothems indicate that the beginning of formation of some caves took place during the Late Glacial. The subsequent cave development and transformation, marked as the change from concentric to eccentric speleothem growth caused by rotation of rock blocks, occurred in the periods of increasing in climate humidity during the Holocene, particularly in the Preboreal phase, at the transition from the Boreal phase to the Atlantic phase, during the climatic optimum in the decline of the Atlantic phase, at the beginning of the Subboreal phase, and at the beginning of the Subatlantic phase, as well as in the Little Ice Age (Fig. 19.9a) (Urban et al. 2015; Margielewski and Urban 2017). During these phases of more humid climate, an increase in the intensity of mass movements is observed in the Outer Carpathians (Alexandrowicz 1997; Margielewski 2006b, 2018; Pánek et al. 2013; Starkel et al. 2013).

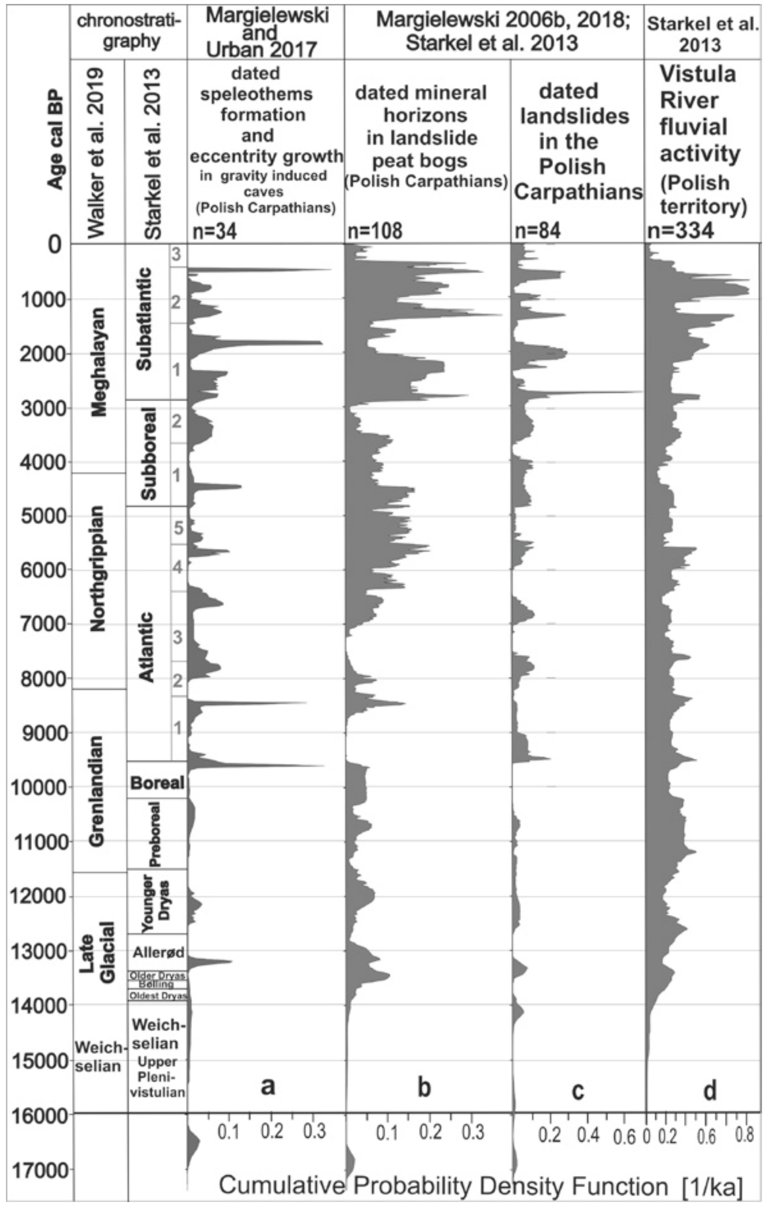

Fig. 19.9 Time range of the formation and transformation of non-karst caves in the Polish Carpathians, on the basis of distribution of radiocarbon dates of non-karst cave speleothems on the cumulative probability density function (column **a**) and correlation with the activity of mass movements (columns **b**, **c**) (after Margielewski and Urban 2017; Margielewski 2018, supplemented), compared with Late Glacial–Holocene phases of climate humidity growth expressed as Upper Vistula River activity (column **d**) (after Starkel et al. 2013). Holocene chronostratigraphy after Starkel et al. (2013) and Walker et al. (2019). Late Glacial chronostratigraphy after Litt et al. (2001). Cumulative probability density function shows the distribution (concentration) of calibrated radiocarbon dates (see Sokal and Rohlf 1981; Michczyńska and Pazdur 2004)

Confirmed by radiocarbon dates, the long-term existence of cracks/caves indicates a long-lasting, continuous evolution of mountain slopes of the flysch Carpathians since the Late Glacial. The system of widened cracks (caves) has existed for thousands of years, which means that the rock massifs, cut by cracks, are in a state of permanent gravitational stress. During more humid phases of the Late Glacial and Holocene, characterized by heavy rainfalls, continuous rains and intensification of river erosion, strong intensification of mass movements in the Carpathians resulted in the finalization of disintegration of rock massifs, which had been long prepared due to crack propagation in response to the gravitational stress. Consequently, the phases of intensification of mass movements (Fig. 19.9b, c) are well correlated with the phases of the increase in fluvial activity of rivers which reflected climate humidity growth (Fig. 19.9d) (Starkel et al. 2013).

19.6 The Value of Caves, Their Protection and Accessibility

The development of gravitationally induced caves has been closely connected with the evolution of slopes in the Outer Carpathians since the Late Glacial. Therefore, scientific studies of these caves, involving observations of their shapes, spatial positions within the slopes/rock massifs, structures outcropped in the caves, ages of cave formations and deformations, provide basic data about the nature of these slopes. Consequently, studies of non-karst caves have been performed in the Outer Carpathians, not only in the Polish segment, for at least two decades (e.g. Margielewski and Urban 2003, 2017; Lenart et al. 2014; Urban et al. 2015; Lenart and Miklin 2016), in order to better understand processes responsible for the morphogenesis of this mountain range. These caves also have significant educational significance as objects illustrating the internal structure of slopes in the Outer Carpathians and processes that have been shaping these slopes. However, the majority of them is hardly accessible for tourists and general public. Firstly, there are natural reasons of this inaccessibility such as difficult exploration of dark, "dirty", and narrow or vertical passages, but the second reason, which recently has limited access to many caves, is closures of entrances to several tens of long caves by steel bars, installed by forestry services in order to protect bat hibernacula and colonies, although the validity and effectiveness of this activity is questioned by some speleologists and naturalists.

The only cave which is intentionally left as accessible for the public and adequately prepared (equipped with ladders) is the Jaskinia Malinowska cave (see Sect. 19.4.1) in the Beskid Śląski Mts. Moreover, descriptions of several other caves situated close to touristic trails and easy to penetrate were published in touristic guidebooks (e.g. Zimna Dziura w Szczeblu—Fig. 19.1b—site 6).

The state of legal protection of caves in Polish part of the Outer Carpathians is not sufficient. Some 20% of these caves, representing about 10% of their total length, are protected in national parks and nature reserves, whereas several per cent of them, but ranging some 25% of their total length, have been declared as nature monuments. Amongst them are four longest caves, exceeding the length of 1 km. Much more caves are situated in landscape parks and special areas of conservation Natura 2000. Nevertheless, the relevance of these caves for abiotic and biotic nature as well as their importance for scientific research has been increasingly realized, and the public attitude to them is changing. This is due to the general increase in environmental awareness in the society related to the development of media, especially the internet, intensively used by groups of naturalists, as well as touristic and caving clubs.

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