15 The Tatra Mountains—Host of the Deepest Caves in the Carpathians

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Abstract

The Tatra Mountains are the highest mountain massif in the Carpathian range, hosting the deepest caves in the belt, reaching a depth of 824 m in the the Wielka Śnieżna Caves System. Cave evolution started at the end of the Miocene and is related to the Tatras' asymmetrical uplift and, during the Pleistocene, to the existence of mountain glaciers. Karst in the Tatras is strongly controlled by fold-and-thrust setting, which influences both underground flow pathways and cave passage morphology. Caves in the Tatras are the only alpine-type karst phenomena in the Western Carpathians and can be defined by containing deep, epigenic multi-level cave systems with proglacial vadose avens, all in the high-relief area shaped by glaciers. Although surface forms are poorly developed, the underground karstic landscape is rich and diverse, with more than 175 km of cave passages. During over a century of research, Polish speleologists have made numerous discoveries, and several of them have become embedded in the global literature, such as the theory of proglacial caves.

Keywords

Cave · Karst · Speleogenesis · Geochronology · Tatra Mts · Carpathians

15.1 Introduction

Caves in the Tatra Mountains (also referred to as "the Tatras") may not seem highly spectacular since speleothems are rare and underground voids are not as roomy as those in other Carpathian caves south of the Tatras. Yet, the uniqueness of the Tatra caves lies in their evolution linked to an uplifting mountain range and mountain glaciers. Interpenetrating these two phenomena on different time scales drove the deepest cave formation in the entire Carpathians. Caves in the Tatras are the only alpine-type karst phenomena in the Western Carpathians. They are deep, epigenic multi-level cave systems with proglacial vadose avens in the high-relief area shaped by glaciers. The only factor distinguishing the karst in the Tatras from those in the Alps or Pyrenees is the scarcity of surface karst phenomena due to the domination of glacial morphology (Kłapyta and Zasadni 2024).

Karst phenomena, especially caves, have been of interest to travellers to the Tatras for centuries. Random visits in Tatra caves began in the early nineteenth century, but the first regular, well-organized exploration was led by the brothers Stefan and Zbigniew Zwoliński from 1913. They explored several caves known by shepherds, mostly horizontal ones, with some short vertical sections. After World War II, caving took on a sporting character, and rope techniques, climbing, diving, and camping in caves started to be popular. The first speleoclub was founded in Kraków in 1950, and later, caving clubs were established in most major Polish cities. Thus, cave mountaineering was born, but since clubs were often located at academic centres, shortly after cave mountaineering, cave research began. In 1960, the seventh deepest cave in the world was discovered, the Śnieżna Cave, with a depth of 563 m, which, in 1968, has been connected to the Nad Kotliny Cave, reaching a depth of 742 m and becoming the sixth deepest cave. Since then, several generations of Polish cavers have been trained in and explored more inaccessible caves. Although the karst area of the Polish part of the Western Tatra only covers about ca. 30 km^2, new caves or new parts in known systems are still being discovered.

In the Polish part of the Tatra Mountains, 860 caves have been mapped to date, with a total length exceeding 175 km; 79 caves are longer than 100 m, and 23 caves are

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Table 15.1 The longest and the deepest caves in the Polish part of the Tatra Mountains

	Cave	Depth (m)	Cave	Length (m)
1	Wielka Śnieżna	824	Wielka Śnieżna	23,619
2	Śnieżna Studnia	805	Śnieżna Studnia	14,020
3	Bańdzioch Kominiarski	562	Wysoka—Za Siedmiu Progami	11,700
4	Mała w Mułowej	555	Miętusia	10,780
5	Wysoka—Za Siedmiu Progami	435	Bańdzioch Kominiarski	10,010
6	Kozia	389	Czarna	7247
7	Ptasia Studnia	352	Ptasia Studnia	6283
8	Miętusia	305	Zimna	5480
9	Czarna	303	Mała w Mułowej	3863
10	Siwy Kocioł	295	Kozia	3470

Source Tatra National Park

longer than 1 km. Only 38 caves are deeper than 50 m. The longest system in Poland and the deepest one in the whole Carpathians is the Wielka Śnieżna cave system (Table 15.1), combining five caves (entrances) with the uppermost one, Wielka Litworowa Cave, located at 1906 m above sea level. Currently, all data, including maps, entrance location, morphometric data, and cave descriptions are freely available at the Central Geological Database, hosted by Polish Geological Institute (http://jaskiniepolski.pgi.gov.pl/). In the Tatra National Park, seven caves have been made accessible for tourists, with marked tourist trails. These are Mylna, Raptawicka, Obłazkowa, and Mroźna in the Kościeliska Valley, Smocza Jama in the Kraków Gorge (with a descent to the Kościeliska Valley), and Dziura Cave in the Ku Dziurze Valley.

A detailed literature review of Tatra cave research was presented by Gradziński et al. (2009). Therefore, the aim of this chapter is to highlight both key historical as well as the most recent (post-2009) discoveries relevant to karst and cave development in the Tatra Mountains.

15.2 Geological Setting and Its Influence on Caves

The Tatra Mountains are a small, 57-km-long range on the Polish-Slovak border, extending W-E, located in the northernmost part of the Central Western Carpathians (Fig. 15.1a). They represent a basement-involved fold-and-thrust structure (Jurewicz 2005) composed of a Palaeozoic crystalline basement overlain by Mesozoic sedimentary rocks in the north and west (Nemčok et al. 1994; Fig. 15.1b). The Tatric sedimentary cover is topped with nappes belonging to Tatric (Czerwone Wierchy, Giewont, Široká nappes), Fatric (Križna nappe), and Hronic units (Choč nappe; Nemčok et al. 1994; Fig. 15.1b). Simplified, the Tatric sedimentary succession starts with Lower Triassic terrestrial siliciclastic deposits and shallow-marine carbonates, is followed by Middle Triassic to Lower Cretaceous limestones (with an Upper Triassic-Lower Jurassic hiatus in the nappe successions), and topped with Albian to Cenomanian marls and sandstones (Nemčok et al. 1994). Therefore, successive tectonic units are separated by non-karstic Lower Triassic or Albian strata, forming distinct hydrogeologic units (Fig. 15.1c, d). Limestone thickness does not exceed 600 m, with an average thickness varying around 400 m (Kotański 1961). Yet, a cave with a depth of more than 800 m could develop due to the asymmetrical uplift. The Tatras constitute a horst exhumed from a depth of at least 5 km since the Miocene to present, with rock uplift rates of 100–500 m/My (Králiková et al. 2014; Anczkiewicz et al. 2015). There is a strong west-to-east gradient in the initiation of rock uplift, with the highest rates in the south-eastern corner of the Tatras (Anczkiewicz et al. 2015). Yet, limestone has been exhumed first in the Western Tatras in the latest Miocene (Králiková et al. 2014), which was the beginning of karst system evolution as we know it today. With the highest exhumation rates along the Sub-Tatra Fault, bounding the Tatras from the south, the Tatra block has been tilted northwards by ~ 40° (Jurewicz 2005). This rotation gave rise to conditions where, despite 400–600 m thickness of limestone, elevational differences between the uppermost limestone outcrops in the summit parts, where the karstic system is recharged, and the lowermost limestone outcrops in the valleys, where karstic springs are located, reached ~ 900 m.

Most caves are in the most uplifted Tatric unit, where carbonate successions are folded and cut by faults that determine the course of drainage and morphology of the cave passages (Szczygieł 2015). In contrast to many large alpine cave systems developed in a monoclinal structure, in which passages developed along facies particularly susceptible to dissolution due to physical, lithological, or chemical properties, the so-called “inception horizons” (e.g. Filipponi et al. 2009), cave passages in the Tatra Mountains were mainly guided by tectonically involved steep initial fissures in both phreatic and vadose passages (Szczygieł 2015; Szczygieł et al. 2015a). The fold geometry has also been influential. Fold hinges facilitated hosting of roomy chambers in chevron folds, whereas in the concentric folds, chambers developed in the fold core and deep shafts in the outer part, along steep bedding planes (Fig. 15.2) (Szczygieł 2015). Faults were used by speleogenesis primarily within the massive and thick-bedded limestone of Upper Jurassic-Lower Cretaceous age (Szczygieł 2015; Szczygieł et al. 2015a). In the thin-bedded limestone and

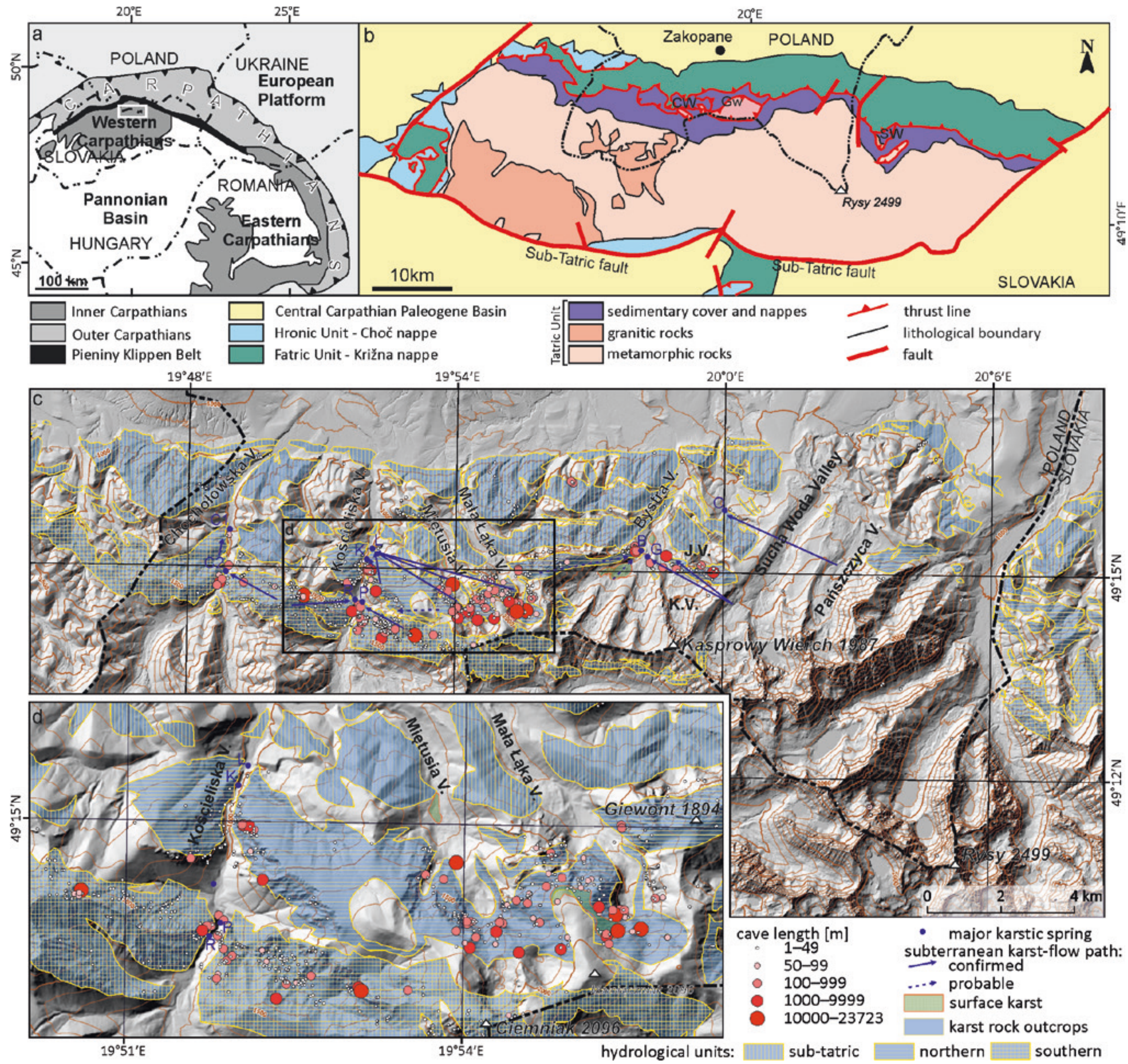

Fig. 15.1 Location of the study area. **a** Simplified geological sketch of the Carpathians with the location of the Tatras marked as the white rectangle. **b** Tectonic map of the Tatra Mountains (after Nemčok et al. 1994, modified), explanation: CW—Czerwone Wierchy nappe, Gw—Giewont nappe, SW—Szeroka Jaworzyńska nappe. **c, d** Outcrops of carbonate rocks and concentrations of surface karst landforms and caves in the Polish part of the Tatra Mountains, overprinted on shaded relief with digital elevation model (based on Szczygieł et al. 2015b); hydrological units after Głazek (1995)

dolomitic limestone of Middle Triassic age, which are usually steeply dipping, the most favourable structures guiding speleogenesis are bedding planes (Szczygieł 2015). The steep bedding resulted in the development of characteristic caves of the Tatra Mountains, which comprise steep vadose passages, the ramps, in Polish called "płytowiec". The floor of such a steep (40–80°) ramp, which is nothing more than a bedding plane, can be as long as ~300 m, with some ledges. Not only tectonic structural geometry affects the drainage, but also neotectonic processes, before and during the formation of the caves. Extending fissures to proto-conduit size, the Quaternary faulting set favourable paths for water drainage, often using the same fissures in subsequent phases of speleogenesis (Szczygieł 2015).

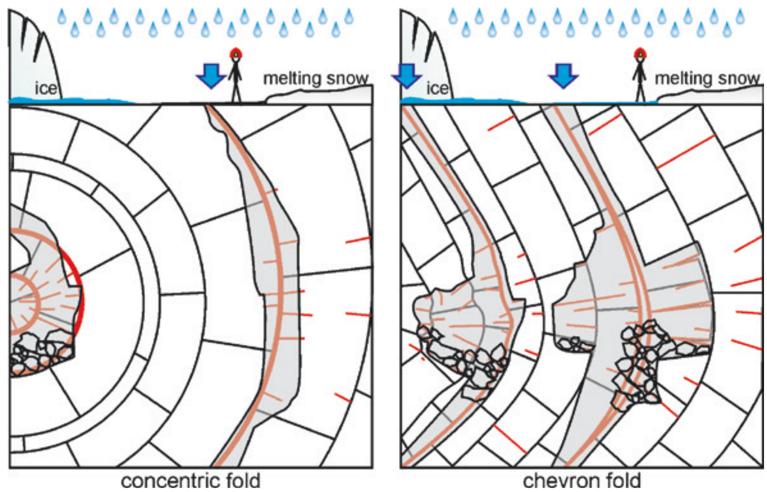

Fig. 15.2 Schematic depiction of the development of chambers and shafts within geometrically different folds; thick red lines—fault; thin red lines—fractures; black lines—bedding planes; grey polygons—cave cross-section. Caver figure is posted to give the definition of a human-accessible passage (a real cave); schematic rain, melting glacier, and snow represents past and present water recharge sources in the Tatra Mts

15.3 Karst Hydrology

Two flow directions dominate in the rocks of the Tatra Mountains: latitudinal flow, consistent with bedding strike and the general structural trend and longitudinal flow, parallel to the surface drainage, i.e. main valley direction. These two directions allow the contact of surface waters with groundwaters of all types (pore, fissure, fissure-karstic groundwater; Małecka 1993). Since the limestone successions are separated from one another by non-karstic rocks, mostly Albian marls, the Tatra karst does not form a single hydrological system but a series of smaller systems isolated from one another. Głazek (1995) distinguished the following hydrological units (Fig. 15.1c, d):

(1) Southern unit, consisting of the Tatric autochthonous sedimentary cover, within which two karstic systems have been developed. The first is the Wypływ spod Pisanej outflow, draining the Kraków Gorge and including the Wysoka—Za Siedmiu Progami Cave; the second one contains the Chochołowskie Spring and Wypływ spod Raptawickiej outflow, draining, among others, Bańdzioch Kominiarski and Szczelina Chochołowska caves. The mean discharge for the Chochołowskie Spring is about 400 dm^3/s (Barczyk 2003).
(2) Northern unit, consisting of the Tatric nappes. It includes the Lodowe (Ice) Spring with a mean minimum discharge of 700 dm^3/s (Barczyk 2003) that drains the Czerwone Wierchy nappe, from the Mała Łąka Valley through the Miętusia Valley to the Kościeliska Valley, and, among many others, the Wielka Śnieżna cave system; the Kraszewski Gate outflow, to which water is supplied, among others, by the Zimna Cave; Bystra and Goryczkowe Springs draining the Giewont nappe, as well as allogenic waters from the upper part of the Sucha Woda Valley (Barczyk 2003), built of crystalline rocks. Spring mean discharges have been estimated at 350 and 800 dm^3/s for Bystra and Goryczkowe Springs, respectively (Barczyk 2003).
(3) Sub-Tatric (*reglowy* in Polish) unit, in which the Olczyskie Spring is located, draining the Pańszczyca Valley, with a mean discharge of 780 dm^3/s (Barczyk 2003). There are no large caves in this unit, and the relatively high discharge is due to allogenic supply from crystalline outcrop areas.

15.4 Surface Karst Landforms

Surface karst forms in the Tatra Mountains are rare and usually isolated or clustered in small areas up to 0.5–2 ha. The only karren field morphologically comparable with the alpine landscape is located in the upper part of the Mała Łąka Valley on the NE slopes of Mt. Małołączniak (Fig. 15.3a). Here, solution dolines and truncated karstic shafts occur within partly bare limestone surfaces with karren, among which rinnenkarren dominate over rundkarren. The most widespread and yet least evident ones are suffosion dolines developed above focused karstic drainage on the top surface of limestone concealed beneath unconsolidated glacial deposits (Fig. 15.3b). Suffosion dolines are commonly found in the lower parts of valleys in the northern part of the Tatras (Sucha Woda Valley, Pańszczyca Valley—Fig. 15.1c), where glacial sediments cover the limestones (Szczygieł et al. 2015b).

Kraków Gorge is a unique karstic landform in the Tatras (Fig. 15.3c) with its upper part called "13-steps couloir" (*pol. Żleb Trzynastu Progów*; Fig. 15.3d). It is a non-glaciated valley, only periodically drained by a surface stream, characterized by vertical or overhanging walls of which the highest one, the Ratusz, is 170 m high. The meandering gorge is locally as narrow as 3 m and is interspersed with a series of steps ranging in height from 2 to 8 m, with plunge pools beneath. Lindner (1985) hypothesized that the Kraków Gorge developed from a collapsed cave. However,

Fig. 15.3 Examples of surface karst morphological features from Tatra caves. **a** Karren in the upper part of the Mała Łąka Valley (photograph by M. Golicz). **b** Suffosion doline in the upper part of the Sucha Woda Valley (photograph by A. Tyc). **c** Kraków Gorge (photograph by J. Nowak). **d** "13-steps couloir" (*pol. Żleb Trzynastu Progów)* in the upper part of the Kraków Gorge (photograph by J. Szczygieł)

this model is neither supported by the gorge morphology, which indicates successive deepening, nor by the chronology that clearly shows that the gorge is older than Lindner (1985) suggested (Szczygieł et al. 2020).

15.5 Cave Morphology

Cave systems in the Tatras have developed simultaneously to mountain uplift and following valley incision, expressed in a vertical pattern where paleo-phreatic cave levels are connected or intersected with vadose vertical sections. Cave levels as an indicator of former positions of valley bottoms have been recognized in the Polish Tatra by Rudnicki (1958), who first distinguished three levels and, later, four (Rudnicki 1967). Wójcik (1960), based on the occurrence of allochthonous gravels within the caves, claimed the existence of eight levels. However, this was not reflected in the vertical distribution of the corridors relative to the valley bottoms. Rudnicki´s observations, based on approximately 20 km of known cave passages at that time, are still valid, even with a much larger dataset established recently. One more level has, however, been added, which was undiscovered at that time, namely the uppermost relict cave level. Currently, five cave levels are distinguished in the Tatras, including the active one (Szczygieł et al. 2020; Fig. 15.4). The vertical span of the cave levels is more extensive in the lower parts of the valleys. Moreover, according to the analysis of paleoflows, some deep paleo-phreatic caves in the Tatras, e.g. the Czarna Cave with the depth exceeding 200 m, represent one cave level, resulting from the formation by deeper circulation in the so-called "phreatic loop" (sensu Ford and Ewers 1978). The above conditions have caused more cave levels to appear in purely morphometric terms than implied by the karst system's evolution, which might explain the excessive number of cave levels designated by Wójcik (1960, 1968) and later by Grodzicki (1991).

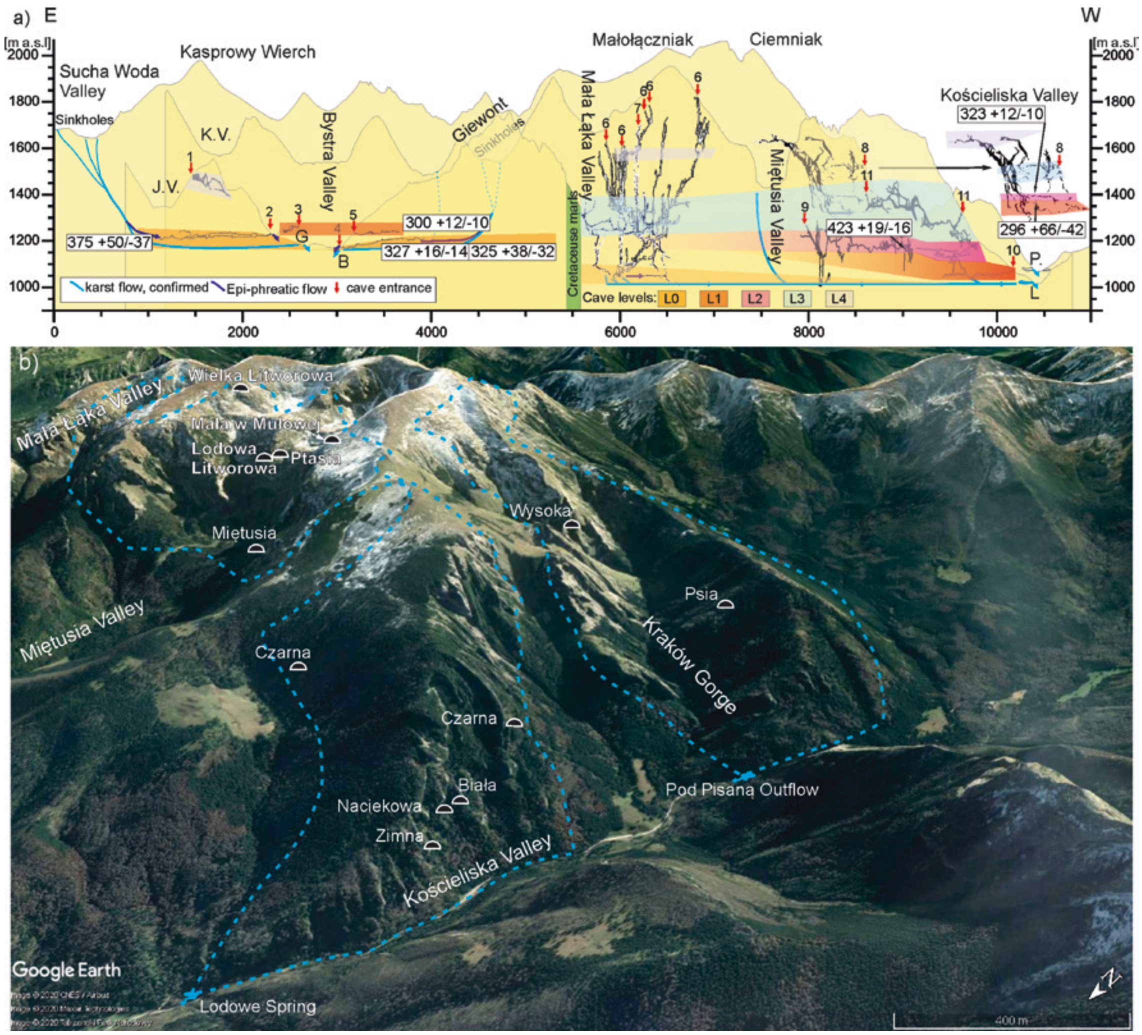

Fig. 15.4 Setting of major cave systems in the Polish part of the Tatra Mountains. **a** Cave systems projected onto superimposed topographic profiles across the Bystra and Kościeliska valleys. Cave levels are colour-coded, from the oldest (L4) to the youngest (L0) (after Szczygieł et al. 2020). K.V.—Kasprowa Valley, J.V.—Jaworzynka Valley; Springs: G—Goryczkowe, B—Bystrej, P—Pod Pisaną, L—Lodowe; Caves: 1—Magurska; 2—Kasprowa Niżna; 3—Goryczkowa; 4—Bystra; 5—Kalacka; 6—Wielka Śnieżna; 7—Śnieżna Studnia; 8—Wysoka; 9—Miętusia; 10—Zimna; 11—Czarna. **b** Panoramic view of the central-eastern Kościeliska Valley with the position of caves mentioned in text and the outlines of catchments (blue dashed lines)

At the passage scale, cave morphology is dominated by two genetic types: vadose and phreatic. Vadose conduits, if horizontal or gently inclined, are high and narrow canyons, often meandering (e.g. Wodociąg passage in the Śnieżna Cave). Sub-horizontal sections are frequently divided by vertical steps. The steeper sections often widen downwards, with overhanging walls due to headward erosion (e.g. Majowy Meander in the Ptasia Studnia Cave; West Gang in the Śnieżna Studnia cave, Fig. 15.5a). The canyons usually have a width of 0.3–2 m (e.g. Lodowa Litworowa Cave). Although height cannot be measured precisely, the most spectacular passages could be as high as 40 m (e.g. Wielki Kanion passage in the Wysoka—Za Siedmiu Progami cave system, and Kanion in the Ptasia Studnia Cave, Fig. 15.5b). Among steep and vertical conduits, besides shafts, the above-mentioned ramps are common (Fig. 15.5c). The deepest, 230-m-deep Wazeliniarzy shaft (Fig. 15.5d), is located in the Śnieżna Studnia Cave. Shafts follow the canyon/meander curvature due to headward erosion or are tube-shaped (e.g. Wielka Studnia shaft in the Śnieżna Cave, see Fig. 15.5e, or the entrance shaft of the Ptasia Studnia Cave). It is assumed that the vertical tubes have been produced by whirlpools resulting from the vast amount of glacial meltwater during deglaciation, hence the term "proglacial cave" (Głazek et al. 1977). The original concept by Głazek et al. (1977), linking the origin of high-elevation vertical caves, as well as steep parts in other caves, with the action of waters from melting glaciers, should be emphasized since the expression "proglacial cave" has subsequently become an established term in the world literature.

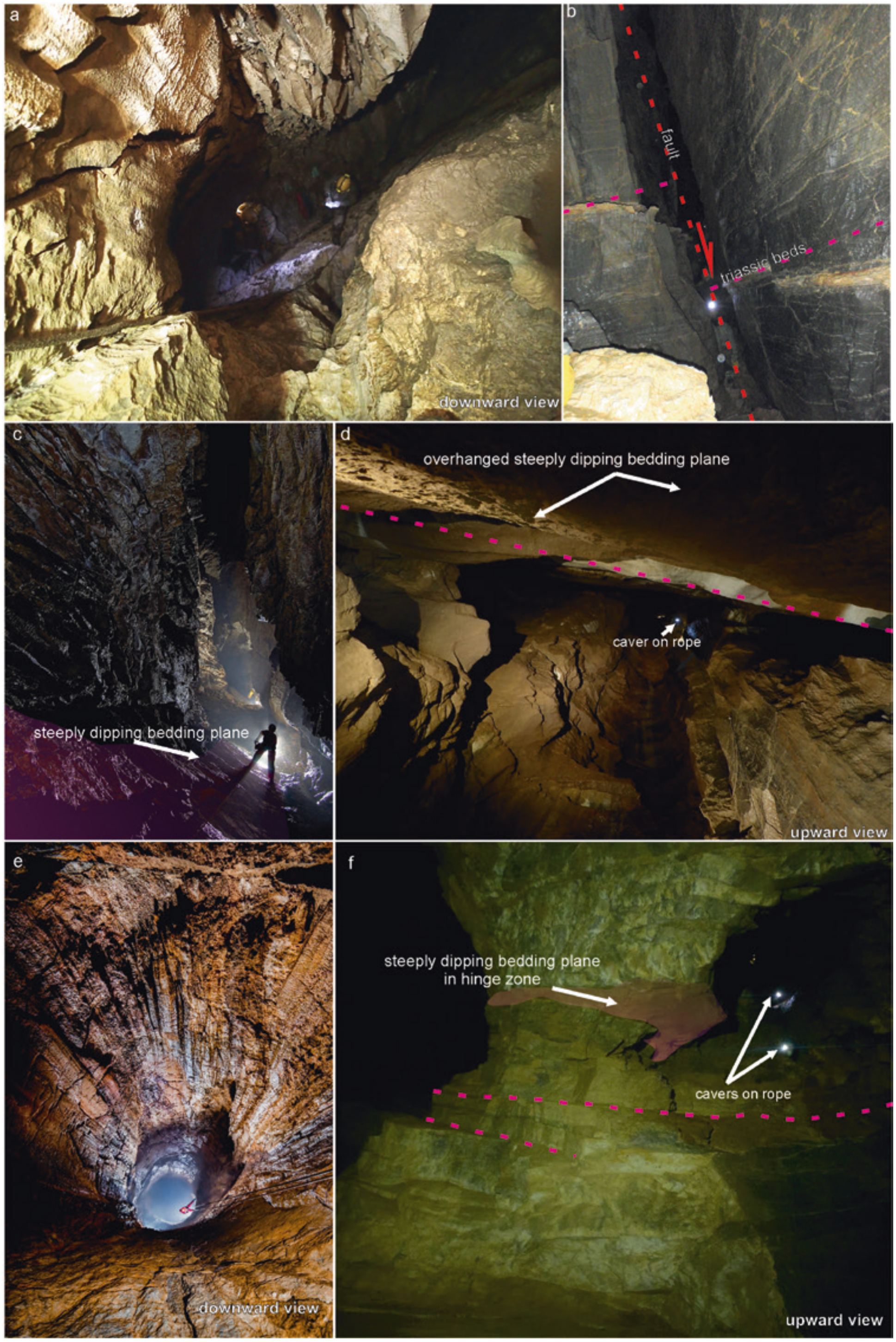

Fig. 15.5 Examples of vadose morphological features from Tatra caves. **a** overhanging step in the Śnieżna Studnia cave. **b** Kanion passage in the Ptasia Studnia cave. **c** Płytowiec in the Wielka Śnieżna cave. **d** Wazeliniarzy Shaft in the Śnieżna Studnia Cave, note the guiding bedding plane. **e** Wielka Studnia in the Wielka Śnieżna Cave, note circular cross-section. **f** Fakro Chamber in the Mała w Mułowej Cave (photographs c and e by J. Kućmierz; a, d, and f by M. Golicz; b by J. Szczygieł)

Along with typical tube-like phreatic conduits (Fig. 15.6a), lens-shaped passages, elongated vertically or diagonally, are also frequent. There are cases in which the ratio of height to width of such lenses exceeds 10, or several enlargements are formed on a single fissure, and the cross-section resembles an elongated figure eight (common in the Szczelina Chochołowska cave—Fig. 15.6b; Zimna and Czarna caves). Phreatic passages are from 0.3 to 2–4 m in diameter (e.g. Wysoka, Miętusia, Szczelina Chochołowska caves). The exceptionally roomy ones are conduits in the Czarna Cave, with an average height of 10–20 m (locally even ~ 30 m) and a width of 5 m (Fig. 15.6d, e). In cases where water was drained through the fault zone in massive limestones, via a network of

Fig. 15.6 Examples of phreatic morphological features from the Tatra caves. **a** Phreatic tube, the Szczelina Chochołowska Cave, note circular cross-section. **b** Passage with the cross-section of an elongated “8”, the Szczelina Chochołowska Cave. **c** Looping conduits in the Kasprowa Niżna Cave. **d, e** Conduits in the Czarna Cave. **f** Keyhole passage leading to the Zwolińskich Sump in the Miętusia Cave, note the line indicating sump-level fluctuation (black arrow) (photographs by J. Szczygieł)

fissures, maze caves with loops and anastomoses have developed (e.g. Goryczkowa and Kasprowa Niżna caves, Fig. 15.6c); those passages are usually narrow (up to 1 m wide). Noteworthy are the conduits going around the siphon filled with deposits, first described in the Zimna Cave by Rudnicki (1960) as a corkscrew (pol. *korkociąg*), later described by Ford (1965) as a bypass. If the paleo-phreatic cave level was intersected with vadose conduits, water used the existing paleo-phreatic conduits by cutting a channel into their bottoms, creating a keyhole cross-section (e.g. Galeriowy passage in the Zimna Cave, or passage leading to Zwolińskich Sump in the Miętusia Cave, Fig. 15.6f).

In both genetic types, paleo-phreatic and vadose, conduits may expand over time due to collapses and/or local geological settings (see Sect. 15.2) to form larger voids customarily referred to as chambers or halls. Although chambers are not precisely defined, and generally, their designation is quite arbitrary, there are several distinctly more “roomy sites” in the Tatra caves. The biggest one is the Fakro Chamber in the Mała w Mułowej Cave, with floor dimensions of 85 m × 45 m and 90 m in height (Fig. 15.5f). It has been formed at the junction of two vadose shafts, in the core part of the concentric and recumbent Organy syncline hinge zone (Szczygieł et al. 2014; Szczygieł 2015). Deeper in the Mała w Mułowej Cave, the Na Luzie Chamber is located. Although not as large, the chamber is genetically unique since it developed along the thrust of the Czerwone Wierchy nappe over the autochthonous sedimentary cover. The Na Luzie Chamber and the passages leading to and from it were formed within the Albian marls due to mechanical fluvial erosion of low-resistant rocks. The Middle Triassic limestones form an overhanging ceiling (Szczygieł et al. 2014), often bearing no signs of karst erosion. One of the roomiest among the caves of the Tatra Mountains is the entrance part of the Magurska Cave, which is situated within the syncline hinge (Hercman 1989), just as the Fakro chamber. These entrance chambers, however, are paleo-phreatic, with a more arch-like ceiling. They are, however, more spacious than the passages leading deeper into the massif, which were closed by sediment-filled siphons until as late as the twentieth century. The disproportionately large volume of the entrance part may be a partial result of frost weathering, a process that has been described in detail in the Alps (Oberender and Plan 2015). Thus, the passage volume, or rather the cross-section area, is not necessarily proportional to the paleoflow as it may have been enlarged after the cave was drained.

A unique cave in the Polish part of the Tatras is the Dziura Cave, as it is hypogenic and not epigenic as the other caves. Bac and Rudnicki (1978) inferred the thermal stage of development of this cave based on the ceiling morphology of this roomy chamber, which was later confirmed by geochemical studies (Gradziński et al. 2007).

15.6 Cave Development in the Tatra Mountains

The cave levels described above demonstrate a multi-stage development of the karst system in the Tatras. Turmoil, with the determination of these levels, indicates that the evolution of caves in the Tatra Mountains is not easy to decipher. In general, dating of cave sediments is crucial in reconstructing karst system evolution. Isotopic dating of sediments from the Tatra caves began early and has long followed global trends (Głazek 1984; Hercman 1991). However, in the twenty-first century, Polish speleothem researchers turned to palaeoclimatic studies, whereas palaeogeographic reconstructions (in terms of dating) became less popular. Consequently, the U–Pb speleothem dating or Be/Al cosmogenic nuclide burial age dating, which have been developed in the last two decades, have not yet been employed. However, this does not mean that data obtained from "classic" U-Th dating of speleothems cannot be used to disentangle the evolutionary history of the caves; quite to the contrary.

The oldest relict karst forms are assumed to have formed in the latest Miocene or Pliocene (Rudnicki 1967; Hercman 1991). Although there is no direct geochronological evidence, this is inferred from their topographic position relative to Miocene exhumation rates (Szczygieł et al. 2020). Hitherto, the oldest ages were yielded by speleothems from the Czarna Cave, cave level L3 (Fig. 15.4a). Although the speleothems' age is out of range of the applied dating method (i.e. 0.6 Ma), based on the U^{234}/U^{238} ratio, their age can be estimated at being older than 1.2 Ma, indicating that the phreatic evolution of the Czarna Cave had ended by that time (Nowicki 2003). The age of speleothems in the Naciekowa Cave (cave level L2; Fig. 15.4a) ranges between 0.6 and 1.2 Ma, pointing to the interval in which the L2 level was dried out (Nowicki 2003); thus, the L1 level must have operated as active drainage at that time. The speleothems from active epiphreatic caves, at or below the valley bottoms, belong to the modern cave level (L0; Fig. 15.4a), with yield ages between 284 and 325 ka. This shows that the modern karst drainage system of the Tatra Mountains was established before the late Middle Pleistocene (Szczygieł et al. 2020). Since then, no significant valley deepening occurred, which would force the water table to lower and result in the development of new phreatic conduits.

From the palaeogeographic point of view, the main directions of the drainage network did not change over time. Already since the formation of the oldest cave levels, the major valleys ran south to north, and groundwater was transported along the W–E structural trend, with minor exceptions representing underground flow of surface streams from S to N. As inferred from scallops—erosional forms on cave walls whose asymmetry is related to the flow direction—the paleoflow directions in caves located between the Mała Łąka and Kościeliska valleys were from east to west (Gradziński and Kicińska 2002; Kicińska 2005; Fryś et al. 2006). The Lodowe Spring system has not experienced direction change but only successive deepening following base-level lowering. Only in some caves, whose entrances were covered by glaciers, the paleoflows from entrances into the cave were recorded. These scallops, however, are overprinted on the original ones and represent the stage of backflooding connected with the rising of the water table during glaciation (Kicińska 2005).

The karst system in the Bystra Valley is fed, in addition to autigenic supply, with allogenic water from the upper part of the Sucha Woda Valley. As inferred from the scallop asymmetry and heavy minerals analysis, the allogenic water was initially transported to the Jaworzynka Valley, which is now dry. Later, this water was captured by the incising Kasprowa Valley (Kicińska et al. 2017), which must have taken place no later than ~ 300 ka, as inferred from the oldest dates obtained from the Kaprowa Niżna Cave (Szczygieł et al. 2020).

15.7 Conclusions

The caves in the Tatra Mountains are an outstanding phenomenon of both scientific and touristic/sport value. This system represents the only high-mountain karst system in the Western Carpathians and the deepest one in the whole Carpathian Mountain range.

Polish speleologists began research in this area in the early twentieth century, but great progress has been made since the

1950s. Jan Rudnicki made many pioneering observations, published in Polish, such as the idea of "bypass passages" (1960). One of the most important contributions to speleology seems to be the concept of proglacial caves, described by Głazek et al. (1977). Geochronological research followed global trends in the twentieth century, slightly lagging behind in the last 20 years. However, nowadays, research using cosmogenic nuclide dating is being carried out, which will certainly help to set another milestone in the research of the Tatra Cave evolution. Although much has been done, there are still many unsolved questions about the timing and rates of the morphogenetic processes in terms of karst system development as well as the Quaternary evolution of the Tatra Mountains.

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