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Subterranean Physiography

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Abstract

This chapter is a general overview on caves. It presents a genetic classification of caves, a description of their patterns and a systematization of karstic cave types. The hydrology, morphology, fill, climate, and development of caves are also included here.

***Keywords:** syngenetic cave, postgenetic cave, non-karst cave, karst cave, cave genetics, cave pattern, epigene cave, phreatic cave, hypogene cave.*

Introduction

Cave is a natural cavity with a longitudinal axis of more than 2m which is passable by humans. Not every cavity is a cave only that which has an entrance. Caves might have had entrances at the time of their evolution, but many cavities did not have any. These latter could have reached their form with an entrance during opening-up. Opening might be caused by the collapse of the cavity [1,2], fluvial erosion [3], glacial erosion [4], abrasion, the karstic denudation of the terrain of the karst or by human activity (for example mining).

According to the development age of their host rock, caves can be syngenetic and postgenetic (later we will see that this classification also means a genetic classification). Both syngenetic and postgenetic caves may be paleokarstic cavities (they developed in the geologic past) and recent. The development age of syngenetic caves coincides with the development of the host rock (rock development results in cavity development). The development of postgenetic caves is younger than that of their host rock. The two development ages may be significantly different, the age of the host rock may also be some 100 million years, while the age of the cave may be younger than some million years. In spite of this, the age of caves (development age and age of existence must be distinguished, where the latter is larger than the former) may be very different. In relation to the age of caves, the term potential maximum age is used which may be the age of the host rock too (at syngenetic caves) and the potential minimum age which is the age of the oldest rock in the cave. Potential lifespan is the difference of the two [5]. Paleokarstic caves, which in principle, could have been formed at any time in the geological history, may be fossil (filled) and relict (non-filled). Recent caves, the evolution and development of which began preceding the Holocene, may be active (they develop and grow) and inactive (they are destroyed and become filled). The active state coincides with the evolution and development of the cave. Apart from paleokarstic cavities, the caves are young. Regarding potential minimum age, caves older than 150 thousand years rarely occur among postgenetic caves. There are only some caves older than the Pleistocene, for example the 3.5-million-year-old Mammoth-cave [6] (Kentucky, USA). Their active state is even shorter. The duration of existence of a cave depends on (this is the time between the start of the development and the decay of the cave), the speed of infilling, the thickness of the ceiling, the size of the cave, the characteristics of the flow system of the karst and on the quality of the host rock. Thus, if the host rock is a loose sediment (loess), the cave survives at most until a hundred or a thousand years. According to the above-mentioned things, the age of existence of postgenetic caves or their potential minimum age may range from some thousand years to some million years. The fill of fossil caves may be destroyed in a suitable environment and in this case, they are often transformed in a renewed condition and continue their development.

A genetic classification of caves

The here presented genetic types are based on the works of Sweeting [7], Balázs [8], Müller [9], Jakucs [10], Szunyogh [11], Jennings [12], White [13], Halliday [14], Veress [15], Ford and Williams [16], Klimchouk [17,18], Passini [19] Goldscheider et al. [20], Martini and Grimes [21], Veress and Unger [22] and on the related chapters of the work, "Encyclopedia of Caves and Karst Sciences" published in 2004 and 2012.

The evolution and development of caves is determined by the geological characteristics of the host rock thus, rock quality, stratification and crust structure. In well-bedded rocks, cavity development starts along bedding planes. As regards rock quality, caves develop in strata or beds which is less resistant to the effect of cavity formation, or caves may also be formed in a more resistant bed, but there the cave is less developed. Caves of dissolution origin mainly develop above impermeable beds since the water that accumulated above the impermeable beds causes increased dissolution. The degree of stratification may also affect the site of cavity formation: cavity formation often takes place in thinner beds surrounded by thick beds probably because there are several water discharging paths along the bedding planes and thus, dissolution is cumulated. However, erosion caves often develop in the intercalated non-karstic beds since their resistivity to erosion is of lower degree than that of soluble rock. Among the elements of crust structure, faults, fractures and folds control cavity formation. Caves that developed along bedding planes are of small height, while the height of those which were formed along fractures exceeds their width. The spatial position of caves that developed along bedding planes coincides with the spatial position of the bed, while that of caves which developed along fractures corresponds with the spatial position of the fracture. In case of caves guided by folds, the caves are situated in the core or at the outer surface of the anticlinal.

Both syngenetic and postgenetic caves may be of non-karstic (pseudokarst caves) and karstic origin. Syngenetic, non-karstic (pseudokarst) caves may develop by wreathing or by the cooling down of the melt. In case of wreathing, the crust-like development of the developing (precipitating) travertine encloses cavities. There is beard moss on the precipitated limestone on which a crust develops by further precipitation and a new moss beard grows on it. Finally, the crust developing in this way surrounds and encloses space sections. The enclosed cavities have a diameter of some metres, they are spherical and may be aligned in all directions of the space. The cavities are isolated and are connected by human activity. The Anna Cave in the Bükk Mountains (Hungary) is an example for this.

Coral caves also develop by wreathing. In this case, the growth of corals results in the development of more or less enclosed cavities. Solidification fissures and lava caverns develop by cooling down. Solidification fissures are formed by volume decrease during the cooling down of the melt. They are characteristics of granite. Lava cavities include lava caves, amygdales, lava shafts and tree mould cavities. Lava caves develop when the surface of the thinly fluid lava (mainly basalt, basalt lava) gets a crust during its cooling and then it receives a load from the upper end of the lava. The still molten material breaks through the crust and flows from beneath. Tube-like caves with a length of several kilometres and with a height and width of more than 10 metres may develop in this way. (They often occur in Iceland and on the Hawaii islands.) Gas bubble cavities (amygdales) are formed at sites where the gases leaving the lava expel the melt. Caves developing in this way have a diameter of some metres and are spheroid. Lava shafts develop by the collapse of the ceiling of lava caves. Tree mould cavities are formed when trees are covered by lava. The material of trees are coalified to heat-effect and then they are destroyed and a cave is formed whose size is identical with the size of the trunk. Such caves commonly occur on Mount Fuji (Japan) where the fill was removed by mining activities. Caves of syngenetic origin may also develop by the dissolution of the calcareous sand of coastal dunes.

As it has already been mentioned, postgenetic caves may also be of karstic and non-karstic origin. Those of non-karstic origin are not formed by dissolution, but they develop by any other process, while caves of karstic origin develop by dissolution. Caves of non-karstic origin develop by volcanic processes, tectonics, mass movement, volume change, abrasion, deflation, fluvial erosion, suffosion, partial dissolution and ice melting. Fissure caves are of tectonic origin which develop by the drawing-away of rock blocks along fissure from each other. (These often continue their development to a greater or lesser degree by dissolution if they were formed in a soluble rock.) In ground plan, these caves are vertically elongated cavities surrounded by straight and parallel walls. Caves of mass movement develop as a result of the displacement of rock blocks. It may occur that falling rock blocks or rock blocks slipping from each other (the bedrock becomes smooth because of absorption of water) surround cavities. In the former case, the cavity is small and irregular, while in the latter it is vertically elongated. In case of absorption of water (anhydrite is transformed into gypsum) volume increase takes place. Beds of an increased volume deviate upwards and thus, a cavity is formed below them. Sea caves develop in the intertidal (low-tide - high-tide) zone in any rocks to the effect of waves. They can develop along fractures or at sites in the intertidal zone where the shore is built up of rocks being less resistant to waves. The upper end of sea caves is marked by the high-tide level. Caves that developed along less resistant rocks are wide and their position is similar to the spatial position of the rocks. Deflation caves develop on cliff walls being exposed to wind especially in deserts, in beds that are less resistant to the destruction of the wind. The size of these caves is small. Erosion caves are formed at the concave side of river bends. Here, the sidewall is undermined at the drift line that fits close to the channel wall. These caves are wide and their length is short. To the effect of frost weathering the rock is destroyed along fractures or karstic cavities with a wide entrance are transformed. Tafoni are spheroidal, spherical cap-like, short features of some metres that mainly develop in granite. On granite their development may be influenced by the role of the rock structure, weathering, thermal fluctuation, insolation, wind erosion, hydration and salt corrosion.

Pseudokarst caves develop in sediments (clay, volcanic tuff, laterite). Their length is not significant, but it can exceed 100 m sometimes. A development factor may be piping, suffosion or the decay of rock grains by which residue grains are separated from the rock and transported away. Pseudokarst caves may occur in different environments (permafrost, badland, peat).

Pseudokarst caves may also develop during partial dissolution though in this case other processes also affect cavity formation. Partial dissolution may take place on greenschist, on limestone phyllite, and on loess. On greenschist or on limestone phyllite, cavities are formed on the calcareous intercalation. (The size and position of the cavity coincides with the size and position of the calcareous intercalation.) On loess, inflow caves or through caves may develop in a length of some ten metres to the effect of dissolution, suffosion and erosion. Through caves also have horizontal parts above the calcareous and partly impermeable beds in loess.

Glacial caves develop in ice. The surface meltwaters of the ice get into the glacier through the fissures and ponors of ice or the waters of the surrounding terrain at the margin of the glacier. The inflowing waters melt the ice and create caves in or under the glacier. A cave system with a length of several kilometres consisting of a main branch and tributary branches may especially develop along the glacier stream in larger glaciers. Caves that developed in ice are not stable features.

Caves of karstic origin develop by dissolution and then they continue their development by dissolution (and by closely related erosion). Dissolution is caused by waters of low pH on carbonate rocks (limestone, dolomite), by neutral waters on evaporates (gypsum, halite) and by waters of high pH on sandstones. Mainly dissolution of low pH value (mainly carbonated) has the following varieties:
- Since surface waters have a carbonic acid content (which is formed by the consumption of the CO_2 of water), they dissolve the rock until they become saturated.
- In case of mixing corrosion, dissolution effect occurs at saturated waters of various hardness and temperature.
- The upward pushing hot water causes dissolution.
- The rising water takes CO_2 and H_2SO_4 with it.
- The ascending hot water cools down its equilibrium CO_2 (which keeps its dissolved material in solution) is released and produces carbonic acid.
- Warm waters of caves evaporate, as vapour precipitates on the ceiling of the cavity, it produces condensing water. Carbon-dioxide enters this and thus, the condensing water will have a dissolution capacity.
- The rising water gets into an environment of pyrites where H_2SO_4 is produced.
- Paragenetic dissolution takes place. As a result of the infilling of caves, water fill is pressed to the ceiling where an upward migrating dissolution takes place.

On karsts, cave development has at least two special cases: cave development of carbonate islands and of glaciokarsts. On ocean islands, freshwater limestone zone is solely built up of carbonate rocks which floats on saline water due to its lighter specific gravity, along the lower and upper surface of this zone cavities are formed by mixing corrosion. If they open up, they are called banana holes. Where the two boundaries are close to each other, the cavity development is added. Caves are constituted by rows of chamber called flank margin covers and tributary branches branching out of chambers. If non-carbonate rock is situated below carbonate rocks, seepage dissolution effect taking place along the rock boundary also plays a role in cavity development in addition to the above effect. On glaciokarsts, the alternation of glacials and interglacials influenced cave development. For example, during the glacial, the karstwater level decreases, surface streams enter the caves and erosion takes place. In the interglacials first the quantity of meltwater increases and then the CO_2 content of infiltrating waters and thus, dissolution effect too. The cavity development of coasts is also affected by the alternation of the glacials and interglacials. In the interglacial, abrasion cavity and karstic cavity development is shifted upwards due to the rising altitude and caves of lower elevation are filled with saline water. Dissolution stops in the latter. In the glacials, cavity development is shifted downwards due to altitude lowering and older cavities may be reactivated.

The decrease of the karst base level of erosion or the elevation of the karst results in the development of cavity formation levels. The above processes result in the sinking of the karstwater level (sinking of the base level of erosion) and the increase of the thickness of the vadose zone (the elevation of the karst). The sinking of the karstwater level or the increase of the thickness of the vadose zone result in the development of spring cave levels where the spring caves with the lowest elevation are the youngest and active, while those of greater elevation are older and waterless. Cavities that became dry may develop into erosion caves by erosion, later storeyed cave systems may develop during discontinuous elevation (see below).

According to the development site of the cave, epigene caves, vadose caves, epiphreatic caves, phreatic caves, deep-phreatic caves, artesian water caves, cold-water caves, warm-water caves and hypogene caves can be distinguished (Fig. 1). Epigene caves develop by surface streams with dissolution capacity or by erosion at the descending branches of regional flows and at local flows and they are mainly of vertical position. Epigene caves consist of vertical (or nearly vertical) and canyon-like corridors.

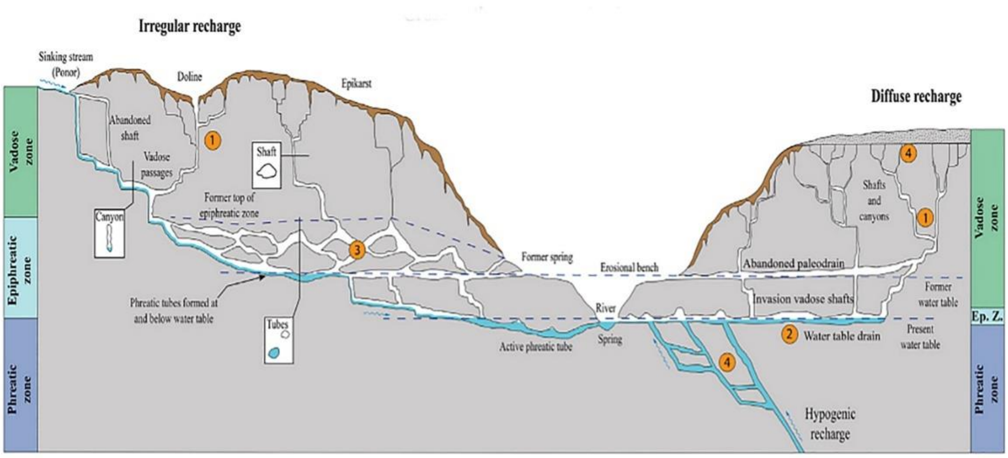

Figure 1: Zones of cave development [23]

Legend: 1. Branchwork cave, 2. Elongated branchwork, 3. Anastomotic maze, 4. Angular maze

Epiphreatic caves are situated in the fluctuation zone of karst water, phreatic caves are located at the upper part of the zone permanently filled by karstwater, while deep-phreatic are at the lower part of the zone permanently filled by karstwater. While caves being close to the karst water level are rather of horizontal position, deep-phreatic caves are dissected and are constituted by sections with various inclination and they often have a round diameter. Epihreatic caves are of horizontal or oblique position. Artesian water caves develop in the flow zone of artesian water. Mixing corrosion, erosion and paragenesis play a role in the development of caves of the epiphreatic zone. Deeper and deeper downwards in the karst (phreatic, deep-phreatic, artesian water caves) mixing corrosion, paragenesis and hypogene effect will become dominant and more and more significant. Hypogene karst and its caves develop at the ascending branches of regional flows (Fig. 2). These flows have warm water or lukewarm water if they are mixed with cold karstwater. Cave development is influenced by the high CO_2 content of the water (carbonated dissolution), the high H_2S content (sulphuric acid dissolution) and mixing corrosion. The caves are developed spatially, but expanded vertically, their ground-plan is network-like (Fig. 3), their features are mainly spherical cavities, but concretions of hot water origin and mineral concretions are also common (gypsum crystals, aragonite, barite, hot-water calcite). (By cold water we mean water with a temperature below 20°C, by lukewarm water, water with a temperature of 20-36.7°C, and by hot water, water with a temperature above 36.7°C). It often occurs that phreatic caves of cold water origin are transformed into warm-water caves during their development since warm water or hot water is injected into the zone filled by karst water.

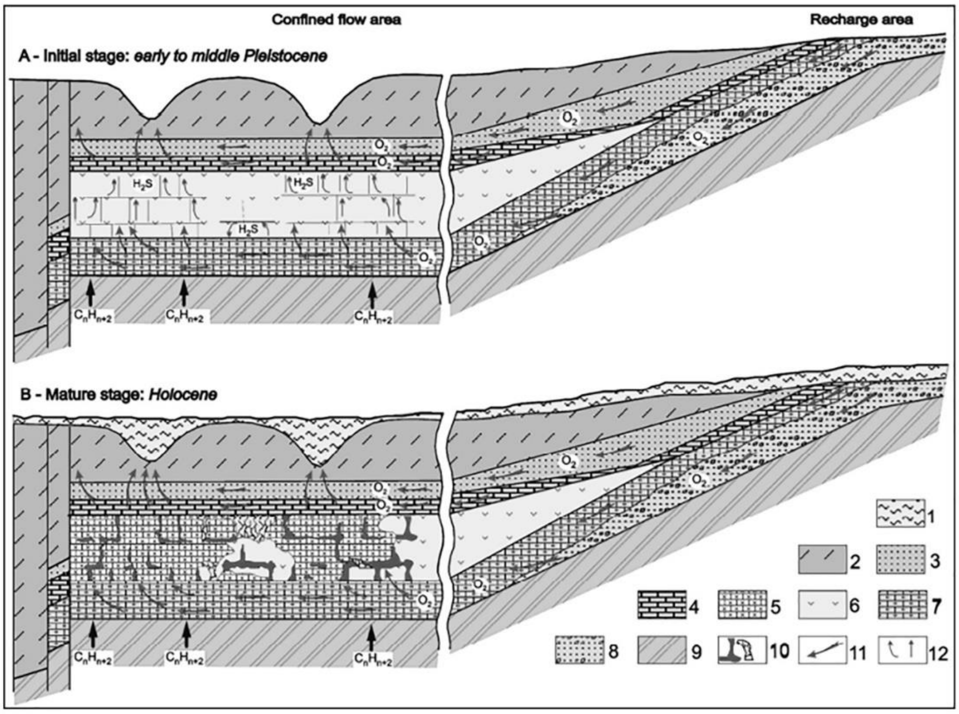

Figure 2: Conceptual model of hypogene caves [17]

Legend: 1. sand and loam, 2. clay and marl, 3. sandstones, Ratynsky limestones, 5. epigenetic sulfur-bearing and barren limestones, 6. gypsum and anhydrite, 7. lithothamnion limestone, 8. sand and sandstone, 9. marl and argillaceous limestone, 10. dissolutional cavities, 11. flow patterns in main aquifers, 12. flow patterns through karst systems.

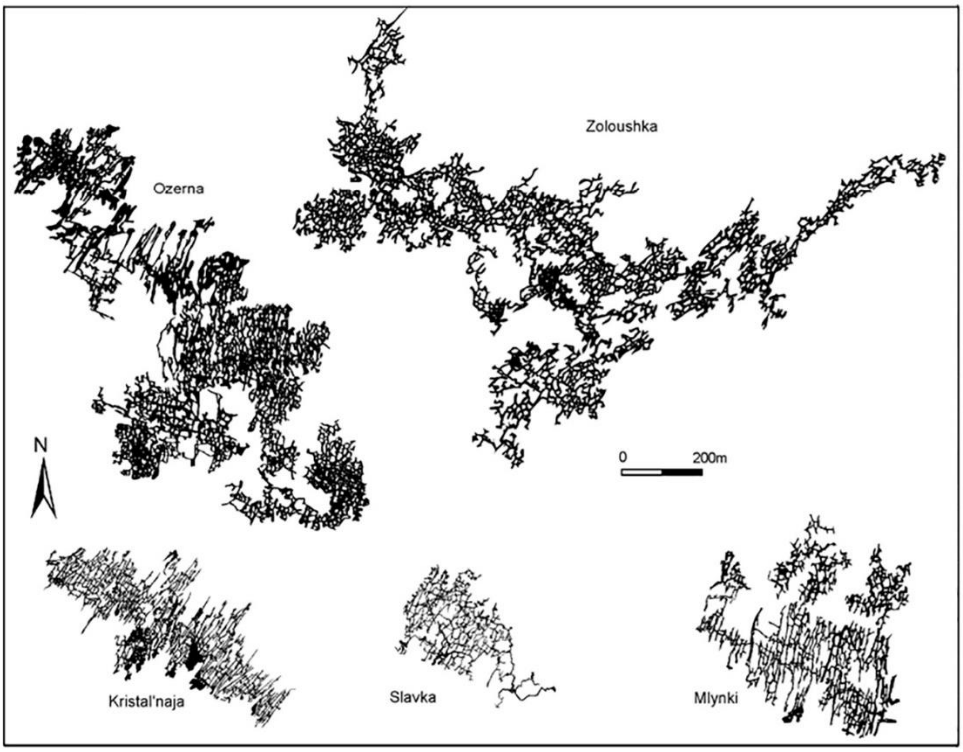

Figure 3: Maze gypsum caves in Ukraine [17]

According to the site and direction of cavity formation, karst caves can be shafts, inflow caves, footcaves, spring caves, through caves and multilevel caves. Shafts, inflow caves, through caves, multilevel caves, footcaves and katavotra develop at the water supply places of the karst. Shaft caves (Fig. 4ABC) are the epigene caves of the vadose zone with a nearly vertical position (Fig. 5), but half tubes branching out of these and low-inclined passages connecting shaft sections, the vadose canyons are also common. They are more widespread on karsts where superficial water supply is significant and the vadose zone has a great thickness (glaciokarst). If the vadose zone is thick, they may have a depth of several hundreds of meters.

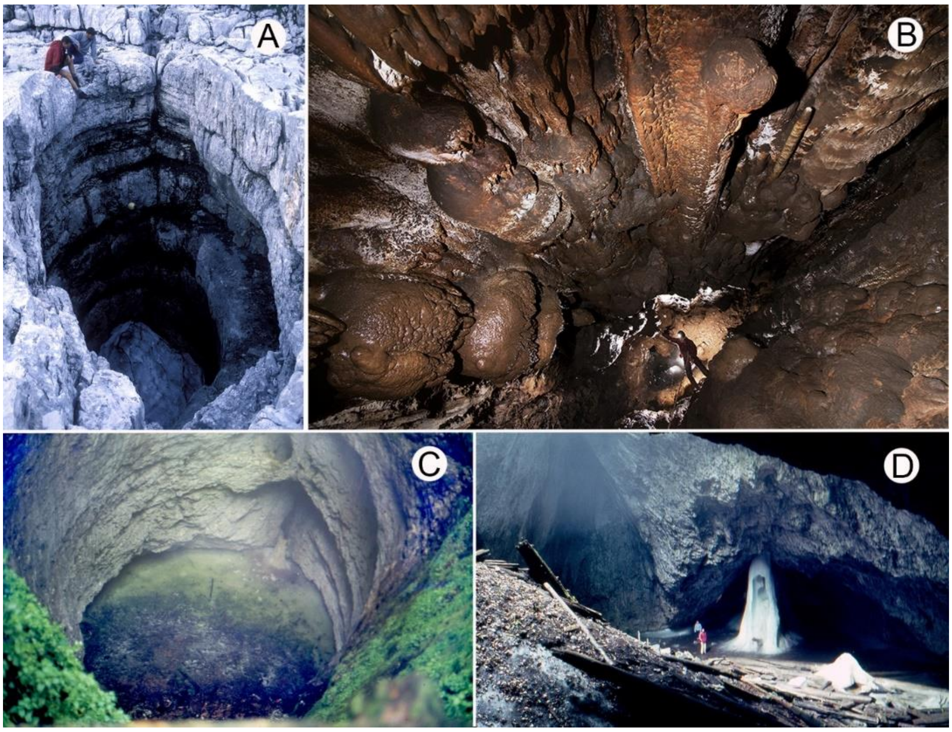

Figure 4: Shafts and ice cave A: shaft (Totes Gebirge, Austria), B: inner part of a shaft (Also Hill, Hungary) [24] C: shaft with ice (Porcika, Pádis, Romania), D: ice cave (Tűz Cave, Pádis, Romania)

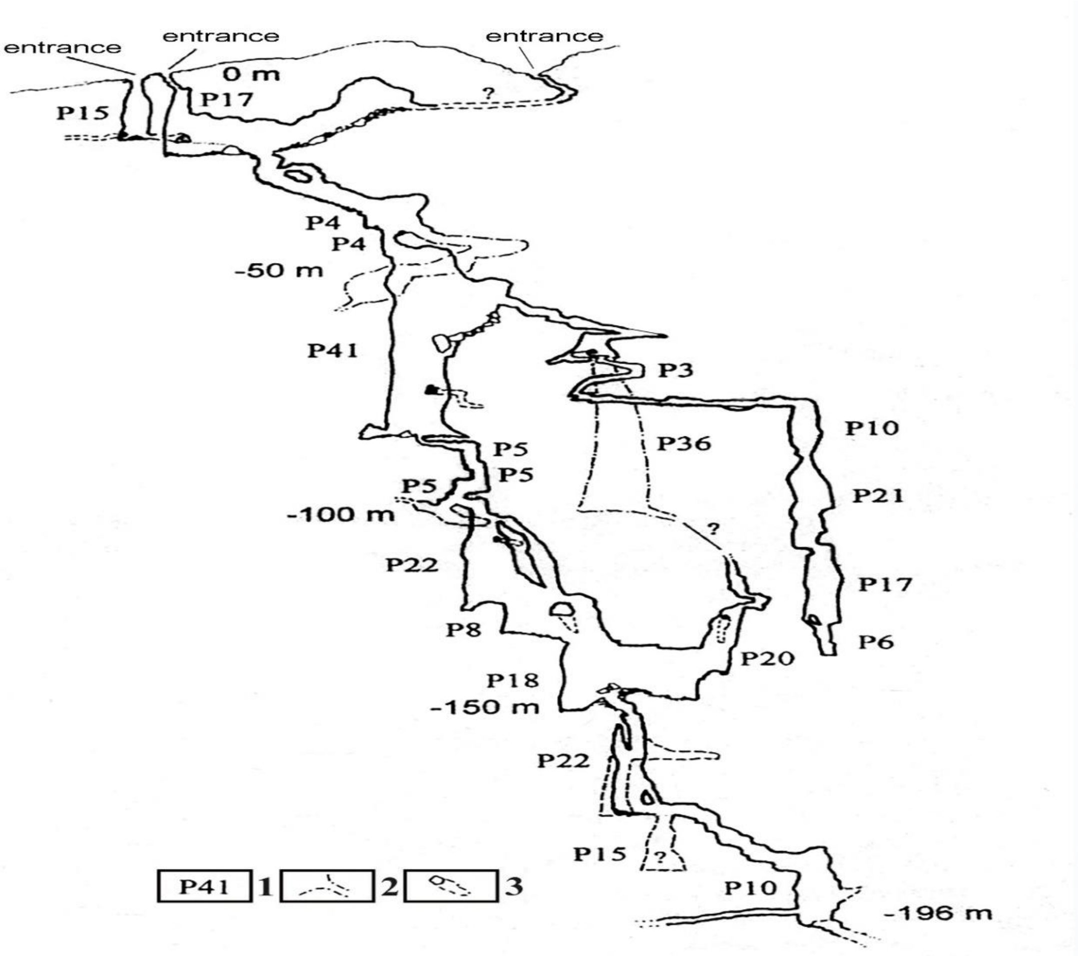

Figure 5: Longitudinal section of shaft [25]
Legend: 1. length of shaft section, 2. passage outside the longitudinal section, 3. impassable passage

Inflow caves and through caves are connected to ponors that developed at rock boundary which are fed by the streams of the surrounding non-karstic terrain. In these caves intermittent streams or streams with permanent water can be found, their floor is inclined from the ponor to their spring, they are often canyon-like. Inflow caves and through caves are more and more erosional since stream load (gravel) arrives from the non-karstic terrain through the ponors. Through caves (for example the Škocjanske jama) are passable to their springs. Both their upper and lower ends could be separated to several branches. At the lower end, this is caused by the subsidence of the spring site (which follows the subsidence of the base level of erosion), at the upper end it is the result of the retreat of the sinkhole point. The significant subsidence of the base level of erosion results in the development of newer levels (multilevel caves, Fig. 6). The formation of a new level is possible because shafts or ponors of higher level lead the water of the cave stream deeper (such a cave is for example the Mammoth cave).

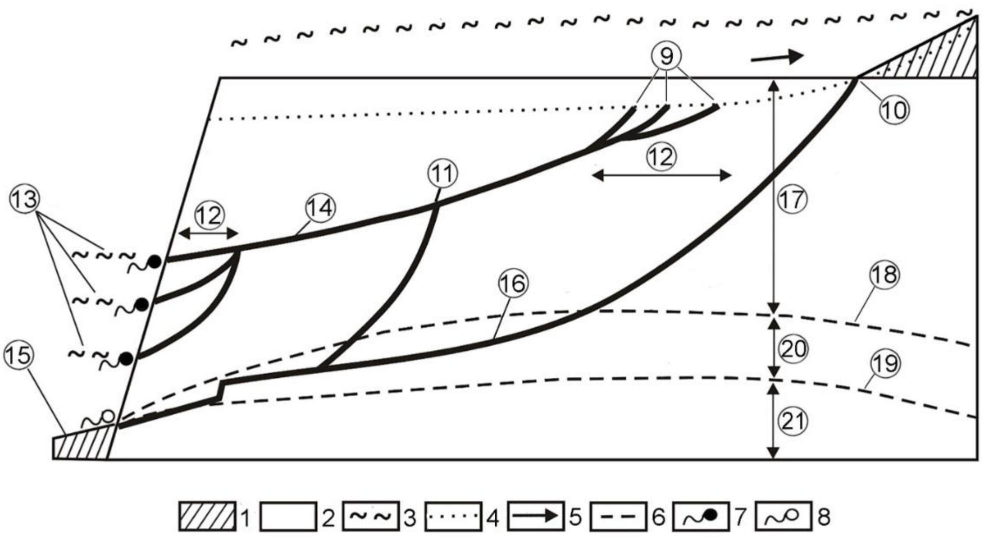

Figure 6: Multilevel cave [15].

Legend: 1. non-karstic rock, 2. limestone, 3. original surface of superficial deposit, 4. floor of epigenetic valley, 5. retreat of sinkhole site on the valley floor, 6. karst water level, 7. inactive (or periodically active) spring, 8. active spring, 9. inactive ponor, 10. active ponor, 11. active ponor in the cave, 12. delta formation of a cave corridor, 13. former base level of erosion, 14. upper level, 15. present base level of erosion, 16. lower level, 17. vadose zone, 18. high karstwater level, 19. low karstwater level, 20. epiphreatic zone, 21. phreatic zone.

Spring caves develop at the outflow sites of the karst water. Away from the entrance, these caves branch out and branches become more and more narrow. Their floor and ceiling is separated into parts of various direction, being opposite to each other. As a result of the rising of the bearing terrain or of the subsidence of the base level of erosion, the site of water outflow gets into a lower position and thus, a newer spring cave develops. Consequently, spring cave levels develop on the karsts. The spring cave is active (filled with water) at the present site of water outflow, the cave situated above it is not active any more. Inflow caves and through caves develop in the vadose zone and the epiphreatic zone, while spring caves are formed in the phreatic zone.

At katavotra, there are ponors and springs depending on the fluctuation of karst water level being close to the surface. In their continuation there are half tubes and oblique passages connecting the half tubes. These caves develop in the epiphreatic zone.

Footcaves are the caves of tropical inselbergs (fenglin). They develop because the waters of intermountain plains with high dissolution capacity dissolve the rock at the foot of inselbergs. With other caves together, the footcaves of the former levels of the plain may create cave levels going transversely through the inselbergs (Figs. 7.8.).

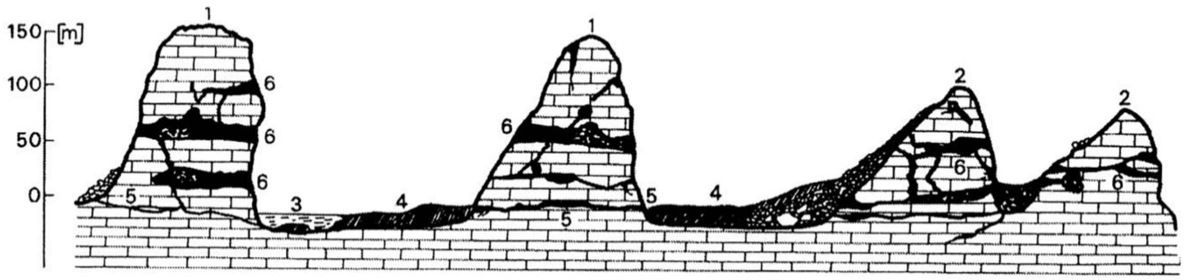

Figure 7: Cave levels of inselbergs [26]
Legend: 1. tower-shaped inselberg, 2. cone-shaped inselberg, 3. river, 4. intermountain plain, 5. footcave, 6. inactive cave

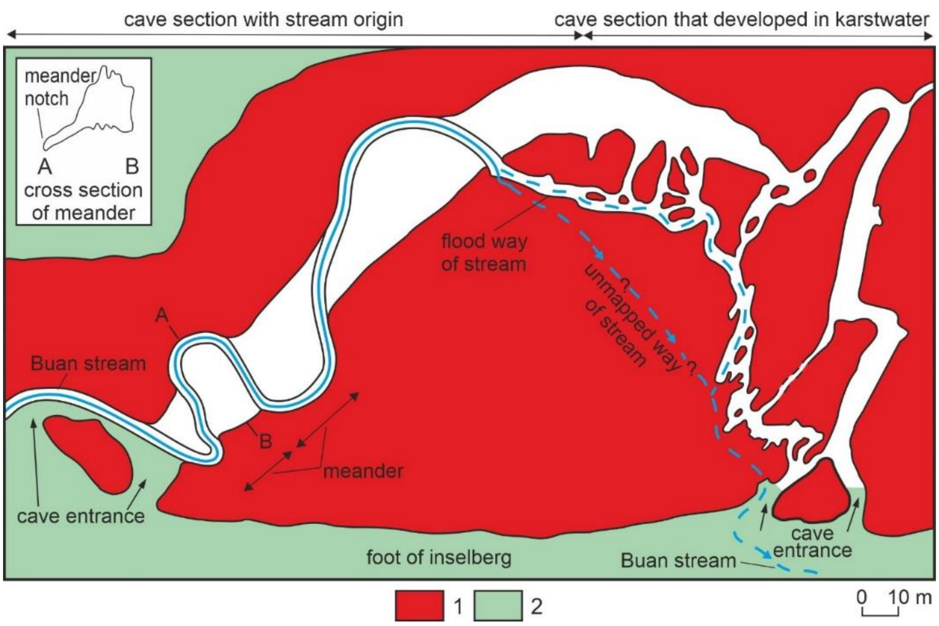

Figure 8: Cave going transversely an inselberg [27]
Legend: 1. limestone inselberg, 2. foot of inselberg

Expansion and pattern of karst caves

The expansion of caves is well-characterised by their length, depth, interior height and the size of their galleries. Table I includes the characteristics of various caves.

Table I [28]
Cave records

Record	name	size	location
The longest cave	Mammoth	676 km	USA, Kentucky
The longest underwater cave	Sistema Ox Bel Ha	256,9 km	Mexico, Quintana Roo
The deepest cave	Kubera Cave	2191 m	Caucasus, Georgia
The deepest shaft	Vrtiglavica Cave	603 m	Julian-Alps, Szlovenia
The largest cave chamber	Miao chamber	length: 852 m width: 191 m	in the Gebiha cave system, China
Height of the largest chamber	Hang Son Doung	200 m	Vietnam

For the description of cave patterns the works of Palmer [29, 30], Jennings [12], Jakucs [10], White [13], Ford and Williams [16], Audra and Palmer [6] were used.

The majority of caves is well-developed in space thus, their description is mainly possible in 3D. This description is less widespread because of its expensive nature. The pattern can be studied well on traditional cave maps as well. The theoretical classification of patterns is also based on traditional cave maps. Because of their spatiality, caves are described in groundplan (groundplan projected onto a plane), in longitudinal section (outstretched longitudinal section in plane) and in characteristic cross-section by cave maps. Thus, the theoretical classification of patterns is also based on this.

In longitudinal section, the caves of the vadose zone may consist of one oblique or vertical passage or they may have stairs when they are constituted by parts with different steepness (Figs. 1, 5). Some sections of the caves of the phreatic zone are inclined towards each other and form loops. The deeper the passage as compared to the karst water level, the larger the inclination of their sections and the more widespread the loops are vertically (Fig. 1).

In groundplan, simple caves can be solitary corridors (straight, meandering, zigzagged) and galleries. According to White [13], complex caves can be of network, anastomoses, and spongework development, while according to Palmer [29, 30], they may have a pattern of branchwork in prominently bedding strata, branchwork in prominently fractured strata, anastomotic maze, network maze, sponge work maze, and ramiform pattern (Fig. 9).

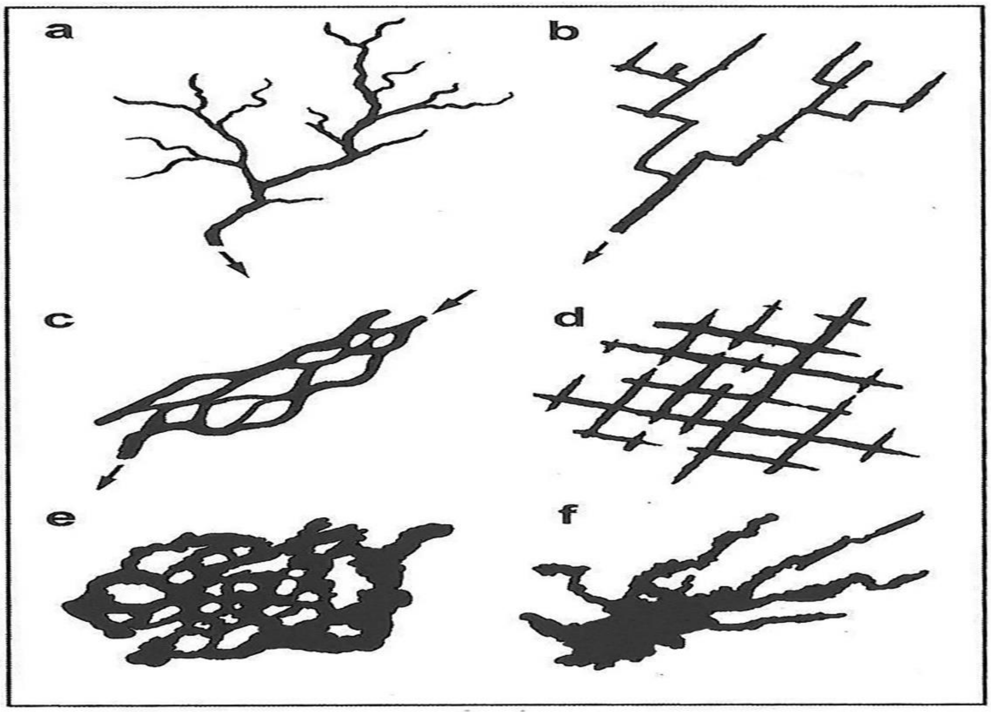

Figure 9: Pattern of caves [30]
Legend: a. branchwork in prominently bedded strata, b. branchwork in prominently fractured strata, c. anastomotic maze, d. network maze, e. spongework maze, f. ramiform pattern (arrows indicate flow directions)

In case of caves with a pattern of network maze, the corridors are parallel and perpendicular to each other (Fig. 9d). This groundplan is mainly characteristic of hypogene caves that predominantly developed along fractures (Fig. 3).

Caves with an anastomotic pattern are constituted by ramifying corridors of identical development (Fig. 9c). The groundplan of caves with a spongework development are irregular, they are mainly built up of galleries which enclose the irregular remnants of the bearing rock (Fig. 9e). In case of ramiform pattern (Fig. 9f) large galleries are connected by passages. At a pattern of branchwork in prominently bedding strata, passages enclosing an acute angle with each other unite into wider and wider passages (Fig. 9a), while at a pattern of branchwork in prominently fractured strata (Fig. 9b) the passages also unite into wider and wider corridors, but they are straight, the tributary and main passages are perpendicular to each other. The two latter pattern is characteristic of those caves of the vadose zone which predominantly developed along bedding planes (Fig. 9.a), or predominantly along fractures (Fig. 9.b). The pattern of inflow caves and through caves makes us remember a river system [10]: the main channel, which widens downstream, is joined by narrower tributary channels. The position and number of tributary channels is significantly influenced by the site of the non-karstic terrain as compared to the main channel and its expansion.

Independent of development environment and genetics, the shape and position of cross-sections emphasize the role of the characteristic features of the host rock in cave development. The cross-section of the cavity reflects the distribution of dissolution intensity. Sites of great dissolution intensity coincide with well-soluble rock parts and with water movement sites and their direction. If the cave was formed along a vertical fracture or vertical beds, then vertical caves develop that are elongated in this direction (Fig. 10a-b). As the position of the above factors changes in space, the position of the cave alters too (Fig. 10c). Caves that developed along horizontal beds have a small height and they are wide (Fig. 10d). A cave with a triangle cross-section is formed if its development was affected by oblique beds and fractures simultaneously (Fig. 10e-f).

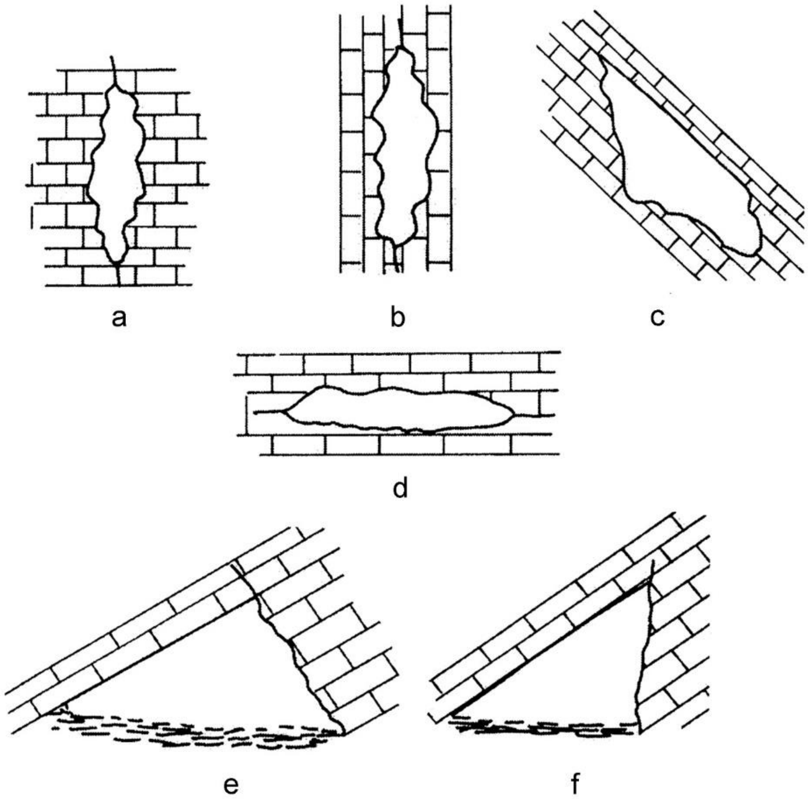

Figure 10: Cross-sections of dissolution caves determined by bedding planes and fractures [13]
Legend: a. cross-section of cavity guided by fracture and horizontal bedding, b. cross-section of cavity developed in vertical beds, c. cross-section of cavity developed on oblique beds, d. cross-section of cavity developed in horizontal beds, e-f. cross-section of cavity developed along fracture and bedding plane.

If the passage develops in a homogenous rock, in a phreatic environment, it has a round cross-section (Fig. 11a), if it is formed along bedding plane, its cross-section is elliptic (Fig.11b), passage development along fracture results in oval cross-section (Fig. 11c), and at the boundary of rocks with various thickness, the cross-section is semicircular (Fig. 11d). A ceiling channel may be formed to the effect of air bubbles (Fig. 11e) or as a result of paragenesis (Fig. 11f). A corridor can develop on the floor of a phreatic cavity during downcutting (Fig. 11h), and during meandering (Fig. 11j) if the cave gets above the karst water level. In the vadose zone, the ceiling of passages may grow higher by collapses and becomes uneven. The passages of the vadose zone that were formed along fractures develop into wider passages or galleries by joining each other due to collapses.

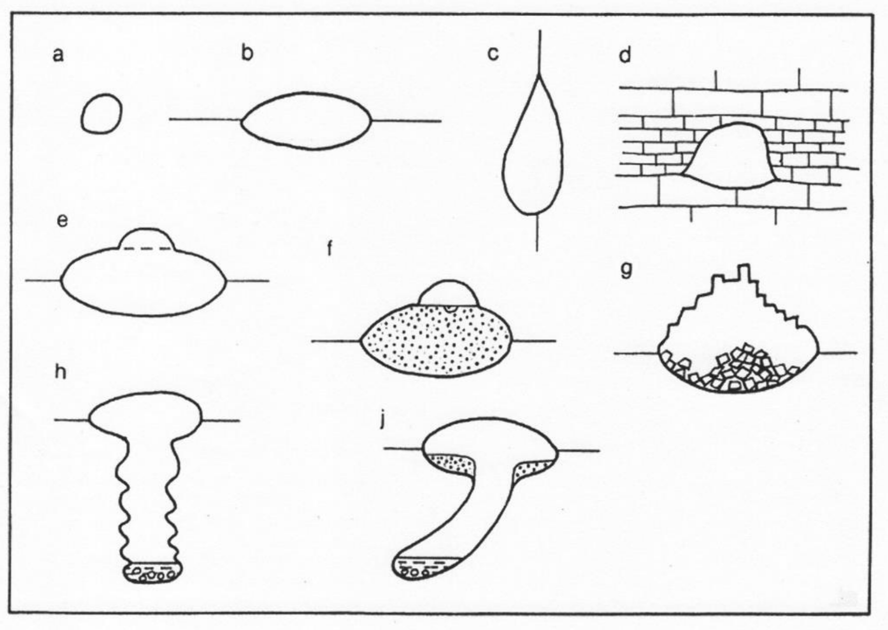

Figure 11: Cross-sections of phreatic caves and of phreatic caves getting into vadose setting [12]
Legend: phreatic passages: a. circular in massive rock, b. elliptical in horizontal bedding, c. elliptical in vertical joint, d. in a group of more soluble beds, e with ceiling half-tube due to bubbles along roofline, f. aggraded to form ceiling half-tube paragenetically, g. modified by breakdown, vadose canyon: h. incised in the floor of the phreatic passage, with channel incuts, j. with inward meandering during incision into the aggraded floor of the phreatic passage.

Hydrology of caves

The water-filled state of caves can be permanent, periodical or absent too. Permanent water-filled state may be complete or partial. A complete water fill occurs if the cave developed below the water table (caves below the karst water level) or because the cave got into an aqueous environment. This may occur at coastal caves if the bearing area subsides or the sea (lake) level rises. Caves filled completely or partially by water can be found on the Yucatán Peninsula (as a result of the rise of the water level) or on the Adriatic coast (because of the subsidence of the land and of the rise of the sea level). The Blue Holes of the Bahama Islands are also worth mentioning. Here, the shafts (and dolines) of the vadose zone were inundated by the sea [31]. As it has already been mentioned, caves being filled with seawater do not continue their development since brine does not dissolve the rock.

Caves periodically filled with water can be found in the vadose zone or in the epiphreatic zone. In the former case, the cause of the phenomenon is surface water supply (through ponors) during which cave floods may develop. In the epiphreatic zone, the temporary rise of the karst water level causes a water-filled state. A partial or even a permanent water-filled state occurs at stream caves. The cave is characterised by infiltrating waters if meteoric water gets into the cave through the cracks of the ceiling. Since caves have different widths and heights, different sections may be filled by water to various degree. A cave section completely filled by water is called siphon. The water-filled state and the dry, water-free sections can alternate several times in case of the same cave.

Morphology of karst caves

The description of features is based on the works of Jakucs [10], Slabe [32], Jennings [12], White [13], Ford and Williams [16].

Features can be of erosion, dissolution and mass movement origin. Erosion features are potholes, scallops and terrace ruins. Potholes are bowl-like depressions with steep walls in the channel of the cave stream. They are formed in the stream channels of the caves of the vadose zone where vortexes move debris. Scallops occur on walls, they develop by vortexes by erosion or dissolution. They may develop in vadose environment, epiphreatic or phreatic environment too. Terrace ruins are the remnants of the cemented fill of cave walls.

Dissolution features are notches, dissolution windows, anastomoses, ceiling meanders, pendants, spherical cavities, chimneys, karren, pillars, pedestal rocks, and dead-end passages. Notches are hollows of cave walls. Notches develop in the caves of the vadose zone. They can be mirror notches and curve notches. Mirror notches (Fig. 12A) are hollows situated at a similar height on the opposite cave walls. They can develop in case of an increased amount of water (in an erosional way) or by more intensive dissolution which takes place at the level of the cave stream. Curve notches are hollows developing at the concave wall of meandering cave corridors where the channel line sits tight to the cave wall (as a result of faster water motion, dissolution will be more intensive). The cave meander can be dissolved through at its neck part. The neck part of the meander is cut through, and a dead-end passage develops. The cave creek may create a new meander by downcutting.

Figure 12: Specific cave features: A: Mirror notch with scallops on the walls (in one of the branches of Baradla Cave, in the Retek branch, Hungary), B: spherical cavity (Józsefhegyi cave, Buda Hills, Hungary taken by Berentés Á.), C: pedestal rock (Grönli cave, Sweden), D: window (Vásárosúti cave, Mecsek Mountains, Hungary)

Spherical cavities are common features of caves Fig. 12B). These features have a diameter of some tens of centimetres (those having a diameter of one metre are called solution pockets), they are spherical cap-like hollows on walls and ceilings. There are various explanations for their development (according to one of them, they were formed by mixing corrosion), but they may have developed in several ways. They can be associated with the phreatic zone.

Pillars are dissolution remnant features expanding from the ceiling to the floor, pedestal rocks do not reach the ceilings (Fig. 12C). Dissolution windows develop when the thin dividing walls between the chambers are dissolved through locally (12D). These windows can also develop on ceilings, but those developed by collapses are more common among the latter (see below). Among cave karren, grikes, lattice-like karren of cave stream channels and wandkarren of walls, the so-called scallops (solution ones) can be mentioned. However, features that developed during paragenesis (see below) are also ranked here, in fact these can be regarded as karren being only characteristic of caves, while other karren are not cave specific.

Paragenetic solution features are ceiling anastomoses, ceiling meanders, half tubes and pendants. Anastomoses are smaller (with a width of some centimetres) channels on the ceiling, having a cross-section similar to a reversed letter 'V' and are situated next to each other. Ceiling meanders are larger (wider than 20 cm) having a Ω cross-section. In the development of anastomoses, the water is pressed to the ceiling at several sites (after the passage becomes filled with sediment), while in case of ceiling meanders, the water is pressed to the ceiling at one site only. Pendants are ceiling cliffs resembling hanging stalagmites which are the remnants of the dividing walls of the channels of anastomoses. Half tubes are features trending upwards from the ceiling, terminating in the rock and having a diameter of some decimetres or metres. Paragenetic features develop in phreatic and epiphreatic environment, but they may probably be formed locally in the vadose zone.

Piles (hills) of breakdown materials may be aligned on the floor of caves. These are formed during the breakdown of ceilings.

Cave fills

Fills may originate from the host rock (cave clay, breakdowns), from water, from cave organisms or from the surface. Their age may be identical with the development of the cave or they may have been formed during the inactive or destroying phase of the cave. Calcareous sinter and ice may develop from cave waters.

Calcareous sinter may be formed from percolating, dripping and flowing water and from aerosol. Rimstone bars (tetarata, Fig. 13A) of cave streams develop from flowing water. Concretions from percolating water cement cave sediments together thus, cave breccia or cave conglomerates develop. Sediment may be washed out below the cemented material, a pseudo floor develops and the cave is transformed into a multilevel cave.

Figure 13. Concretions A: travertino (Baradla cave, Hungary), B: helectites (Baál Cave, Australia, taken by Leél-Őssy Sz.), C. hanging stalagmites and standing stalagmites (Gombaszögi Cave, Slovakia), D: giant gypsum crystals (La Cueva de los Crystals Mexico) [33]

Stalagmites, stalactites and columns and their varieties develop from the dripping water (Fig. 13C). These are gravitational dripstones. Helictites (Fig. 13B) develop from the aerosol of the flowing air thus, they are not vertical. They may branch out, have a horizontal position, and they may be upward growing too. Under special circumstances giant crystals may develop too (Fig. 13D).

In ice caves (Fig. 4D), there is ice fill and ice features. The ice can originate from the glacial or from the period after the glacial. Glacial ice developed as a result of colder climate or the expanding glacier penetrated into the cave [34]. Cave ice after the glacial develops if the air temperature is permanently below 0°C in the cave. Ice caves can be dynamic ice caves when draught is present in the cave and air with a temperature below 0°C flows there or static ice caves when there is no airflow in the cave, cold and thus, heavy air flowing through the entrance accumulates on its lower part [35].

Development and decay of caves

During their existence, caves go through various development stages thus, embryonal, infantile, juvenile, adult and senile phases are distinguished. In embryonal, infantile and juvenile phases, the volume of the cave increases, in adult stage, its volume becomes stable, in senile phase, the volume of the cavity decreases or the cavity state ceases.

Caves are not long-lasting features. The cave state can finish by alluviation (which can be caused by the inward transported sediment or in case of those of karstic origin, the precipitated material) or by the decay of the host rock. This latter may happen by truncation and by the collapse of the ceiling. In case of truncation, the cave becomes shorter as a result of the destruction of the rock around the entrance. In case of collapse, a collapse doline develops (Fig. 14AB). Between the rows of collapse dolines (which are the windows) arches (Fig. 14C) survive and later only some arches survive following their destruction (Rakek, Slovenia, Fig. 14D). With the destruction of all arches, valley sections without ceilings (gorges) are formed. First of all, through caves are destroyed in this way, but windows often develop at caves being close to the surface by the collapse of the ceiling. Cliff corridors with steep sides are formed by the destruction of the ceiling of smaller caves. Caves of vertical position are more long-lasting features. Cave ruins develop by the lateral opening of caves which is caused by fluvial erosion or glacial erosion.

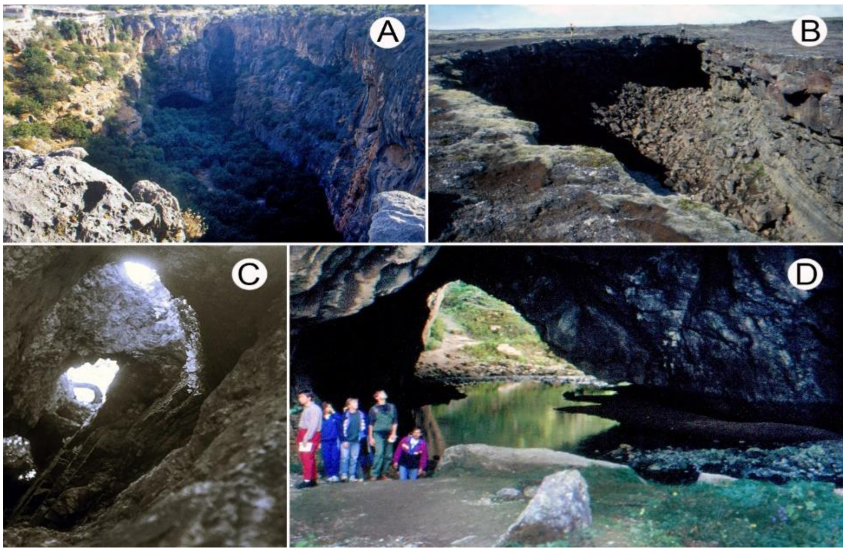

Figure 14: Denudation of caves A: collapse doline (Turkey), B: collapse doline on the ceiling of a lava cave (Surthellir lava cave, Iceland), C: Roof windows that developed under collapse dolines (Aragyásza Cave, Romania) D: arch (Rakov cave, Slovenia)

Cave climate

Cave climate can be characterised by air composition, temperature, relative humidity and draught.

There are permanent and changing gases in the cave air. The proportion of permanent gases like oxygen, nitrogen etc. is almost identical with the proportion of surface air. Among changing gases, CO_2 is to be emphasized, the proportion of which can significantly change since equilibrium CO_2 leaves cave waters and this proportion may reach a volume percentage of 0,3. The aerosol of cave air is rich in Mg-ions and Ca-ions.

The temperature of cave air is identical with the annual average temperature of the surface. Annual heat fluctuation remains below 1°C in caves. However, there may be deviations, thus, to geothermic effect, when the air of the cave can reach 40°C because of heating-up (Grotta Giusta, Italy) or it can even exceed this value. The temperature may also change periodically. During snow melting it can decrease by 3-4°C, while it can increase by 2-3°C during summer showers. According to the degree of temperature fluctuation, a climate of the entrance section and a climate of the cave section can be distinguished. The daily temperature fluctuation in the entrance section may exceed 1°C, while this value is lower in the cave sections. Cold point can be found between the two sections where the temperature is lower both in summer and winter than in other parts of the cave. Here, the outflowing summer air of higher temperature cannot compensate the cooling effect of the inflowing air in winter.

Relative humidity is high especially in caves with water or those conveying water where it can reach 100 %. The flow of cave air (cave draught) is caused by the specific gravity difference between surface air and cave air. Its velocity is influenced by several factors (the degree of the warming of the surface, cave morphology, the degree to what extent the cave is filled, etc.). The flow direction of cave air changes seasonally. In summer, it flows from the cave towards the surface, while in winter its direction is from the surface towards the inner side of the cave [36].

Conclusions

Syngenetic caves are caves that developed by wreathing and by the cooling of the melt. Among postgenetic non-karstic caves there may be caves determined by rock quality (on granite, greenschist, clay and on loess), and caves that were formed by processes (fluvial erosion, mass movements, crust structure, wind, abrasion, volume increase, melting and frost weathering).

Karst caves develop by dissolution as well as by dissolution and erosion. They may be of epigene, epiphreatic, phreatic, deep-phreatic, and hypogene position, which are lukewarm water, cold-water caves, warm-water caves and artesian water caves. According to their position, karst caves can be shaft caves, inflow caves, spring caves, through caves, multilevel caves, katavotra and footcaves.

The pattern of caves can be described by their groundplan, longitudinal section and cross-section. Mainly their cross-section refers to their genetics. Their features may be of dissolution, erosion and collapse origin. Different features develop in various development environments. Cave fill can be formed in situ or it can be transported from the surface. From cave waters cave ice and calcareous sinter may develop. From a hydrological point of view, caves can be wet (completely or partially filled with water) and dry caves. Their destruction takes place by their filling or by the collapse of their ceiling. During the latter process gorges are formed.

References

1. Mylroie, J.E., Carew S.L. (2000) Speleogenesis in Coastal and Oceanic Settings – In: Klimchouk et al. (eds): Speleogenesis, NSS, Huntsville, 226-233.
2. Takács Bolner K. (2007) A Bermuda-szigetek korallhomokkő-barlangjai (Bermuda's coral sandstone caves) – Karsztfejlődés XII:303-313. (in Hungarian)
3. Veress M 2016. Covered Karst. Springer, Berlin, Heidelberg, New York 536 p. DOI 10.1007/978-94-017-7518-2
4. Klimchouk A, Bayari S, Nazik L, Tork K (2006) Glacial destruction of cave systems in high mountains, with a special reference to the Aladaglar Massif, Central Taurus, Turkey. Acta Carsologica 35/1: 7-21

5. Ehenberg K. (1960) Über Alter und Lebensdauer von Höhlen. Die Höhle 11:89-97.
6. Audra, Ph., Palmer A. (2013) The vertical dimension of Karst: Controls of Vertical Cave Pattern – In: Shoder J., Franklin A: Treatise on Geomorphology, Academia Press, San Diego, pp. 186-208.
7. Sweeting M.M. (1973) Karst Landforms. Columbia University Press, New York, 362 p.
8. Balázs D. (1974) Lávaüregek keletkezése, típusai és formakincse. (Development of lava cavities, their types and features) Földrajzi Közlemények XXII. 135-148 (in Hungarian)
9. Müller P (1974) A melegvizes barlangok és gömbfülkék keletkezéséről (On the development of warm-water caves and spherical cavities). Karszt és Barlang I: 7-11 (in Hungarian)
10. Jakucs L. (1977) Morphogenetics of Karst Regions. Adam Hilgar, Bristol, 284 p.
11. Szunyogh G (1982) A hévizes eredetű gömbfülkék kioldódásának elméleti vizsgálata (A theoretical study of the dissolution of spherical cavities with hydrothermal origin). Karszt és Barlang II.:83-88. (in Hungarian)
12. Jennings J.N. (1985) Karst Geomorphology. Basil Blackwell, New York, 293. p.
13. White W.B. (1988) Geomorphology and Hydrology of Karst Terrains. Oxford University Press, New York – Oxford 464 p.
14. Halliday W. (2004) Piping Caves and Badlands Pseudokarst. In: Gunn J.: Encyclopedia of Caves and Karst Science. Fitzroy Dearborn, New York, pp. 589-593.
15. Veress M. (2004) A karszt (The karst) BDF Természetföldrajzi Tanszék, Szombathely 215 p. (in Hungarian)
16. Ford D.C., Williams P.W. (2007) Karst Geomorphology and Hydrology. Unwin Hyman, London, 561 p.
17. Klimchouk A.B. (2007) Hypogene Speleogenesis: Hydrogeological and Morphogenetic Perspective Special Paper no 1. National Cave and Karst Research Institute, Carlsbad, NM 106 p.
18. Klimchouk, A. (2012) Speleogenesis, Hypogenic. Encyclopedia of Caves, 748–765. https://doi.org/10.1016/B978-0-12-383832-2.00110-9
19. Pasini G (2009) Terminology matter. Paragenesis, antigravitative erosion or antigravitational erosion? International Journal of Speleology. 38:129-138
20. Goldscheider N., Mádl-Szőnyi J., Erőss A., Schill E. 2010: Review: Thermal water resources in carbonate rock aquifers – Hydrogeology Journal 18 pp. 1303-1318.
21. Jacques, E J Martini Ken G Grimes. (2012) "Epikarstic Maze Cave Development: Bullita Cave System, Judbarra/ Gregory Karst, Tropcical Australia." *HELICTITE: JOURNAL OF AUSTRALIASIAN SPELEOLOGICAL RESEARCH* 41: 37–66.
22. Veress, Márton, and Zoltán Unger. (2015) Kab Mountain: Karst under a basalt cap. *Landscapes and Landforms of Hungary*. Springer, Cham, 2015. 55-62.
23. Jouves J., Viseur S., Arfib B., Baudemen C., Camus H. (2017) Speleogenesis, geometry and topography of caves. A quantitative study of 3D karst conduits. Geomorphology 298:86-106.
24. Gruber P, Szunyogh G., Telbisz T. (2022) The caves of Aggtelek Karst, Szalonna Karst and Rudabánya Mountains – In: Veress, Leél-Őssy (eds) Cave and Karst Systems of Hungary (in press)
25. Nyerges A. (2002) Kutatási eredmények a Canin-fennsík barlangjaiban. (Research results in the caves of the Canin Plateau) Karsztfejlődés VII: 251-257. (in Hungarian)
26. Balázs D. (1962) Beiträge zur Speläologie des südchinesischen Karstgebietes. Karszt- és Barlangkutatás, 2:3-82.
27. Wilford GE, Wall JRD. (1965) Karst topography in Sarawak. Journal of. Tropical Geography.21:44-70
28. hu.vikipedia.org/viki/Barlang
29. Palmer A. N. (1991) Origin and morphology of limestone caves. Geological Society of America Bulletin 103:1-21.
30. Palmer A. (2004) Patterns of Caves. In: Gunn J.: Encyclopedia of Cave and Karst Science. Fitzroy Dearborn, New York pp. 573-575.
31. Mylroie J. (2004) Blue Holes of Bahamas. In: Gunn J: Encyclopedia of Caves and Karst Science. Fitzroy Dearborn, New York pp. 155-156.
32. Slabe T. (1995) Cave Rocky Relief. Znanstvenaraziskovalni Center Sazu, Ljubljana 128 p
33. https://es.slideshare.net/universidadpopularc3c/la-geometra-encarnada-en-la-naturaleza-los-cristales
34. Ford, D. C., P. L. Smart, and R. O. Ewers. (1983) "The Physiography and Speleogenesis of Castleguard Cave, Columbia Icefields, Alberta, Canada." *Arctic and Alpine Research* 15, no. 4: 437–50. https://doi.org/10.2307/1551231.
35. Jakucs L. (1963) A jégbarlangok képződése. (Development of ice caves) – Földrajzi Zsebkönyv 14: 50-62 (in Hungarian).
36. Fodor I (1981) A barlangok éghajlati és barlangklimatológiai sajátosságai (Climatic and cave climatic characteristics of caves). Akadémiai Kiadó, Budapest 191 p (in Hungarian).