# Unroofed Caves Provide Important Clues to the Karst Development

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Unroofed caves (Fig. 7.1) are old caves that were revealed on account of the lowering of the karst surface. They are preserved by their infill—mostly alluvium and flowstone. We were able to identify their most typical incarnations and their significance for the research of the karst aquifer cavernosity, the epikarst and topography.

It became clear during the motorway construction undertaking in Slovenia that unroofed caves constitute a relatively common karst landform. In fact, more common than we had imagined before the karst surface was uncovered through earthworks. The various types of notches occurring on the surface have long been interpreted as types of dolines or as the result of the lithological properties of rock and its fracturing. 75 km long and, on average, 25 m wide stretch of the motorway gave up 350 caves, of which 90 are unroofed caves. Some of them make up the same cave system. New findings prompted us to become more aware of these unique surface karst forms. In the process, we discovered numerous unroofed caves filled with all types of alluvium (Mihevc 2001; Šušteršič 1978). There were several attempts at typification of the characteristic shapes of unroofed caves (Mihevc et al. 1998; Knez and Slabe 1999b) and to design partial models to explain their typical formation processes (Šušteršič 1998; Mihevc 1999a; Knez and Slabe 2002a).

This paper sums up our years of experience gained in the study of this fascinating karst feature, while it was also supported by the latest insights. We believe that this, even though a familiar karst feature, deserves more spotlight than it has received in the past. For the purpose of this paper we shall provide examples from the Classical Karst.

The surface and subsoil dissolution of carbonate rock and its disintegration from back in the Ice Age, brought about the lowering of the karst surface. Old caves, which were formed by erstwhile water flows and are partly intersected by shafts which drain water from the permeable karst surface, pop up as either empty or filled with alluvium. The caves were formed as a part of a system of cavities in a period when impermeable rocks had enclosed the aquifer higher up, causing the underground water in the aquifer to be at a higher level. The hypothesis was that the karst topography and its remarkable systems of valleys can be traced back to former surface water throughflow. However, revealing the surface did not provide us with the evidence to support the hypothesis, instead we identified obvious signs of former water throughflow in carbonate rock—manifested as open and cut through old caves.

## 7.1 Identifying Unroofed Caves on the Karst Surface

Drawing on our years of experience, which we have obtained during planning and construction of motorways across the Slovenian Karst region, we were able to pool the insights on the type of the unroofed cave on the karst surface. This proved to be of great help for our study of the karst surface. The distinctive shape of the unroofed cave which is set in the karst surface is the result of the type and form of the alluvium-filled transformed cave, and of the development of the karst surface. Surface development is in turn dictated by the rock structure and fracture as well as point surface



M. Knez and T. Slabe (eds.), *Cave Exploration in Slovenia*,
Cave and Karst Systems of the World, DOI 10.1007/978-3-319-21203-6_7

Fig. 7.1 An unroofed cave

permeability, the geomorphologic embeddedness of the aquifer and its development in specific climate conditions. The distinctiveness of the unroofed cave surface form is associated with the washout velocity of the cave alluvium.

The dissected karst surface is dotted with caves of different shapes. We can single out two of the most obvious examples which dictate the shape of unroofed caves. In the first instance, the passage which had opened up in the surface runs parallel to said surface (Fig. 7.2), in the second the passage cuts through the surface (Figs. 7.3 and 7.4). A very specific version of an unroofed cave emerges when the surface opens up in several higher parts of a winding passage or, alternatively, when dolines are formed within one passage (Fig. 7.5). In the first instance, unroofed caves occur as elongated notches, individual dolines or dolines lining up in the open passage. Unroofed caves that are born from passages which had been laterally intersected by the surface come about as doline-like forms. The repeatedly pierced winding passage therefore appears as a string of dolines and notches.

To a large part, the degree of recognizability of an unroofed cave on the karst surface is the result of the velocity with which the sediments were washed out of the cave. The most prominent shapes occurred in instances where the velocity of the sediment washout from the caves exceeded the downcutting rate of the adjacent carbonate terrain. Obviously, empty caves merged with the surface much easier.

When we set out to study the karst features that had been discovered in the southeastern part of the Slovenian Karst region in the framework of the motorway construction, we concluded that the Cretaceous limestone terrain is dissected with sharp features such as very developed, partly subsoil karren and dolines. Yet it is necessary to distinguish between karren grooves and the notches that originated in unroofed caves.

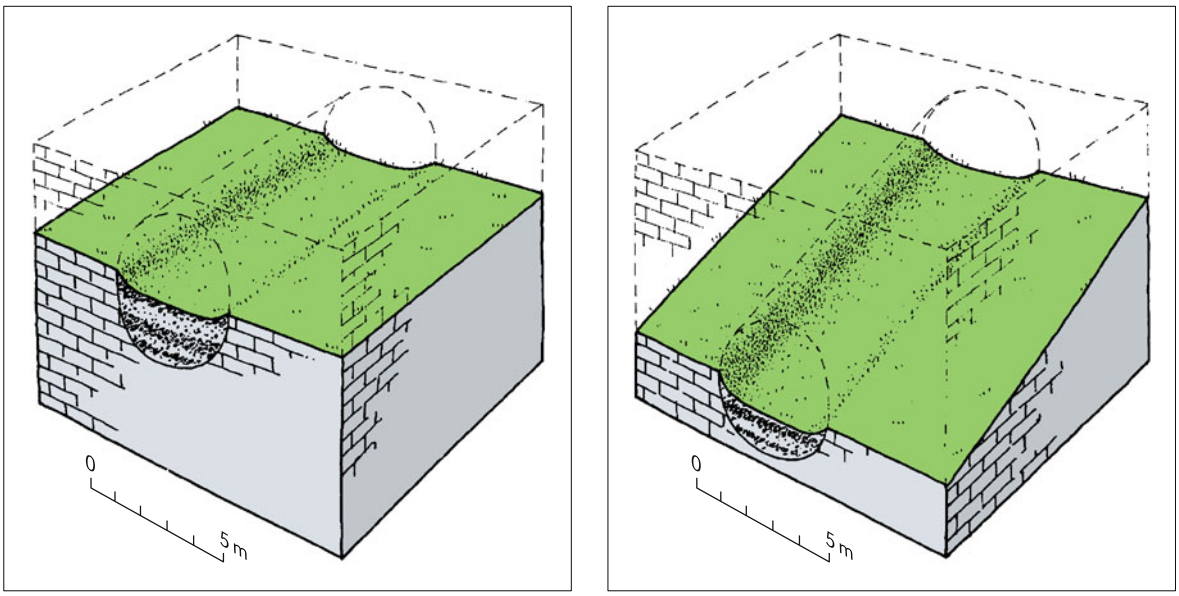


Fig. 7.2 Two unroofed caves and an elongated indentation on a horizontal and inclined karst surface (the legend provided in Fig. 7.6)

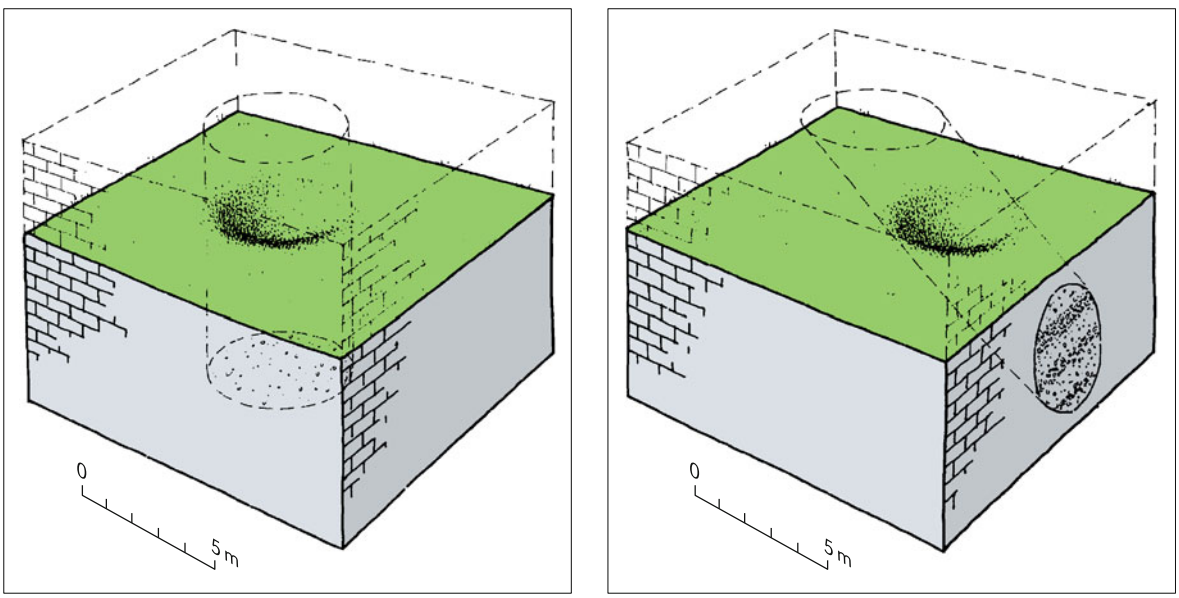


Fig. 7.3 Two unroofed caves, doline-like forms (the legend provided in Fig. 7.6)

Palaeogene limestone terrain, overlain by coarse rubble from the same period, is characterized by greater smoothness, occasional dolines and less visible notches. Flowstone patches may be recognizable after it is denuded.

The unroofed caves, which are the subject of our research, were filled with several metre thick pebble layers and fine-grained sediments, and displayed traces of fluvial action and flooding. The infill in some consisted of coarse rubble emerging in response to

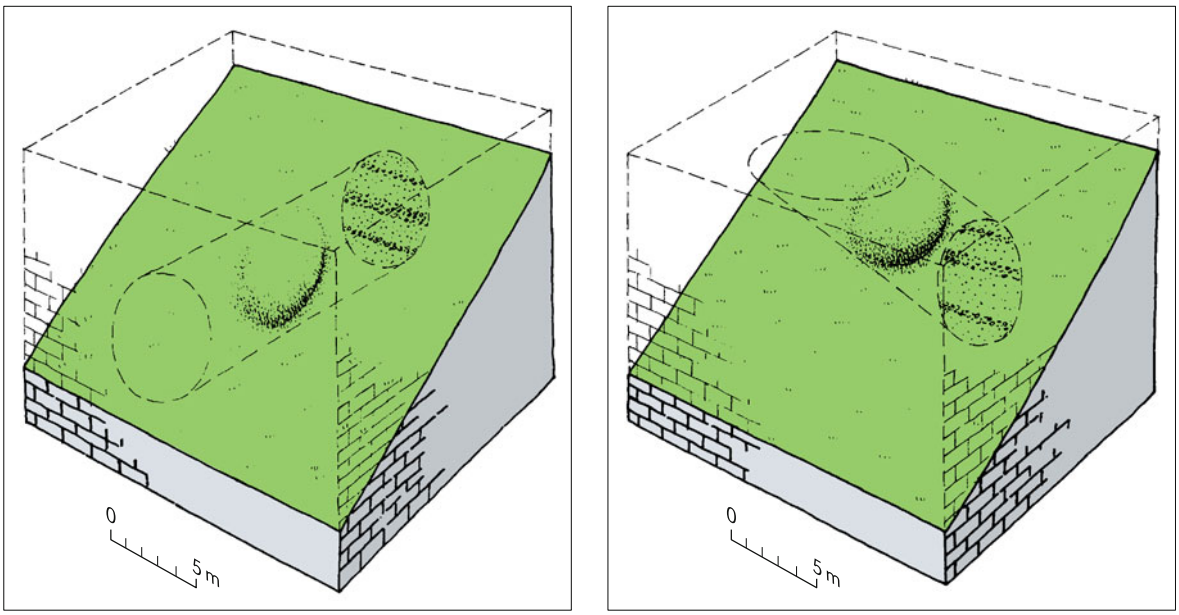


Fig. 7.4 Two unroofed caves, doline-like forms on an inclined surface (the legend provided in Fig. 7.6)

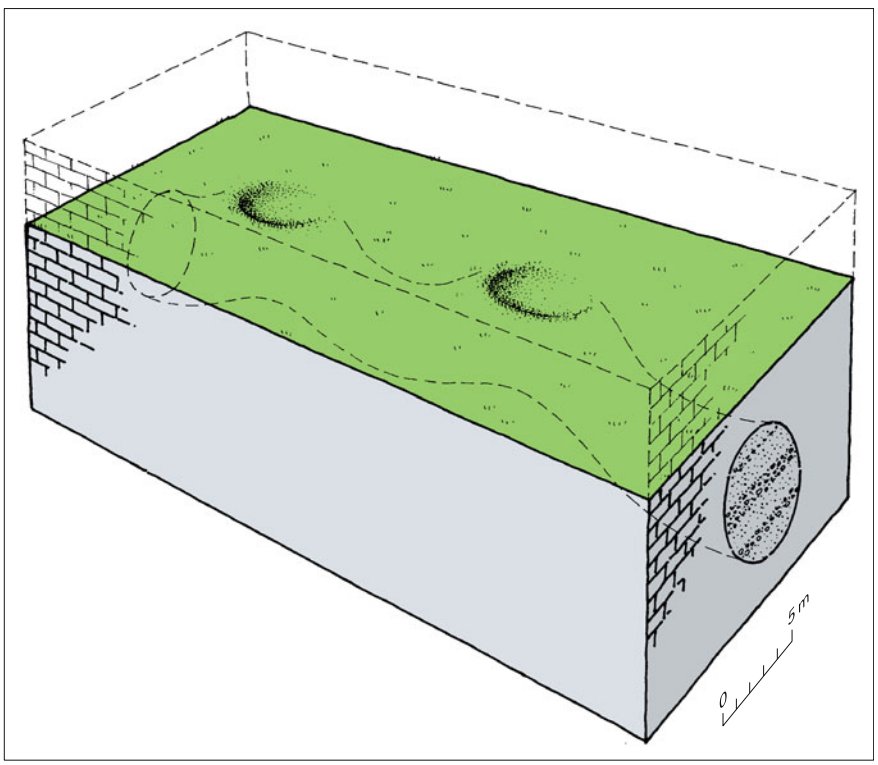


Fig. 7.5 A winding passage cut by the karst surface (the legend provided in Fig. 7.6)

rock weathering in cold Pleistocene periods. Almost all caves featured masses of flowstone and stalagmites.

The flowstone from unroofed caves included specimens with remarkably large calcite crystals and flowstone with tiny sugar-like crystals. The colour scale of the flowstone spanned from pure white to yellow, red and brown to black. In the process of sedimentation and later recrystallization and weathering, iron and manganese cations present in the solution formed calcite crystals. After the cave chambers were filled in, silt, clay and organic matter were included.

Due to the recrystallization process, flowstone is often made up of large calcite crystals and only rarely do we encounter large crystals that may be the reason for the clear, oozing and saturated water from the primary sedimentation environment. The share of finely crystalline flowstone was much smaller. In this case, flowstone was either white or yellow-white. Many flowstone samples contain clay or its own weathered material, layered in individual colour-distinct bands. On few occasions, three chronologically different generations of flowstone from different events have come in contact at one point. Most of the discovered flowstone is consolidated, although small sections do disintegrate into calcite fragments in contact with the surface. The large and tiny crystals from unroofed caves are likely the result of long-term weathering in non-carbonate alluvium. The varied inventory of flowstone occurring in a myriad of morphological and genetic variations deserves far greater attention than was given up to date, and not only in terms of dating.

In many instances the cave rock relief was preserved overlain by alluvium and flowstone. Of course, the velocity of alluvium washout from the caves also depends on the type of alluvium, its disintegration and dissolution rates.

We took sediment samples for palaeomagnetic, pollen and mineralogical research (Mihevc and Zupan Hajna 1996) and for dating. Palaeomagnetic reversal in the alluvium suggests that the caves are older than originally hypothesised by karstologists attempting to explain their evolution, particularly throughout Pleistocene periods. In one of the higher-lying caves, right below the surface, we were able to detect a reversal somewhere around 1.6–1.8 million years, but it can also be older, ranging from 3.8 to 5 million years, but there are no additional indications to support this dating result (Bosák et al. 1998b).

### 7.1.1 Types of Unroofed Caves

Unroofed caves, which are characterized by slow washout of alluvium, may be recognized based on the following signs:

- patches of karst terrain which are covered by unique soil and vegetation,
- flowstone and cave alluvium lying open on the karst surface.

In contrast, unroofed caves characterized by a fast washout rate of alluvium comprise:

- dolines and semidoline-like shapes (Figs. 7.3 and 7.4),
- strings of dolines (Fig. 7.5) and
- notches spanning over 100 m or even several kilometres (Fig. 7.2).

### 7.1.2 Patches of Karst Terrain Which Are Covered by Unique Soil and Vegetation

One of the most striking features of unroofed caves, which we had the chance to observe in the field, is that the patches of karst terrain are marked with a typical pedological horizon and vegetation cover.

The most obvious signs of an unroofed cave in the karst terrain are smaller areas of grass or perhaps areas with lush vegetation set between woods or shrubbery.

Unlike the adjacent terrain, grassy areas also do not have larger rocks strewn around. If there are any rocks, they are covered with a relatively thick layer of soil. This is especially the case with Cretaceous rock which appears in the region of the Karst as distinctive and jagged karren which can be up to several metres high, and is difficult to pass. Palaeogene limestone in contact with Cretaceous limestone is mechanically significantly less stable and resistant against weathering on account of its different lithostratigraphic properties. In contact with Cretaceous limestone, Palaeogene limestone tends to fuse with the surface almost seamlessly over time, obscuring the traces of unroofed caves.

Another indicator of an unroofed cave, in addition to the typical surface form described above, is the presence of a cultivated area. Beside fields where soil is on top, the meadows too signalize a more favourable pedological horizon, which may indicate the contact

between a filled-in intersected underground passage with the surface.

We had been aware of these forms before initiating earthworks and had marked them on the prognostic map. Once the terrain was uncovered, it turned out that our assumptions were correct.

### 7.1.3 Flowstone and Cave Alluvium on the Karst Surface

Unroofed caves which we identify on the karst surface by recurring pieces and flowstone blocks of sizes up to several 10 $dm^3$ can be described as longitudinal areas, tens to hundreds of metres long and several metres wide or mere patches.

In this case, the surface karst morphology reflects the lithostratigraphic foundation. This particular karst surface is characterized by the prevalence of Palaeogene limestone, and is relatively levelled, with slight waves, and marked by the absence of jagged karst forms indicative of surface erosion. On the other hand, the part of the karst surface exposing Upper Cretaceous rock has been intensively eroded, demonstrating numerous karren and various surface notches. Bands of weathered flowstone are much more obvious on Palaeogene terrain than odd Cretaceous rock, although, statistically speaking, Cretaceous rock in the Karst region displays twice the amount of karst forms.

Seeing as Palaeogene limestone in this part of the Karst region occurs in thin beds which are tectonically badly fractured and hence susceptible to weathering, they have disintegrated into coarse rubble, particularly under the influence of cold Pleistocene periods.

Coarse rubble, which allows us to trace flowstone bands, can occasionally cover areas stretching several 100 $m^2$, and act as cave infill elsewhere. It was commonly found to be overlying old alluvial deposits or filling the space below the abris. The Pleistocene material displacement caused the coarse rubble to become combined with loam, flysch alluvium, fine sand and flowstone pieces that were sometimes found in their original manifestation (stalagmites).

### 7.1.4 Doline-like Shapes and Strings of Dolines

Unroofed caves can appear similar to dolines (Figs. 7.3 and 7.4) when the karst surface is pierced by an old shaft (Mihevc et al. 1998, 169), for instance a phreatic jump in an old cave, which was filled with deposits and flowstone. Unroofed caves (Fig. 7.4) which are formed when an oblique or horizontal

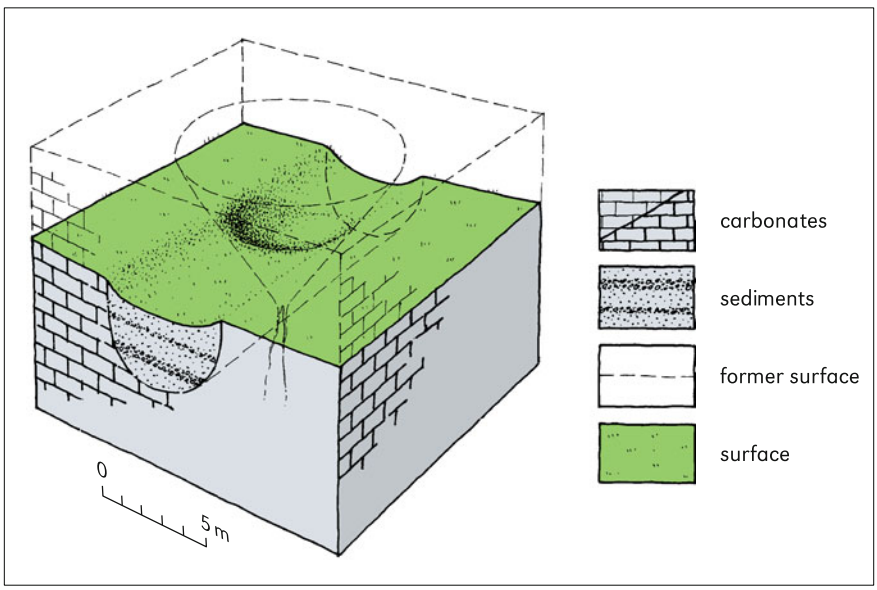


Fig. 7.6 An unroofed cave as a composed karst form

passage cuts through a steep side appear as semi-dolines with an elliptical cross-section (Knez and Slabe 1999b). In addition, single doline-like unroofed caves can emerge within old passages. In this case, only a part of the passage opens up or the doline is formed amidst an old unroofed passage (Fig. 7.6). Dolines can also form in old cave alluvium which was washed away in a funnel shape by the percolating water. Later, the alluvium is covered with layers of rubble and soil in various thicknesses. The so-described dolines can have a diameter of several tens of metres. Also, dolines can cut through old passages or merely encroach on new ones.

Strings of dolines occur when a passage gets opened in several places or, alternatively, when several dolines line up in a passage. We can often identify the direction and size of larger caves based on strings of dolines.

### 7.1.5 Notches

Notches are created from old unroofed passages which run parallel to the karst surface (Fig. 7.2). They may extend several hundred metres or even kilometres. They may occur as uninterrupted formations, or interrupted with preserved roofs or pitted with dolines. They may run several metres wide and several metres deep. They feature alluvium-filled bottoms, overlain by soil; their rims are often lined with flowstone. Notches may occur on horizontal or sloped sides either transversely or longitudinally.

### 7.1.6 Variegated Shapes of Cave Systems

A system consisting of various shapes (described in the preceding sections of this paper) was unearthed as the result of denuding a larger and complexly formed cave.

The largest cave system (400 m long) that had been discovered at the start of the route near Kozina was made up of empty passages, one of which was already recognized before the earthworks, and alluvium-filled passages with thin roofs, as well as passages with no roof at all. On the surface, the cave was recognizable as a system of more or less distinctive notches, the most prominent ones dotting the slopes of the dolines and acting as connection between dolines, and of smaller, relatively shallow dolines. Most of the cave was filled with fine-grained alluvium, in some parts there were even layers of flysch pebble. The bottom of the southwestern part was almost completely covered with heaps of flowstone, stalactites and stalagmites. Fine-grained alluvium was deposited over flowstone. Coarse rubble was covering the surface or acted as cave infill in some locations; it was commonly overlying old alluvial deposits or filling the space below abris, which had formed in the beginning sections of the passages. The rubble came about as the result of rock disintegration during the cold Pleistocene periods. The bottoms of the two larger dolines that had formed at the perimeter of the old cave system were covered with layers of brown and red soil a few metres deep. Their rim featured rock formations suggesting notable water percolation. Also at their bottoms were entrances into narrow vertical shafts.

It was observed that the most distinct surface forms of unroofed caves were in fact notches that had formed on the edge of the dolines where high water velocity facilitated sediment down-washing. Shallow dolines were formed in old alluvium within passages. The unroofed passage which had a well preserved alluvium cross-section was used to take alluvium samples for palaeomagnetic and pollen analysis.

## 7.2 Conclusion

Unroofed caves have recently come to the fore as a surface karst form that is increasingly distinguishable. Unroofed cave shapes depend on the type and shape of the original cave and on the development of the karst surface. They also reflect the evolution of the aquifer with its typical geological, geomorphologic and hydrological properties, as well as the climate conditions. Doline-like shapes are formed when the lowering surface is intersected in its cross-section by an old passage, filled with alluvium and flowstone. Alternatively, they can be formed if the surface encroaches on the passage at a specific point or when dolines are formed in the cave alluvium choking a large denuded passage. A line-up of these forms can often provide information about the shape and size of the transforming cave. Notches emerge from old unroofed passages which run parallel to the surface. The degree of recognizability of an unroofed cave on the karst

surface comes about as the result of the difference between the surface lowering rate and the rate at which the sediments were washed out of the cave. The connections between the varied karst surface forms often suggest the presence of cave systems which are subjected to modern transformation of the karst surface and the epikarst.

Other types of karst also boast their own distinctive and peculiar unroofed caves. In front of many entrances into old caves, which hollow out the heaps of flowstone in the fenglin karst in Puzhehei, Yunnan Province, China, there are bands of flowstone and dripstone which can extend 10 m and more. These are remains of former passage extension.

It may be summarized that unroofed caves are an important feature on the karst surface and on the epikarst, providing us with remarkable clues to the development of aquifers.

Ultimately though, the wealth of information we have assembled thus far about the various shapes of unroofed caves is highly conducive to the effective planning involving human interventions in the karst.