Evolution of caves in response to base-level lowering.

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Abstract: Base-level lowering plays an important role in cave passage development and morphology. Commonly cave conduits are formed at depth below the water table, and sub-horizontal conduits can form at depths of more than 100m below the water table. The depth of formation is a function of flow path length and stratal dip. Subsequent base-level lowering is responsible for evolution from a deep phreatic to a shallow phreatic to a vadose, water-table setting, and is accompanied by gradational features such as bypass passages, vadose entrenchment, and undercapture passages. This pattern of evolution expands on the two-cycle hypothesis of Davis (1930), is compatible with a gradual lowering of base level, and is common. Most caves do not evolve to a vadose passage stretching from sink to spring because the flow is redirected by undercaptures, which are at a lower elevation and are usually formed below the water table. Undercaptures frequently form distributary springs and provide much of the complexity seen in cave maps. Distributary springs and bypass passages can also be formed during short-term rises in base level that also produce wall notches.

INTRODUCTION

Many accounts have been published about the formation of conduits in caves, and in recent decades their relationship to the water table has been linked to external base-level changes (Palmer, 1987), to the abundance of open fractures (Ford and Ewers, 1978), and to stratal dip and flow path length (Worthington, 2001, 2004). The response of conduits to base-level lowering provides a separate but associated issue. Davis (1930) proposed a "two-cycle" hypothesis of cave development, with conduit formation at depth below the water table. Gradual base-level lowering would result in the water table eventually dropping below the level of the conduit, abandonment of the conduit and the formation of a new, lower-elevation conduit. However, Davis gave no details of conduit evolution during these stages, and Ford (1965) was the first to describe gradational features associated with a falling water table, including vadose entrenchment, bypass passages, and (under)captures.

Many cave passages show clear evidence of vadose modification of an earlier phreatic passage; the main stream passage in Ogof Ffynnon Ddu (South Wales) is an excellent example. This has evolved from being predominantly phreatic with conduits to at least 70m below the water table to an almost completely vadose stream passage (Smart and Christopher, 1989). However, recent summaries such as Ford (2000, 2004), Veni (2005) and Palmer (2005) place little emphasis on gradational processes, implying for instance that water-table passages are usually formed from scratch at the level of the related water table rather than possibly evolving from a pre-existing, formerly deeper phreatic conduit.

The following account seeks to explain how passages evolve over time, how grading mechanisms may be recognized in caves, and how significant such grading is in overall cave development.

CONDUIT EVOLUTION IN RESPONSE TO A FALLING BASE LEVEL

In many caves it is possible to identify two main passages types:
  i)   predominantly vadose passages, where flow is largely downdip along (or incised below) bedding planes and vertically down joints, and
  ii) predominantly phreatic (or phreatic with vadose modification) base-level passages, where flow is largely horizontal.

Passages between King Pot and Keld Head (Yorkshire, England) provide an excellent example. The vadose passages follow the stratal dip towards the north, whereas the phreatic base-level passages drain southwards to Keld Head (Figure 1).

The low-viscosity enhancement of flow deep below the water

table suggests that caves, especially in catchments longer than about 3km, should commonly be initiated as a single loop at some depth below the water table (Worthington, 2001, 2004). The simplest pattern is where there is a sinking stream flowing via a cave to a spring, as shown in Figure 2. The initial flow is shown as a curving path below the water table, with the depth of flow being a function of stratal dip and flow path length (Worthington, 2001).

Figures 2b to 2d show changes in the cave in response to a steadily falling base level. In Figure 2b, the vadose, upstream part of the cave has increased in length as the water table has dropped, and the crest of one loop has developed an isolated vadose trench (Ford, 1965). Further increases in the length of vadose passages occur in Figures 2c and 2d. New passages may also form. These are of two types, and were named bypass passages and capture passages by Ford (1965), though Palmer (1969) referred to both types as diversion passages. Bypass passages are new, higher passages that form by sedimentation, roof collapse, or a rising base level. Capture passages have also been called phreatic captures (Smart and Christopher, 1989), diversion passages (Ford and Williams, 1989), undercaptures (Jeannin *et al.*, 2000), and tapoff passages (Veni, 2005). They are new, lower passages that form as a result of steepened hydraulic gradients due to base-level lowering. Sediments aggrading on the cave floor can result not only in bypass passages but also in upward dissolution of the cave ceiling. Such upward dissolution has been called paragenesis by Ford and Ewers (1978), although the term paragenesis was first used by Renault (1968) to signify the reduced rate of dissolution of the walls of a cave passage as a result of shielding by clastic sediments.
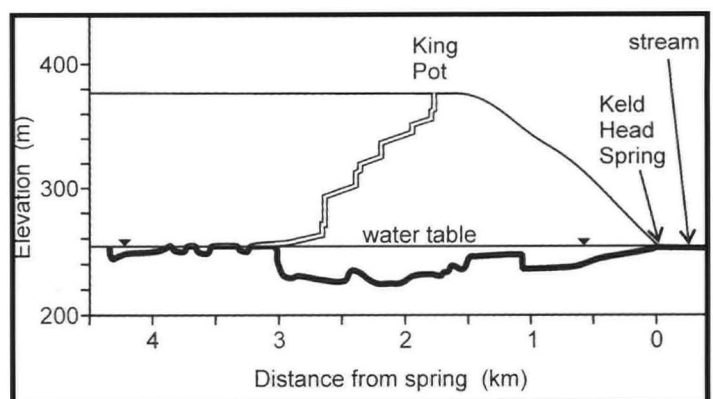
Figure 1. Extended profile of the base-level conduits under East Kingsdale and of the vadose tributary of King Pot (compiled from Brook et al., 1994 and Monico, 1995)
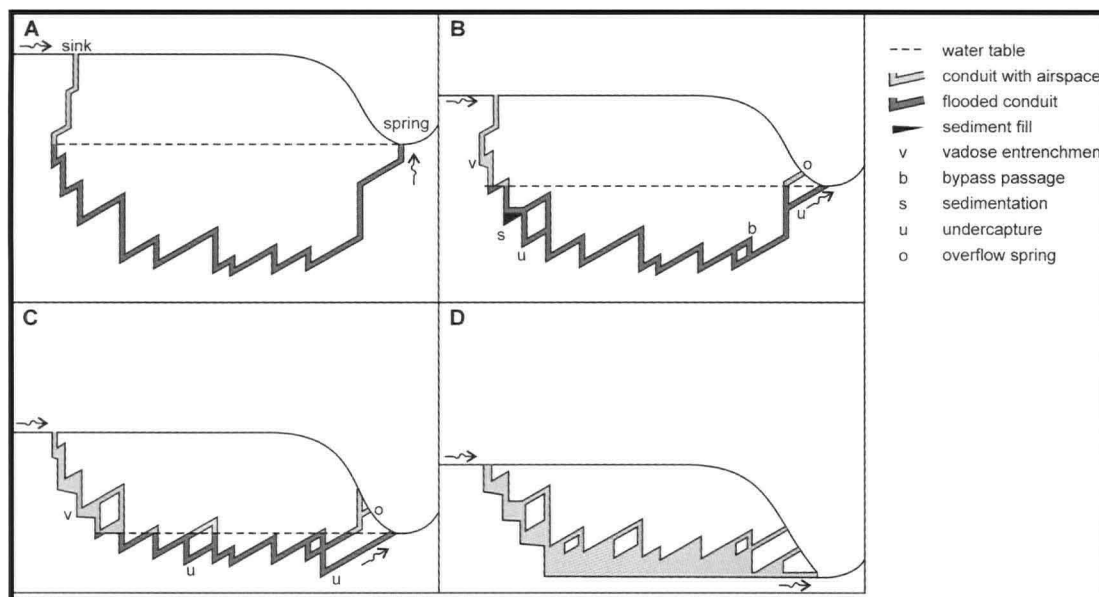
Figure 2. Evolution of a conduit as base level drops: A) initial flow path deep below the water table with a single spring, B) shallow phreatic conduit with gradational features and multiple springs C) mixed phreatic - water-table cave with multiple springs D) water-table cave.

The falling base level in Figures 2a to 2d shows the idealized evolution of the cave from a deep phreatic cave to a shallow phreatic cave to a water-table cave. Figure 2d shows the beginning of the final phase in the evolution of a cave passage – its demise. Unroofing commonly commences close to the sink and less frequently close to the spring. Excellent examples of such unroofing are seen at the Long Churn caves in England (Figure 3), as well as at Porth yr Ogof in South Wales and the Cullaun caves in Ireland (Waltham *et al.*, 1997; Tratman, 1969). Complete unroofed caves have also been described (e.g. Knez and Slabe, 2002).

Figure 2 is idealized, and examples illustrating the features shown are described in the following sections.

FEATURES RESULTING FROM BASE-LEVEL LOWERING

Vadose canyons

The simplest response in a conduit to a falling base level is vadose entrenchment. The eventual product is a stream or river cave that can be followed from sink to spring. If the initial flow path was a single loop deep below the water table, then this may be preserved in the ceiling of a river cave, with the initially deeper centre part of the cave having a lower ceiling than either entrance, as in Figure 4a. Some river caves have passages that reach 100m in height (Figure 4b). It is probable that the deep vadose entrenchment in such caves is favoured by a number of factors, including low uplift rate, low base-level lowering rate, high discharge, high sediment load, and high dissolution rate. However, the great majority of karst springs do not

emerge from open caves, and most abandoned vadose passages in caves are less than 20m high. Thus the deep vadose entrenchment and open passages from sink to spring shown in Figures 2d and 4 occur only in a small fraction of conduit pathways.

Porth yr Ogof has one of the best examples in Britain of a vadose river passage. It has a length of 300m from the main upstream entrance to the resurgence entrance and is the underground path of the River Mellte. The cave was formed when the river flowed along the valley (now dry) above the cave (Waltham *et al.*, 1997, p.236). The upstream end of the dry valley is 12m above the cave roof, and so the cave developed at least 12 m below the water table and was large enough to capture surface flow when it was still 12m below the water table. Thus, it clearly records the effect of base-level lowering in transforming a formerly phreatic conduit into a currently vadose one.

In addition to base-level vadose caves, there are numerous vadose canyons that descend steeply to former or present water tables, such as in King Pot (Figure 1) and Swinsto Hole (Waltham *et al.*, 1981). There are many other similar caves in the Yorkshire Dales, as well as numerous examples in areas such as the Burren (Ireland), Waitomo (New Zealand) and West Virginia and Tennessee (USA).

Distributary springs

Springs in carbonate aquifers are commonly located close to base-level streams. Subsequent stream downcutting will result in a spring orifice being raised above base level. The steep hydraulic gradient and short horizontal distance facilitate the formation of new, lower-

Figure 3. Unroofed cave in Yorkshire. The person is standing at the junction of the unroofed passages from Wilson's Cave (on the left) and from Upper Long Churn Cave (on the right). In the background is the entrance to Lower Long Churn Cave.
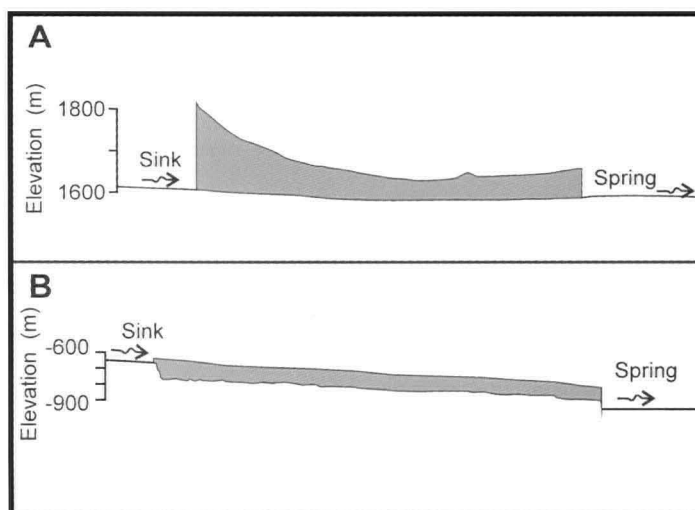
Figure 4. Projected profiles of large river caves in China A) San Cha He Dong (after Waltham, 1986), B) Xio Zhai Tien Ken - downstream section (after Senior, 1995)

level conduits, and such undercaptures are shown in Figures 2b, 2c and 2d. The lower conduit will enlarge steadily until it can discharge all the flow from the conduit system. The diminishing flow in the upper spring will result in it becoming intermittent at first and then abandoned. The resulting patterns of distributary passages associated with groups of springs were named underground deltas by Martel (1894), who also described the association of lower-elevation perennial springs and nearby overflow springs, which are both at higher elevation and are intermittent. Figure 5a shows one of several underground deltas mapped and described by Martel (1894).

Figure 5 also shows three more examples of distributary springs. The Gouffre de Padirac in France is currently the world's longest explored cave stream; this has been followed for 19km to Finou Spring and has four other distributary springs (Figure 5b). The Cheddar caves provide one of the best examples in Britain of distributary outlets, with former springs at elevations of 93m, 61m, and 33m, a current major spring at 25m, and one or more lower-elevation underflow springs (Figure 5c). There is a perennial spring for the Foussoubie System (France) in the bed of the Ardèche River and two more springs just above the river. In addition, there are two overflow springs up to 15m above the river and three former springs up to 118m above the river (Figure 5d). In low-flow conditions there are many pools and sumps, and the passages display an epiphreatic morphology due to the extensive flooding of the cave at times of high flow (Figure 6 and Minvielle, 1977).

Distributary springs are very common in karst aquifers. Some of the best-documented are in the Mammoth Cave area (Kentucky, USA), where individual groundwater basins drain to two to 46 springs (Quinlan and Ewers, 1989). These springs include Gorin Mill Spring and Graham Spring, which are the two largest springs in Kentucky. Both springs have approximately constant discharge, and at low flow are the sole springs for their respective groundwater basins. At high flow there are four overflow springs associated with Graham Spring and 45 overflow springs associated with Gorin Mill Spring (Ray, 1997; Quinlan and Ewers, 1989). Underflow springs have low discharge variance and are typically perennial, whereas overflow springs have high discharge variance and are commonly intermittent (Smart, 1983; Smart and Ford, 1986).

In Britain, three springs draining Penyghent Hill and adjacent areas (Yorkshire) show similar contrasts. The perennial Brants Gill Head has little variation in discharge, but two higher-elevation overflow springs, at Douk Gill Head and Dub Cote Cave, display much larger variations in discharge. The limited capacities of Brants Gill Head and of Gorin Mill Spring and Graham Springs were noted by Waltham et al. (1997) and by Ray (1997), respectively, and are probably because these springs are of recent origin and are in the process of capturing flow from their respective overflow springs. There are many other examples of distributary springs in Britain, including those at Leck Beck Head, God's Bridge, White Scar Cave, Turn Dub / Footnaw's Hole, Malham Cove / Aire Head Springs, Sleets Gill Cave and Nidd Heads in the Yorkshire Dales (Waltham et al., 1997), at Ilam and Castleton in the Peak District (Christopher et al., 1977, Gunn, 1991), at Clydach Gorge, Shon Sheffrey, Porth yr Ogof and Nedd Fechan in South Wales (Gascoine, 1989), and at Havant in the Hampshire Chalk (Atkinson and Smith, 1974).

Although distributary springs are common, there are some situations where their development is unlikely, including vadose river caves (e.g. Porth yr Ogof, San Cha He Dong, Xio Zhai Tien Ken - see above and Figure 4) and springs perched on low-permeability strata (e.g. Guiers Mort, France: Lismonde, 1997).

Undercaptures

Undercaptures can form distributaries leading to multiple springs, and these normally form close to the springs, as described above. However, undercaptures can form at any location along a conduit flow path (Figures 7, 8 and 9). Figure 7 shows a small part of Ogof Ffynnon Ddu, and the complexity seen is due to extensive undercapturing (Smart and Christopher, 1989). An initial phreatic tube followed a vertically and horizontally looping course, but successive undercaptures provided a progressively shorter pathway. Most abandoned passages saw little vadose entrenchment, but the modern stream passage has been entrenched by as much as 15m in
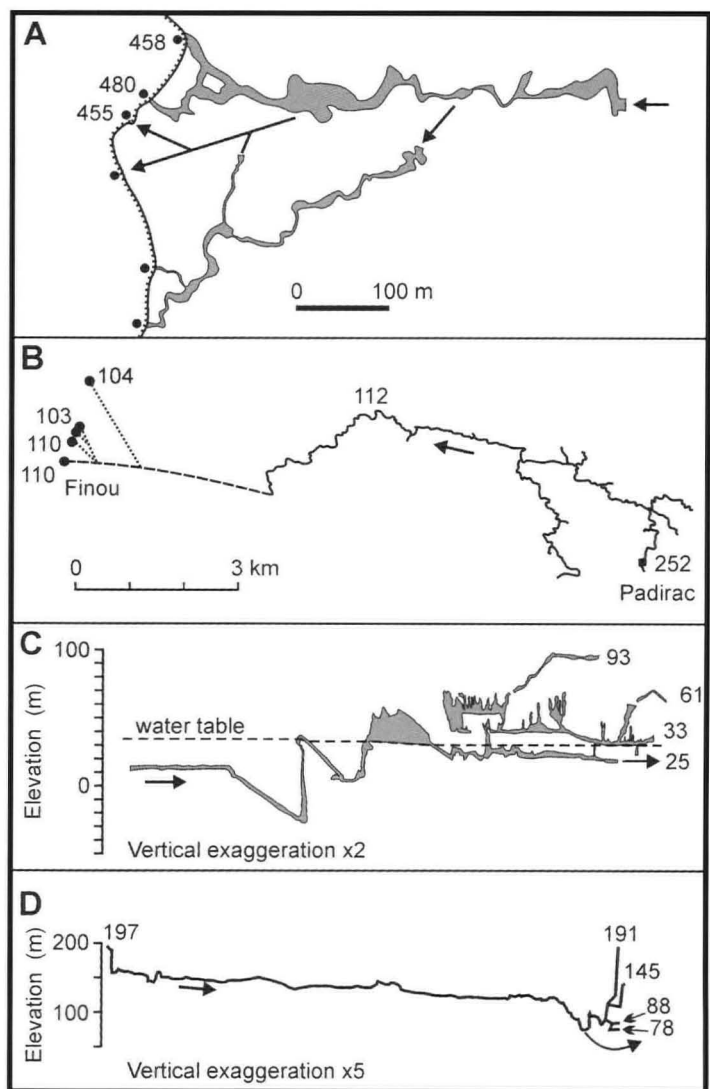

Figure 5. Conduits associated with distributary springs A) Plan of Salles-la-Source, France (after Martel, 1894), B) Plan of Gouffre de Padirac, France (after Anon. 1979, Salomon, 2000) C) Projected profile of Cheddar caves, England (after Ford, 1965 and Farr, 2000), D) Projected profile of Foussoubie system, France (after Le Roux, 1984)

this part of the cave.

The most common morphology observed in a cave passage when the water table drops below conduit level is that of a phreatic tube in the roof and a vadose canyon below. The phreatic tubes might be well developed and account for much of the passage cross-section, as in the upstream part of White Scar Cave (Yorkshire), or might have only rudimentary development, as in the downstream part of this cave (Figure 8a). Undercaptures can also occur before substantial vadose entrenchment can take place, as in the base-level passages in the West Kingsdale System (Yorkshire) and in Hölloch (Switzerland) (Figures 8b and 8c).

Passage development is somewhat more complicated where there is a substantial seasonal variation in water table elevations. In Hölloch the cave passages primarily have phreatic forms, but these are partly due to dissolution during high-flow events when the water table rises more than 100m (Wildberger and Ziegler,1992; Jeannin, 2001). Figure 9a shows high-flow and low-flow water tables in Bärenschacht (Switzerland) at a time when base level was 200m higher than today. There are three main elements to the passage network: phreatic passages about 100m below the water table that were able to transmit low-flow discharge but not all of high-flow discharge; second, epiphreatic passages that discharge the excess high flow (these were formerly phreatic passages when the water table was higher); third, connecting passages called soutirages, which drained the base of the epiphreatic loops (Häuselmann et al., 2003). Figure 9b shows an interpretation of the formation of undercaptures; major ones form some 100–200m below the water
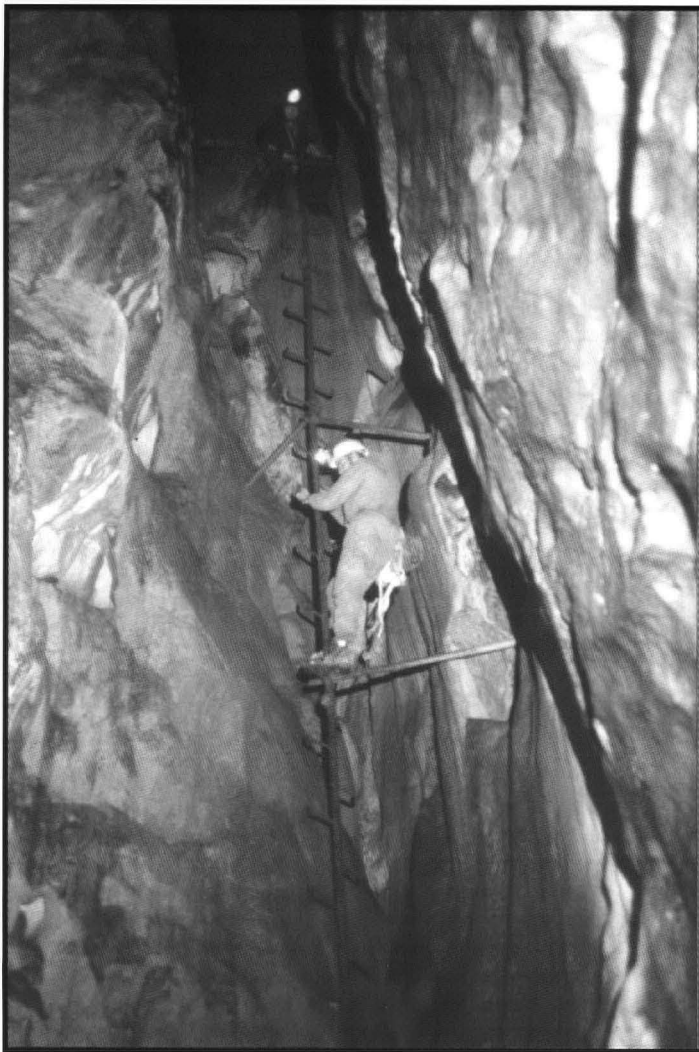
Figure 6. Epiphreatic passage in Foussoubie System, France. Fixed ladders are in place to facilitate a rapid exit when the cave floods.

table and have lengths of several hundred metres.

Some undercaptures in Mammoth Cave have much greater lengths, with diversions to springs that were several kilometres distant from the earlier outlets (Figure 10). For a time there would have been distributary flow to both old and new springs until the new conduit was able to capture all the flow. Modern distributary springs have been widely documented in the Mammoth Cave area, as noted above. The large scale of undercaptures at Mammoth Cave is due the low dip of the limestone and the extensive outcrops of limestone along the Green River, which facilitated the diversions shown in Figure 10. By contrast, caves with steeper stratal dips, such as Ogof Ffynnon Ddu, Hölloch, and Bärenschacht, have much more restricted zones where the caves have discharged into base-level streams or lakes.

The undercaptures shown in Figure 10 occurred towards the upstream end of their groundwater flow paths. Similar examples in Britain include Swildon's Hole (at Tratman's Temple), Giants Hole (below Garland's Pot), Ogof Ffynnon Ddu (at the Crevasse), Easegill Caverns (near Easter Grotto), and Gaping Gill (at Main Chamber). However, such undercaptures are less common than undercaptures closer to springs, where the shorter flow path will result in more rapid creation of new conduits (Figure 5).

The undercaptures discussed so far have been in base-level passages, but they can also occur in the vadose zone substantially above base level. Lost John's Cave (Yorkshire) offers several fine examples, with successive flow paths via Hammer Pot, New Roof Traverse and Old Roof Traverse (Waltham, 1974).

The examples described above display the complexity that can result during the evolution of a single tier of cave passages. Further complexity can occur where a cave has multiple tiers, and this is described below.
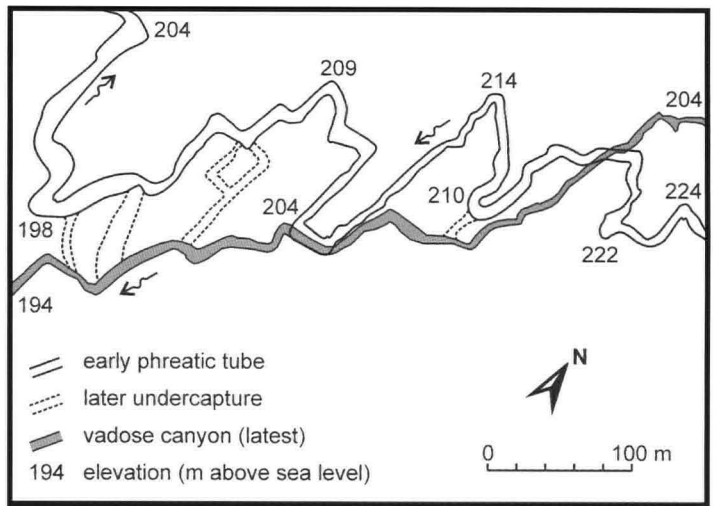
Figure 7. Passages in a small part of Ogof Ffynnon Ddu, Wales, showing early phreatic looping, successive undercaptures, and modern vadose stream flow (after Glennie, 1950 and Railton, 1953)

CAVE TIERS

Relation of tiers to base level

In some caves there are distinct tiers or levels of cave passages, where there appear to be a clustering of major passages at a particular elevation. In discussing Mammoth Cave, Davis (1930) recognized that the formation of four tiers could be explained in two ways:

> "The one-cycle theory, or theory of corrasion and
> solution by vadose and water-table streams, will .... be
> here compared, in its modified form as demanded by
> four pauses in elevation, with the two-cycle theory, or
> theory of ground-water solution, for which a
> continuous elevation suffices" (Davis, 1930, p.596).

Davis favoured the two-cycle theory, where there is a steady lowering over time of base level so that passages formed at depth below the water table gradually become vadose as the water table drops. Other workers, both before Davis and more recently, have interpreted tiers as having formed at the same levels as base-level rivers (the one-cycle theory of Davis, 1930) and cave tiers have often been linked to fluvial terraces (see Davis, 1930, pp.595–600; Sweeting, 1950; Palmer, 1987; Anthony, 2005). This latter hypothesis assumes that cave tiers are formed when rivers have long periods when there is negligible base-level lowering, and that such periods alternate with short periods with substantial river incision and thus base-level lowering.

Several tiers are found in some caves and in studies before 1973 tentative correlations were made with Pleistocene glacial episodes. Sedimentation was considered to occur in caves during glacial stages and lowering of base level was thought to occur during interglacial or interstadial periods (Ford, 1964; Atkinson, 1967; Miotke and Palmer, 1972). The concept of a simple correlation between cave tiers and glaciations was, however, found to be inadequate when absolute age dating results became available. First, Shackleton and Opdyke (1973) showed that there were many glaciations during the Pleistocene, with a periodicity of about 100,000 years in the Late Pleistocene. Second, absolute dating methods have shown that base-level lowering rates may be very slow (Atkinson et al., 1978; Gascoyne and Ford, 1984) and that some caves may be several million years old (Ford et al., 1981; Granger et al., 2001; Worthington and Medville, 2005). Consequently, a single cave tier may have been active over a number of successive glacial and interglacial periods. Sea level can drop about 100m during major glaciations and so it seems likely that in many caves there may have been several substantial erosional and aggradational changes in base level during the formation of a single tier. Such rapid changes during the Pleistocene provide a challenge to the assumption of cave tiers being formed at a stable base level.

A second challenge is provided by the discovery that near-horizontal passages can form at substantial depths below the water
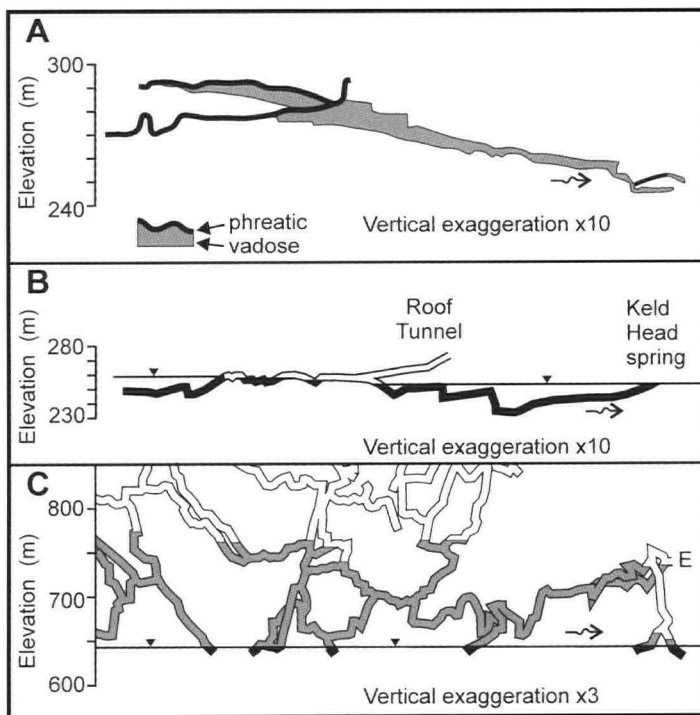
Figure 8. Profiles of cave passages with contrasting undercaptures. A) White Scar Cave, England, B) West Kingsdale System, England, C) Hölloch, Switzerland (A adapted from Waltham, 1977; B adapted from Brook and Brook, 1976 and Monico, 1995; C after Wildberger and Ziegler, 1992)

| Cave	Criterion*	Tier spacing (m)	Reference
Carlswark, England	tiers	14, 13, 13	Christopher and Beck, 1977
Mammoth, Kentucky	transition	21, 21, 16	Palmer, 2004
Friars Hole, West Virginia	tiers	18, 17, 15, 24, 27	Worthington, 1984
Demänová, Slovakia	tiers	18, 30, 32, 20	Droppa, 1966
Archway - Terikan, northern Mount Benarat, Mulu, Malaysia	tiers	35, 35, 30	Eavis, 1981
Gua Harimau - Lubang Sakai, southern Mount Benarat, Mulu, Malaysia	tiers	120, 90, 110	Eavis, 1985
Agujas, Spain	tiers	55, 25, 44, 21, 13, 55, 50	Rossi et al., 1997
Daren Cilau - Craig a Ffynnon, Wales	tiers	40, 27, 48, 63	Smart and Gardener, 1989
Nettlebed, New Zealand	tiers	65, 90, 60, 65	Ford and Williams, 1989, p.122
Siebenhengste, Switzerland	transition	150, 80, 135, 80, 65, 550, 85, 45, 60, 40, 102	Jeannin et al., 2005
Hölloch, Switzerland	tiers	160, 120	Bögli, 1980
Nelfastla de Nieva, Mexico	tiers	230, 230	Worthington, 1991

Table 1: Vertical spacing of cave tiers
* The criterion for recognition: either the transition in a passage from vadose shape to phreatic shape or the vertical spacing between tiers of

table (e.g. Waltham and Brook, 1980). Figure 11 provides some examples, which are described by Worthington (2004). A hypothesis for the formation of such conduits is described below.

Formation of tiers below base level

Flow deep below the water table is favoured in many settings because geothermal heating reduces viscosity and thus enhances flow. The resultant enhanced flow at depth below the water table results in increased dissolution and preferential conduit enlargement, and is thus a more favourable setting for cave formation than at the water table (Worthington, 2001, 2004). Sub-horizontal flow deep below the water table is likely in particular where flow is along the strike of the strata, as with the examples in Figure 11a-d.

Figure 12 shows a model for how cave tiers may form deep below the water table. Figures 12a, 12b, and 12c are similar to the progression shown in Figure 2, with base-level lowering resulting in a conduit evolving from deep phreatic to shallow phreatic to vadose. Eventually a new, lower-elevation conduit will capture some of the flow (Figure 12c) and over time this will enlarge and pirate all the flow from the upper conduit, leaving it abandoned (Figure 12d).

Worthington (2004) used regression of the data from twenty cave system surveys to show that the depth of conduit development below the water table can be described by:

$$D = 0.18 (L\ \theta)^{0.81} \qquad (1)$$

where D is the mean conduit depth in metres below the corresponding water table, L is the flow path length in metres and θ is the dimensionless stratal dip (equal to the sine of the dip in degrees). This regression shows that conduit development deep below the water table is associated with long flow paths and with steeply-dipping strata.

Assuming that flow path length and stratal dip remain constant for succeeding tiers, then it follows that each new tier will be formed at a similar depth below the contemporary water table and hence tier spacing will be constant for a given cave. The vertical distance between tiers varies substantially between different caves (Table 1). However, these is a tendency in many of these examples for tier spacing to be near-constant, thus supporting the concept that new tiers form according to Equation 1.

It is likely that the hydraulic gradient is the major driving force behind the formation of a new tier. Hydraulic gradients in mature phreatic conduits are extremely small. Well-documented cases

include gradients of 0.0006 – 0.0015 for Jortulla Cave, Norway (Lauritzen et al., 1985), and 0.0012 – 0.004 for Mangle Hole – Banwell Spring, England (Hobbs, 1988). The geometric mean hydraulic gradient of these phreatic passages is 0.0014.

By contrast, the gradients of vadose cave streams are much steeper. Gradients in some notable vadose stream passages are 0.007 in Sinks of Gandy, West Virginia (Dasher, 2000), 0.019 in San Cha He Dong, China (Figure 4a), 0.022 in Porth yr Ogof, Wales (Lloyd, 1980), 0.03 in White Scar Cave, England (Waltham, 1977), 0.044 in Dan yr Ogof, Wales (Coase and Judson, 1977), 0.045 in Lancaster-Easegill, England (Ashmead, 1974), 0.093 in Ogof Ffynnon Ddu, Wales (Smart and Christopher, 1989), 0.098 in Xio Zhai Tien Ken, China (Figure 4b), and 0.2 in Giant's Hole, England (Ford, 1977). The geometric mean gradient of these vadose streams is 0.064, which is 45 times greater than for the average gradient in the two submerged conduits.

The hydraulic gradient in the partially vadose upper conduit in Figure 11c will be much steeper than in the phreatic conduit in Figure 11a, thus greatly increasing the flow through the lower, immature conduit. It is common for flow to be captured to the lower conduit before extensive vadose development has occurred in the upper conduit, and Figure 11 shows five such examples. Hölloch and Bärenschacht are two additional examples of caves that lack vadose base-level passages because all the passages shown in Figures 8c and 9, respectively, are tubes that were formed and enlarged under phreatic or epiphreatic conditions. In each case, the passages were abandoned by the cave streams that formed them before they could develop beyond stage B in Figure 12.

Conduits in some caves progress to develop vadose canyons before capture to a lower tier. Agujas Cave System (Spain) provides

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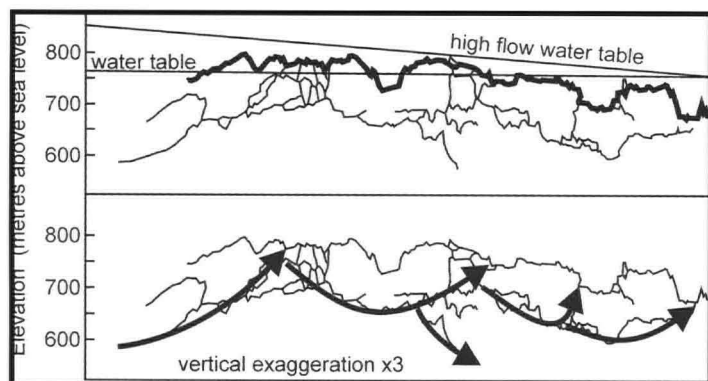
Figure 9. Profiles of Bärenschacht, Switzerland. (a) Profile of the cave when the water table was at 760 m, showing passages up to 200 m below the current water table and in bold the main epiphreatic flood overflow passage (after Häuselmann et al., 2003). (b) Interpretation of the development of five major undercaptures.

a spectacular example of a multi-tier cave where each phreatic passage has evolved to a vadose canyon (Figure 13). The cave is developed in overturned limestones that have a 50° dip, and the passages cut across the bedding. The canyons are up to 20m in height. Other examples of conduits with extensive vadose development are shown in Figures 4, 5a and 5b, 7, and 8a. In Mammoth Cave, Palmer (1987) showed that about half of the base-level passages have negligible vadose development (e.g. Cleaveland Avenue, Marshall Avenue, Swinnerton Avenue, and Turner Avenue in Figure 10) and the remainder have developed substantial vadose canyons (e.g. Echo River and Mather Avenue in Figure 10).

The phreatic conduits shown in figures 9 and 11 were all abandoned before significant vadose erosion took place. These caves are all situated in major mountain chains and it seems likely that the lack of vadose flow may be due largely to rapid base-level lowering rates. Such rates have been measured for several of these caves: 130–1120m/Ma in the Yorkshire Pot area (Ford et al., 1981), <440m/Ma at Nettlebed Cave (Ford and Williams, 1989, p.122), 190m/Ma for the Mulu caves (Farrant et al., 1995), and <600m/Ma at Bärenschacht (Häuselmann, 2002). By contrast, vadose stream passages are more common in lowland karst areas such as Mammoth Cave and the Yorkshire Dales, where much lower base-level lowering rates occur. These average 20m/Ma at Mammoth Cave
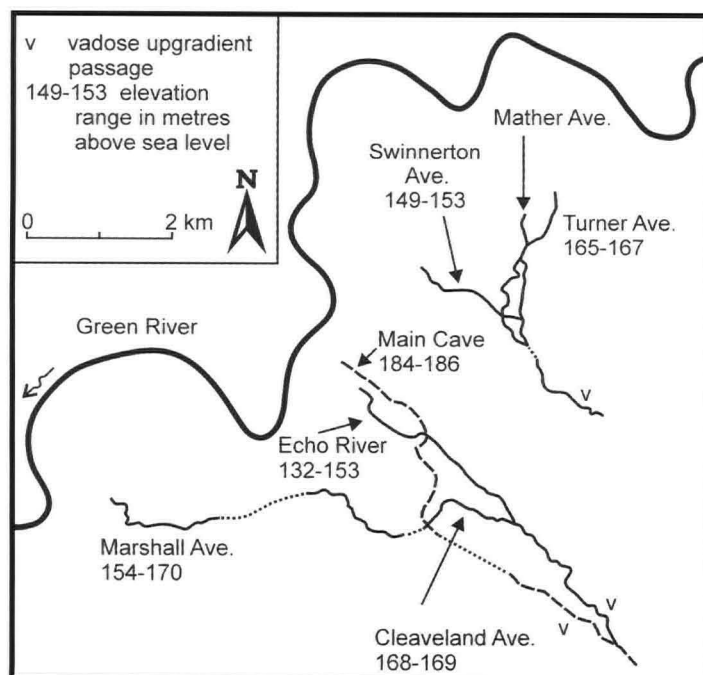
Figure 10. Some major passages in Mammoth Cave, showing undercaptures under Flint Ridge (Mather Avenue then Swinnerton Avenue) and under Mammoth Cave Ridge (Cleaveland Avenue then Echo River), with range of elevations of passages in metres above sea level (adapted from Palmer, 1987 and Palmer, 1989b)

(Granger et al., 2001) and 20–80m/Ma in the Yorkshire Dales (Gascoyne and Ford, 1984). However, this correlation does not hold in all cases; Agujas Cave, for example, is in a mountainous area, yet has substantial vadose development. It is likely that several other factors also influence the transition from one cave tier to a lower one, including stream discharge and variability and stream clastic sediment load.

Testing the two hypotheses of tier formation

It is clear from the above section, and particularly from the examples shown in Figures 5c, 5d, 9 and 11, that there can be extensive sub-horizontal cave development at substantial depths below the water table (the two-cycle theory of Davis, 1930). This contrasts with the evidence that Palmer (1987) found to support tier formation at stable base levels (the one-cycle theory of Davis, 1930). The evidence in support of these two hypotheses in three cave areas (Mammoth Cave, the Mulu caves, and the Yorkshire Dales) is discussed below.

Palmer (1987) carried out extensive levelling in Mammoth Cave to determine the elevations of major passages and of vadose/phreatic transitions, which are an important indicator of former water tables. Palmer identified four major levels of major cave passages at Mammoth Cave at elevations of 210, 180, 168, and 152m. These were later shown to have been active from before 3.3 Ma to 0.7 Ma before present (Granger et al., 2001). Lower passages in the cave, down to river level at 128m, lack well-defined levels.

Davis suggested that evidence to test his one-cycle and two-cycle hypotheses should include determining whether "all the caverns in the district should probably have the same number of gallery-levels separated by essentially the same vertical intervals" (Davis, 1930, p.596). Some major passages associated with levels C (167–169m) and D (152–153m) in Mammoth Cave are shown in Figure 10. Vadose to phreatic transitions occur at these elevations in widely separated passages, which provides strong support for the one-cycle hypothesis. Passages such as Cleaveland Avenue also provide strong support. This passage is an almost horizontal phreatic tube that appears to follow a former water table with exquisite fidelity for 1500m (Palmer, 1981, pp.101–103). Support for the one-cycle hypothesis would be substantially strengthened if major passages in other caves in the area were found to correlate with the Mammoth Cave levels. One possible cave is Ganter Cave, which lies on the opposite side of the base-level river to Mammoth Cave and has been reported to have "five well-defined cave levels" (George, 1989, p.217).

Other evidence at Mammoth Cave supports the two-cycle theory. For instance, Marshall Avenue, the downstream continuation of Cleaveland Avenue, has a phreatic loop that descends 14m below the level of Cleaveland Avenue (Figure 10). Furthermore, when an undercapture from Cleaveland Avenue developed, it descended at Echo River to at least 23m below the water table (Palmer, 1989a). Thus, not all phreatic passages have formed at the main levels described by Palmer (1981). Such variability demonstrates the complexity of cave formation, with different passages at Mammoth Cave supporting either the one-cycle or the two-cycle theories of Davis (1930).

In the Mulu area (Sarawak, Malaysia), cave wall-notches correlate with the benthic oxygen isotope record, and the correlation of wall-notch elevation with time shows that the base-level lowering rate has been a constant 190m/Ma for at least the last 700 ka (Farrant et al., 1995). Many of the passages in the Mulu caves were formed at depths of at least some tens of metres below the water table and such passages may be near-horizontal for substantial distances (Figure 11 and Waltham and Brook, 1980). The wall notches provide evidence for water-table modification of existing passages, but the evidence for the formation of new conduits at the water table is limited and equivocal (Waltham and Brook, 1980). This lack of water-table caves is consistent with the constant base-level lowering rate at Mulu. Water-table caves are thought to occur principally when there is a long period with no base-level lowering (Palmer, 1987). In the absence of such a stable base level it follows that water-table caves will not develop.

Sweeting (1950) correlated cave levels in the Yorkshire Dales with erosion surfaces, but later work has shown that there is a sequence of major inception horizons in the limestone and that these

provide the primary guidance for sub-horizontal passages (Waltham, 1970; Lowe, 2000). The concept of base-level control is further challenged by differences in the elevation of major relict cave passages in adjacent caves. For instance, the most prominent level of relict passages under Casterton Fell drained to a spring at 250m and there is also an erosion surface at this elevation (Ashmead, 1974), but Waltham *et al.* (1997, p.37) found the two major relict water tables in Leck Fell caves were at 290m and 225m. Both Casterton and Leck fells drain to the same spring, Leck Beck Head, and so the same relict water tables would be expected in both areas if base-level control were paramount in determining passage elevation. These differences between the cave levels under Casterton and Leck fells suggests that the relict levels were not formed as water-table caves during periods of base-level stability. This view is supported by the lack of association of modern base-level caves with the water table, because the caves under Casterton Fell and Leck Fell have been explored to depths of -32m and -64m, respectively, below the current water table (Monico, 1995).

The evidence from Mammoth Cave, Mulu, and the Yorkshire Dales provides strong evidence that a stable base level is not necessary for the formation of cave tiers. Some passages at Mammoth Cave appear to have formed in proximity to contemporary water tables that may have been stable for long periods, thus supporting the one-cycle theory of Davis (1930). However, other passages at Mammoth Cave and as well as caves at Mulu and in the Yorkshire Dales better support the two-cycle theory of Davis (1930), and this is summarized in Figure 12.

DISCUSSION

Passages possibly associated with a rising base level

The model described above and shown in Figure 12 is associated with a base level that falls steadily over time. However, there are a number of situations where base level can rise. Examples include aggradation in valleys, short-term rises in water level following flooding, and the rise in the Mediterranean Sea following the Messinian regression.

Aggradation in valleys can result in the formation of bypass passages, wall notches, and distributary springs. Bypass passages can result from sedimentation at the base of a phreatic loop, from roof collapse within a cave passage, or from sedimentation at a spring, and the likelihood of occurrence is enhanced where there is a large range in discharge (Ford, 1965; Palmer, 1975, 1991). Wall notches in Mulu caves correlate with aggrading alluvial fans outside the caves (Farrant *et al.*, 1995; Waltham, 2004). The principal explanation given earlier for distributary flow is that it is caused by a lowering of the water table and that this results in undercaptures. This explanation appears best to explain many examples such as those shown in Figure 5. In other cases, such as at Mammoth Cave, it may not be possible to tell whether distributaries were formed by a falling or by a rising base level. However, the long-term trend in any
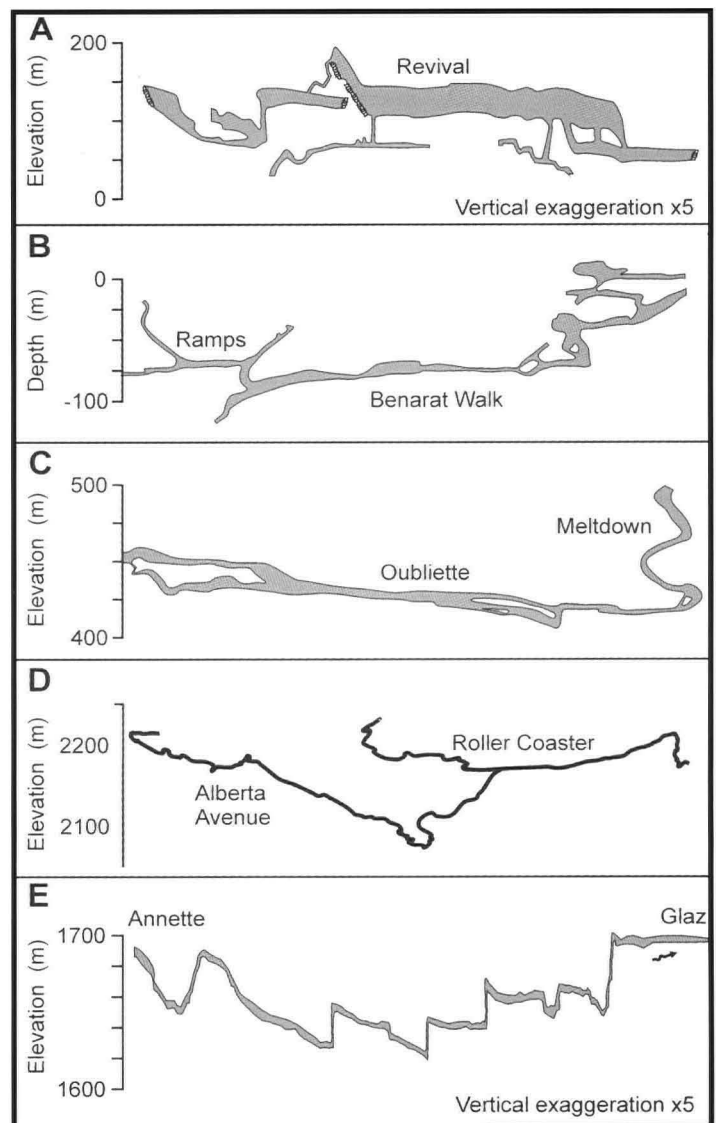

Figure 11. Profiles of conduits formed well below the water table. A) Clearwater Cave, Malaysia, B) Tiger Foot Cave, Malaysia, C) Nettlebed Cave, New Zealand, D) Yorkshire Pot, Canada, E) Dent de Crolles, France (A and B after Waltham and Brook, 1980; C after Pugsley, 1979; D after Worthington, 1991; E adapted from Lismonde, 1997)

area is usually for base level to fall and so distributaries are more likely to be associated with a falling base level.

Audra (1994, 1997) noted that the water table can rise more than 100m during the snowmelt period in some mountain areas, and he proposed that the epiphreatic or floodwater zone can be a major

Figure 12. Development of a new conduit as base level drops: A) initial conduit flow path deep below the water table with a single spring, B) shallow phreatic conduit with gradational features and multiple springs C) water-table cave with some flow being pirated to a developing conduit D) all flow captured by the deep conduit.
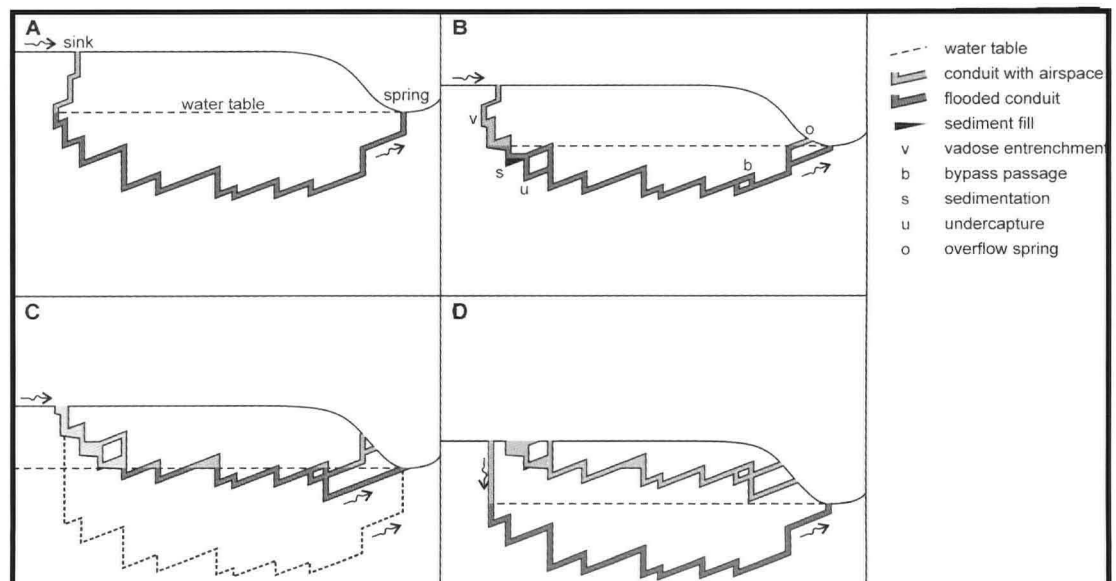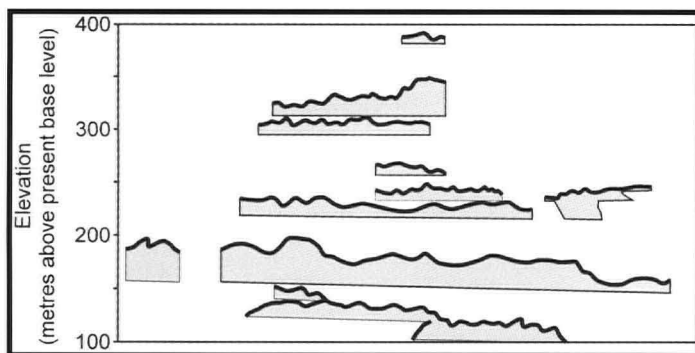
Figure 13. Profile of Agujas Cave System, showing a succession of tiers, with initial phreatic tubes (in bold) and subsequent vadose canyon entrenchment (in grey) (after Rossi et al., 1997)

locus for cave development. This hypothesis is supported by a detailed study at Bärenschacht, where Häuselmann *et al.* (2003) showed that much conduit enlargement takes place in the epiphreatic zone and that some passages (soutirages) are also formed in this zone. Nevertheless, most of the major passage formation takes place some 100m below the water table in the phreatic zone (Figure 9).

There are a number of karst springs in southern France that have been dived to great depths. These include the Fontaine de Vaucluse (-308m), Goul de la Tannerie (-209m), Goul du Pont (-178m), Font Estramar (-167m), Port Miou (-147m) and Source du Lez (-101m). Audra *et al.* (2004) suggested that the karst systems draining to these springs were formed during the Messinian age (5.96 to 5.32 My before present) when the Straits of Gibraltar were closed and sea level in the Mediterranean dropped by at least 1500m. Subsequent transgression would have flooded these caves and extensive alluvial sedimentation would have blocked the original spring outlets. This would have caused water to back up and form springs at what might earlier have been vadose shafts. This explanation implies that the passages feeding these deep springs are more than five million years old; this exceptional longevity is much greater than in most caves, where passages are usually active for much less than one million years.

An alternative explanation for the deep karst springs in southern France is that their deep flow is predicted on hydraulic grounds due to the long flow paths feeding the springs (Worthington, 2004, Equation 10). This also explains the deep flow in French springs such as Source du Bouillant (148m), Fontaine de Lussac (-142m) and Fontaine de Chartreux (-138m), none of which is in the Mediterranean basin and therefore cannot be attributed to the Messinian sea level changes.

In all the cases described above there is a long-term trend of base-level lowering. Consequently, cave formation is associated primarily with falling base levels, and the rising base levels described above add only second-order effects to cave patterns.

Trends in loop amplitude over time

Ford (1965) found evidence for former deep phreatic flow in the caves of the Mendip Hills (England), with flow to depths of -50m at the Cheddar caves, -85m in St Cuthbert's Swallet, -27m or -43m in Swildon's Hole and -43m in Wookey Hole. Processes such as undercapture, vadose entrenchment, and development of bypass passages later reduced the depth of looping over time at Swildon's Hole to -21m, then to -14m, and finally to -5m in the then-known streamway (as far as Sump 6: Ford, 1965). Similar processes occurred at Wookey Hole, so that based on then-available evidence it was inferred that "it now constitutes a water table cave" (Ford, 1965, p.124).

Ford (1968, Figure 2) inferred from the above observations that there had been a general increase in fissure frequency (the number of open fractures that conduits would develop along) over time in the Mendip Hills. This then resulted in a concomitant decrease in the depth of phreatic looping in successive cave tiers because it was thought at that time that conduits were more likely to develop close to the water table. It was later suggested that this model of increasing fissure frequency and decreasing loop amplitude over time was widely applicable (Ford and Ewers, 1978; Ford and Williams, 1989,

pp.265–270). However, Hölloch was given as an example of a cave where there has been no tendency towards decreasing loop amplitude over time (Ford and Williams, 1989, p.267).

Over the last 40 years there has been substantial exploration by divers in Mendip caves, and this has now shown that there is no overall trend over time towards shallower phreatic loops. Divers have reached depths of -20m in Sump 12 of Swildon's Hole, -58m at Cheddar (Figure 5c), and -94m in Wookey Hole. Similarly, analysis of loop amplitude at Hölloch and of maximum depth of flow at Mammoth Cave and at Agujas Cave show that there is no trend towards shallower phreatic flow in successive tiers (Figure 14). This lack of a trend in successive tiers contrasts with the trend in a single tier, where decreasing loop amplitude is common. This is caused by gradational processes such as vadose entrenchment, sediment fill, bypass passage development, and undercaptures, which were identified by Ford (1965) in Swildon's Hole.

CONCLUSIONS

The explanation of cave evolution described above expands on the two-cycle hypothesis of Davis (1930) and incorporates the gradational processes described by Ford (1965). This model is supported by extensive evidence from caves.

Cave conduits commonly form as a single loop below the water table, with the depth of flow being a function of flow path length and the dip of the strata (Worthington, 2004). As base-level lowering progresses, the outlet elevation falls and the water table drops, so that conduits evolve from being deep phreatic to shallow phreatic to vadose water-table passages. Only in rare cases does the process evolve to completion, with a vadose passage stretching from sink to spring. In most cases the process is interrupted at an earlier stage by the capture of flow to a new, deeper, phreatic conduit.

Gradational features such as vadose entrenchment, bypass passages, and undercaptures are common. They occur in most caves and account for much of the complexity seen in cave maps. Well-defined cave tiers are found only in a minority of caves and in most cases appear to have formed well below the water table rather than at it. It seems likely that further insight on cave evolution processes will follow from measurement of pertinent variables such as base-level lowering rates, uplift rates, discharge and sediment fluxes through conduits, and conduit wall-retreat rates.

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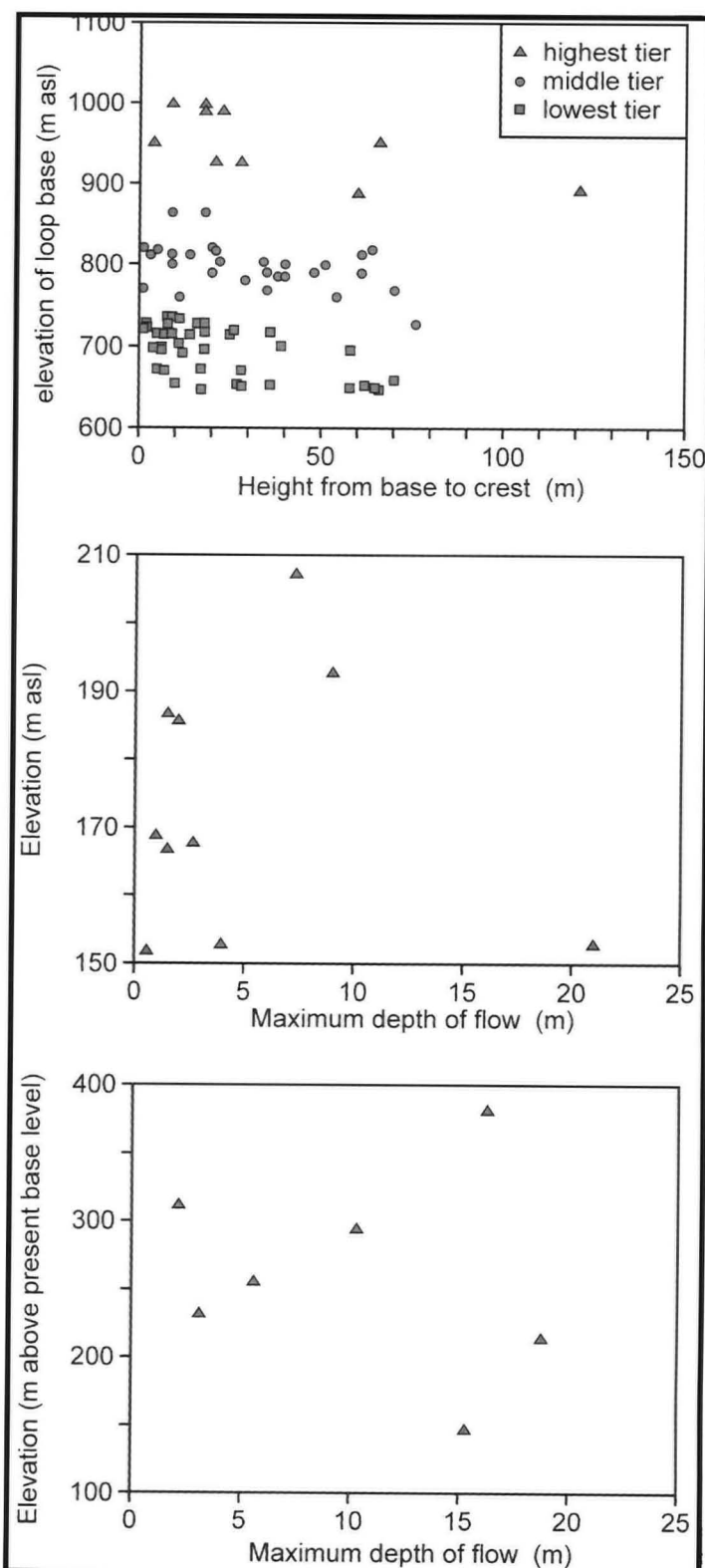
Figure 14. Depth of flow trends with passage elevation: loop amplitude at Hölloch Cave (top); maximum depth of flow for major passages at Mammoth Cave (middle); maximum depth of flow for the tiers at Agujas Cave (bottom). Data from a) Bögli, 1980, (b) Palmer, 1987, (c) Rossi et al., 1997.

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