THE ORIGIN AND FORM OF CAVE SYSTEMS

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INTRODUCTION

It is probably fair to say that the scientific understanding of the origin of caves was fairly complete by about 1960 (Lowe, 2000a). Around that time, various apparently conflicting theories on cave development were notionally unified into a broad concept that cave passages were polygenetic, but all caves fitted into the one grand system of karst geomorphology that was developed through bedrock dissolution in various environments (Palmer, 1991; Klimchouk et al, 2000; Ford & Williams, 2006). Since that time, there has been major progress in analysis of the detailed kinematics of carbonate dissolution chemistry (White, 2000; Dreybrodt, 2000), but there have also been significant adjustments to speleological thought, partly derived from studies of newly explored caves in remote parts of the world.

CAVES AND KARST

The vast majority of the world's caves lie in karst terrains that have been eroded out of carbonate rocks, essentially limestone, and only those are considered in this brief review. Caves in gypsum and salt are also formed by dissolution and therefore have some similarities, but caves in basalt are totally different and are a feature of pseudokarst.

Subsurface caves and surface karst landforms are formed by dissolution in natural waters, at rates and scales that are largely governed by the carbon dioxide content of the water, as this is directly proportional to the amount of carbonate that can be taken into solution. The groundwaters that form caves derive their dissolutional capability from biogenic carbon dioxide. This is largely collected during the waters' previous passage through the soil cover and its concentration is therefore related to the extent and activity of the plant cover. The size of cave passages is a function of dissolution rates and geomorphological history; the larger caves and the more mature karst are developed in regions of

Figure 1 Immature karst in the Canadian Rockies (left), and mature karst at Shilin, China (right).

warmer and wetter climates (Figure 1). Arctic environments have small caves and minimal karst features; temperate zones have the scale of cave and karst features that we know in Britain; Mediterranean regions are typified by caves that are larger and more richly decorated with secondary calcite; the wet tropics have the most spectacular karst terrains and the largest caves (Figure 2). Rainfall has an added influence, with minimal karst developed in both arid and frozen terrains.
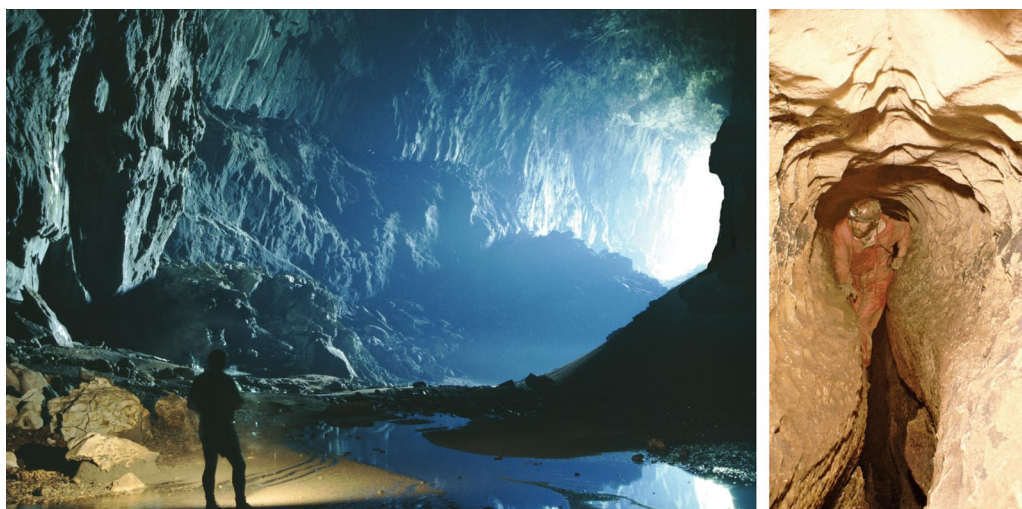

Figure 2 The giant Deer Cave in the wet equatorial Mulu karst in Sarawak (left), and a small keyhole passage in the Gaping Gill cave system in the less mature Yorkshire Dales karst (right).

Caves of significant size are formed by through-flows of water. The inflow is either a stream sink, directly into an open cave, or percolation through networks of narrow fissures that only coalesce into a cave passage at depth. The outflow is a rising, which may be either a freely-draining cave passage or a flooded conduit, and is normally fed by a converging system of caves and fissures. Influent and effluent caves are not entities (except in the context of exploration limits) and all caves are parts of total drainage systems. The size of cave passages is partly a function of the size of their formative stream or river, and therefore relates to catchment area and rainfall level. Cave passage size is also a function of climate and of time; the largest caves have histories back into the Pliocene, while many smaller caves formed entirely during one or more of the warm stages within the Pleistocene (when dissolutional activity may have been interrupted during phases of glaciation or permafrost).

CAVE PASSAGE MORPHOLOGY

The overall shapes and patterns of cave passages and systems are strongly influenced by geological structure, as most passages are initiated on bedding planes, within certain beds, on joints or faults, or on the intersections of these structural breaks. The detailed shapes of the passages are largely functions of their hydrological environment - whether they were formed above, at or below the contemporary water table, and these details are superimposed on the geological controls.

Within the vadose zone, above the water table, a vadose cave passage is essentially a free-flowing stream canyon with a roof on it. In cross section it is commonly a squared canyon with a planar roof on a bedding structure (Figure 3), or a narrow fissure aligned on a vertical or inclined fracture. The long profile is continually downhill, with meandering canyons between waterfall shafts that are either rounded by spray corrosion or elongated by waterfall retreat; inlets join in a dendritic pattern that may include additions through the roof. A vadose cave may be many kilometres long, and its depth is only

limited by the vertical range from mountain catchment to valley-floor rising; the Krubera Cave in the Georgian Caucasus has recently been explored to a depth of 2080 m. A vadose cave may drain out into a valley where geological structure (notably the base of the limestone) dictates. However most continue into a flooded phreatic passage.

Within the phreatic zone (or phreas) below the water table, cave passages are full of water so that dissolution of walls, floor and roof tends to produce a tubular cross section. This may be circular (Figure 3), or elongated into an ellipse along a geological feature. The long profile may go up or down, and may be a short, flooded down-loop dictated by geological structure, or may lie through a long flooded zone in limestone that reaches far below any available valley-floor rising. A major phreatic

Figure 3. A vadose canyon in Mammoth Cave in Kentucky (left), and a drained phreatic tube in Castleguard Cave in the Canadian Rockies (right).

lift may emerge in the valley floor to create a deep vauclusian rising, named after the site in France where the water rises more than 300 m. A phreatic system may be dendritic or braided, or can be a maze (especially if on two intersecting systems of joints) or spongework (developed on three dimensions). Systems may reach many hundreds of kilometres in total length, as in the active phreatic caves of Mexico's Yucatan, and in the now-drained, dry caves of Kentucky's Mammoth Cave System (Beddows, 2004; Palmer, 1981).

Many cave passages are formed at the water table (which is virtually horizontal within a highly permeable limestone aquifer), where dissolutional effort is increased by the mixing of different waters and also contact with the atmosphere above the flooded zone. The concept of water table caves once went out of favour within western speleo-literature, when many horizontal caves were recognised as being vadose or phreatic on horizontal geological structures. But since then, water table notches and foot caves at the toes of cliffs have been widely recognised in tropical environments, especially at the margin of alluviated plains within mature karsts. Vertical sequences of water table caves have been recognised within the mountains of Sarawak's Mulu karst, and each level corresponds with the remnants of a gravel terrace identified in adjacent fluvial basins (Farrant et al, 1995).

A sub-group of water table caves includes those formed at sea level, within the tidal range, in coastal limestones. Notable are the many through the limestone towers that are now islands within the drowned karst of Vietnam's Halong Bay (Figure 4); some of these link through to hongs, lagoons in

half-flooded dolines in the centres of the larger islands and most easily reached through the caves during low tide. A second locus of dissolutional activity due to mixing of waters occurs at the halocline, the boundary between the freshwater lens and the underlying salt water in a coastal aquifer (Mylroie & Carew, 2000). Some of the Blue Holes, in the Bahamas, descend to caves where development is enhanced at the halocline. Horizontal cave development at both sea level and the halocline is now recognised as significant in modern reef limestones, along ancient limestone coastlines and within carbonate petroleum reservoirs.

Horizontal cave passages may also develop in a very mature karst where cave development matches river development by evolving towards a graded profile at base level. Vadose caves evolve towards base level by down-cutting. Phreatic caves do so by paragenesis - the continuing process of cave roof dissolution while the cave floor is shrouded by accumulating clastic sediment; the result can be a canyon passage that has evolved from bottom to top. An initial switchback profile can therefore evolve into a level cave as vadose canyons cut through the up-loops and paragenetic canyons cut through the down-loops. The Hinboun River Cave, in the mature Khammouan karst of Laos, is 6 km long and graded to the regional base level, so that it is entirely navigable by boat, and also defines a uniform water table within the limestone (Waltham & Middleton, 2000).

Maturation of a cave to a perfect graded profile is rare, and interruptions to erosional maturity are more common. These include rejuvenations, including those caused by successive Pleistocene glacial deepening of valley floors, which instigate drainage of previously flooded caves; this is widely seen in keyhole cave passages that derive their name from their cross section of a vadose trench cut into the floor of a phreatic tube (Figure 2). Tectonic uplift may also rejuvenate caves, especially in coastal regions, and drowned caves may be left by subsidence. Pleistocene sea level declines also influenced caves, notably in Mexico's Yucatan, where the underwater caves decorated with stalagmites were initiated as phreatic tubes, gained their calcite deposits in vadose interludes during the glacial phases, and are now retuned to the phreas.

An important sub-group of limestone caves includes those formed by dissolution by sulphuric acid. Brines and connate waters from deep-seated evaporite sequences or hydrocarbon reservoirs carry hydrogen sulphide into the limestone, where it oxidises to form the acid. Powerful dissolution

Figure 4 A sea level cave through to a hong in Halong Bay, Vietnam (left), and the Big Room in Carlsbad Caverns, New Mexico, with thick gypsum beds in the foreground (right).

therefore occurs where the brines meet the karst water, forming large cave chambers with radiating passages. In New Mexico, USA, Carlsbad Caverns and the adjacent, fabulously decorated Lechuguilla Cave were formed by H_2S from the Delaware Basin; both caves are now distinguished by their gypsum deposits (Figure 4), formed as a by-product of the carbonate dissolution (Taylor, 1991). Rising geothermal waters may be similarly enriched in H_2S (but not necessarily so) and have created caves with random morphology and distinctive mineral precipitates in the Buda Hills of Hungary and elsewhere. Hydrothermal dissolution may have contributed to the early genesis of many caves, including the extensive Jewel Cave in South Dakota, where it left the thick crusts of calcite crystals over the rock walls.

Beside the creation of this special group of caves, sulphuric acid may have played a role that was much more widespread in the initial genesis of caves. Within limestone sequences, some horizons are prime loci of cave development, but it can be difficult to ascribe the very first stages of cave inception to meteoric waters that would have had very limited access to tight bedding planes at depth (Lowe, 2000b). Though minor in quantity, mineral acids, notably sulphuric acid derived from pyrite within interbedded shales, may have had a relatively important role in these early stages, before they were eclipsed by through-flows of water charged with biogenic carbon dioxide. The debate remains open on the processes of cave inception.

EVOLUTION OF CAVES

Once formed, most caves are then destroyed in the natural cycle of geomorphic evolution. As caves are enlarged, their roof spans may fail, and rock collapse hastens destruction. Large cave chambers are typically modified by roof and wall collapse (though "collapse chambers" are not formed by collapse, as the collapse must take place into a pre-existing void). Collapse may migrate through to the surface, an event hastened by surface lowering during regional or localised denudation. The cave may therefore evolve into a collapse doline or collapse sinkhole that is small or large (or known as a tiankeng if greater than 100 m in depth and diameter). But limestone gorges very rarely originate as "collapsed caverns" (contrary to popular opinion, most limestone gorges, including Cheddar, are fluvial features formed before underground drainage developed or when it was interrupted in phases of periglacial environment). Similarly, dolines are rarely formed by rock collapse; the vast majority are subsidence dolines formed where the soil mantle is washed down into karstic fissures, perhaps taking with it any roads or buildings on shallow foundations, and therefore creating the main karstic geohazard (Waltham et al, 2005).

Doline fills and soil mantle washed into caves are added to the fluvial debris carried in by sinking streams, to constitute the host of clastic sediments that can line, fill or choke caves. Their lithology is partly a function of the contemporary surface geography, and their greater chance of preservation in segments of abandoned cave passages makes these valuable records of paleo-environments. Clastic cave debris also combines with various organic materials, that includes thick beds of guano accumulated below tropical bat roosts, material carried into caves by man or animals, and also animal skeletons that become valuable paleontological deposits when they collect in natural pitfall traps in steep-sided dolines.

Secondary calcite deposits (speleothems in the form of stalactites, stalagmites and flowstone) are largely formed by percolating soil water dripping into air-filled caves and being forced to deposit carbonate as carbon dioxide exsolves into the cave air. They may decorate a cave in spectacular style (Figure 5), but they may also choke a cave. They are also a record of paleo-environments, as their
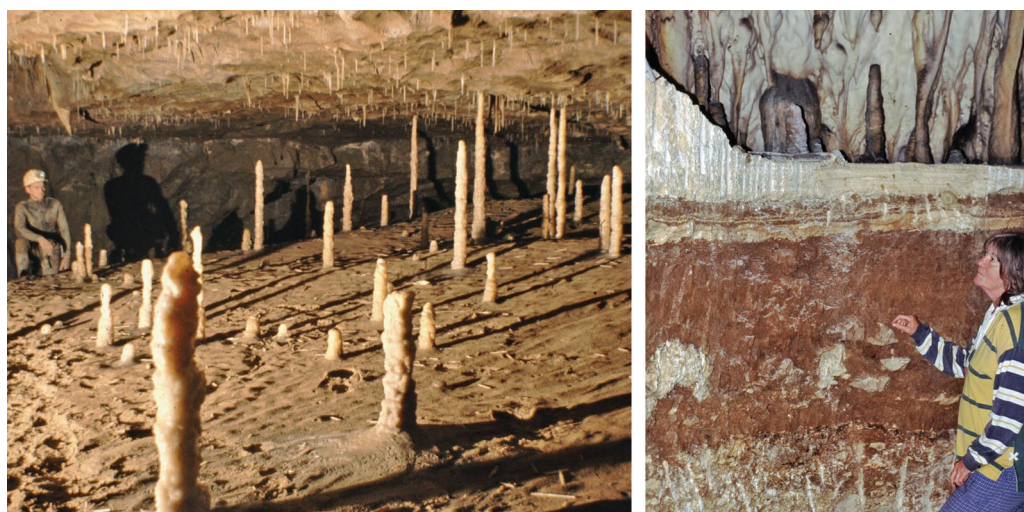
Figure 5 Interglacial stalagmites on early glacialfluvial clastic sediments in Pippikin Hole in the Yorkshire Dales (left), and a dated sequence of clastic and calcite sediments in Postojna Cave, Slovenia (right).

formation is sensitive to climate. Hence they formed in Britain's caves only during the interglacial stages of the Pleistocene (and not during the cold stages), in Mexico's Yucatan caves only during the glacial stages (when temporarily drained by sea-level decline) and in Oman's caves only during past interglacial stages (when the arid climates were broken by pluvial conditions).

The ages of calcite stalagmites are indicated by their ^{230}Th/^{238}U isotope ratios, and some quartz sediments may be identified from their ^{26}Al/^{10}Be ratios, with the latter yielding dates as old as 3M years (Granger et al, 2001). Combined with sedimentological interpretations, and with contemporary temperatures indicated by ^{18}O/^{16}O ratios, interbedded sequences of clastic and calcite cave sediments (Figure 5) that survive in abandoned passages therefore constitute a major resource of paleo-environmental data (Sasowsky & Mylroie, 2004). Correlations of cave morphology to surface landforms then allow detailed interpretation and dating of physiographic evolution, whether this be the glacial rejuvenations of the English Pennines or the steady tectonic uplift of Borneo. While caves are a fascinating and perhaps beautiful component of limestone geology, they also have scientific values that reach well beyond their karst terrains.

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