### 6.9 Preservation and Burial of Ancient Karst

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### Glossary

**Breakdown**  The process of failure of cave voids, particularly their walls and ceilings, and the debris produced by this process.

**Caymanites**  Marine turbidite palaeokarst deposits (graded bedded laminated limestones) formed when marine sediment flows into caves flooded during a marine transgression, first described from the Cayman Islands.

**Ceiling**  The upper inner surface of a cave void.

**Cupola**  A cave void with a dome-shaped ceiling and a circular to elliptical plan with a diameter or long axis in plan greater than 1.5 m.

**Endokarst**  Karst features formed deep within the rock mass, antonym of epikarst.

**Gossan**  Weathered surface exposure of an ore deposit.

**Hypogene**  Processes, or formed by processes, originating from inside the Earth.

**Morphostratigraphy**  The order of formation of morphological features. In caves the order of formation of voids and speleogens.

**Overhand stoping**  The physical removal of Earth material from the bottom-up.

**Roof**  The rock mass between the cave ceiling and the surface.

**Undercapture**  The capture of water flow from a higher-level passage into a lower-level passage in fluvial caves.
6.9.1 Introduction

Karst has existed since soluble rocks first appeared on the Earth. If we restrict our consideration to carbonates, that means largely since the Proterozoic, but it is not too difficult to imagine surface and underground landscapes forming in noncarbonate rocks under the range of atmospheric and hypogene chemistries that existed in earlier times.

When we consider the problem of ancient landforms, it is possible to recognize three general types, paleo landforms that are now preserved in the rock record, relict landforms that are the product of processes in the distant past and are now inactive, and ancient landforms where the processes that formed them are still active whereas the landforms have survived due to the extremely low rate of these processes. For example, a cross-bed might be a paleo-dune or ripple preserved in the rock record, glacial valleys in the Alps are relict landforms, as the glaciation that formed them has ceased, whereas valleys incising plateaus in stable cratons can be ancient active landforms with downcutting acting at the same locality for a hundred million years or more.

A great deal has been written, and there is much confusion about the definition of paleokarst (Osborne, 2000). If we apply the above ideas to karst, then paleokarst must be evidence of karst processes from the past, which is now part of the rock record. Put another way, if a karst feature is filled by or buried under strongly lithified rock, such that the fill and the host rock behave as a single unit then it is paleokarst (Figure 1). Paleokarst by this definition does not have to be particularly old. Caves containing well-lithified fill, perhaps only 1000 years old, occur in raised coral reefs in the Hawaiian Islands.

A vast literature on paleokarst exists, but much of this refers to ‘paleokarst facies’, small-scale features produced during brief periods of exposure and buried rapidly by the next depositional episode. Although this is of great interest to geologists, particularly those in the petroleum industry, it is unlikely to excite karst geomorphologists or speleologists. Paleokarstification is not always a permanent condition and given the right chain of events the paleokarst of today could become the relict karst of the future.

If a karst feature is neither paleokarst, nor a product of currently active processes, then it is either relict or buried. Relict karst includes abandoned stream cave passages and inactive hypogene caves. Karst features, including caves and dolines, filled by unlithified sediment, which are capable of being exhumed are considered buried karst here. Like paleokarst, relict and buried karst features do not necessarily have to be old, just isolated from the processes that formed them. All dry, air-filled fluvial cave passages are by this definition relict.

Ancient active karst features could include seasonally dry valleys, surface karst features in areas with low relief and rainfall, and some karst towers. Undercapture and development of new conduits at progressively lower levels make ancient active fluvial cave passages less likely, but it will not be surprising if some are discovered in unexpected places, with increasing work being undertaken in both dating and measuring the rates of processes.

The terms ‘fossil karst’, ‘fossil cave’, and ‘fossil passage’ are probably best avoided as they have been applied to paleokarst, relict karst, and to caves containing fossil-bearing sediments. Since karst landforms, including most hypogene caves, form at, or relatively close to, the Earth’s surface, one might expect that it would be quite rare for relict or ancient active...
karst to survive over geologically significant periods of time. Ancient land surfaces, however, are commonly preserved in the geological record as unconformities. Paleokarst features can be exposed when unconformity surfaces are re-exposed at the Earth’s surface and when rocks containing endokarstic paleokarst (i.e., former caves filled with now solid rock) are exposed or incised. Sometimes, buried and filled paleokarst features are exhumed to produce relict karst.

### 6.9.2 The End of Karstification

Before considering the survival of ancient karst features, it is important to have an understanding of their demise. Until about 25 years ago, it was generally agreed that karst features, and in particular caves, were quite young (Osborne, 2010). Although geomorphologists such as Jennings (1982) considered that “…the probability is that most caves developed during the course of the Quaternary,” many geologists thought that caves were somewhat older but were pessimistic about their survival: “…every large cave is probably at least half a million years old”, “All important limestone caves in the world are less than 10 million years old”, “Geologically, caves are very short-lived (see Anonymous, 1968). Only a few million years can intervene between the initiation of a cave and its destruction by roof collapse.”

There is now so much literature on multiphase karst and exhumed karst for it to be clear that burial is not necessarily the end of the karst history of a body of soluble rock. As Osborne (2004) pointed out, caves are difficult to destroy and “the only reliable way to destroy cave voids is to emulate the natural process and remove the enclosing rock from around them.”

From this viewpoint, the cessation of karst occurs at one of its most active points, the rock/air interface. Here, endokarst features and the karst rock mass itself meet their demise as CaCO₃ returns to its origins in the air and waters.

### 6.9.3 Examples of Extreme Preservation

#### 6.9.3.1 Ancient Paleokarst

If rocks from the distant past can survive in the geological record, then paleokarst from the distant past should survive also. Reports of early Proterozoic paleokarst from the Transvaal by Martini (1981) have been followed by numerous reports of Proterozoic paleokarst from Northwest Canada (Pelechaty et al., 1991) and North Greenland (Smith et al., 1999).

#### 6.9.3.2 Positive Paleokarst Forms

Most paleokarst exposures are usually level with or are negative features in the landscape. If the material filling ancient caves or dolines is strong enough, paleokarst features can be preserved as positive features protruding above the general level of the land surface. An example of this is the pyroclastic dyke at Wombeyan, NSW, Australia described by Osborne (1993) (Figure 2).

It is likely that many so-called ‘false gossans’ reported by mineral prospectors from limestone areas are in fact positive paleokarst forms, representing paleokarst ore bodies from which the original carbonate host rock has been removed by solution.

#### 6.9.3.3 Ancient Relict Surface Karst

Limestone towers and pinnacles in Tibet (Cui et al., 1997) and northern Australia (Robinson, 1978, Grimes, 2009) have been interpreted as exhumed relic karst features that originated in Permian or Cretaceous times. The origin of the shinlin (stone forests) in China appears to be more complex and may involve a combination of subcutaneous development and exhumation.

#### 6.9.3.4 Ancient Relict Caves

Caves have one major advantage over surface features; they form underground and so are separated from surface processes by their overlying rock mass. Hypogene caves have the extra advantage of being originally isolated from the surface and thus their destructive influence.

Until relatively recently, there were no dated examples of naturally open caves that were older than the Pliocene. By 2006, only five karst areas were reported to contain open relict caves older than 65 Ma: the Bohemian Karst of the Czech Republic 67–70 Ma (Bošák, 1998), the Guadalupe Mountains of New Mexico 92 Ma (Lundberg et al., 2001), the Black Hills of South Dakota 310–320 Ma (Palmer and Palmer, 2000), Jenolan Caves, NSW, Australia 339–345 Ma (Osborne et al., 2006), and possible Silurian Caves from West Ohio (Kahle, 1988). Although all of these caves are in Palaeozoic rocks, and some are in old landscapes, none are in very ancient landscapes or in Proterozoic rocks. Burial and exhumation have probably played an important role in the survival of ancient caves in the Black Hills and at Jenolan, but this and slow landscape processes are probably not enough to explain the survival of early Carboniferous caves at Jenolan.

#### 6.9.3.5 Caves without Roofs

Caves without roofs are a special type of relict cave as they represent the last remnant of karst, prior to its annihilation.
Caves without roofs have been reported in eastern Australia since 1870 with the recognition of flowstone, stalagmite bases, and vertebrate fossils at the Earth’s surface (Thomson, 1870; Broom, 1896). Due to the isolation of Australian scientists from mainstream karst research, these unroofed caves were considered unexceptional features, resulting from normal surface processes.

Although unroofed caves were recognized in Europe by Dawkins (1874) (see Mais, 1999), the recognition of unroofed caves in southern Europe in the 1990s (Mihevc et al., 1998) was noteworthy and at the time controversial. Inspired by the karst cycle of Cvijic (1918), a tradition had developed that interpreted unconsolidated sediments on karst plateaux as pre-karst fluvial deposits. New evidence from the expressway excavations in Slovenia showed that these sediment masses filled unroofed caves and that unroofed caves were quite common features of karst plateaus. Studies of unroofed caves revealed something quite surprising; they contained little or no breakdown debris (Figure 3). This suggested that rather than being produced by catastrophic underground ceiling failure, caves are unroofed mostly by the gradual removal by solution of the cave roof, that is, the rock mass between the cave ceiling and the surface. The walls of unroofed caves also generally remained intact as the surrounding surface was lowered, gradually bringing it level with the floor of the unroofed cave.

Most unroofed caves are elongate trenches, but more complex forms occur when the surface above and beside hypogene caves is denuded. These forms include multiple thin arches formed by the unroofing of cupolas such as those forming the Angel Gate above Szétkópuszta Cave in Hungary (Figure 4) and caves without floors and walls occurring in the sides of limestone monadocks in the Krakow-Częstochowa upland of Poland (Figure 5).

### 6.9.3.6 Ancient Active Surface Karst

In areas where the land surface in general is known to be ancient, surface karst features are also likely to be ancient. In plateau surfaces in eastern Australia where there has been insignificant lowering during the Cenozoic (Nott et al., 1996), karren on the plateau surfaces and limestone gorges incised into them are likely, as with the rest of the landscape, to have been active since the Mesozoic. Surface karst forms developed on Cambrian and Proterozoic carbonates of the arid and seasonally wet tropical cratons in the Gondwana fragments may have been active for even longer periods of time and should be investigated with this in mind.

### 6.9.3.7 Ancient Active Subsurface Karst

It is more difficult for subsurface karst forms to be active over significant time periods than for surface forms. If we consider
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6.9.4 Conditions and Mechanisms for Survival

6.9.4.1 Location

Ancient landforms, both relict and active, are best preserved in situations where the host rock is old, the relief is low, average rainfall is low, and the last deformation or uplift occurred in the distant past. Thus, ancient landforms are more likely to be preserved in ancient cratons than in active alpine foldbelts. This would suggest that Proterozoic and Cambrian carbonates in the cratonic regions of Africa, Australia, and South America would be highly likely to host ancient relic karst and ancient active karst. The lack of reports from these locations is probably due to a lack of research, in these areas. There are promising indications from work now underway in the cratonic areas of Brazil.

6.9.4.2 Isolation

Since the final destruction of karst features is a result of surface processes, isolation plays an important role in their preservation. Caves are particularly well suited for long-term survival as they form underground and are separated from the surface by the overlying rock mass. Once the active stream has left a fluvial cave or the fluids cease rising in a hypogene cave, things slow down. There might be some breakdown here, or speleothem growth there, but the cave wall itself commonly largely remains intact, or is even strengthened by precipitation of carbonate in cracks.

Because they generally lack significant connection with the surface, hypogene caves may have a greater likelihood of survival than their fluvial counterparts. Besides downcutting, uplift may result in caves becoming isolated from geomorphic activity. Some complex caves began life at depth as hypogene features, were uplifted into the dynamic phreatic zone, and then completely isolated from all but vadose seepage by further uplift.

6.9.4.3 Low Rates of Denudation

Low rates of denudation are essential for very old relict karst and caves to survive but they are probably not enough. Areas where ancient landforms survive tend to have low denudation rates, low relief, and low rainfall.

Low denudation rates, low relief and low rainfall, can only go so far to preserve very old landforms. As Gale (1992) recognized: “Although low rates of denudation are an important factor in ensuring the survival of ancient landscapes, this alone is inadequate as an explanation of the maintenance of landforms over ten and even hundreds of millions of years” (Gale, 1992, p. 337). Gale proposed that denudation needed to be localized if old land surfaces were to survive.

6.9.4.4 Sequential Vertical Motion on Faults

The survival of 340-million-year-old relict caves at Jenolan Caves cannot be explained by a combination of isolation, low denudation, or burial and exhumation. The vertical relationships between the old caves and the planated surfaces that intersect batholiths younger than the caves suggest that survival is only possible if vertical relationships between the rock mass containing the caves and the adjoining rocks have changed over time. Osborne (2007a) called this process the Fault-Block Shuffle and envisaged that the block containing the caves was downfaluted when the planation took place. In fold belts with many faults, this type of process may be responsible for the localization of denudation proposed by Gale (1992).

6.9.5 Filling and Burial

It is important to distinguish between filling and burial of karst features. Filling affects negative karst forms such as caves, grikes, and dolines. Filling may be partial or complete. Complete filling results in the whole of the feature being filled to the level of the surface. Burial occurs when the whole landscape is covered by material above the level of the karst surface. Burial generally, but not always, results in complete filling of underlying negative karst features.

A large range of geological materials can fill and/or bury karst features, including terrestrial, marine, and aeolian sediments; lava and pyroclastics; internal karst sediments; ore bodies and biogeochemical deposits.

6.9.5.1 Filling

Filling is most common in boundary karsts and impounded karsts because they have an immediate source of clastic sediments available. Ponor caves in boundary and impounded karsts can become blocked by debris, leading to flooding of upstream blind valleys and the subsequent filling of both the cave and the valley with sediment. This can raise the water table in the karst, leading to paragenesis in the caves. In some small impounded karsts, caves may undergo a sequence of filling and emptying events. Loess, slope sediments, and tephra can fill surface karst depressions and caves with dry entrances.

6.9.5.2 Burial

Burial occurs where a whole karst landscape is covered by sediment as a result of geological processes such as marine transgression, basinal subsidence, down faulting, or volcanic eruption.

Burial may lead to the preservation of both surface and subterranean karst features if the burial is not too deep. Loucks (2007) described the destruction of cave systems and their
conversion into breccia zones by overburden pressure when they were buried at depths of more than 3000 m.

Although burial will fill cave entrances, it need not result in the whole cave being filled with sediment. Burial can block cave entrances, with the result that inner spaces of the cave may fill with fluids, including petroleum, but not clastics. Where clastics do enter caves during a marine transgression, they may take the form of fine turbidite deposits, as occurs with caymanites (marine turbidite paleokarst deposits; Figure 6).

Burial should also affect cave sediments. If the burial is sufficient, then speleothem should recrystallize and diageneisis should be evident in the matrices and cements of clastic sediments. There has been little study of the diageneisis of cave deposits. Osborne et al. (2006) dated hairy illite regrowth on large illite crystals at Jenolan Caves, NSW, Australia to the late Permian and attributed this regrowth to diageneisis caused by burial under the Sydney Basin.

6.9.6 Exhumation

Exhumation refers to the reversal of either burial or filling. Exhumation may be localized or widespread, resulting in a whole buried landscape being exposed from cover. Incision and/or stripping, usually associated with uplift, are often involved in exhumation; however, hypogene speleogenesis can also exhume filled or buried caves.

Whole landscapes, including surface karst and caves, can be exhumed at the margins of uplifted sedimentary basins where the underlying unconformity surface becomes re-exposed. Where incision cuts below the buried land surface or into the beds of exhumed valleys, new fluvial caves can form below old filled caves, leading to their exhumation.

In broadly folded sequences, unconformity surfaces are most likely to be exposed and buried karst exhumed along the axes of anticlines. In this situation, surviving ancient features will retain their original vertical orientation.

Impounded karst, particularly long, narrow impounded karsts in steeply dipping limestone are ideal situations for filled caves to be intersected and exhumed because the number of structural paths available for water, fluvial or hypogene, to pass through is limited. In these situations, new caves are likely to intersect or undercut filled ones, leading to exhumation.

6.9.6.1 Vadose Fluvial Exhumation

If caves are filled with permeable material, then surface water can penetrate through the fill after uplift or incision and simply wash the fill out. This process can involve either high-energy work by sinking streams or the slow, low-energy action of rain-wash or seepage entering through entrances and cracks.

6.9.6.2 Exhumation by Stoping

Overhand stoping is one of the most important processes for the removal of unconsolidated and unstable internally weathered fills. This occurs when a new cave system develops below and partly intersects a higher-level filled system. The fill, now hanging in space, falls away aided by lubrication from seepage water. This process can exhume very large, filled chambers.

6.9.6.3 Exhumation by Vadose Weathering

Caves filled by strongly lithified deposits may be intersected and exposed on the walls of more recent hypogene caves, but are rarely exhumed in the process. The exception is where the lithified fill contains minerals that are unstable under vadose conditions. If these minerals are more abundant in the fill than in the bedrock, then the fill can weather out, exhuming the ancient cavity. This process has been observed where caymanite and quartz sandstone fills contain pyrite and there is little or no pyrite in the enclosing limestone (Figure 7).

6.9.6.4 Exhumation by Removal of the Host Rock

Although we generally think of exhumation as referring to the removal of material overlying or inserted within a cave or doline, the gradual denudation of the karst surface progressively exhumes and then destroys caves and other endokarst forms. Thus, the production and destruction of unroofed caves is a special form of exhumation.

6.9.7 Difficulties with Recognizing Exhumation

It is not always easy to distinguish between exhumed karst and some other types of karst features. The most difficult issues involve distinguishing between exhumed karst and epikarst.
and distinguishing between exhumed small-scale endokarst forms and epikarst.

One significant issue with the identification of exhumed ancient surface karst is distinguishing between it and exhumed subcutaneous karst. Subsoil landform development has long been recognized as a significant process in both noncarbonate and carbonate rocks (Twidale and Mueller, 1988). Slabe and Lui (2009) provided a contemporary summary of subsoil karst forms.

Both subsoil forms and buried paleokarst forms can be exhumed by contemporary processes. Distinguishing between the two is not always straightforward. Subsoil channels as in Slabe and Lui (2009, figures 2 and 3) are difficult to distinguish from exhumed and modified subsurface forms, whereas subsoil half bells in figure 13 of Slabe and Lui (2009) look very much like exhumed and penetrated cave cupolas.

Definitional problems also arise with exhumed subsoil and subjacent karst forms. One model for the origin of shinlin (stone forests) in China interprets them as exhumed subjacent karst features, resulting from processes that were initiated in the early Permian (Knez and Slabe, 2009, Song and Liang, 2009).

In many karst areas, particularly those with hypogene caves, features in the epikarst are a combination of true epikarst forms, small-scale exhumed endokarst forms (tunnel fragments, small cavities, etc.), and exhumed endokarst forms that have been modified by epikarst processes. It is commonly not easy to distinguish between the two.

6.9.8 Implications of Preservation, Burial, and Exhumation

6.9.8.1 Cave–Landscape Relationships

The traditional view of the relationship between caves and the landscape was that caves were either the same age or younger than the landscape in which they occur. As Susmilch (1923, p. 15) commented about Jenolan Caves (NSW, Australia): “…the caves themselves cannot be older than the valley in which they occur” In the case of Bungonia Caves (NSW, Australia), where a series of relatively deep caves occur adjacent to a limestone gorge, James et al. (1978) concluded that: “…most of the caves could be considerably younger than the rejuvenation which formed the gorge” (James et al., 1978, p. 61).

A clear link between landscape and cave evolution was the basis for some of the most influential work on cave chronology, for example, Droppa (1966) on the caves of the Demänovská Valley, Slovakia, which correlated levels in the caves with river terraces in the surrounding landscape. Emerging views about hypogene speleogenesis (Klimchouk, 2007) make the reverse assumption that many hypogene caves are older than the present land surface and are later intersected by surface processes such as valley erosion.

6.9.8.2 The Surprising Fate of Stalagmites and Flowstone

Old geography books and even some university websites refer to the vulnerability and short survival time of speleothems in general and stalagmites and flowstone in particular. Cavers and cave managers also relate how vulnerable these features are to damage by careless humans and removal by vandals and climate scientists.

Observations of unroofed caves and denuded karst surfaces have shown that rather than being the most vulnerable of karst features, stalagmites and flowstone frequently survive after the roof and walls of the cave in which they were deposited have been completely removed by denudation (Figure 8).

6.9.8.3 Complex Caves

Taken together, the combination of preservation and intersection of paleokarst, exhumation of paleokarst and filled relict cavities, and preservation of ancient open cavities results in the production of complex caves. Such caves may intersect several generations of paleokarst, incorporate exhumed cavities, and their unfilled sections may be the product of multiple phases of different types of speleogenesis.

Jenolan Caves intersect at least three generations of paleokarst and consist of interlinked hypogene, paragenetic, and fluvial cavities dating back to the Carboniferous (Osborne, 1999; Osborne et al., 2006), whereas Cathedral Cave at Wellington, NSW, Australia, intersects at least four generations of paleokarst resulting from the overprinting of at least five phases of hypogene speleogenesis (Osborne, 2007b).

In complex multiphase and multiprocess/multiprocess caves, there is no simple answer to the question “how old is the cave and how did it form?” A morphostratigraphy must be...
established from a combination of crosscutting relationships between cavities and dating of sediments where possible.

References


Biographical Sketch

Armstrong Osborne has been investigating caves, karst, and paleokarst in the complex impounded karsts of eastern Australia for the last 35 years. A geologist by training, his original focus was on the stratigraphy and petrology of cave sediments and paleokarst deposits. During the 1990s he realized that while the sediments and paleokarst in eastern Australian caves made sense, the caves themselves did not, so his interests expanded to include cave morphology and hypogene speleogenesis. Over the last 14 years, he has been involved in collaborative studies of cave minerals, palaeokarst, and hypogene caves with colleagues in central Europe and more recently on gneiss caves in Sri Lanka.

Armstrong has been actively involved in karst and geodiversity conservation through advisory committees, consultancies, contract research, cave guide training, and as an expert witness in court cases. He is a visiting fellow of the Karst Research Institute, Postojna Slovenia, a research associate of the Australian Museum, and serves on editorial and advisory boards for journals related to caves and karst. As Associate Professor, science education at the University of Sydney, he coordinates and teaches science units for primary education students along with earth science and ‘science as a human endeavor’ units for secondary education students.