CHAPTER 7

Cave geomorphology

Tony Waltham and Phil Murphy

A key component of the Yorkshire Dales karst is its suite of long and spectacular cave systems (Fig. 7.1). More than 500 kilometres of cave passages have been mapped and documented within the Dales (Table 7.1), and there are certainly many more still to be discovered. A single cave system with more than 88 km of interconnected passages lies beneath Casterton, Leck and Ireby Fells at the western end of the Dales karst. Between its 52 entrances, this cave system crosses the county boundary from Yorkshire into a narrow tongue of Lancashire and then into Cumbria, hence its name as the Three Counties Cave System (Table 7.2). The same cave is the deepest in the Dales, with a vertical range of 253m. While further discoveries will surely lead to even greater lengths of the cave systems, depths are constrained in the Dales by the thickness (and the low angle of dip) of the Great Scar Limestone (Table 7.3).

The earliest stage of cave genesis, known as inception, is perhaps the least understood. The initial dissolutional openings were strongly guided by the geology of the limestone, with groundwater exploiting existing weaknesses in the rock (see Chapter 8). The weaknesses included bedding planes and lithological boundaries from the original sedimentation, and also bedding structures, faults and joints that were developed during tectonic deformation. At that stage, the limestone permeability was very low, groundwater flows were minimal, and dissolution was extremely slow. The inception stage therefore lasted for millions of years, perhaps stretching back to include expulsion of connate water, some component of hydrothermal water and input of groundwater through adjacent aquifers. Inception was largely unrelated to rainwater input through outcrops of the limestone, as it was a feature of early hypogene systems with their deep-seated circulation of fluids, but the sizes reached by any fissures or conduits within these remain unknown.

After inception, most caves in limestone have developed largely through dissolution of the rock by groundwater that originated as rainfall. Allogenic streams drain off outcrops of shale or impermeable till, sink into the limestone at upland sites, flow through the caves, enlarging them on their way, and return to daylight at resurgences that are generally close to the levels of the dale floors. In contrast, much of the meteoric water enters fissures and fractures within the limestone as autogenic recharge; this may percolate through to open caves where it re-deposits calcite and partially blocks the passages.

The various processes of cave inception continue unabated in the limestone, developing new proto-caves and ever greater levels of karstic maturity. But it was only after exposure of the limestone by surface denudation that significant through-flows of water could pass through the limestone, between sinks and risings at disparate altitudes. At that stage, cave development could accelerate hugely to create the extensive systems of accessible passages that now penetrate and drain the karst. In the main part of the Yorkshire Dales karst (in the Great Scar Limestone across the southern dales), the earliest caves were formed beneath the southern fringes, adjacent to the Craven Faults, where the geological structures are highest and the regional topography is lowest. As the ground surface was lowered, and the valleys were entrenched, the limestone was more widely exposed, and caves developed across wider areas, along longer flow paths and to greater depths. Initial geological guides on the patterns of cave development were then partly overcome by hydrological factors. Lines of through-drainage, from the sinks of allogenic streams (derived from adjacent non-karstic outcrops) through to available resurgences, then became the foci of dissolutional (and mechanical) erosion, and hence

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Number of cave entrances	>2000
Number of caves >5m long or deep	~1500
Total length of mapped cave passages	>500 km
Cave systems >1 km long	65
Cave systems >100m deep	41

Table 7.1*. The extent of known caves within the Yorkshire Dales.*

Figure 7.1*. Calcite straws of The Haywagon, in Voldermort Pot, part of the Three Counties Cave System (photo: Mark Shinwell).*

Three Counties Cave System	Casterton Fell and Gragareth	88 km
Kingsdale Cave System	Gragareth and Whernside	27
Gaping Gill Cave System	Ingleborough	17
Mossdale Caverns	Grassington Moor	11
Langcliffe Pot	Great Whernside	9.6
Goyden Pot System	Nidderdale	7.1
Gingling Hole	Fountains Fell	6.9
White Scar Cave	Ingleborough	6.5
Stump Cross Caverns	Greenhow Hill	5.8
Penyghent Pot	Pen-y-ghent	5.2
Dale Barn Cave	Whernside	5.0

Table 7.2*. Cave systems longer than 5 km in the Yorkshire Dales. These are surveyed lengths. The total length of passage explored in the Three Counties System is nearer to 90 km at the time of publication, and is continually being increased by new discoveries.*

enlarged to develop from small conduits into larger cave passages. These drainage lines and their caves were far from straight, as they were still greatly influenced by the geology.

Once they had reached the stage of cave passages with significant through-flows, development and enlargement continued in line with the hydrological and geological influences. All caves were initially phreatic, as they were full of water until they had developed to sizes where the aquifer could freely drain down to a water level at or close to the contemporary outlet resurgence. From then on, caves matured both above and below this water table, to create vadose and phreatic passages respectively. The water table itself became a complex feature, partly controlled by the caves, and partly controlling some of the cave features. Surface lowering, especially during the Pleistocene glacial episodes, caused repeated rejuvenations of the surface and the caves when base levels and water tables fell to lower altitudes. Some, but not all, phreatic caves were drained and subsequently modified by vadose processes, and new cave passages developed at lower levels. At the same time, clastic sedimentation, calcite deposition and rock collapse further modified the cave passages, and some caves were truncated when denudation and surface lowering removed the rock that contained segments of their passages. The end result is a complex system of multi-phase caves. To some extent, this sequence of events is recognizable in most karst terrains. It is certainly true in the Yorkshire Dales, where there are many components to the morphology of the caves and the processes within them.

More examples and further details of all the cave features and sites described in this chapter can be found in the chapters of Volume Two, which describe in words, maps and photographs the main caves within each of the different parts of the Yorkshire Dales.

Three Counties Cave System	Casterton Fell and Gragareth	253 m
Gaping Gill Cave System	Ingleborough	197
Penyghent Pot	Pen-y-ghent	196
Meregill Hole	Ingleborough	181
Gingling Hole	Fountains Fell	177
Long Kin West	Ingleborough	168
Kingsdale Cave System	Gragareth and Whernside	165
Dale Head Pot	Pen-y-ghent	165
Black Shiver Pot	Ingleborough	157
Strangle Pot	Fountains Fell	157
Tatham Wife Hole	Ingleborough	155

Table 7.3*. Caves deeper than 150m in the Yorkshire Dales.*

Active vadose caves

The archetypal Dales cave is an active streamway that can be followed along canyons and down waterfall shafts. For the visiting caver, it typically ends at a sump. But that pool of water is not the end; it merely marks the transition to a phreatic cave that continues, and is seen only by the cave diver or has to be conceived by the geomorphologist. The descending streamway is the perfect example of a vadose cave, and Swinsto Hole, in Kingsdale, has been suggested as the type example of vadose development in a Dales cave (Waltham *et al*., 1981).

A vadose cave stream has a free air surface to its water, so is analogous to a surface channel cut into bedrock except that water cannot overflow the channel margins during times of high discharge (though it may be re-routed into other passages). Vadose erosion primarily lowers the canyon floor (Fig. 7.2), and incision thereby advances headwards. The classic Dales stream caves, exemplified by the tributary inlets in the Ease Gill Cave System and the Long Churn passages above Alum Pot, are gently graded with ceilings formed along gently dipping bedding planes or shale beds (Fig. 7.3). The canyon ceilings are almost uneroded, indicating that vadose entrenchment took place from a very early stage; others were rounded by dissolution, some to the point of being well-formed half-tubes, indicating that there was significant phreatic development before the aquifer matured sufficiently to allow drainage to a vadose state. Some canyons have been entrenched in the floors of older, mature phreatic passages, creating the keyhole profile of a multi-phase cave passage.

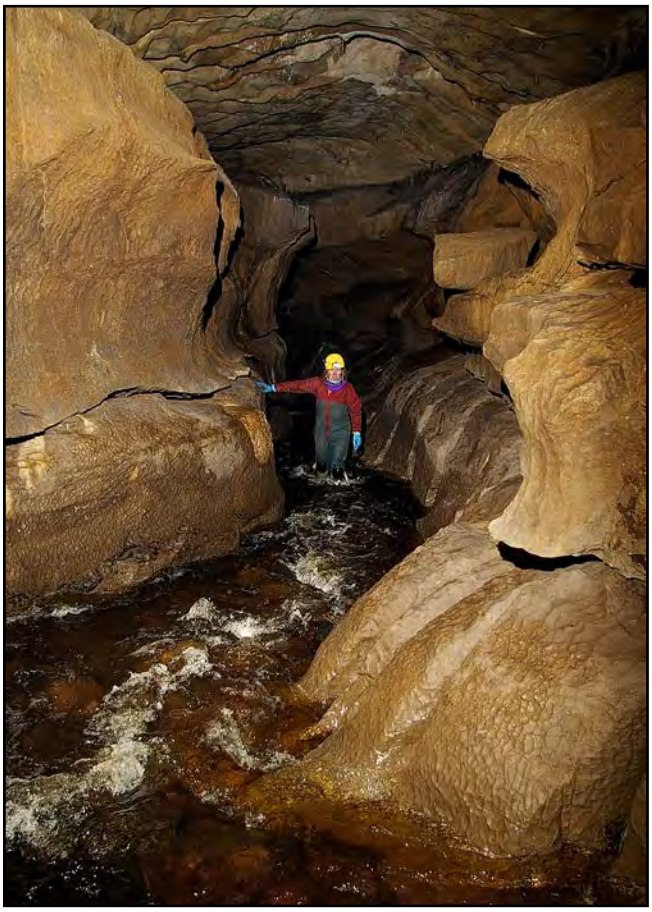


Figure 7.2*. A powerful stream in the clean-washed vadose canyon of Dow Cave, Wharfedale (photo: John Forder).*

***Figure 7.3**. The vadose canyon beneath a bedding plane roof in the Upper Long Churn Cave, Ingleborough, with a thin rib of rock inside a short passage loop (TW).*

***Figure 7.4**. Small scallops in the walls of a vadose streamway in County Pot (photo: Mark Shinwell).*

Anastomosing channels, left as branching and braiding half-tubes in the roof bedding planes, are rare, but some passages are notable for immature tributaries, distributaries and loops on the same bedding plane; the Long Churn streamway is unusual in that many of these roof branches are large enough to be accessible. Some stretches of the initial openings are aligned on joints, but others meander considerably, though commonly with an overall down-dip direction. Meanders along the streamway canyons have generally deepened by almost vertical entrenchment, with only modest degrees of migration or exaggeration that create those canyons that lean to one side or other.

Canyon width is largely dependent on mean stream-flow, with most canyons in the Dales caves no more than a metre wide. Larger canyons occur in some of the main drains, and there are also many much narrower canyons. Typically, canyons in the Dales caves are a few metres tall, though some have been entrenched by more than 10m and others form only the smallest of incisions in the floors of low bedding-plane passages. Many have high-level loops and ox-bows. The floors and walls of the vadose canyons are commonly etched into asymmetrical scallops, with the steeper faces on the upstream sides. Scallop sizes are inversely related to stream velocities (Curl, 1974); scallops a few centimetres long are common in the Dales stream caves, formed by water flowing at around a metre per second (Fig. 7.4).

In a typical Dales cave, a vadose streamway descends through the limestone by dropping down joints or faults in

Research in cave geomorphology

Studies of cave origins and their subsequent development could be viewed as maturing through three main phases within the last hundred years, focussing first on the environments of cave genesis, then on the geological influences over cave morphology, and latterly on the evolution of caves.

Davis (1930) proposed that most cave development had been phreatic (beneath the water table), with only minor vadose modification occurring above the water table after rejuvenation and drainage. Bretz followed the same line, and also produced his classic paper (1942) on vadose and phreatic cave morphology. Within the Yorkshire Dales, Simpson (1935) indicated that most caves were largely vadose, following Dwerryhouse (1907) who had suggested the same; earlier ideas have been reviewed by Halliwell (1974). Myers (1948) concurred, but also recognised that many of the phreatic high-level passages were much older. Meanwhile, Swinnerton (1932) proposed that cave development occurred mainly at or just below the water table, thereby accounting for 'levels' of cave passages left behind by rejuvenations. This led the way for Sweeting's description (1950) of levels and rejuvenations in the Dales caves.

Geological factors were emphasized by Waltham (1970), who described Dales caves that are both old and young, and both phreatic and vadose. Research on the geological influences evolved into Lowe's concepts of cave inception, which have specific reference to the Dales (2000). Outside the Dales, geological factors were eventually given due recognition in a wider model by Ford and Ewers (1978), and maze caves (important in the northern Dales) were assessed by Palmer (1975). The understanding of dissolution chemistry in cave waters advanced with Bögli's recognition of mixing corrosion (1964), though its role was subsequently re-assessed (Gabrovsek and Dreybrodt, 2000). Hydrological processes were clarified by Thrailkill (1968) and followed by major researches into dissolution kinetics by Palmer (1981, 1991) and Dreybrodt (1990). Many other landmarks and advances in cave geomorphology were reviewed by Lowe (1992), and more recent research relevant to the Dales is covered within this chapter. Most aspects of cave geomorphology are well summarised by Palmer (2007).

Studies of cave geomorphology in the Dales gained the beginnings of an absolute chronology with the first radiometric age determinations of stalagmites (Waltham and Harmon, 1977; Atkinson et al, 1978), followed by a much larger programme by Gascoyne and colleagues (1983, 1984). Subsequent isotope studies to determine both ages and palaeo-environments are reviewed in Chapter 10. Much of the future of cave research, in the Yorkshire Dales and elsewhere, lies in the information that cave sediments can provide with respect to wider investigations into landscape and climate development.

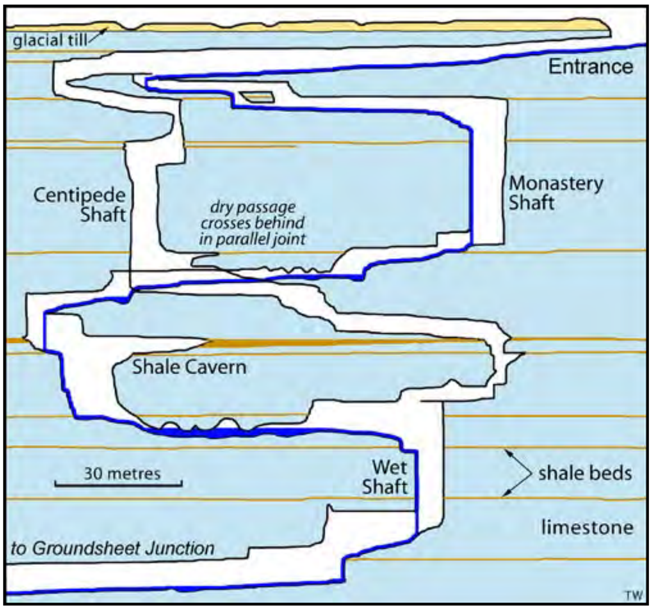


Figure 7.5. Profile of the Old Roof Traverse and Centipede routes through the entrance series of Lost John's Cave, with shafts and rift passages descending on joints and faults between canyons that are largely entrenched beneath bedding planes and shale beds (after surveys by London University Caving Clubs and University of Leeds Speleological Association).

While bedrock fractures are recognizable in the origins of nearly all the vertical elements within a vadose stream cave, they also constitute the inception features behind some of the sub-horizontal elements. Rift passages, enlarged along vertical joints, include those that are largely phreatic and others that are almost entirely vadose. Sections of the stream passages in the Lost John's entrance series are clearly aligned along fractures, and include some that were cut by vadose streams and others that are still short, perched, phreatic loops. Almost the whole of Juniper Gulf is formed within a single fissure system on a strike-slip fault, where vadose enlargement has created deep, straight canyons with floors descending in steps to the lip of the deep final shaft (Fig. 7.7). Within the Yoredale limestones, many of the stream caves, mostly with small passage cross sections, have zig-zag patterns as they follow the joints. The streamway in Smeltmill Beck Cave is more than 1500m long, yet it covers a straight-line distance of less than 500m. In many Yoredale caves, much of the passage enlargement was phreatic (as in the more mature mazes in the same limestones), but vadose development has continued. This is most noticeable where the order to step down through a sequence of bedding planes and thin shale beds. The multiple routes down the entrance series in Lost John's Cave all have shafts dropping between shale beds (Fig. 7.5), though passages in the middle levels are primarily developed along the same fractures that determine the positions of the shafts. Many waterfall shafts are wider than their canyon inlets and outlets, because they have been enlarged by spray corrosion, as is apparent from the fluted walls on some (Fig. 7.6). Others have cut back into deep stream notches, and some of these have eliminated the initial shaft to leave steeply descending canyon floors upstream of steps in the roof profile.

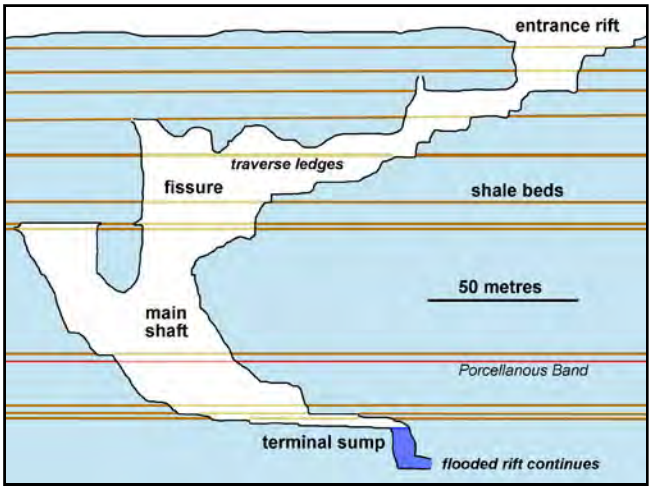


Figure 7.7. Long profile of Juniper Gulf, on Ingleborough, stepping down the shale beds and then back beneath itself all within the single fissure system; the one thick shale bed has been eroded out to create the long high-level traverse in the deep and narrow rift (after survey by University of Leeds Speleological Association).

Figure 7.6. The fluted shaft of Boxhead Pot, on Leck Fell, formed on a vertical joint but enlarged by spray corrosion into an almost cylindrical section (photo: Robbie Shone).

Figure 7.8*. The sandstone floor that is continuous through the long and tortuous crawlway passages of the Marathon Series in Mossdale Caverns (photo: Dave Judson).*

cave streams have sandstone floors at the base of the limestone, most famously in the Marathon Passages of Mossdale Caverns (Fig. 7.8), where vadose widening at floor level has given many small passages a triangular cross sections.

Many of the Dales stream caves have walls and floors of clean-washed rock because they are active features still in the process of dissolutional erosion and enlargement. Once a cave has been formed, modifications are inevitable, and include rock breakdown, calcite deposition and clastic sedimentation. These are consequences of age, and become increasingly dominant factors in the older cave passages.

Active phreatic caves

The lower ends of the great majority of cave systems in the Yorkshire Dales consist of phreatic passages that loop below the levels of their own resurgences. These active phreatic cave passages are not as well known as their vadose inlets, simply because they are only ever seen by the small numbers of cave divers. They are however equally important components of the Dales cave systems. Keld Head was proposed as the type example (Waltham *et al*, 1981), when only a single passage had been mapped right through to its resurgence. As an example Keld Head is still valid, except that a modern map of the underwater cave shows a much more complex pattern of branching and looping passages that have subsequently been explored (Murphy *et al*, 2008).

Figure 7.9*. An active phreatic passage in Boreham Cave, Wharfedale, developed from a bedding plane and almost achieving a circular cross-section (photo: Oliver Statham).*

The basic phreatic cave is a tube (Fig. 7.9). In a cave that is permanently full of water and without extensive sediments, dissolution is equal across walls, floor and ceiling. A circular cross section therefore forms, and this is also the most efficient in terms of hydraulic flow (Lauritzen *et al*., 1985), though it is commonly distorted in response to geological factors. The dominance of bedding planes and shale beds as inception features, on which the caves developed in the Yorkshire Dales, means that the phreatic tubes are commonly widened out to elliptical cross-sections. Long sections of underwater passage behind both Malham Cove Rising and Keld Head are bedding planes up to 10m wide and only around a metre high.

In similar style, vertical joints guide tall rift features within the phreatic conduits, either as segments along the passages with upright elliptical profiles, or as tall cross rifts, some of which rise far enough to create air-bells. Many of these phreatic rifts rise above the main conduits much further than they extend laterally or below the conduit level. They are unlikely to have been initiated by mixing dissolution where water entered through the guiding fractures, as the water is unsaturated in most Dales cave streams. Their upward development appears to be a feature of phreatic water stratification whereby chemically aggressive flood water remains in the roof pockets while less aggressive base-flow water passes beneath (Cordingley, 1991). At some sites, clastic sediment may prevent or reduce dissolution of the floor, but tall roof rifts also occur above uniform floors that are devoid of sediment.

Some phreatic caves, both active and abandoned, within the Dales are single tubular conduits, but many have loops and braids that constitute complex systems without reaching the stage of true maze caves (Fig. 7.10). Phreatic loops in the lower conduits of the main cave systems are generally no more than about 40m deep, and many reach only to shallower depths. This is due largely to the low dips of the limestone and the numerous joints that allowed initial routes to step between the bedding planes, but depths are also limited by the base of the limestone at many sites. The active phreatic

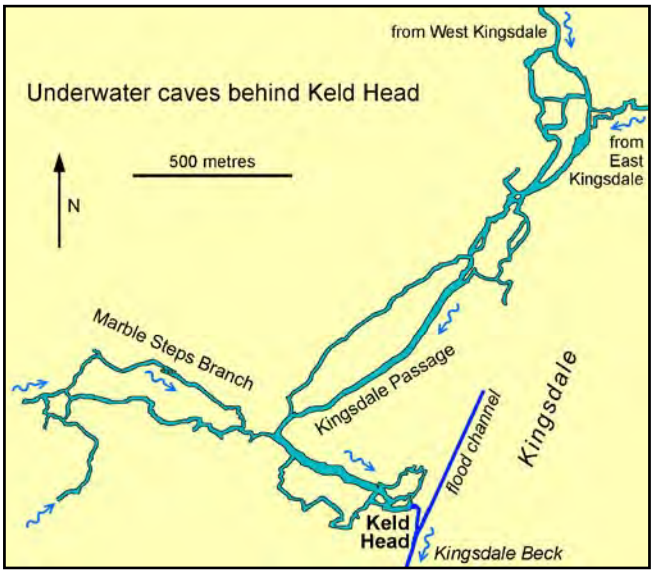


Figure 7.10*. Branching and looping passages in both branches of the active phreatic cave system behind the Keld Head resurgence, Kingsdale (after surveys by Cave Diving Group).*

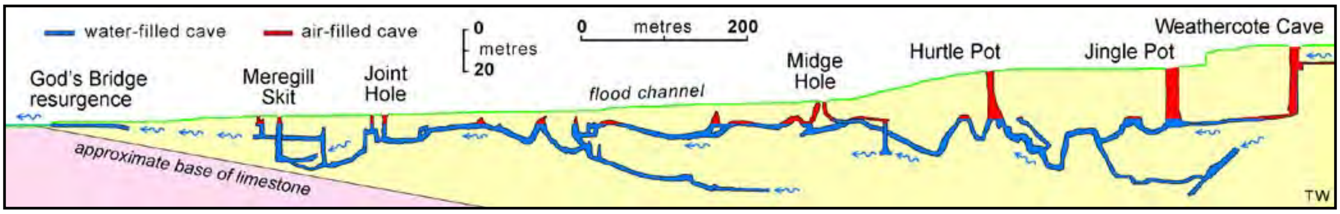


Figure 7.11. Projected profile through the shallow phreatic loops in the main caves behind God's Bridge, Chapel-le-Dale; the vertical scale is exaggerated by 2.5 (after surveys by Cave Diving Group).

Figure 7.12. Scallops on the floor of the underwater passage in Joint Hole, Chapel-le-Dale, with sand and pebbles that are entrained during flood events; the image is 50 cm across (photo: John Cordingley).

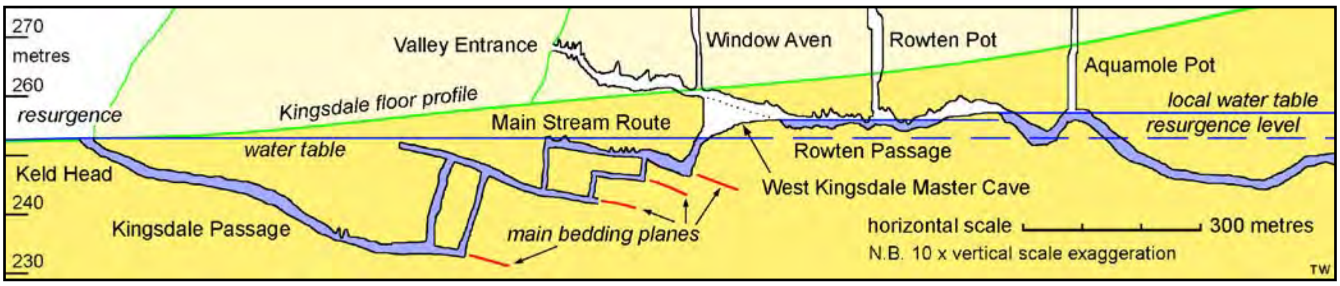
caves beneath both Kingsdale and Chapel-le-Dale have saw-tooth profiles where they rise along gently-dipping bedding planes and then descend joints to repeat the pattern on lower bedding planes(Fig. 7.11).

The deepest known active phreatic lift (the downstream, rising end of a downwards phreatic loop) rises more than 60m in Gavel Pot, beneath Leck Fell (Monico, 1995). This lift is up an almost vertical shaft, but steeply inclined ramps also occur, including one that rises nearly 20m just inside Leck Beck Head, further down the same drainage route. Comparably steep descents are also known in the active conduits. Deeper phreatic loops have existed in the past, when resurgence levels were further above the base of the limestone (see below). Despite the abundance of available fractures, many of the phreatic cave passages in the Dales gain or lose much of their depth by following the gently dipping bedding planes. Descending loops are created where passages swing obliquely down the dip and then obliquely back up, at some sites guided by intersecting joints.

Perched phreatic loops create flooded sections part-way along some vadose streamways. Invariably, these are determined by local features of the geology that guided inception away from the down-dip staircase profile that is dominant in the Dales caves. As they are components of small active streamways, many of these short loops, or sumps, are in passages that are smaller, to the point of being constricted, compared with the large tubes that form the trunk passages with their greater water flows out to the main resurgences.

The walls of the phreatic conduits are commonly indented by scallops, typically much larger than those in the vadose streamways as they are etched by waters moving more slowly within the phreas. Scallops on the roof of the main passage of Boreham Cave, in Littondale, form two generations. Those with wavelengths of about 300 mm formed in water flowing at about 0.1 m/sec; superimposed scallops about 60 mm long were formed by a later phase of flooding by waters moving at about 0.6 m/sec. Some conduits in other caves have scallops that are smaller on the floor than on the roof, and both sets are formed under flood conditions when abrasion by entrained sediment becomes a factor, as in the trunk passage beneath Chapel-le-Dale in Joint Hole (Fig. 7.12) (Murphy *et al*., 2000). In the same cave, large moulins in the floor of the phreatic tunnel contain rounded boulders up to 600 mm across, which are swirled around in every flood event, leaving snowflake bruises (impact marks, generally of paler rock that has locally been crushed) on the moulin walls. Ramps of cobbles, rising in the downstream direction, are features of many large conduits, and their debris is moved up on each flood before slumping back on the wane. Flood transport of clastic debris is a significant factor in the erosion of the phreatic conduits; clearly these are not purely dissolutional features. Recesses, domes and alcoves may be created by eddies within complex flow patterns through the flooded tunnels, but the morphologies of most of these are determined by geological structures. Multiple loops are a feature of some phreatic caves (Fig. 7.10), with some loops lying almost dormant as very slow-moving backwaters at times of low flow but becoming active in flood conditions. Looping and branching also includes passages at different levels within the phreas (Fig. 7.11).

Figure 7.13. Profile through the cave passages draining beneath the western flank of Kingsdale and out to Keld Head, with water surfaces (and hence local water tables) stepping down between short sections of descending vadose streamway; the passages behind Keld Head are formed mostly on four bedding planes, and vertical curvature is largely due to gentle folding; a fifth bedding plane guides Rowten Passage across a shallow syncline and also guides most of the passage to Valley Entrance (after surveys by University of Leeds Speleological Association and Cave Diving Group).



Cave development at the water table

The interface between air and water has long been recognised as a prime site for limestone dissolution, both within surface karst at the edges of alluvial flats and underground at a water table. The nature of the water table is complex in karst, in which its conduit systems do not conform to the normal hydrological rules that dictate features in a diffuse aquifer (see Chapter 9). Individual conduits may change along their lengths between vadose and phreatic conditions, so that a water table related to them is not necessarily related to a water table applicable to percolation flows within the rock's fissure networks. However, the cave conduits contain a large proportion of the groundwater flow, and it is reasonable to conceive a regional karst water table that conforms to the resurgences. This dictates groundwater conditions in that all caves at lower altitudes must be phreatic, but active phreatic passages can also exist above resurgence level where perched loops drain out into vadose streamways. The regional karst water table falls in a series of steps, with vadose streamways descending from one ponded section to the next. In Kingsdale, a phreas has a water table that is horizontal (but for a minute hydraulic gradient) extending for nearly 2 km upstream of Keld Head and beneath the valley floor. Except that, under the western flank, the short canyon streamway of the Kingsdale Master Cave descends about 3m, so that the phreatic caves upstream of the canyon are beneath water surfaces some 3m and 4m higher than Keld Head for at least another 1500m up the valley (Fig. 7.13).

Of more than 20 km of cave passages mapped at low level in Kingsdale, only about 200m are at the water table, where phreatic tubes are half-filled with long canals of slowly moving water. But these canals only exist by chance behind a small local rise in the floor of the half-drained phreatic tube (Fig. 7.13). No true water table caves, actually formed at the water table, have yet been identified in the Yorkshire Dales. Only in the Morecambe Bay karst, west of the Dales, have some of the maze caves formed at least in part at the water table in the low hills adjacent to the poljes (Ashmead, 1974; Waltham *et al*, 1997).

Within the Dales, some cave passages pass through the local water tables, following the geological features (mostly the dipping bedding planes) that guided their initial profiles. Each such passage therefore transits from a vadose canyon into a phreatic tube, though the passage morphology is more complex and variable due to bedding and rift features superimposed on the simple profile. The transition occurs at each downstream sump in the active stream caves, and has also survived in some of the older passages where the original water table has fallen to new levels.

Concepts of 'water table caves' are widely taken to include cave passages formed just below the water table, so that they are also described as 'shallow phreatic caves' (Swinnerton, 1932). Purely in terms of hydraulics, there are advantages to groundwater flow just beneath the water table, which therefore becomes a focus for cave development (Worthington, 2004). These shallow phreatic caves are more widespread than true water table caves that are largely restricted to 'foot caves' around the margins of alluvial flats in tropical karsts. Extensive cave passages formed at altitudes just below a resurgence constitute a 'level' of development, and successive rejuvenations and water table declines create multiple levels within a cave system or a group of caves. Within the Yorkshire Dales, three levels of cave development have been recognized by the abundance of cave passages within three zones, close to the top of the Great Scar Limestone, near its base and at about mid-level. These have been interpreted as levels at and beneath successive water tables during the Quaternary (Sweeting, 1950). However, cave levels can develop in response to a variety of factors, which are extremely difficult to differentiate without accurate surveys that are specifically designed to identify the relative positions of the passages (Palmer, 1987). Furthermore, cave levels are most difficult to interpret in limestones that lie close to the horizontal. It is now recognized that the 'levels' within the Dales caves are largely features of the geology, notably the very uneven distribution of the shale beds that are so important among the features that guided the initial positions of the caves (Waltham, 1970, 1971a).

Paragenetic canyons develop upwards within the phreas, by dissolutional erosion of the roof over accreting layers of clastic sediment, thereby eliminating the down-loops in a switchback profile of a cave passage as is matures towards a graded profile (Farrant and Smart, 2011). None has been recognised in the Dales caves, and it may be that none exists, as the sub-horizontal limestones do not favour development of the steep phreatic loops that are prime candidates for paragenesis. Commonly associated with paragenesis are notches cut into cave walls at past levels of standing water. A notch is conspicuous in the walls of Rowten Passage in the West Kingsdale System, at a level about 600 mm above the present level of ponded water; it originates from a past water level held behind a knick point over a rock lip that has now been entrenched by the same 600 mm at the Master Junction (Brook, 1969). Wall notches can also be recognised within Broadway, a segment of relict passage that crosses beneath Ease Gill; these probably relate to local ponding of water behind ephemeral clastic fills during the changing environments of the Pleistocene (Fig. 7.14). Comparable notches have also been observed in some active phreatic

***Figure 7.14**. A notch, about 150 mm high, in the wall of the Broadway passage directly beneath Ease Gill, appears to have been created by water flowing over a floor of clastic sediment in the past; the notch's fluctuation in level reflects the changing positions of the active sediment surface prior to all being eroded away (TW).*

Figure 7.15. Ledges formed by more resistant bands of limestone, in Far Streamway of White Scar Cave, beneath Ingleborough (TW).

tunnels; it may be possible that these relate to corrosion within contrasting layers of stratified water in the past (Cordingley, 1981), or they could have formed over layers of sediment that were once present.

Elsewhere in the Dales caves, wall notches may not easily be recognised where they are masked by stratigraphical features within the limestone. The entrance canyons of Lost John's Cave and the main streamway in White Scar Cave are both notable for their numerous, thin, rock ledges that are formed by more resistant, and probably less soluble, beds, leaving lithologically guided notches and undercuts between them (Fig. 7.15).

Erosion rates and cave enlargement

There is no simple answer to the old question of how long it takes for a cave to be formed. A concept diagram (Fig. 7.16), has up to 5000 years for the initial stage up to the breakthrough where turbulent flow and accelerated erosion develop once a fissure is more than about 5 mm wide (White, 1988). Its time-scale does not include the even longer period of inception required before laminar flow can develop in fissure networks (Lowe, 2000; and Chapter 8). Conduit diameter at breakthrough can be greater or smaller than the 5 mm depending on the hydraulic ratio (head/length squared) of the flow path (Dreybrodt, 1990; Faulkner, 2006), and the time to breakthrough has similar variation. Subsequently, the rate of wall retreat may be up to about 1 mm per year (Palmer, 1991; Faulkner, 2006), but this is only achieved under ideal environmental conditions. Through glacial stages, in long spells of periglacial conditions in shorter and less intense stadials, and during cold winters in all but the warmest of interglacials, dissolutional wall retreat in the caves of the Dales was at much lower rates.

From breakthrough time, a cave conduit several metres in diameter can develop within a period of 5000 to 20,000 years, but field evidence (without quantification) suggests that caves may take more like 100,000 years to develop (White, 1988). The chronology of Mammoth Cave, USA, suggests that phreatic tubes with diameters in the range of 1–5m took at least 100,000 years to mature, whereas postglacial caves in upstate New York have developed to about 1m in diameter within 13,000 years (Palmer, 2003), a figure matched broadly for caves in the Bahama Islands (Mylroie and Carew, 1987). Aspects of dissolution kinetics suggest cave passages of that size can form within about 10,000 years (Dreybrodt, 1987). Wall retreat can be much faster, allowing caves to form in shorter time scales (Palmer, 2007). Phreatic caves up to 2m in diameter are considered to have developed within only a few thousand years of flooded conditions beneath ice-dammed marginal lakes in the Scandinavian karst (Faulkner, 2009), and it is reasonable to expect that similar conditions could have pertained in the Dales during Quaternary deglaciation.

The youngest of the Dales caves include many small vadose canyons. Five dated flowstones, growing close to their floors, indicate that maximum rates of incision in them are 22–83 mm/ka (Gascoyne *et al*., 1983). The only one of these flowstones that was *in situ* came from Lost John's Cave, where the stream is entrenched by about 2.5m below the flowstone dated at 115 ka, at a maximum mean rate of 22 mm/ka. But this is in the cave's low-level, main drain, where water velocities are low except during flood and transient sediment commonly masks the floor (Fig. 7.17); furthermore, stream flows were interrupted during the Devensian glaciation within the time-span of the interpretation. Comparable low incision rates have been recorded in stream canyons in New York caves (Palmer, 2003). However a rate of 1200 mm/ka was recorded (the mean of 91 direct measurements with a micro-erosion meter over a period of 26 months in 1969–1971) in the Lower Hughes Cave in West Virginia (Julian Coward, *pers. comm.*). This was in a clean-washed vadose

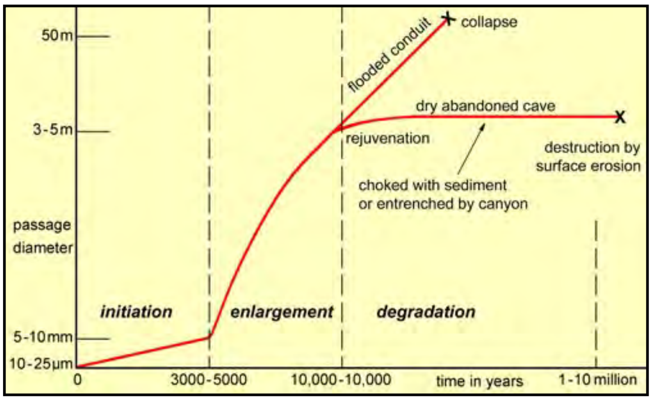


Figure 7.16. A concept of the evolution of a cave passage from initiation (including inception) through enlargement and eventually to decay (after White, 1988). Both the size and time scales are generalizations as they can vary even beyond the ranges quoted; caves in the Dales do not reach the 50m diameter that causes widespread collapse. The enlargement stage is more commonly phreatic, whereas the degradation stage is more commonly vadose.

Figure 7.17. *Midway along the low-level trunk streamway that is the Lost John's Master Cave under Leck Fell, with the remains if a pre-Devensian phreatic tube above the younger vadose canyon (TW).*

canyon carrying a small stream not far downstream of its entrance sink, in a situation and environment that are very similar to those of typical Dales cave entrance passages. Within the Dales caves, mechanical incision rates may be expected to be higher beneath fast-flowing streams through high-level canyon passages, whereas chemical incision rates are likely to be maintained along the active passages as most stream waters remain unsaturated and aggressive through to the resurgences (see Chapter 9).

The interpreted and theoretical rates of cave expansion indicate that some of the smaller cave passages in the Yorkshire Dales could have developed in the period since retreat of the Devensian ice cover (though this excludes the longer stages of inception before the caves accelerated their growth rates). This is compatible with field evidence in terms of the passage morphology and the cave locations beneath hills and plateaus that were modified by glaciation. Within the Dales, many small stream canyons, entrenched by a metre or so beneath bedding plane roofs, extend downstream of stream sinks at positions that appear to have been exposed only by Devensian glaciation and retreat of the shale margin. The West Virginia data on streamway incision may well be matched in these Dales caves if ever it was measured, and could support the concept that most of the growth of these cave passages has been post-glacial.

Solute loads in karst waters do not offer evidence of the rates of cave enlargement, because it is the dissolution rate that is important, and because so little of the solute pick-up takes place within the open cave stream routes. Most dissolution takes place on first contact with the limestone. Soil-derived percolation water dissolves large amounts of limestone, principally in the epikarst, and contributes most of the carbonate increase from sinking streams to resurgent streams. Solute measurements along streamways in Swinsto Hole and White Scar Cave confirm that the downstream increases are due almost entirely to additions of inlet water and not to streambed erosion (Halliwell, 1980). Most cave waters in the Dales are chemically aggressive at the sink entrances, and their short traverse times mean that they are still aggressive at the resurgence exits after having continued to enlarge both their vadose and phreatic passages.

Abrasion is a nearly ubiquitous component of cave erosion (Newson, 1971), and clastic sediment is continually in transit through the Dales caves. Abrasion by sand grains is recorded even in phreatic conduits (Murphy and Cordingley, 1999), but amounts of abrasion and sediment transport have not been measured in the Dales caves.

Abandoned cave passages

A feature of all the major cave systems within the Yorkshire Dales is the presence of older, mainly large, high-level passages that are no longer active. Notable among these are the phreatic tunnels that appear to have carried the trunk drainage once the Great Scar Limestone was exposed and the karst was established. Most of these tunnels were only active prior to the main deepening of the dales by subsequent glaciations, when they were abandoned as resurgence levels dropped past them and new cave passages developed beneath them. Many are more than 5m in diameter over lengths of more than a kilometre, though much of their height may be obscured by sediment fills and breakdown (Fig. 7.18). At

Figure 7.18. *Monster Cavern, a part of the abandoned high-level passage from Ease Gill through to Lancaster Hole beneath Casterton Fell; parts of a half-tube survives in the roof bed, but the floor is formed by large-scale breakdown (photo: Mark Shinwell).*

Figure 7.19. Drained phreatic tube that forms part of Southeast Passage in the Gaping Gill Cave System (TW).

most sites, only fragments of these abandoned passages have been discovered and mapped, and their continuations are either obscured beyond boulder chokes or sediment fills, or have been truncated by surface lowering.

Some of these relict passages had developed into mature phreatic tubes (Fig. 7.19), but most have cross profiles distorted to some degree by enlargement along bedding structures or fractures. Flat roofs are commonly defined by bedding (though many in the older caves are features of subsequent breakdown). The extreme example of bedding development is the well-known Hensler's Crawl in the Gaping Gill System (Fig. 7.20); for more than 500m in length this is 2–6m wide and is nowhere more than a metre high. Tall rift passages along joints are also common as distortions from a circular cross section (Fig. 7.21). Cross rifts, also developed on joints, are prominent features that create repeated local enlargements along many of the passages; these may be the only open sections of an old cave passage where mud and sand were deposited by a declining stream until it filled to the roof in the low sections between the cross rifts. While the large relict trunk passages are conspicuous within the cave systems of the Yorkshire Dales, there are also extensive networks of smaller phreatic tributary passages, which are noted for the arduous or unpleasant caving that they offer. Most of these networks appear as 'levels of development', because they are constrained to the zones of clustered bedding planes that were their inception horizons.

The old phreatic caves were the lower ends of drainage routes that largely developed as equally old vadose canyons at their upper levels. The finest example is the main streamway of Short Drop Cave, under Leck Fell, which descended gently to its contemporary water table and continued as the phreatic tube in Gavel Pot (Fig. 7.22); it still carries a stream, which is now vadose as far as the current resurgence level some 90m below its ancestral position when the passage was largely formed. Many of the older vadose inlets are preserved only as fragments forming high-level ox-bows in canyons that are still active, and commonly are distinguished only by their more extensive calcite deposits. Many more of the earlier vadose caves were lost to surface erosion as the dales were deepened and widened, and there is a disproportionate scarcity of old vadose passages when compared to the extent of their contemporary phreatic caves. This also reflects the situation that when the dales were shallower, and had more limestone beneath their floors, more cave development could have been within the larger volume of a deeper phreas.

The classic two-phase cave is the 'keyhole' passage with a vadose canyon cut into the floor of a phreatic tube. Without diversion of its stream into a newer, lower route, the keyhole passage is the automatic consequence of the decline of regional base level or local water table in an evolving karst. Small keyhole passages developed over short time-scales, with smooth transitions from phreatic to vadose flow taking place as and when their downstream continuations permitted free drainage (Fig. 7.23). The larger keyhole passages in the Dales include the relict trunk caves with much younger canyons sunk into their floors (Fig. 7.24). Many parts of the long, high-level tunnel from the earlier phase of Ease Gill inlets through to Lancaster Hole have the younger canyon entrenched in its floor, though in other sections the canyon

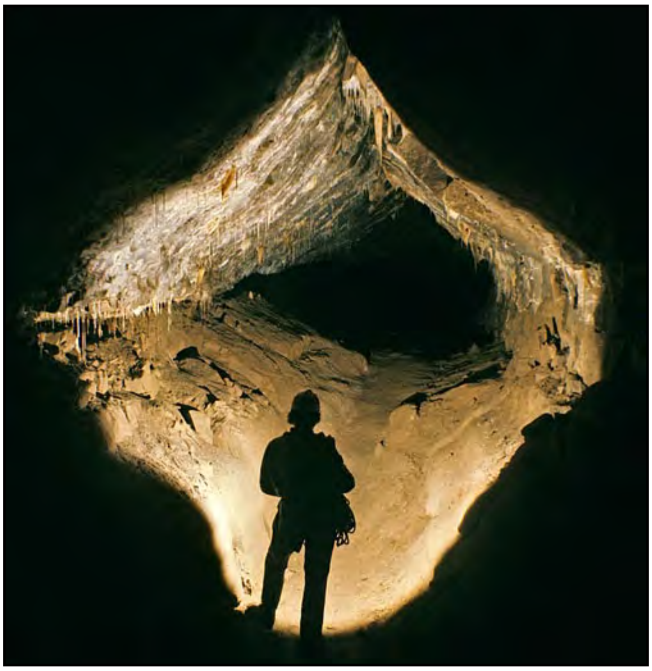


Figure 7.21. One of the Minarets, developed within the phreas on a joint/bedding intersection along a part of the old, high-level trunk route from Ease Gill Caverns to Lancaster Hole (TW).

Figure 7.20. Hensler's Crawl, a long, low and wide passage developed on a bedding plane under phreatic conditions, in the Gaping Gill Cave System (TW).

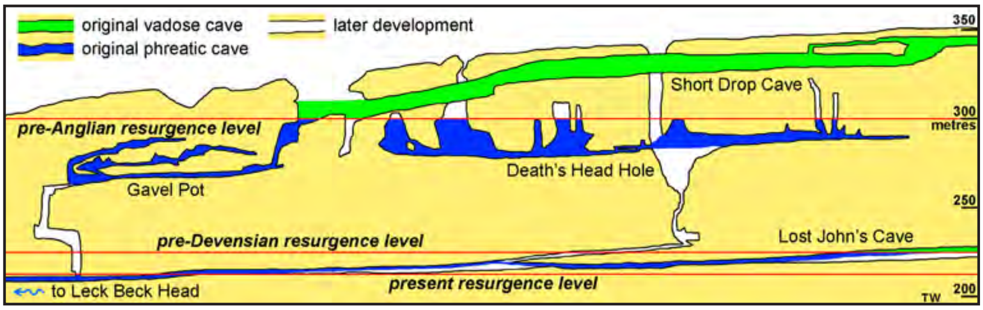


Figure 7.22. *Simplified profile of the cave passages under part of Leck Fell, showing passage morphologies related to three successive resurgence levels; the horizontal scale is roughly that of the vertical but some parts are projected and fore-shortened. The pre-Anglian age of the upper resurgence level is interpreted from stalagmites older than 350 ka in related passages of nearby caves; the middle resurgence level is not reliably dated but is likely to be pre-Devensian. Passage continuations in Death's Head Hole and Gavel Pot are blocked by sediment and breakdown. The apparently large passages in Death's Head Hole are mainly tall rifts just a few metres wide.*

Figure 7.23. *Keyhole passage with a vadose canyon beneath a phreatic tube, in Avalanche Pot, Gaping Gill (TW).*

Figure 7.24. *Similar but larger keyhole passage in White Scar Cave (TW).*

has formed loops separate from the older passage. In some caves, the older phreatic tubes and the younger vadose canyons formed in very different flow regimes, in which cases there may be considerable disparity in size between the two elements of the keyhole.

Most of the large, relict, trunk passages in the Dales caves have very little gradient because they largely follow the sub-horizontal dip of their guiding inception horizons. These levels were not at past water tables, and their depths below the contemporary water level cannot always be recognized. Beneath Leck Fell, the phreatic tube in Gavel Pot appears to have been about 30m below its vadose feeder in Short Drop (Fig. 7.22). Its exact depth is not known, as the passage appears to have descended straight through the contemporary water surface, but the transition from vadose to phreatic morphology at that level is lost behind the collapse features and subsequent vadose modification beneath the Gavel entrance. Phreatic lifts do occur to indicate minimum depths of the earlier phreatic zones. The two great ramps in Sleets Gill Cave, in Littondale, rise from an almost horizontal main tube (Fig. 7.25); the inner ramp was a phreatic lift of at least 70m, but the outer ramp, at the cave's present entrance, was truncated by glacial widening of the dale. Little is known for certain about the depths at which the very old complex of relict phreatic tunnels developed as the main level of the Gaping Gill System, but it is possible that Bar Pot was an outlet above a phreatic lift of about 100m (Glover, 1974). Major phreatic descents are also known in some caves. In the Lost John's Cave under Leck Fell, the high-level passage above Lyle Cavern descended 40m, and this has left a steeply inclined half-tube down one wall of the chamber (Waltham, 1974b), and the main roof tube above the Notts Pot 2 streamway appears to descend about 30m into a sediment floor in the Kleine Scheidegg chamber.

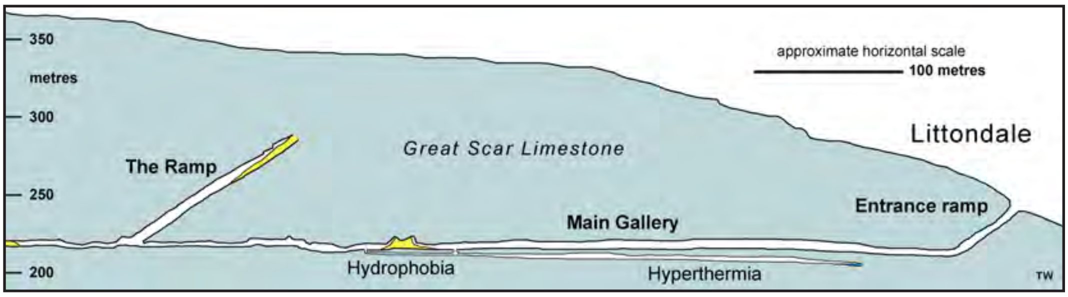


Figure 7.25. *Profile of the old passages in Sleets Gill Cave, in Littondale, with the two phreatic ramps rising from the low-level phreatic tube; the small lower streamways are later developments (after survey by University of Leeds Speleological Association).*

Geological influences on the cave systems

If a single overall model is to be recognized within the Yorkshire Dales caves, it is that of a sink high on a limestone bench, draining into a down-dip vadose cave (generally northwards), descending in steps, until resurgence level is met, from where a shallow phreatic loop reaches (generally up-dip and southwards) to a resurgence in a dale floor. Clearly this is a generalization, but it is the pattern at a large number of sites, including the Kingsdale system from Swinsto Hole to Keld Head that serves as the type example of a Dales cave (Waltham *et al*., 1981). The many variations from this model relate either to particular geological features or to hydrological influences that are related largely to the local topography.

Groundwater that did not derive directly from rainfall is also recognized as a factor in developing some caves. Waters rising from hydrocarbon reservoirs can produce sulphuric acid that is extremely corrosive, and this has been shown to be a significant factor in the development of some large caves in other parts of the world (Hill, 1987; Palmer and Hill, 2005). Hydrothermal waters, rising from depth, are also warm and corrosive, and are recognized in forming an important suite of hypogene caves (Klimchouk, 2007). No evidence has yet been found of either of these styles of cave within the Dales, though sulphuric acid, derived from oxidation of pyrite, may have played some role during the earliest stages of cave inception. Hydrothermal mineralisation pre-dates the main phase of cave enlargement by a long interval (see Chapter 2); the zinc minerals in the Pikedaw Calamine Caverns are secondary deposits (Raistrick, 1954, Arthurton *et al*., 1988). The mineralizing fluids must have impacted on the fissure permeability of the limestone, and very likely left traces that were subsequently exploited by development of some cave passages and shafts; but nothing has yet been recognised in the Dales caves that is comparable to the large vein cavities in the caves of the Peak District (Ford, 2000).

Shale beds and inception horizons

It has long been recognized that large proportions of both the active stream caves and the abandoned phreatic tunnels in the Yorkshire Dales have very low gradients because they are broadly aligned on the sub-horizontal bedding of the limestone. This was ascribed to many of the passages initially developing along the many thin shale beds (Fig. 7.26) within the limestone sequence (Waltham, 1970), but the concept has now been extended to encompass the caves formed initially on inception horizons that are more than just the shales (Lowe, 2000). The inception horizons may be shale beds, but may also be shale-free bedding planes distinguished by lithological contrasts or palaeokarst surfaces (see Chapter 8). Cave development has been found to be broadly favoured in limestones that have smaller dolomite fractions and are lower in clay and other impurities, though the matrix of variations makes cave distributions with respect to lithology very complex (Rauch and White, 1970, 1977). The same research, in America, found more caves in fine-grained micritic limestones, whereas a limited survey in the Yorkshire Dales recorded only more breakdown in the micritic limestones and less in the stronger, coarser, massive, sparry limestones (Sweeting and Sweeting, 1969). A pilot project in the Dales caves, to identify chemical and physical contrasts between pairs of limestone samples, from above and below bedding planes that had cave passages developed on them, was inconclusive (Waltham, 1971b). It may be significant that all this research examined the lithology of the beds, and none was directed towards the exact nature of the bedding planes or the lithologies immediately above and below them (on the millimetre scale). It is the variations away from absolute purity of the limestones that appear to create the chemical opportunities for cave inception, whether these are visible shale beds or much more subtle lithological contrasts within the limestone.

The morphology of the deep caves of Gragareth and Kingsdale reveal more than 15 stratigraphical horizons on which cave inception has been followed by significant passage development (Fig. 7.27). Each of these horizons is either a shale bed some centimetres thick (and locally up to about a metre thick), or a bedding plane that may or may not carry a visible paper-thin parting of shale. One notable inception horizon is the Porcellanous Bed, a thin micritic limestone that may lack any shale on its margins, may form multiple beds, and may be locally absent (see Chapter 2). Altitudes of the horizons around Gragareth vary due to the gentle northerly dip, and this structural influence is indicated on Figure 7.27 by the position of the widely recognisable Porcellanous Bed. Correlation of the other horizons is difficult. Though shales were recorded on the original cave surveys, these were incidental observations and not the primary target of the mapping, so some exposures in the caves may remain unrecorded. Many shale beds are seen to be laterally extensive, but their regional continuity cannot be confirmed from the isolated cave exposures. It is likely that variations of the limestone bed thicknesses account for much of the non-correlation of the horizons that is apparent on Figure 7.27. Though the details remain uncertain, the shale beds and bedding planes have certainly been significant factors in the inception and development of the Dales caves (see also Chapter 8).

Cave inception also takes place on joints and faults within the limestone, and may develop into passages either along or up and down the fractures. Many sub-horizontal caves originated along the intersections between favourable fractures and bedding horizons. All the open potholes that characterize the limestone landscapes in the Dales, and the

***Figure 7.26**. A shale bed about 400 mm thick exposed in the wall of a passage in the Ease Gill Cave System (TW).*

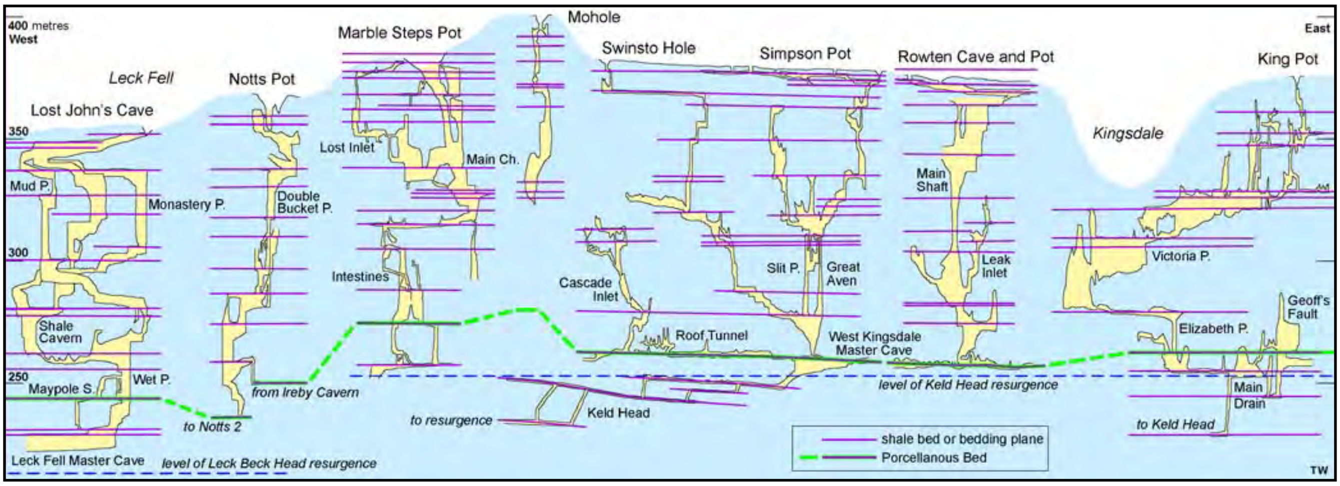


Figure 7.27. The many shale beds and bedding planes that have guided sections of sub-level passage in the cave systems of Gragareth and Kingsdale. Horizontal scales are greatly compressed, as are the distances between the caves. From Lost John's Cave to King Pot is 5.5 km along the line of the profile. Some passages have been omitted for clarity; in Notts Pot, only the Left Hand Route is shown, and the Porcellanous Bed is displaced by a fault. No account is taken of sediments that hide some lower floor profiles. Variations in altitude between bedding features in the different caves are largely due to the gentle, and slightly variable, dip of the limestone, but may also include local variations in bed thickness; contrasts in dip between the Keld Head and Swinsto Hole passages are largely artefacts of the survey projections, but may be distorted by some minor faults. The Kingsdale profile is only symbolic as its floor is close to the level of Keld Head (compiled from surveys by Dave Brook, Tony Waltham, John Thorp and John Cordingley that recorded the shale beds, with some additional survey interpretations).

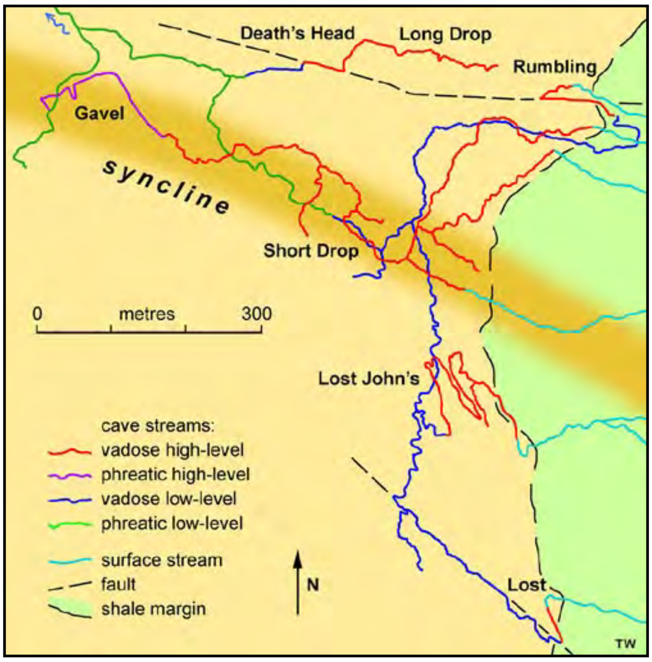


Figure 7.28. Convergence of underground drainage into a gentle synclinal trough across Leck Fell; vadose streamways follow bedding planes, so are broadly aligned down-dip; some passages are influenced by faults and joints, notably the zone of deep joints or strike-slip faults that constrain the streamway in the Lost John's entrance series; the high-level streamway in Short Drop Cave is about 100m above the low-level main drain from Lost John's Cave; part of the low-level passage developed within the phreatic zone and could therefore rise out of the synclinal trough, but was subsequently rejuvenated and now lies above the phreas (survey from Waltham and Hatherley, 1983).

waterfall shafts that create steps within the cave passages below, can be traced to origination on some joint or fault that breaks the limestone and provided the initial pathway through a rock that is essentially impermeable in its unfractured state. Physical opening of joints takes place due to stress relief or unloading following surface denudation that reduces the rock overburden, notably on de-glaciation in mountainous karst (Faulkner, 2010). The impact of unloading by denudation is greatest near the surface, and the process may have been important in opening up bedding planes between the uppermost beds in the Great Scar Limestone to allow initiation of the large number of long and nearly horizontal cave passages that form the entrance crawls of so many Dales cave systems and lie only a few metres below the glacially stripped plateau surfaces. Stress relief by unloading could be significant with respect to permitting the initial entry of water into both the fractures and the bedding planes, but the scale of its role has not been identified in the Dales caves.

With so much cave inception on bedding planes and shale beds, the dip of the limestone beds becomes a guiding factor with respect to gravitational drainage within the vadose zone. Though cave inception takes place prior to any opportunity for vadose drainage, subsequent enlargement of the proto-caves may be in a vadose environment, where the opportunity for faster drainage favours those proto-passages that are broadly aligned down-dip and therefore enlarges them into stream caves. The gentle regional dip therefore accounts for the northerly orientation of so many cave streamways in the Dales, and also for the convergence of vadose caves in the gentle synclines that flex the limestones on the Askrigg Block. Beneath Leck Fell, the high-level and low-level vadose streamways each collect in a single syncline, plunging to the northwest, with Short Drop Cave lying directly above Lost John's Cave (Fig. 7.28). Synclinal influence is also apparent in West Kingsdale (Waltham, 1970), and detailed mapping may reveal it elsewhere. Phreatic flow does not have to be down the geological structures, but it may be influenced by the partial tectonic opening of fractures along fold axes, both synclinal and anticlinal. Passages in Bull Pot of the Witches are aligned in the small (and relatively steep) folds adjacent to the Dent Fault. There may well be other locations where very gentle flexures of the limestone have guided cave development within the bedding, but these may be too gentle to be recognized by any practicable mapping, whereas they may be enough to influence vadose drainage.

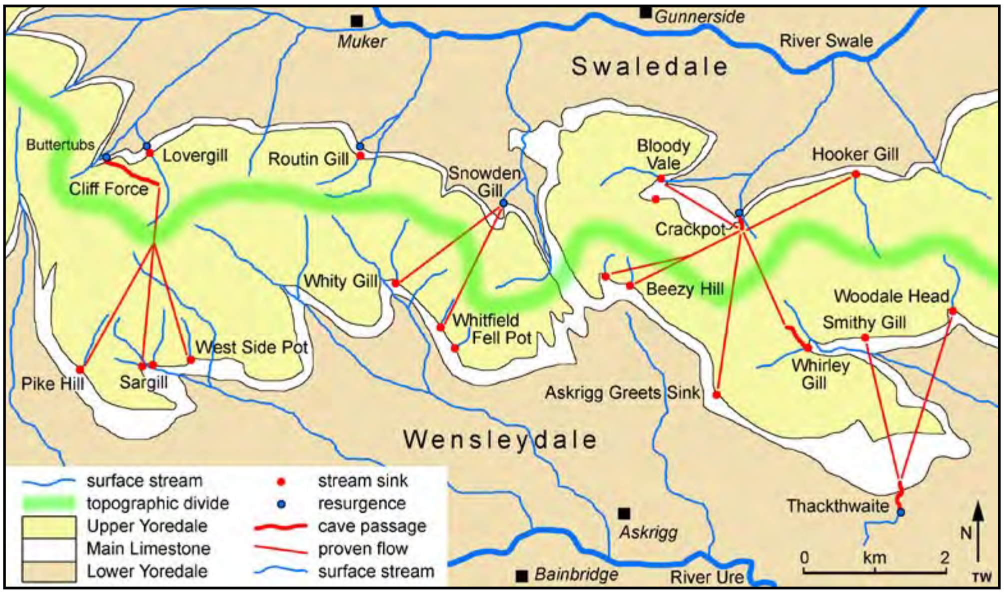


Figure 7.29. Underground flows in the Yoredale Main Limestone that largely passes beneath the topographic divide between Wensleydale and Swaledale; Thackthwaite Beck Cave is in the underlying Underset Limestone where the local dip is gently to the south (after Ryder, 1975, and work in progress by Tony Harrison).

Gravitational flow down-dip can also account for drainage that passes beneath surface interfluves. Many of the sinks into the Yoredale Main Limestone on the northern slopes of Wensleydale drain north beneath the topographic divide to resurgences on the southern slopes of Swaledale (Fig. 7.29). Most of this current vadose drainage appears to be through the joint-guided fissure passages that characterize the caves in the Yoredale limestones (Myers, 1963). Though inception along the joints determined the details of the cave passages, down-dip flow within the thin bed of limestone determined the overall lines of underground drainage.

Figure 7.31. The tall and narrow descending rift in Diccan Pot, formed on the Alum Pot Fault, Ingleborough (TW).

Figure 7.30. The main shaft of Rowten Pot, in Kingsdale, developed on a major fracture that is probably a minor strike-slip fault (photo: John Forder).

Joints and faults

Minor faults are scattered throughout the limestones in the Dales, and many have some degree of cave development on them. Within the Great Scar Limestone, the deep potholes of the Allotment on Ingleborough, including Juniper Gulf, Rift Pot and Nick Pot, are all developed on faults, though displacements and brecciation are minimal (Fig. 7.30). Fractures are features of most caves, where they have either been picked out by dissolution or determine the locations of shafts on which passages step from one bedding plane to another. The great majority are simple joints that developed in the limestone in order to relieve tectonic stresses. Some of the more extensive fractures have been popularly described as master joints, but are probably small strike-slip faults which have no vertical displacements to indicate movement in the sub-horizontal limestones. Much of Tatham Wife Hole is formed along a fault that does reveal normal displacement with shale beds at levels half a metre apart in opposing walls, and there are many other cave passages that are developed along faults and not just down them (Fig. 7.31).

A notable example of fracture guidance in the Dales caves is the Dowbergill Passage in Wharfedale; this passes beneath a shoulder of Great Whernside, from sinks in the Dowber Gill valley to an inlet in Dow Cave, which resurges in the Caseker Gill valley. Over a length of 1300m, the passage is almost perfectly straight, forming a vertical rift 10–25m

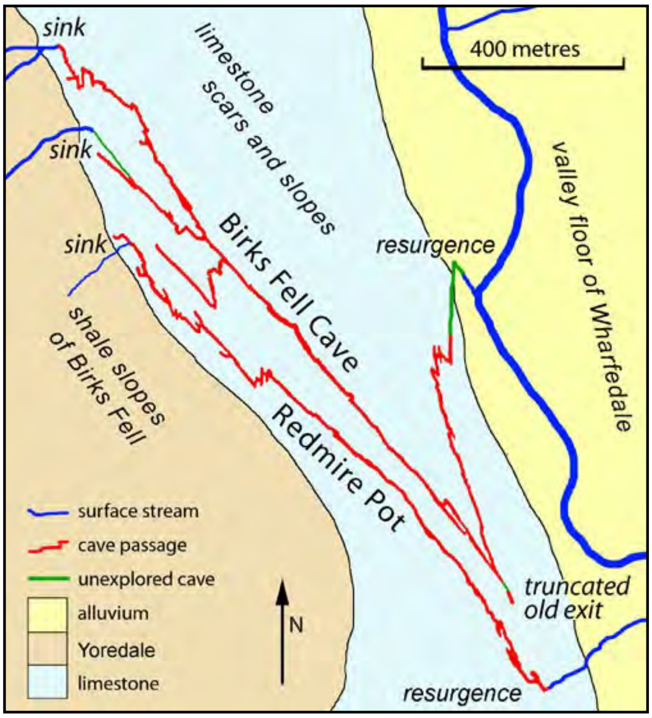


***Figure** 7.32. The parallel fracture-guided caves of Birks Fell and Birks Wood, in upper Wharfedale; the sinks along the shale margin are about 140m above the dale floor (after surveys by Craven Pothole Club and Cambridge University Caving Club).*

high but rarely more than a metre wide. Its guiding fracture appears to be a major joint or a strike-slip fault, as there is no evidence of fault displacement (Halliwell, 1979). The rift passage is largely phreatic in origin, though vadose flow has modified its floor profile.

Also in Wharfedale, fracture control of cave development is conspicuous in Birks Fell Cave (Coe, 1968) and the parallel system of Redmire Pot through to Birks Wood Cave (Fig. 7.32). Most of Birks Fell Cave is developed along a single, vertical, strike-slip fault, whereas inlet passages and Redmire Pot are developed on sub-parallel joints and minor faults. Even though these two caves are formed on major fractures, it is significant that both their profiles are stepped with sections of almost level passages following shale horizons between waterfall shafts along the same fractures (Coe, 1968; Monico, 1995).

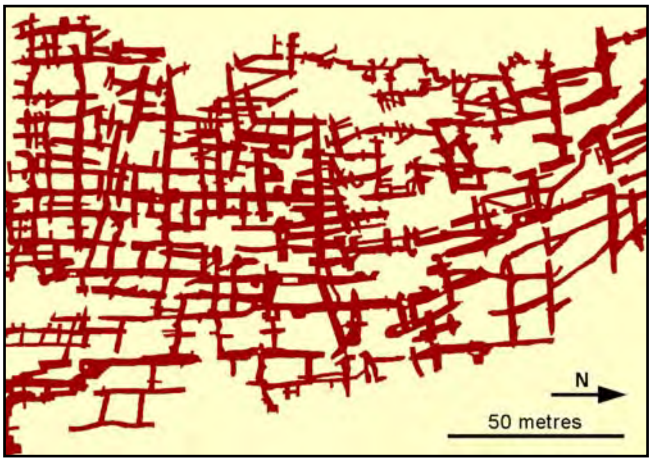


***Figure** 7.33. The central part of the joint-guided maze of rift passages in Knock Fell Cave, in the Yoredale Great Limestone on the Alston Block (after survey by Gritstone Club).*

Caves within the Yoredale limestones

There are some long streamway caves in the Yoredale limestones, including Fairy Holes in the northern Pennines (Jones 1957; Waltham *et al*., 1997), Cliff Force Cave in Swaledale (Ryder, 1981) and those in the eastern Dales (described below). These mainly linear caves have varying degrees of vadose development superimposed on phreatic origins, and are largely comparable with caves in the Great Scar Limestone except for their constraint within the thin beds of the Yoredale sequences. However, the Yoredale limestones are most distinctive for their maze and network caves that were developed entirely under phreatic conditions when strictly guided by bedrock joint systems (Ryder, 1975).

These maze caves are developed in the Main Limestone on the Askrigg Block, and also in the Great Limestone on the Alston Block (both are now formally described as Great Limestone within the Yoredale succession – see Chapter 2). The caves consist of spectacular mazes of phreatic rifts developed on multiple sets of intersecting joints (Fig. 7.33). Most of the rifts stay within limited stratigraphical zones and their walls are ribbed and fretted to etch out small differences in the limestone lithology (Fig. 7.34). Their morphologies include no flow features, and they were enlarged by slowly moving water when the Yoredale aquifers were confined. The Yoredale limestones are characteristically underlain by porous and fractured sandstones (locally known as

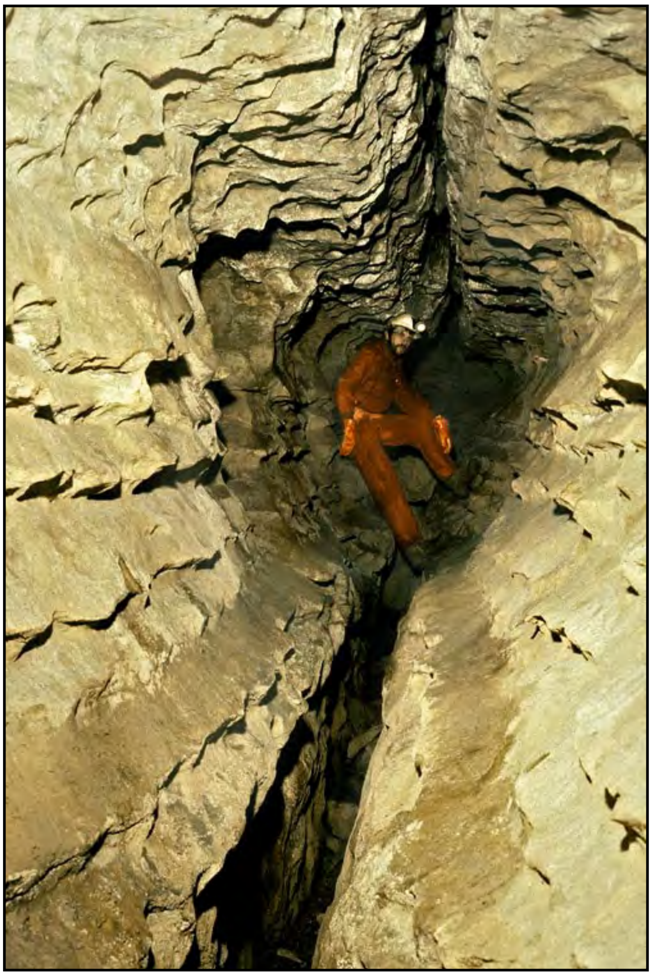


***Figure** 7.34. A rift passage in the Knock Fell Caverns maze, with wall ledges picked out on lithological variations within the Great Limestone of the northern Pennines (TW).*

grits), and the larger phreatic maze caves lie in areas where unconformities also bring similar sandstones to the tops of the limestone. Groundwater input, upwards or downwards, from these permeable sandstones appears to have been a factor in the development of such extensive maze caves, in addition to the very slow lateral flow through the limestones themselves (Ryder, 1975; Palmer, 1975). Hypogene development of maze caves within the Yoredale limestones, with water migrating in from adjacent aquifers and by transverse flow, may be suggested by their maze patterns and by features of their passage morphology (Klimchouk, 2007). Though hypogene caves are increasingly being recognized, dissolution kinetics indicate that hypogene speleogenesis has significant limitations in limestone, and may not be as widespread as it is in gypsum (Palmer, 2011).

Alternatively, the maze caves may have been wholly or partly developed by sub-glacial or deglacial meltwater impounded by warm-based ice. Such an origin has been inferred for many maze caves along the narrow marble outcrops in the stripe karst of Norway (Skoglund and Lauritzen, 2011). In the Pennines, Knock Fell Caverns lie largely beneath the outcrop of the limestone and are reached through a small shaft (Sutcliffe, 1985), whereas the maze caves of Swaledale all lie well back beneath their covers of shale and sandstone and are only reached from old mine levels (Ryder, 1975; Harrison, 2006, 2012a, 2012b). None has yet been found with passages opening onto, or truncated along, a valley-side outcrop, as is normal in the Norwegian caves. This would be surprising if they had formed beneath Devensian ice by meltwater flows into the limestones at their subglacial outcrops; any formed beneath earlier ice sheets would probably have been removed by the Devensian glaciation. Neither the sug-glacial nor the hypogenic processes are compatible with all the features in the Pennine maze caves, and origins and subsequent development of this type of cave remain unresolved (Palmer, 2011).

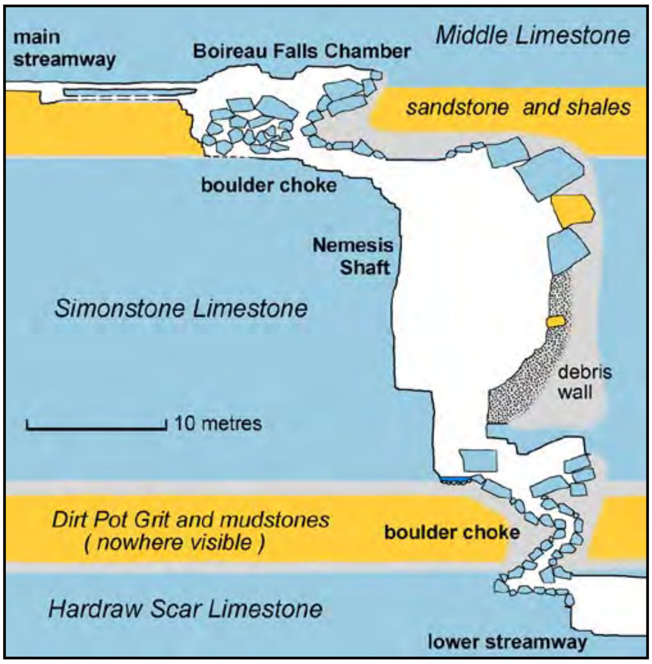


***Figure 7.35**. Sketch profile of a part of Langcliffe Pot, Wharfedale, where its stream descends through non-carbonate beds between the Yoredale limestones; grey areas are unseen (survey by Dave Brook).*

***Figure 7.36**. The main stream passage in New Goyden Pot, carrying the River Nidd beneath the grit outcrop (photo: Andy Jackson).*

Langcliffe Pot and Mossdale Caverns, the two long cave systems above Wharfedale, are both formed largely in the Middle Limestone of the Yoredale sequence. They both have long stream passages with significant flows through them, but they are also guided by the joints, so that their plan forms are essentially rectilinear, with little or no trace of passage meandering. Unlike the majority of Yoredale caves, which are each restricted to a single limestone within the Yoredale sequence, both Langcliffe and Mossdale drain through to lower limestones, as they both resurge from Black Keld, which lies at floor-level in Wharfedale near the base of the Great Scar Limestone. The escape from the Middle Limestone, stratigraphically downwards, is seen only in Langcliffe Pot (Brook, 1989), where the stream has cut a canyon through undisturbed shale in Boireau Falls Chamber to reach the lip of a shaft that descends through the entire thickness of the Simonstone Limestone (Fig. 7.35). The cave stream then drops into the Hardraw Scar Limestone, but the boulder choke obscures the bedrock structure and the nature of the descent through the intervening Dirt Pot Grit. The extensive collapse suggests that this is located in a strike-slip fault zone, but the lack of continuous exposure prevents confirmation of the geological details. The Hardraw Scar is continuous with the Hawes and the Great Scar Limestones, but the water cannot be followed beyond a choked sump in the Hardraw Scar (beyond the margin of Fig. 7.35).

The main passages of the known caves beneath the floor of Nidderdale appear to be entirely within the Middle Limestone. The Three Yard and Five Yard Limestones are both exposed in the inliers, and the shafts of New Goyden Pot appear to descend through at least part of this overlying sequence. Downstream from the sinks into Manchester Hole and Goyden Pot, the caves are distinguished by large phreatic conduits, where maze development is subsidiary and may have been caused by flooding at high hydraulic gradients (Palmer, 1991). The main passages cross a number of small faults, and parts of them step up or down to follow stratigraphic inception horizons (Davies, 1974). Some of the faults are marked by cross rifts, have segments of passage aligned on them, or have tributaries joining on them, but others are crossed by passages with no lateral development on the fault plane.

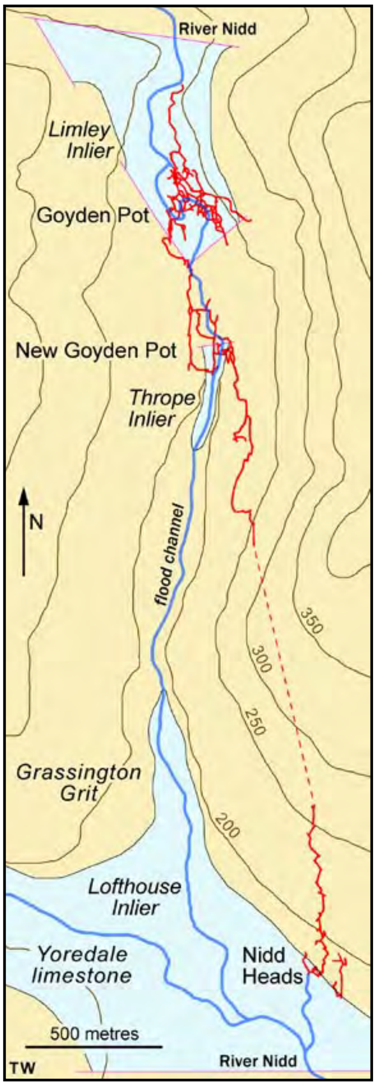


Figure 7.37. The course of the River Nidd through caves beneath the outcrop of Grassington Grit between the limestone inliers of Limley and Lofthouse (after surveys by Yorkshire Underground Research Team, Cave Diving Group and Black Sheep Diggers).

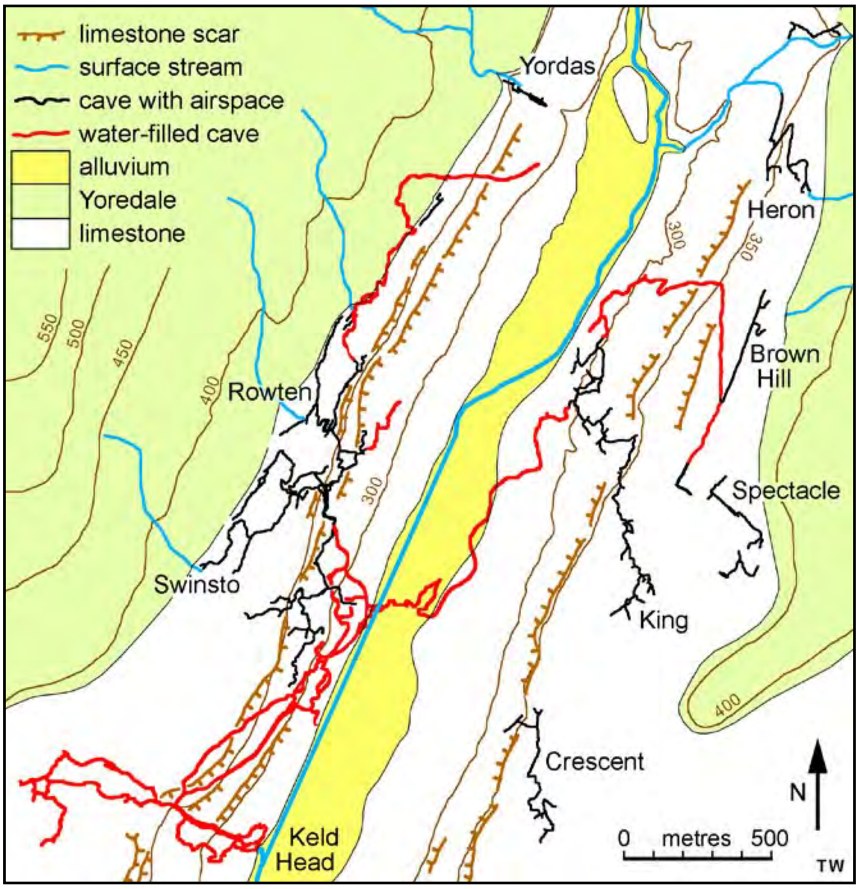


***Figure 7.38**. The caves of Kingsdale, including the flooded passage that crosses beneath the valley floor from the East Kingsdale sinks to the Keld Head resurgence (after surveys by Cave Diving Group, University of Leeds Speleological Association, Northern Cave Club, and a rough sketch of the southern inlet in Brown Hill Pot).*

A notable feature of the Nidderdale drainage is the route of the main conduit, which lies beneath a cap of Grassington Grit for more than 2 km between New Goyden Pot and Nidd Heads (Figs 7.36, 7.37). The cave passage is underwater for most of its length, but has been largely mapped by divers, and it lies well away from small outcrops of the limestone along the river bed (which is dry except for small streams collected on the caprock). This large and mature cave offers some indication of the scale to which passages can grow beneath a caprock prior to its removal by denudation and consequent expansion of the limestone outcrops; such may be relevant to consideration of some of the earliest stages of cave development within the Dales.

Hydrological features of cave development

The concept of the 'master cave' in the Yorkshire Dales caves became established following discovery of the low-level trunk drain in Lost John's Cave under Leck Fell (Foley, 1930). These were conceived as long passages developed at the 'water table', where they collected numerous tributaries, and may then have been exposed as open vadose passage following a slight fall in resurgence level. The notion of a main drain, or a trunk cave on which numerous tributaries converge, is valid, but there is no direct relationship to a water table (except that such a vadose trunk cave commonly defines the local karst water table within a cavernous limestone in the same way as a surface stream controls the water table in a diffuse aquifer). The term 'master cave' has been rather over-used. It may be appropriate for the long, low-level stream caves in Lost John's Cave and Ease Gill Caverns, which collect much of the drainage beneath Leck Fell and Casterton Fell respectively. However, the Out Fell Master Cave in Hammer Pot is merely a powerful streamway at high-level beneath Fountains Fell; this continues down a 15m-deep waterfall shaft to a sump that is perched 30m above passages where the water is next seen in downstream caves.

The active main drains, or trunk passages, within the Dales cave systems are both vadose and phreatic. Keld Head is the outlet of a phreatic system with multiple loops and branches converging from disparate sites, including the East Kingsdale Branch that crosses beneath the floor of the surface valley (Fig. 7.38). The West and East Kingsdale master caves are merely short sections of vadose passage within a dominantly phreatic collector system that drains up-dip. In contrast, the trunk caves beneath Casterton, Leck and Fountains fells, each with multiple tributaries, have long stretches of vadose passage where they are aligned obliquely down the local dip of the limestone.

Development of the trunk cave passages commonly involves multiple stages of under-capture as they adjust to resurgence levels that are declining in response to surface denudation (Worthington, 2005). This leaves some distributary passages at only slightly higher levels, where they can then be re-activated as flood outlets. Such a pattern is almost normal among the larger cave systems in the Yorkshire Dales. Leck Beck Head, God's Bridge, White Scar Cave, Clapham Beck Head, Turn Dub, Brants Gill Head, Aire Head and Nidd Heads all have distributary resurgences; Keld Head is the exception in its present state, but its underwater passages have at least three distributary outlets that have been active in the past. Brants Gill Head is perhaps the most complicated of the Dales underground drainage systems (Fig. 7.39), with tributary streams from at least 20 sinks, many feeding through long stretches of known cave (Fig. 7.40). The waters all drain to Brants Gill, except when flood flows go to Douk Gill Head and Dub Cote Cave, both of which can be dry exits in normal conditions. Dub Cote has 4 km of mapped passages beyond flooded sections that never drain clear, and these carry a base flow that drains through another distributary to the Brackenbottom Rising. The two large phreatic ramps in Sleets Gill Cave, Littondale, appear to have been distributaries that rose from depth in a cave system that was more active prior to glacial rejuvenation of the dale, but it is uncertain if they were contemporary or sequential. The modern stream in the cave has developed its own route beneath the older passages, but water flows up the smaller ramp to emerge at the present cave entrance as a flood distributary.

The present cave systems clearly have an abundance of large trunk passages at altitudes close to the local resurgences; Kingsdale is an example with long sections of low-level main drain both above and below the Keld Head resurgence level.

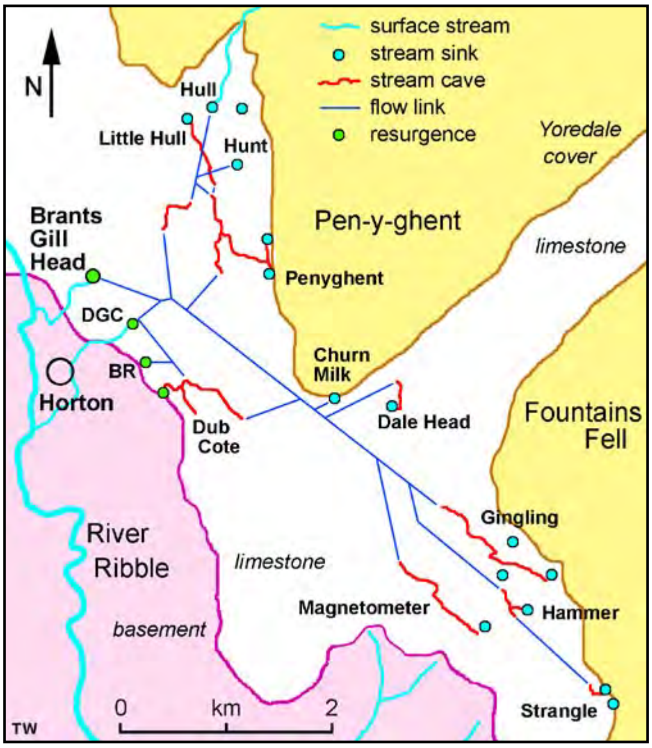


Figure 7.39. The underground drainage system behind Brants Gill Head, in Ribblesdale, with multiple tributaries from sinks on Pen-y-ghent and Fountains Fell, and its distributaries to the flood resurgences of Douk Gill Cave (DGC) and Dub Cote Cave, with base flow to Brackenbottom Rising (BR); the marked links are unknown in detail as they are only part of a complex hydrology within the flooded zone.

***Figure 7.40**. The lower streamway in Penyghent Pot, one of the main feeders to the Brants Gill Head resurgence (TW).*

These would be comparable to the 'levels' of development that might be recognized in the systems of large, old, high-level abandoned phreatic tunnels. But it is notable that the modern caves range between the resurgence-level water table and depths of about 40m, and also include trunk passages significantly above the local resurgences. In detail, the levels of cave development are primarily functions of the geological structure and stratigraphy, and not of resurgence levels. While the higher levels of cave development in the Yorkshire Dales do broadly represent past stages of drainage and dissolutional activity, they can only relate very roughly to the contemporary resurgence positions, except where detailed mapping of preserved underground morphology permits better correlations.

Many of the major active cave systems within the Great Scar Limestone drain to resurgences at or close to the base of the limestone. Little cave development is actually on the base of the limestone, largely because impure basal beds favour cave development at slightly higher stratigraphical levels. Only White Scar Cave has a largely vadose streamway through to its resurgence on the base of the limestone, because it lies in a position where it can drain down-dip into Chapel-le-Dale. Although the resurgence is at the contact with the impermeable basement, most of the cave lies some metres higher within the basal beds of the limestone (Waltham, 1977b). Most of the other major caves drain up-dip to the dale-floor resurgences, because they are at the lower ends of shallow phreatic loops where the drainage descends a joint and then rises along the bedding. Because these are phreatic they are not constrained towards the base of the limestone. Keld Head lies at the truncated end of a phreatic tube that happens to be about 40m above the base of the limestone where it has been breached by the incision of Kingsdale (Waltham *et al*., 2010). Leck Beck Head resurges up a dipping bedding plane, while the God's Bridge risings, in Chapel-le-Dale, are also from bedding planes. Austwick Beck Head has an immature passage rising on a bedding plane about a metre above the base of the limestone, and appears to be a recent under-capture of another passage whose location is unknown.

Many of the smaller cave systems neither penetrate the full depth of the limestone nor reach down to the level of the dale floor. The caves around Birkwith, in Upper Ribblesdale, are the most conspicuous of these perched systems (Fig. 4.25). They are perched within the limestone largely because their passages developed along bedding planes or shale beds and failed to find joints that allowed them to descend to lower levels. One of these, the main streamway in Red Moss Pot, follows a single joint for more than 700m, but nowhere descends through the beds as it was all initiated on a single bedding/joint intersection. The Birkwith caves therefore drained out to the valley sides, though they may originally have continued further and perhaps reached greater depths before they were truncated at their current exits by surface erosion (Fig. 7.41).

A deep cave can form only where there are vertical (or inclined) geological structures (either fractures or bedding planes) to exploit and where the surface relief allows a long descent from sink to rising. In the Yorkshire Dales karst these two requirements are best met along the southern edge of the Askrigg Block, where fracture densities increase on approach to the Craven Faults and where the dales are entrenched deepest before emerging onto the Craven Lowlands. The deep shafts of southern Ingleborough make a clear contrast to the shallow caves of Ribblehead farther north. The scatter of deep caves that do occur further away from the Craven Fault zone are nearly all developed on isolated minor faults (Fig. 7.42). These include Alum Pot and Washfold Pot in Ribblesdale and most of the deeper caves in Upper Wharfedale, including Birks Fell Cave, Pasture Gill Pot and Strans Gill Pot, though all these caves also have some passages that are bedding-guided..

Filling and destruction of the caves

Once a cave passage has matured fully, with a significant stream flowing through it, there is a natural progression towards it losing its stream through rejuvenation and capture, eventually reaching a stage of old age that is distinguished by slow destruction or by infilling and choking. The internal processes of this stage are dominated by collapse and breakdown, and by filling with both clastic sediments and carbonate precipitates. At the same time, surface erosion can breach, un-roof and then totally destroy cave passages

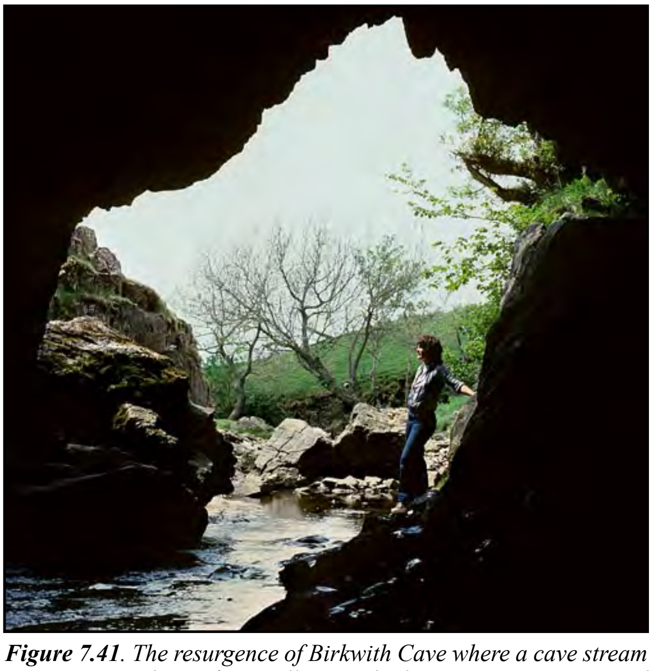


***Figure 7.41**. The resurgence of Birkwith Cave where a cave stream emerges onto the surface well up in the limestone succession and above the floor of Ribblesdale (TW).*

***Figure 7.42**. The fluted walls of the main shaft in Hardrawkin Pot, Ingleborough, where the mismatch of the thin, dark shale beds indicate that the shaft was formed on a small fault that is roughly down the line of the rope (photo: Mark Shinwell).*

during landscape evolution. All these elements of destruction commence as soon as a cave is formed, when rock walls can be displaced between fractures and calcite can fill even a narrow fissure; but their roles increase with age, until they dominate in the older passages abandoned by streams that could have been capable of further enlarging them.

Bedrock breakdown and cave chambers

Breakdown and collapse of cave roofs and walls are inevitable in a bedded and fractured limestone such as that in the Yorkshire Dales. Though unsupported roof slabs can fall away, wall collapse is probably more widespread in the Dales caves. It is particularly prevalent in the zones of heavily fractured limestone that are commonly followed by cave passages, and makes a significant contribution to passage widening, especially where residual screens of rock fall away from passage walls or collapse between parallel rifts (Fig. 7.43). Extensions of the same process have contributed to formation of the larger cave chambers that lie within a number of the Dales caves. Collapse cannot form chambers, but can only modify them, as there has to be an earlier void into which broken material can fall. The collapse process is significant in that it supplies breakdown debris, which is then exposed to dissolution and erosion, but the ultimate size of a cave chamber is the product of rock removal, which is normally in solution in streams that flow across and through its debris floor. Roof stability over cave chambers

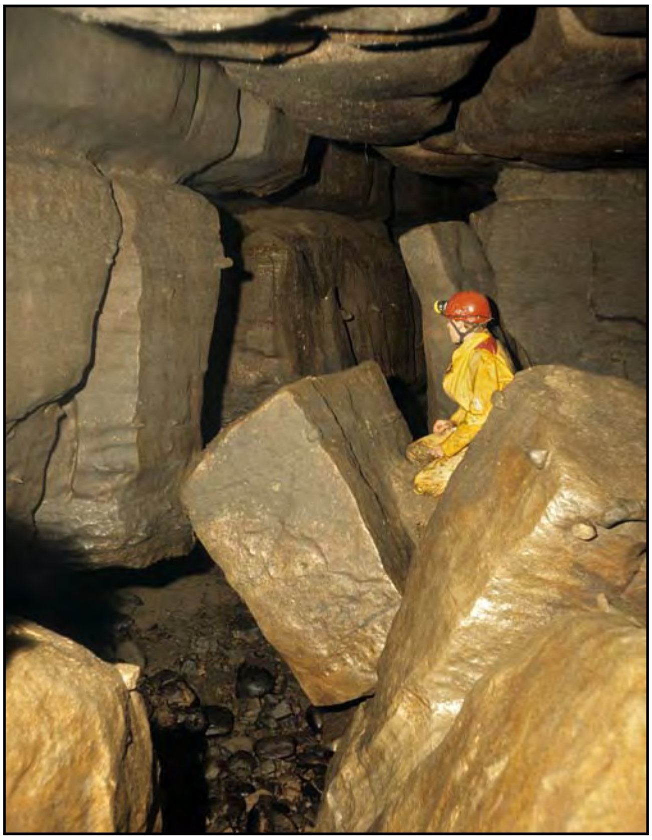


***Figure 7.43**. Wall collapse with a large limestone block toppling out into a cave passage in Scrafton Pot, Coverdale (TW).*

***Figure 7.44**. The Main Chamber in Gaping Gill, looking towards the east with daylight shining down the waterfall shaft; both the vertical wall on the left and the sloping roof on the right are along minor faults or major joints; the floor is water-washed cobbles and sand overlying debris that may be 30m thick (TW).*

can be related to bed thickness and span width (Waltham *et al*., 2005), but this indicates only maximum spans in intact beds. Both in the Dales caves and elsewhere, nearly all roof failures are determined by the local situation with respect to the joints that break the beds.

Gaping Gill Main Chamber is the largest in the Dales, 130m long and about 30m high and wide, with its roof broken by the Main Shaft containing its 100m-deep waterfall where Fell Beck descends from daylight (Fig. 7.44). The chamber is formed at the intersection of various vertical and inclined faults and joints, and the ceiling profile (away from the Main Shaft) is clearly the result of many fracture-bounded blocks falling away (Murphy *et al*., 2005). Most of the chamber floor is close to level on a thick clastic fill. Surveys of this, using ground-probing radar, suggest that the sediments are at least 30m deep, with layering defined by the signals from clay-rich horizons (Murphy *et al*., 2005, 2008), but these surveys are difficult to interpret and have not been verified by any borehole or excavation. There are however no indications of large piles of fallen blocks.

The open pothole of Hull Pot, on Pen-y-ghent, is 90m long and 20m wide, with vertical walls dropping about 20m (Fig. 7.45). Whether it was initially developed as an open hole, or is an un-roofed cave chamber, is open to debate, but its genesis involves dissolution and wall collapse similar to that in underground chambers. It is formed in fractured limestone along a system of small splayed faults, and progressive wall failure has been recorded within the last hundred years (Murphy and Parr, 2004); this is a part of the process that has widened it from an initial one or two fissures. Its level floor is on clastic fill. A radar survey across this suggests a rock floor beneath about 30m of fill (Murphy *et al*., 2008), though a breakdown pile is accessible from a side shaft at a depth of 40m at the eastern end (Pappard, 1976) (Fig. 4.31).

Also on Pen-y-ghent, Sell Gill Holes lead down to a single large chamber that has been heavily modified by collapse on multiple large fractures. Many other chambers within the Dales caves are little more than wider sections

***Figure 7.45**. Hull Pot, on the side of Pen-y-ghent, with the large tilted block at the western end showing the scale of wall retreat by successive failures on parallel fractures (TW).*

along the large, old, phreatic, trunk passages. The Battlefield chamber in White Scar Cave is just such a larger section of the relict high-level passage, though its spaciousness has been enhanced by its floor of breakdown debris settling as some of the blocks have dropped into the younger stream canyon that winds its way beneath the large central section of the chamber (Waltham, 1977a).

Clastic cave sediments

Every cave in the Yorkshire Dales has clastic sediment in some of its passages. Clay, silt, sand, gravel and cobbles are constantly in transit through the active stream caves, with their distribution frequently changed after the flood events during which most sediment transport occurs. Floods pass through, and many vadose canyons are notable for their lack of sediment in conditions of low stage, but easily disturbed mud is almost ubiquitous in the phreatic passages where water velocities are generally lower. Abandoned, high-level caves are characterized by an abundance of clastic sediments, which may completely fill passage segments until an invading stream cuts a channel into them, or until cavers excavate enough of the sediment to allow access to open passages beyond.

Most cave sediment is allogenic, in that it has been carried into the caves by sinking streams. The sand, gravel and coarser materials in the Dales caves are derived largely from the Carboniferous grits and sandstones that crop out in the stream catchments. Fragments of limestone (known as clasts), derived from wall and roof breakdown, form a significant proportion of the coarser material in most stream caves, but are proportionately less abundant in trunk conduits beneath the dale floors where additional coarse material has been carried in by the larger sinking streams. The active phreatic conduit in Joint Hole, beneath Chapel-le-Dale, has gravel as its current sediment bed-load, and this moves as dune forms only during flood events (Fig. 7.46). The low gravel dunes migrate over the top of a cemented cobble deposit that is not involved in the active sediment transport (Murphy, 1999). Protected beneath the cobbles

Figure 7.46. *Low banks of gravel being washed through the main phreatic conduit in Joint Hole, beneath the floor of Chapel-le-Dale (photo: John Cordingley).*

Figure 7.47. *The old phreatic trunk passage of Duke Street, in Ireby Fell Cavern, with a thick bank of sand, silt and clay eroded by a stream that subsequently invaded the passage (TW).*

are pale clays that form no part of the modern sediment regime and may be remnants surviving from the glacial environments of the Pleistocene. Pebbles and cobbles, particularly those of sandstone, commonly acquire black coatings of compound oxides of iron and manganese, largely goethite. These coatings accumulate to create a partial cement in sediment banks, which then become more resistant to erosion and develop into semi-permanent features in some cave streamways. The rapid deposition of coarse sediment in some caves is demonstrated in Mongo Gill Cave where stratified gravels include layers with minerals derived from miners' waste dumps left in the Greenhow Hill area only a few hundred years ago.

Accumulations of clastic sediment within cave passages lead to paragenetic processes whereby walls or ceilings of the passages are eroded by flowing or effectively static water that is impounded above or behind the sediments (Farrant and Smart, 2011). Wall notches are the clearest indicators of paragenesis (Fig. 7.14) but these have not yet been identified widely within the Dales caves. If they can be distinguished from dissolution notches along horizontal bedding planes, they could indicate detail in the stages of passage evolution.

In the relict high-level caves, the coarser clastic sediments have a wide range of lithologies. Poorly sorted material, with more angular clasts, is less mature and was deposited more rapidly, probably in flood events, and notably during phases of de-glaciation. Great banks of coarse, poorly-sorted sediment in Stream Chamber in the Gaping Gill System indicate powerful stream flows that were capable of transporting this material in the past (Ford, 2001). Only 100m from that site, the stratified sands in Sand Cavern may represent a downstream extension of the same sediments that were deposited where water was ponded in the chambers; these sands contain grains of goethite that appear to have been re-worked from elsewhere. The well-sorted sand is more than 10m thick, largely in beds about 50 mm thick that are separated by thin partings of clay. Banded sediments in Sand Cavern, and in other caves, may be varves, but the timing of the cycles has not been investigated and they may represent random flood events rather than being annual features.

Thick sequences of stratified sediments are exposed in many of the large, old, trunk passages. Besides sand, there are massive quantities of silt and clay (Fig. 7.47). These appear to be derived largely from both the Yoredale shales of

***Figure 7.48**. Desiccation cracks in a patch of dried mud in the Battlefield chamber in White Scar Cave (TW).*

the stream catchments and also from the loessic soils washed from the limestone outcrops, but no sedimentological studies have yet revealed the details of their origins. Many of the clay deposits in the Dales caves are laminated, but whether the individual layers represent flood events, seasonal changes or longer periods of climatic fluctuation has not been determined. Exposed tops of the clays are commonly distinguished by deep desiccation cracks (Fig. 7.48). It has been suggested that such may have been deposited beneath subglacial lakes during warm-based glacial maxima or beneath ice-dammed lakes during de-glaciation (Faulkner, 2011). Varved clays in Victoria Cave are also thought to have formed in cave lakes when warm-based ice covered the terrain during at least four glacial maxima (Lundberg *et al*., 2010).

Whereas the sorted and bedded sediments are of largely fluvial origins, some caves in the Yorkshire Dales also contain clastic sediment that displays little or no sorting, and may therefore be described as diamicton. Some of this has been labelled as boulder clay or glacial till, but this cannot have been pushed far into caves by glacier ice, even in the coldest of Pleistocene Ice Age conditions. Except for debris that chokes or partially chokes many entrances, and may be till that has been dragged, squeezed, dropped or washed a few metres into the caves and potholes, much of this material may be better described as glaciofluvial, because it originated from glaciers and ice sheets but was finally emplaced by meltwater (Fig. 7.49). However, similar unsorted fills that choke many entrance shafts can be younger and much later than the glacial activity; debris in the entrance to Shuttleworth Pot, on Leck Fell, contains Bronze Age artefacts less than 4500 years old. A variation in the mode of transport and deposition may be represented by the sediments in the far reaches of Dale Barn Cave where they lie beneath the slopes of Kingsdale. These are thick diamictons interbedded with cross-bedded sand and gravel, and are very similar to debris deposited in pipe-full glacier tunnels and subsequently exposed in eskers; they are interpreted as sub-glacial, phreatic deposits (Murphy *et al*., 2001). A stalagmite, dated to 343 ka, was eroded by the flow that emplaced these sediments, indicating that they originate from a post-Anglian glaciation.

***Figure 7.49**. Poorly sorted sediment left by inflows of meltwater into the Broadway passage beneath the Ease Gill surface channel (TW).*

Burial in a cave of the quartz grains within clastic sediments can be dated by the unequal decay of aluminium and beryllium isotopes (see Chapter 10), but no age determinations have yet been obtained for clastic sediments in the Dales caves. Dating the thick clastic sequences in some of the old trunk passages might indicate stages in the caves development that pre-date glaciations prior to the Anglian, but there may be serious problems in defining the burial history of sediment that may have been derived from older tills before being washed into the caves.

Cave deposits from solution

Calcite deposits are virtually ubiquitous in limestone caves. Most are formed where percolation water, rich in biogenic carbon dioxide from its seepage through a soil cover, becomes saturated with carbonate (largely in its transit through the epikarst) before entering open cave passages. There it precipitates the calcite in response to partial loss of its carbon dioxide in order to achieve equilibrium with the cave air. Nearly all the Dales caves contain some calcite deposits, since few extend far beneath the impermeable shale cap that might prevent percolation water reaching the open passages. The decorative calcite speleothems occur in a huge variety of forms (Fig. 7.50). In response to the cool climates, past and present, of the Dales karst, they are generally less massive than their counterparts in karsts of warmer environments (where percolation waters pick up more biogenic carbon dioxide from the soil cover, because biological activity is greater, and can therefore dissolve more carbonate prior to precipitation when it de-gasses on entering open caves).

Straw stalactites are the most widespread and the most numerous calcite deposits in the Dales caves, with many occurring in large clusters and reaching more than a metre long. Stalagmites are far less numerous, and if any shape is typical in the Dales caves it is a stumpy column with little taper and only about half a metre tall; the Colonnades in Lancaster Hole are exceptional, reaching 5m tall and only about 120 mm in diameter. Large gour barriers are not common, but the largest of nine in Ingleborough Cave were about two metres high and wide before they were broken through in 1837 to gain access to the cave beyond (which is now the show cave passage). The original extent of those gour pools is now indicated by the sub-aqueous ‘cave coral’ coating the passage walls. Elsewhere in the Dales caves, small pool deposits include crystal linings and rare clusters

Above: straws in Glover's Chamber, Gaping Gill Cave System. Below left: cut stalagmite 12,000 years old from White Scar Cave (TW). Below: straws and stalagmites in Easter Grotto, Ease Gill Caverns. Below right: straw bell in Shep Pot, Leck Fell (Mark Richardson).

Left: curtains in Gavel Pot. Above: stalagmites in Cape Kennedy, Lancaster Hole. Right: stalagmites in Slug's World, Lancaster Hole. Below left: flowstone in Ingleborough Cave (John Cordingley). Below: pool deposits in Lancaster Hole (Mark Shinwell). Bottom: cave pearls in Avalanche Inlet, Gaping Gill (TW). Below right: gours in Gour Chamber, Bull Pot of the Witches.

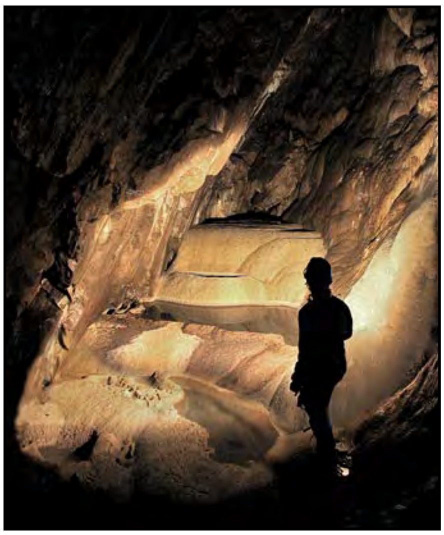


Figure 7.50. *Calcite speleothems in the Dales caves (photos by John Forder except where labelled otherwise).*

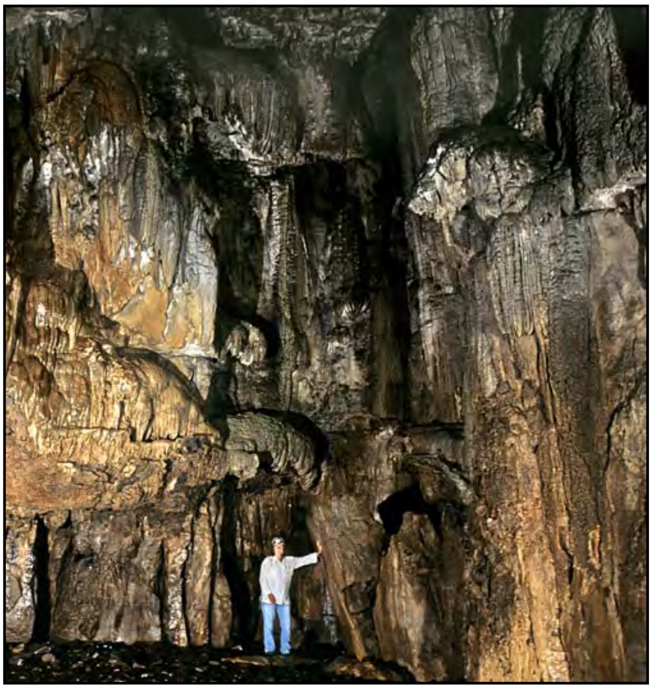


***Figure 7.51**. Remnants of false floors that indicate old sediment levels within the Main Chamber of Yordas Cave, Kingsdale; one level is just above the person's head, and the other is as high again on the right (TW).*

of cave pearls. False floors are common, and are important as indicators of past sediment levels, though many survive only as thin shelves of calcite projecting from passage walls, some with clastic sediment attached beneath (Fig. 7.51).

Pure calcite is white or translucent. Some completely white calcite speleothems do occur in the Dales caves, but most are of various hues from off-white, through cream and yellowish, to various shades of red and brown, all stained by traces of hydrated iron oxides in the water and in the calcite. Dirty greys and brown are due largely to included clay. Some red and yellow colourations are organic staining, and rare pale blues and pale greens are probably due to hydrated iron sulphates and carbonates, though some may contain traces of similar compounds of copper and other metals (Fig. 7.52).

***Figure 7.52**. Calcite at the Painter's Palette, in Lancaster Hole, stained by mineral oxides primarily of iron (photo: John Forder).*

Gypsum is not common in the Dales caves. Crystals of gypsum, also known as selenite, can grow in the muds and silts left in passages where there is any sulphate present from the oxidation of pyrite within the shale beds through the limestone succession. Gypsum Cavern, in the high-levels of the Ease Gill System, originally had thousands of tiny acicular (needle-shaped) crystals protruding from the clay banks, as well as small tabular crystals scattered across the cave walls, but this site is an exception within the known Dales caves.

Calcite stalagmites and flowstones contain traces of the unstable isotopes of uranium that decay at measurable rates and thereby allow estimation of their ages. The dating of stalagmites, and the interpretation of palaeo-environments from their contents of stable isotopes of oxygen, has led to caves being recognized as invaluable sources of geomorphological and palaeo-climatic data, both on a worldwide scale and in the Yorkshire Dales (see Chapter 10).

Evolution of the Dales caves

The earliest stages of cave genesis within the Dales limestones must date back to the expulsion of connate water during the late stages of diagenesis. This was followed by the very small groundwater flows that descended through faults or sandstone aquifers, ascended from hydrothermal sources, or entered laterally as connate waters from basins adjacent to the Pennines. All recognizable traces of these have now been lost, except for the imprint that they left on the patterns of cave inception (see Chapter 8). A landmark event was then the initial un-roofing of the limestone, simply in response to regional denudation and surface lowering.

These first exposures of the limestone were along the southern edge of the Askrigg Block, where the geological structures are highest against the Craven Faults, and where the adjacent topography is lowest in the Craven Lowlands. The first limestones exposed were the higher beds in the local Yoredale succession, but cave development in most of these is, and probably was, quite limited, so the main consideration is with regard to the Great Scar Limestone. It is reasonable to assume that the first outcrops of limestone appeared against the North Craven Fault where it was crossed by the deeper dales. Ribblesdale is the largest southbound dale, is probably among the oldest, and crosses the edge of the Askrigg Block near a structural high (Arthurton *et al*., 1988); the top of the Great Scar Limestone is currently exposed at an altitude of about 550m on Dick Close, at the southern end of Fountains Fell. A broad concept of the Dales landscape evolution, based on an interpolation of incision rates deduced from dated stalagmites, places the early exposures of the limestone west of Ingleborough at about 1.3 Ma (see Chapter 4). The paucity of currently available data makes this a very approximate figure, which is perhaps best interpreted as 'some time before about a million years ago', and the limestone exposures in Ribblesdale may be estimated to date back to 1.5 Ma or probably even earlier.

It is even more difficult to estimate times for unroofing of the limestone across the interfluves, but outcrops on the high ground north of Malham, must have been among the earliest. An early outcrop of the limestone, reaching from Ribblesdale towards the Malham High Country, would have allowed the

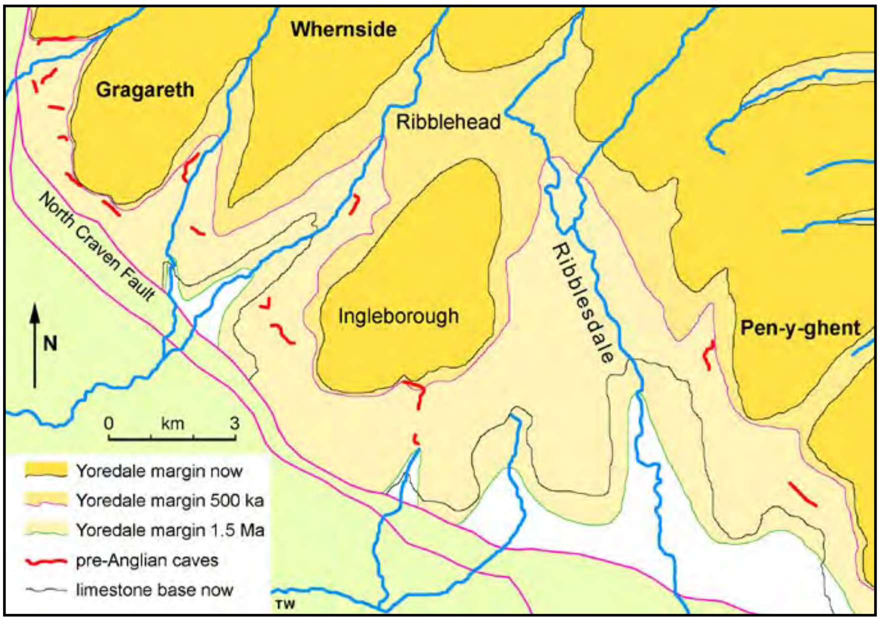


Figure 7.53. *The retreating margin of the Yoredale shale cover that unroofed the Great Scar Limestone and allowed sinking streams to develop the major caves in the Yorkshire Dales. The present margin is drawn along the line of stream sinks where water drops into the main limestone unit. The margin at 0.5 Ma is a reconstruction of conditions just prior to the Anglian glaciation (Waltham, 1990), based partly on the positions of large and old potholes including Rumbling Hole, Great Douk Cave and Alum Pot. Known fragments of large old phreatic cave passage are probably of similar age. The margin at 1.3 Ma is taken from the interpretation of earliest exposures as in Figure 4.13; this is roughly comparable to the outcrop of the present base of the limestone, because it precedes denudation by about 200m, which is close to the thickness of the limestone. No details are known or indicated south of the North Craven Fault. Rivers are shown only at their present positions to aid readability.*

first development of karst (Fig. 7.53), other than small-scale features on the thin Yoredale limestones. This could have been drained underground towards Ribblesdale, and the first caves in the Dales are likely to have developed in this area. Alternatively, the first caves may have been in the smaller limestone outcrop between the North and Middle Craven Faults, reaching from the high ground of the Attermire Scar area again to the floor of Ribblesdale. Victoria Cave may be a remnant of this first generation of caves. It does contain the oldest cave sediments yet dated in the Dales (Lundberg *et al*., 2010), but, determined only as >600 ka, these give little indication of the time when the cave was part of an active conduit. These two parallel sites in the flank of Ribblesdale were not linked as there is no continuity across the North Craven Fault, because its throw locally exceeds the thickness of the limestone.

As the dales were incised deeper into the limestone by surface erosion that was both glacial and fluvial, early phases of caves developed along newly available flow lines. Caves formed beneath and parallel with the trunk streams on the dale floors were doomed to total destruction when the dales were subsequently deepened and widened. Many of the earliest caves, draining from sinks on the shoulders of the interfluves and down to the dale floors, would also largely have been removed by subsequent enlargement of the dales, though some passage fragments could have survived at sheltered locations. Victoria Cave is a very early remnant (Fig. 7.54), but recognition of more of these in the modern landscape is surrounded by uncertainty. Ribblesdale was almost certainly the site of the earliest cave development. Wharfedale (with its Littondale tributary) is another major feature that is likely to have been deep enough to become another site of early karst development, particularly in the Yoredale Middle Limestone, which locally is of significant thickness and is also at high altitude. Chapel-le-Dale and Kingsdale are smaller valleys that were probably later to develop their own cave systems. The age of initial limestone exposure at around 1.3 Ma is largely based on the morphology and the incision rates of these two dales (see Chapter 4), implying that the karst around Ribblesdale dates from well before that. The outer dales, Dentdale, Wensleydale, Swaledale and Nidderdale, all lie where the main limestones are at lower altitudes, so were probably later to develop their first significant karst.

Figure 7.54. *Victoria Cave, a truncated fragment of cave passage that is at least 600,000 years old, in Attermire Scar 300m above the floor of Ribblesdale (TW).*

The first generation of caves

The oldest surviving passages can be recognized within many of the Dales cave systems, because they are isolated segments that lie at high levels and bear little relationship to the later cave development that has intersected them by chance. A number of large, old, high-level passages can be ascribed to pre-Anglian development due to their positions in relation to the glaciated troughs and the depths that they are likely to have achieved prior to Anglian deepening. These provide part of the evidence for the reconstruction of the 0.5 Ma karst margin (Fig. 7.53). It is however very difficult to identify remnants of cave systems that developed in the early part of the time interval between 1.3 and 0.5 Ma, for which no absolute chronology of events yet exists.

Jupiter Cavern (in Ireby Fell Cavern) appears to be very old, and its presence suggests that there was an early outcrop of the limestone in the lower end of Ease Gill. The 1.3 Ma interpretation is too generalised to show this outcrop (Fig. 7.53),

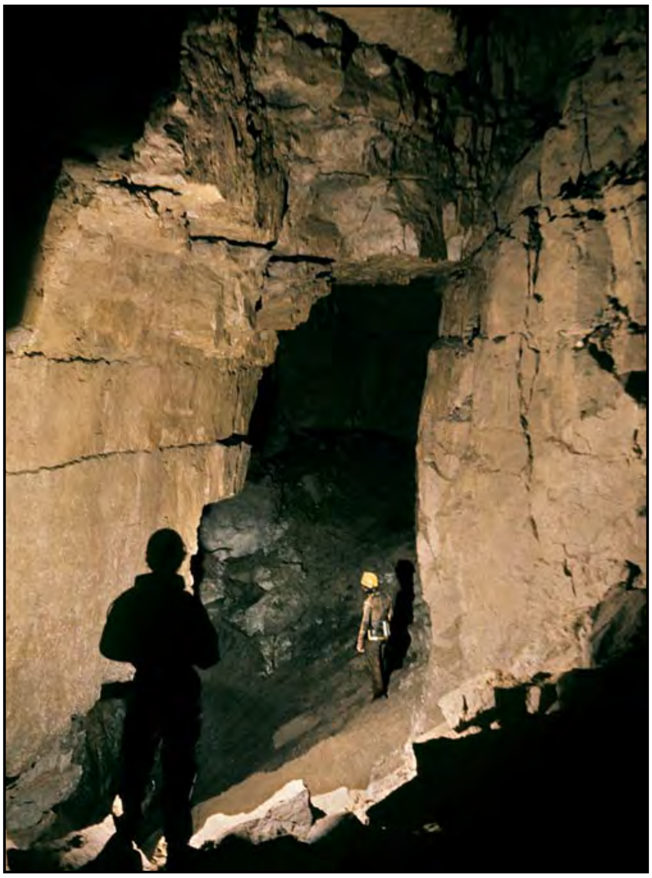


***Figure 7.55**. High Level Mud Caverns, an old abandoned passage in Mossdale Caverns, high above Wharfedale (photo: Dave Judson).*

but it could have developed at an early stage on the folded limestones against the Dent Fault. The phreatic trunk route of Duke Street, which underlies Jupiter Cavern, does indicate early karst development between Kingsdale and Ease Gill, which is likely to pre-date 0.5 Ma (Waltham *et al*, 2010), but this was preceded by Jupiter Cavern. East Passage appears to be one of the older parts of the Gaping Gill System, but it is difficult to see how this could have developed before most of the shale cover had been removed from southeastern Ingleborough; that would have taken some considerable time following initial exposure of the Great Scar Limestone in Clapdale at around 1.3 Ma (Fig. 7.53). Pikedaw Calamine Caverns lie between the North and Middle Craven faults and may have very early origins, perhaps related to Victoria Cave when karst development linked the Ribblesdale and Malham inliers (Fig. 4.13). The inner ramp in Sleets Gill Cave also appears to be unrelated to the present topography, and may be very old, but there is no dated material associated with it. Beneath Grassington Moor, the Mossdale High Level Mud Caverns are relict phreatic tunnels at high altitude (Fig. 7.55), but they lie within the Middle Limestone and cannot be related to any known contemporary caves within the Great Scar Limestone. Each of these fragments of cave passage appears to be very old, but their potential ages are barely constrained, and they could date from any time within about half a million years, from well after 1.3 Ma until well before the Anglian glaciation (which started around 478 ka).

How these early caves related to each other is completely unknown, but long cave systems may have been a conspicuous feature of the earliest karst development when there were few outlets southwards from the Great Scar Limestone aquifer. It is likely that initial dissolutional opening of joints and bedding planes developed into very extensive networks of passages that were mainly of small cross section; but widespread enlargement of their passages was terminated when efficient conduits drained over shorter distances to a scatter of resurgences against the Craven Lowlands. The result was the series of isolated cave systems that are now known. Though the Three Counties Cave System (Brook, 1968), wrapped around Gragareth, is now a reality, and may one day extend to Chapel-le-Dale with the exploration of further links, the concept of a 'trans-Craven cave system' (Brook, 1971) is still very short of solid evidence.

A major stage of cave development in the Yorkshire Dales is clearly recognizable as pre-dating the major deepening of the glaciated troughs that subsequently evolved into the main dales in the modern landscape. These caves post-date exposure of the limestone at around 1.3 Ma, and pre-date the Anglian glaciation that started at about 478 ka, but currently

***Figure 7.56**. Monster Cavern, a part of the ancient high-levels of the Ease Gill Cave System that has been modified by extensive roof breakdown (photo: Ray Duffy).*

Figure 7.57. A fragment of the old trunk passage beneath Chapel-le-Dale, that survives to form the Battlefield chamber above the modern streamway in White Scar Cave (TW).

available data allow no tighter constraint on their likely ages. Caves of this stage include the large, abandoned, high-level phreatic trunk passages that are a conspicuous feature of many of the known cave systems. They include Montague East Passage in Lancaster Hole and the high-level route through to Ease Gill (Fig. 7.56), various passage segments beneath Leck Fell and Ireby Fell, the Battlefield passages in White Scar Cave (Fig. 7.57), much of the main passage network in the Gaping Gill System, the Passage of Time in Strans Gill Pot, and many more. Stalagmites from these passages that have been dated include a number with ages that could only be recorded as >350 ka (see Chapter 10). The suite of samples is small and none has yet been dated by modern methods that can indicate more precise ages of the older material, but the available data support the concept of pre-Anglian development of many or all of these large old phreatic caves.

These systems all lay below contemporary dale floor levels, and deep phreatic lifts, notably in Gaping Gill and Sleets Gill, indicate that some, and probably most, were at significant depths below their resurgences. These caves may not necessarily have been contemporaneous, but could represent many phases within a very broad, post-1.3-Ma, 'pre-dales' stage. Dated stalagmites from many of these old passages indicate that they were drained prior to about 350 ka (see Chapter 10), and most of the phreatic trunk routes appear to have been active prior to the Anglian glaciation, which started at about 478 ka. They could be even older. It is possible that one of the Cromerian glaciations was more profound than the Anglian, and could have been responsible for major deepening of the dales, in which case these relict, high-level, phreatic caves would pre-date its start at around 659 ka. Flowstone on the wall of the chambers above Aven Pot in Simpson Pot, Kingsdale, yielded a date of 424 ka (Smart *et al*., 1988), which could imply that the main level of old phreatic passages was drained prior to the Anglian. However, this was a single date by an experimental method using electron spin resonance (see Chapter 10), with an error bar of +/-57 ka, and the calcite deposition could have followed drainage of the cave consequent on Anglian rejuvenation.

Subsequent surface denudation rejuvenated the karst as the dales were progressively entrenched into the Great Scar Limestone. This occurred in repeated cycles throughout much of the Quaternary. Long interglacial phases of slow, fluvial denudation alternated with shorter phases of glacial denudation that caused major deepening of the U-shaped dales. The rejuvenations allowed new suites of caves to develop along drainage lines to lower resurgences, and the multiple phases saw progressive development of the modern, active cave systems. Notably, the greater relief within the karst landscape permitted deeper and more extensive vadose development. White Scar Cave's Main Streamway became vadose right through to its resurgence, as did various small systems that have perched resurgences in the dale sides. However, the dominant pattern became one of vadose caves draining mainly northwards (down the dip) into shallow phreatic loops that turn more to the south and extend to the resurgences; Keld Head and God's Bridge provide the finest examples. The end result is the suite of cave systems within the present karst of the Yorkshire Dales. Most of the caves that are currently active are reasonably well known from their intensive explorations by cavers, but there are still unanswered questions concerning the role, extent and evolution of the earlier Dales caves.

The caves beneath the Pleistocene ice

Most of the larger Dales cave systems have passages that pre-date the Devensian glaciation, and many also pre-date some earlier glaciations. It is clear that much of the cave development took place during warmer, interglacial stages of the Pleistocene, when dissolutional processes were driven by the available biogenic carbon dioxide that became a component of the karst groundwater. The distribution of stalagmite ages confirms that dissolution and precipitation processes were confined largely to these warmer stages (see Chapter 10). Conversely, major reductions in the scale of karst activity during the cold stages of the Pleistocene are indicated by the lack of dated stalagmites from these cold intervals. Colder climates minimized karst dissolution through a reduction of plant cover and consequent reduction of biogenic carbon

***Figure 7.58**. The static ice plug that blocks the end of Castleguard Cave where it meets the underside of the Columbia Icefield in the Canadian Rockies (TW).*

dioxide. The extreme situation was provided by the periods of maximum ice cover when plant activity declined virtually to zero, and, perhaps more significantly, water flows were reduced to little or nothing.

A key question concerning the Dales caves during the Pleistocene glaciations was whether they became blocked and inactive beneath the ice or remained open as sub-glacial meltwater drains. The classic analogy is with Castleguard Cave, which lies partially beneath the Columbia Icefield in the Canadian Rocky Mountains (Ford, 1983; Ford *et al*., 2000; Waltham 1974c). The long main passage of Castleguard, and its many tributaries end at plugs of ice and debris beneath the icefield floor (Fig. 7.58); they transmit no water into the cave. However, an unseen conduit lies beneath the main cave, and feeds powerful springs below the entrance with flows that show rapid response to melting by solar radiation on the icefield; floodwaters even back up into the older cave system above the active route. Castleguard Cave therefore demonstrates both sub-ice scenarios, of sealed inactivity and of meltwater activity; it also reveals the scale and importance of localized variations. However, it still does not represent an ice sheet that seals the sinks and resurgences of all underlying caves, as occurred in the Dales during the peaks of their major glaciations.

Both the modern Castleguard Cave and the Pleistocene Dales caves respond to the contrasting environments of warm-based ice (also known as temperate ice) and cold-based ice. Warm-based ice has its lower layers at temperatures above the pressure melting point, so meltwater is generated, the glaciers can slide over the terrain and there is considerable erosion of the bedrock. Conversely, cold-based ice does not reach its pressure melting point, so generates no meltwater, and is frozen to the bedrock so that any glacier movement is by deformation of higher ice layers and there is minimal erosion (see Chapter 3). A pattern of activity, with selective erosion by powerful flows of ice along and over the main valleys between areas of slow-moving ice on relatively unscathed highlands, is well-documented in glaciated terrains (Staiger *et al*., 2005).

Pleistocene ice covered the entire karst of the Yorkshire Dales during the maxima of the cold stages. This ice was cold-based on the high plateaus, and was warm-based at lower elevations within the dales and their ancestral valleys (see Chapter 3). While the archetypal glaciated trough of Littondale was being deepened by a powerful flow of ice, dolines were preserved on the Malham High Country when they were buried by slow-moving ice that had spread from Littondale but had lost its erosive power where it was largely frozen to the limestone. In detail, the limestone outcrops of the Dales were probably covered by a complex mosaic of cold-based and warm-based ice that varied in space and time during the growth and decay stages of each major glaciation, as has been recognized more readily in the uplands of Scandinavia (Klemen *et al.,* 2008). In broad terms, the implications of ice temperatures and erosive impact are that the plateaus and benches on top of the Great Scar Limestone were mainly covered by slow-moving, cold-based ice. Frozen to the ground, any movement in the ice would easily have plucked off thin upper beds of the limestone, and thereby left the great stratimorphic benches on the highest bed that was thick and strong. In the main mass of the limestone, most caves were probably sealed off and dry through most of the cold stages of the Quaternary.

***Figure 7.59**. A part of Gypsum Cavern, in the high levels of the Ease Gill Cave System, a cave passage formed prior to the Anglian glaciation, partly filled with mud and sand during later stages that included the Devensian glaciation, before being decorated with calcite straws largely since the last retreat of the Dales glaciers; the chamber was named after gypsum crystals that were growing in its floor sediments (photo: Mark Shinwell).*

Cave passages close to the dale floors may well have carried meltwater from the soles of the more active ice flows, but even they would have had their entrances easily blocked by injected glacial till, as has been recorded in glaciated karst in Newfoundland (Karolyi and Ford, 1983). Till blockages are known where Dales caves were truncated by glaciers, most famously where the Valley Entrance in Kingsdale was excavated by cavers to gain access to the old Roof Tunnel behind a surface layer of till. Glacio-fluvial sediments left by sub-glacial meltwater have not yet been demonstrated conclusively in the Dales caves. The poorly sorted material in Broadway, in County Pot (Fig. 7.49), may be the result of limited meltwater activity beneath the sluggish ice that occupied the Ease Gill valley in Devensian or earlier times, and unsorted sediments in the Kingsdale end of Dale Barn Cave appear to have been emplaced by sub-glacial water under pressure (Murphy *et al*., 2001). Sub-glacial environments and meltwater activity would have seen major local variations beneath the Pleistocene ice sheets. There was clearly a boundary between cold-based ice on the Malham High Country and warm-based ice in the Malham Tarn basin if the latter was the source of jökulhlaup floods that enlarged Malham Cove (see Chapter 4). The impact of those floods on the caves behind the Cove remains unknown.

Whereas inactivity was perhaps widespread during the glacial maxima, the caves must have been invaded by meltwater from moulin streams, glacial lakes and glacier snouts during various parts of the retreat phases of each glaciation. Renewed flows of underground water were fed from a landscape devoid of plant cover, plastered with moraines or sheets of loess, and charged by floods of spring snow-melt. They could have carried huge amounts of sediment into the caves, and may account for a large proportion of the stratified muds, sands and gravels that are now distributed through many of the older passages. Ice-dammed lakes may also have been a feature of tributary valleys on and above the limestone when the ice sheets waned and reduced to valley glaciers between nunataks that were gaining in size. Though no firm evidence of such lakes has yet been found in the Yorkshire Dales, they are considered to have been significant features during de-glaciation of the Scandinavian karsts (Faulkner, 2007). As ephemeral features they could have had significant but local impact on some of the caves.

Only when the ice had completely disappeared did the caves and karst of the Dales emerge into something like the modern environment, where they continue to evolve in interglacial conditions.

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