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THE RELATIONSHIP BETWEEN THE GULL CAVE SALLY'S RIFT AND THE DEVELOPMENT OF THE RIVER AVON EAST OF BATH

by

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ABSTRACT

Exploration of a gull cave in the Claverton Gorge near Bath has revealed an extensive network of rift passages. Uranium series dating of a speleothem from the cave shows that gravity sliding began at least 350 ka ago, which means that the River Avon valley was already well developed by that time.

Solution features within the cave pre-date the mass movement and suggest that groundwater once flowed to a proto- River Avon which lay to the north-west, before the present topography was established. River capture by the proto- Avon of former Thames headstreams created the Claverton Gorge and led to overdeepening of the Avon valley with the associated foundering of rock strata in the Bath region.

INTRODUCTION

Caves are a major source of palaeogeographical information. Sediments carried in by gravity or by running water are often preserved in caves long after erosion has removed contemporaneous deposits from sites on the surface. Flowing water itself leaves traces and caves carry the record of a hydrology that may be very different from that of the present day. Calcite speleothems are sometimes present which, by radiometric dating, allow a time framework to be constructed for the events in a cave's history. The study of limestone solution caves is now a major branch of Geography.

Gravity sliding caves (gulls) are formed by sub-horizontal extension of the strata, not by the erosion of underground rivers. Because this extension takes place within the rock sequence the caves do not necessarily have any openings to the surface, and may contain no allochthanous material. Where gulls are exposed (typically on steep hillsides) they are at greatest risk of destruction by landslip, and commonly are full of surface-derived material of recent origin. Gulls are found both in limestones and in non-soluble rocks, but the majority are of simple form: single rift passages accessible to cavers for no more than a few tens of metres. Explorable gull networks are much less common.

In Britain, the best known gull caves occur in the Hambleton Hills of North Yorkshire (Cooper *et al,* 1976; Cooper *et al*, 1982) and at Portland in Dorset (Ford and Hooper, 1964; O'Connor and Graham, in preparation). Several hundred more have been found at other locations, particularly in north-east England (Brook *et al*, 1988), but reports in the caving literature tend to be brief and are mainly descriptive. The few caves that have been reported in the Cotswolds are mostly gulls, Sally's Rift being by far the longest and most complex. Cooper (1983) made a good general study of mass movement caves and Self (1986) suggested a classification system, based on the system used in Engineering Geology (Hawkins and Privett, 1981). However, in comparison to karst caves, gulls have received little attention either from cavers or cave scientists.

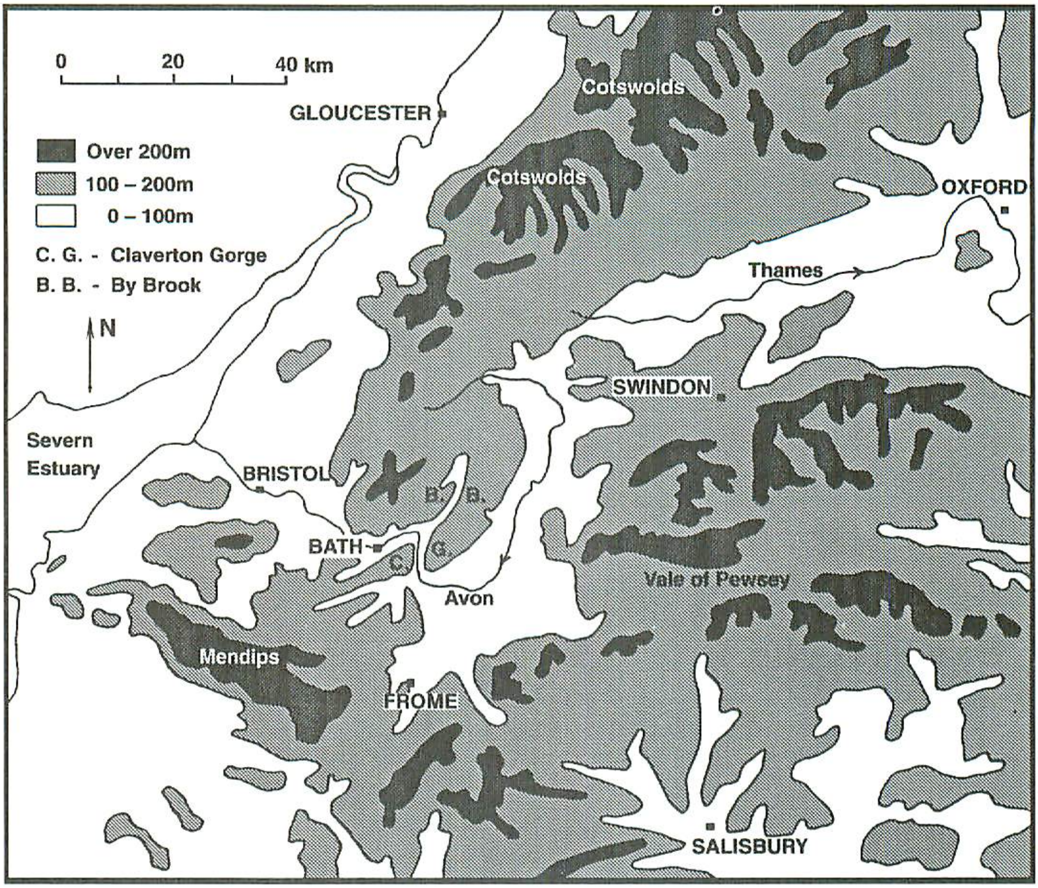

Figure 1. *Topographic sketch map of the region.*

Much more interest in such caves is shown in Eastern Europe, where both surface and underground pseudokarst can be found in the flysch belt of the Sudeten Highlands and the Carpathians. Occasional pseudokarst symposia are held in the region, and the published Proceedings suggest that many slip rifts are geologically young. Some are still in motion, giving rise to occasional catastrophic slope failures (Kalvoda and Zvelebil, 1989). In both Poland and the Czech Republic there are experiments to measure the current rate of movement of the strata (Krticka and Kopecky, 1990).

Sally's Rift in the Cotswolds can be shown to be very old, and this study demonstrates that it is possible to gain palaeogeographical information from a gull cave.

THE CLAVERTON GORGE AND PALAEODRAINAGE THEORIES

The Claverton (Limpley Stoke) Gorge is a short part of the course of the (Bristol) Avon where the river carves through the Cotswold escarpment in its westward course to the

Severn Estuary (Figure 1). The Avon is unusual in this respect, for all the other Cotswold rivers follow a simple drainage pattern: rivers west of the scarp flow into the Severn, those rising on the eastern dip slope flow to the Thames.

The unusual drainage route of the Avon has been the subject of much debate. In the early decades of this century, river capture theories were very popular and several attempts were made to reconstruct the drainage of the Bristol region, one of the better known being by Varney (1921). In later years, superimposed drainage was the explanation: the present course of the Avon and its tributaries having been initiated on a once continuous Mesozoic covering (Kellaway and Welch, 1948), the rivers then eroding down into the older Palaeozoic rocks as the Cotswold scarp retreated to the east.

Modern opinion has now returned river capture theories to favour, one of the most detailed being by Frey (1975). According to Frey, in the Neogene a continuous Mesozoic landscape was drained by east-north-east oriented streams of a former Thames system. Encroachment from the west by the River Severn and its tributaries resulted in a retreat of the Mesozoic scarp. The most vigorous of the scarp streams, the Bristol Avon, locally pushed back the scarp sufficiently into dip territory to progressively capture a series of Thames headstreams. Frey places this capture in the early Pleistocene.

A recent study of the Kesgrave Group of fluvial sediments in the Thames drainage system (Whiteman and Rose, 1992) shows that at the beginning of the Pleistocene the Thames was limited to a drainage basin broadly similar to the one it has at present. In the later part of the early Pleistocene, the Thames catchment extended across much of Wales and parts of the West Midlands, the river gravels containing a significant proportion of far-travelled materials. The beheading of the Thames by the developing River Severn occurred prior to Oxygen Isotope Stage 15 (i.e. before about 600,000 BP).

Kellaway (1991) now also favours a river capture theory, believing that the original Mesozoic covering of the Welsh borderland drained in a south by south-easterly direction via Salisbury. This is the "Southampton River", as previously proposed by Varney (1921). Frey (1975) also noted the dominance of north-south aligned streams in Southern England and south-east Wales, but suggested that they were disrupted first by the intrusion of the easterly-draining Thames, and then again from the west by the developing Severn system. The early Pleistocene drainage of the area has yet to be resolved, and is beyond the scope of this paper.

In middle Pleistocene times the River Avon developed as a tributary to the Severn, capturing by headward erosion some of the streams of the Cotswold dip slope. This sudden increase in catchment caused the valley of the Avon to overdeepen, vertical erosion having been faster than lateral valley slope development. As a result, many of the valley sides have foundered.

Hawkins (1980) has estimated that there are 45 sq km of foundered strata in the Bath region. The steepness of the valley sides and major landslipping in historical times within the city of Bath has led geologists to believe the overdeepening of the valleys to be relatively recent. Partly this is due to an increase in catchment of the River Avon and partly a result of major climate changes occurring in the late Quaternary. Based on the altitude and undisturbed nature of the terrace gravels of the River Avon near Bath, Chandler *et al* (1976) suggested a pre-Ipswichian age for the main period of cambering.

SALLY'S RIFT: THE CAVE AND ITS GEOLOGICAL SETTING

Sally's Rift (ST79416501) is located 4 km east of Bath, high on the east bank of the Claverton Gorge of the River Avon. A full description of the cave has already been published (Self, 1986) so only general details need be given here.

The cave has three entrances, located close together in a small cliff well-hidden in dense scrubby woodland. The middle entrance is the only one large enough for visitors of normal build and leads directly to a pitch of 8 m. A large gull passage, Main Rift, is entered and a devious route can then be followed to the north and east to reach the rest of the cave (Figure 4). Most passages are of the order of 10-12 m tall and 30-60 cm wide, but the caving is strenuous with the need for much climbing. The total length of the cave is 350 m, which makes it Britain's second longest gull network. (Buckland's Windypit in North Yorkshire is the longest at 366 m {Cooper et al, 1982}). Visitors are requested to avoid the winter months, as the cave is an important retreat for the Greater Horseshoe Bat.

The geology of the area is very simple, with Great Oolite limestones of the middle Jurassic conformably overlying a predominantly clay formation, the Fuller's Earth. Limestone forms the plateau surface of the southern Cotswolds, the Fuller's Earth is exposed in the valley sides. The cave Sally's Rift was formed in the lowest beds of the Great Oolite limestone. A simplified regional geology map (Figure 2) and stratigraphical section (Figure 3) are presented.

The dip of the strata is very shallow, about 2° to the south-east, but cambering of the limestone caprock towards the valley of the Avon has caused a local reversal. On the steep flanks of the valley, the lowest beds of the Great Oolite have foundered, the lithological boundary with the Fuller's Earth providing the basal plane of slippage. An upper plane of slippage occurs within the limestone sequence, above which the strata have not been greatly disturbed. Valleyward extension of the strata across the two dominant jointing directions (65° ± 5° and 150° ± 10°) has resulted in the network of rift passages seen in the cave. Similar networks of gulls, as yet unseen, are certain to be present in the region.

GEOMORPHOLOGY OF THE CAVE: SOLUTION

The Great Oolite is a massive current-bedded limestone, strongly fractured and slightly porous. It is underlain by impermeable strata, which make it an important local aquifer. Dye tracing experiments (Smart, 1977a) show that water can travel swiftly along major joints, but that a significant part of any input becomes dispersed in minor fractures. Drainage is through the fissure network instead of in trunk conduits, so there are no karstic cave systems in the Southern Cotswolds. A few exceptional solution caves, in both Great and Inferior Oolite, have been reported, associated with places of concentrated input or outflow. Fish Pot in Gloucestershire is a karst sinkhole (Hatherley, 1981); Cloford Quarry Big Cave on the Mendips is developed on an unconformity with underlying Carboniferous limestone (Drew and Smith, 1972); Charlton Wood Cave in South Somerset carries a small stream in a thin band of oolite between impermeable beds (Price, 1979). None of these caves can be followed for more than a few tens of metres.

Sally's Rift is a mass movement cave, but it has formed in limestone and solution features can also be seen. In many passages the "grain" of the rock has been etched out, both

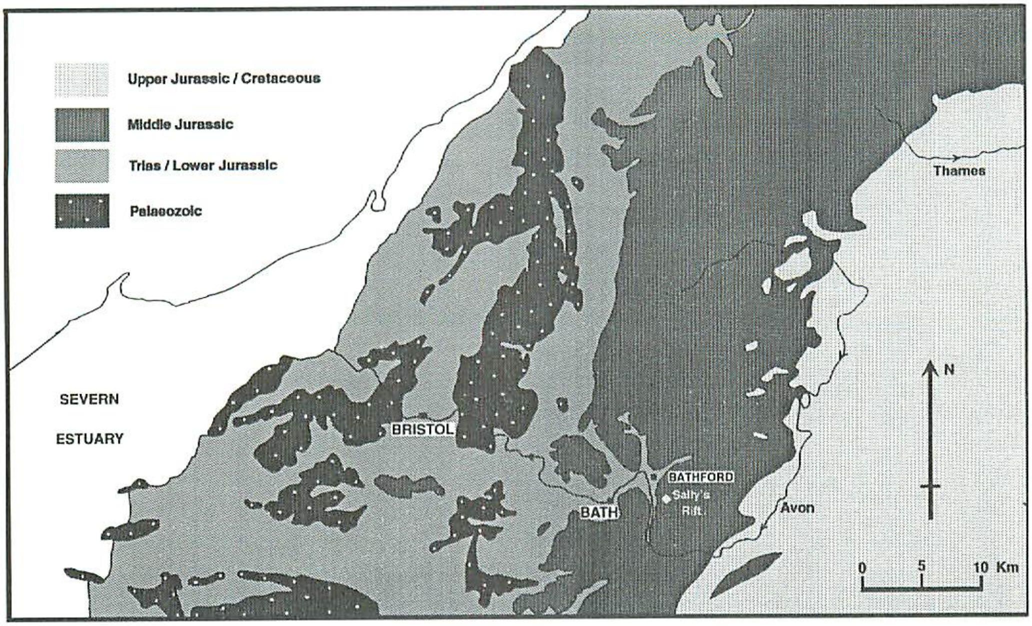

Figure 2. *Geological sketch map of the region.*

bedding planes and the current bedding (Figure 6). Deep solution features are found in the north-west/south-east oriented passages (Figure 5) but only at high level, in the uppermost 6 metres. In the areas of greatest corrosion these bedding features have a depth of 6-8 cm, though in the exceptional case of Parallel Rift there are bedding plane pockets up to 40 cm deep. At the southern end of Far Rift, the rock contains thin calcite veins which protrude from the walls to a height of 15 mm.

In Boulder Chamber, one of the highest parts of the cave, the matrix of the rock has been preferentially eroded to leave fossils standing out from the walls. Some of the roof boulders here have been so heavily pocketed they have the appearance of pumice. Since Boulder Chamber is a stoping chamber, this suggests that the most spectacular solution features may be in the rocks above the level of the cave.

The conjugate north-east/south-west gulls have a much lighter solutional etching, and in their lower parts both sets of gulls show only a little corrosion. All major north-west/south-east joints are corroded in their upper parts; only in Main Rift (which may have suffered frost action) and in parts of Far Rift (which has calcite flowstones) are solution features not clearly visible. Far Rift, with its abundant speleothems, has the superficial appearance of a karst cave but the abrupt termination in narrow cracks of the southern end of the passage is typical of gulling.

These solution features are of phreatic form and so must pre-date mass movement. (Gulling needs a nearby hillslope to allow movement, therefore the joint network and any caves will already be de-watered). The dimensions of this early "cave" are not easy to estimate, but passage widths were probably of the order 5-10 cm. Some of the minor fissures in parts of the

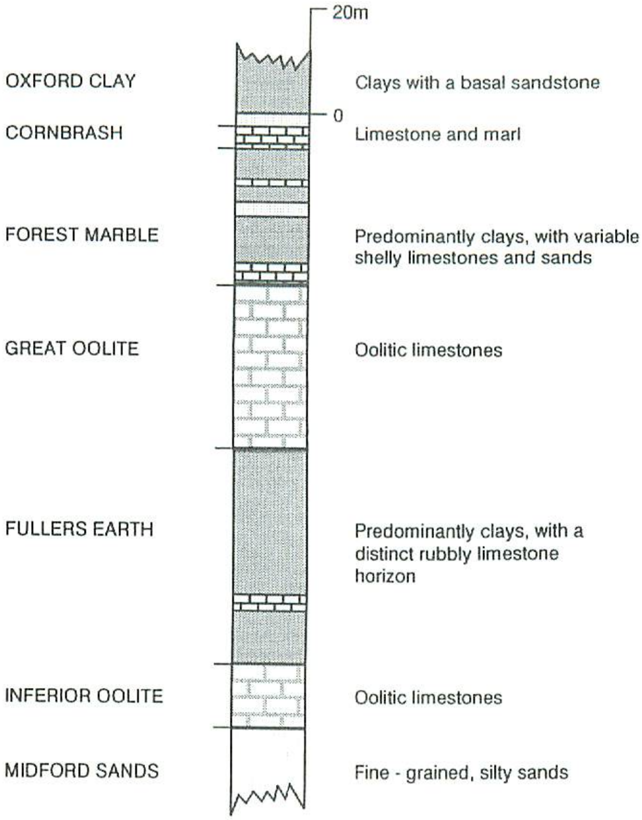

Figure 3. *Generalised stratigraphic column of the middle Jurassic for the area south-east of Bath.*

cave beyond Boulder Chamber are of this size; a couple of them contain typical solution features and seem to have been largely unaffected by later movements. Also, in the major joints oriented north-west/south-east, there is no great change in width between their heavily corroded upper parts and their lightly corroded lower parts.

GEOMORPHOLOGY: MASS MOVEMENT

Mass movement caves are formed when a mechanically strong rock is subjected to extension. In Britain, the overwhelming majority of these caves are the result of gravity sliding and occur on steep hillsides where the rocks are unsupported on their downhill side. Extension takes place along bedding planes with bed-over-bed sliding and the opening of joints. These open joints are known as gulls.

Gulls are particularly common in flat-lying or gently inclined strata affected by cambering. Cambers develop when competent and permeable rocks overlie incompetent and impermeable beds such as clays. Groundwater passing down through the strata mobilises the upper parts of these incompetent beds, which in hillslope regions are extruded onto the surface

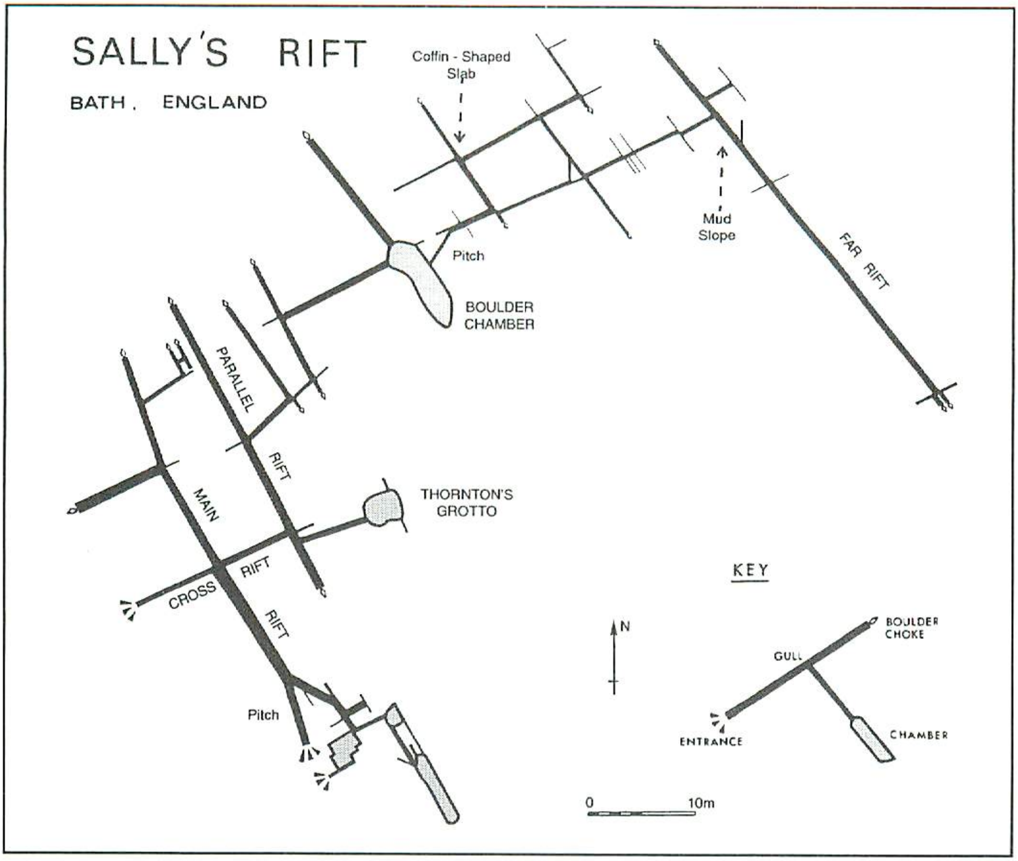

Figure 4. *Structural plan of the cave Sally's Rift.*

– a process known as subrosion. As a result, the overlying competent strata lose their support and camber in the direction of slope. Movement is taken up within the jointing and gulls develop. The angles of both cambering and regional dip are usually quite shallow – steeper angles tending to produce rotational slides.

Gravity sliding does not always operate uniformly through the competent strata. Often there is an upper plane of movement which leaves the near-surface beds largely undisturbed. During cambering, joint-bounded blocks of rock slide valleyward from beneath this horizon to produce gull caves. A possible explanation for this was suggested by Self (1986), who proposed a sequential unweighting theory whereby blocks of rock move independently with respect to their neighbours, sinking and sliding in the substrate as each in turn becomes unweighted. This would allow the camber to develop without dragging open the joints in the overburden.

Sally's Rift has many features typical for a gull network formed in a cambered hillside. Upon entering the cave, the immediate impression is of instability and imminent collapse. The

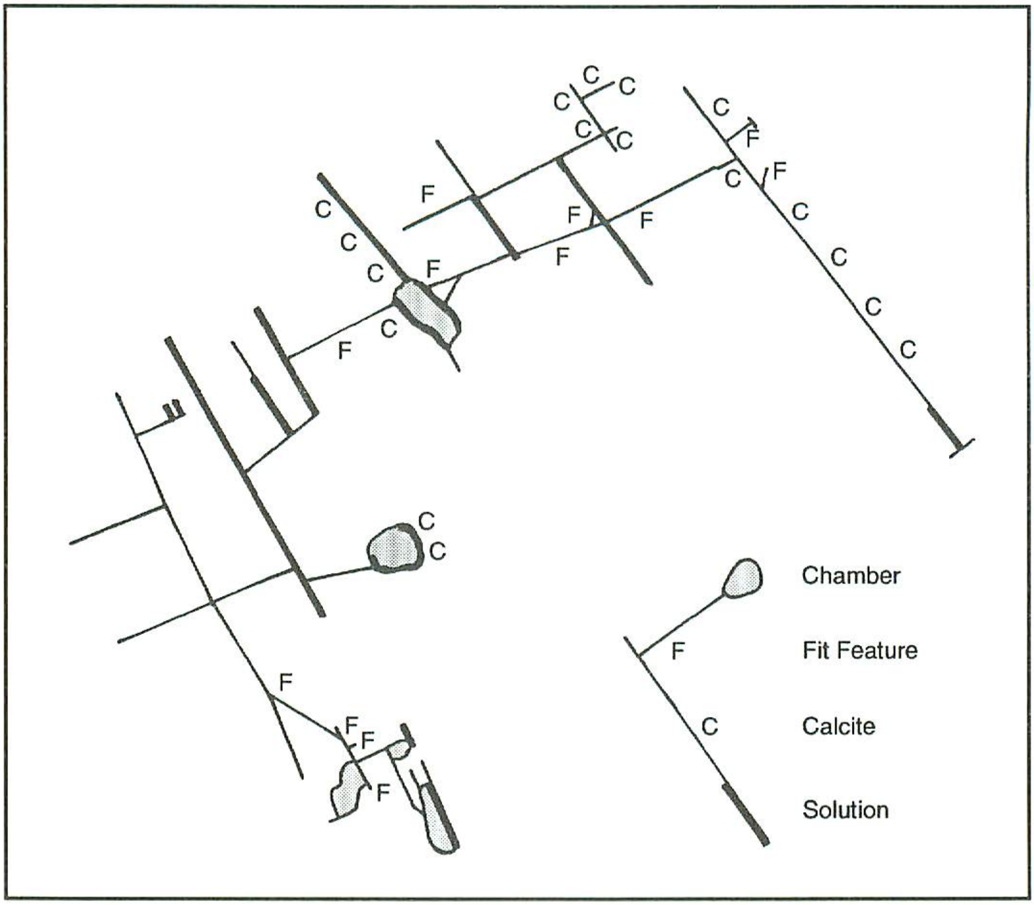

Figure 5. *Geomorphological plan of the cave.*

west wall of the entrance passage has foundered, with open gaps in the bedding tapering away to a thin muddy clastic fill at about a metre into the wall. Such disorder is a common feature of the entrance to gull caves, as the unsupported (valley) side of the most valleyward gull is at greatest risk from foundering. Commonly there is a vertical displacement (downwards) of this block of rock. There may also be rotational movement, shown by the bedding planes tipping back towards the hill. In the case of Sally's Rift, this rotational movement has taken the form of a fan-like opening of bedding planes. The instability of the gull closest to the hillside is the single most important factor that has restricted the exploration of gull caves.

Gulls are easily identified in non-calcareous rocks, but in limestones they are sometimes confused with karst solution passages. One feature unique to mass movement caves is known as a fit feature, whereby a ledge on one wall exactly matches an overhang on the opposite wall. These asymmetric features are due to irregularities in the jointing and are preserved in mass movement caves, when in solution caves they would have been eroded away.

Solution caves tend to be symmetrical, with beds more resistant to erosion protruding from both walls of a passage; asymmetric features are due to the downstream migration of meanders and are not seen in straight, joint-controlled passages.

At the pitch into Main Rift a vertically displaced fit feature can be seen. A large square-nosed overhang some 2 m below the pitch head matches a square-cut sentry box on the east wall of Main Rift. The vertical displacement (down) of the downhill block is 1 m. The downhill block in this case is the east side of the entrance passage. The west side of the entrance passage, which continues as the west side of Main Rift, may have suffered much greater vertical displacement: Main Rift has a very poor correspondence between its walls.

At the Main Rift/Cross Rift junction, another of the diagnostic features of mass movement can be seen. The east walls of Main Rift and the south walls of Cross Rift maintain their alignment, but the passages change width abruptly. Since joint-bounded blocks of rock move independently with respect to their neighbours during cambering (but in the same direction), gulls normally maintain their width between adjacent blocks. At cross joints they abruptly become wider or narrower since they are then bounded by two different blocks of rock. There are many examples in this cave of sudden changes of width, as can be seen in Figure 4.

Fit features are not common in this cave but several examples can be seen, particularly in the north-east oriented passages in the region of Boulder Chamber and beyond. These features all occur at low level, and may be due to a local irregularity in the jointing. The north-west oriented passages in this part of the cave contain much more infil and their lower parts are not accessible.

There is evidence for several phases of mass movement. This is particularly well seen in Far Rift where massive flowstone blocks, up to a metre across, litter the floor. This destruction has been caused by the subsidence of a large joint-bounded section of the roof. The initial phase of mass movement opened the Far Rift joint, speleothems then grew for a considerable length of time but they were later destroyed by further gull widening. Elsewhere in Far Rift, the calcited remains of two false floors can be seen, left stranded by repeated subsidence of the floor debris. Large scale infil from the roof, combined with subsidence of the floor, can only have occurred by passage widening (the cave never having had a vadose streamway).

Recent movements in Far Rift have caused a few minor cross-joints to open. These fractures are very narrow, some no more than hairline cracks in clean white flowstone. Roof falls in other parts of the cave, e.g.. the scarred boulders of the Coffin-Shaped Slab region, are obviously also recent but cannot be directly related to passage widening.

The opening of a north/south joint, in this cave a very rare gull direction, can be proved to post-date the opening of the two main joint sets. The north/south joint in question lies at the end of the passage that runs north-east from the pitch out of Boulder Chamber. Unlike neighbouring gulls, this young gull has neither solution features nor flowstone veneer. There are a few other examples of such young gulls, usually associated with local foundering, e.g.. the pitch passage out of Boulder Chamber.

There are several minor fissures crossing the main passages in the region beyond Boulder Chamber (see above and Figure 4). Some appear to be mainly solutional, others are clearly gull fractures. Their unusual symmetry across the main passages suggests that they were unaffected by the major early phases of mass movement. Some fissures are even offset as a result of movements affecting the main gulls. Their widths (5-10 cm) give an approximate value for the size of the early solution cave and for the scale of a late stage of mass movement, at least in so far as it affected these joints.

GEOMORPHOLOGY: SEDIMENTS

Much of the cave has a thin flowstone veneer over the rock surface, often of a similar light brown colour to the parent rock. In the passages near the entrance, Main Rift in particular, there is also a thin film of mud over the flowstone. Deeper under the hillside the flowstones become cleaner and usually whiter, which may indicate a decrease in soil-derived impurities.

In Far Rift, the bouldery remains of a once-massive stalactitic flowstone can be seen, in places 25 cm thick. A sample, radiometrically tested by the U/Th method, gave a sequence of ages from 350,000 years BP (minimum) near the base to 78,500 years BP near the top (Table 1). A number of hiatuses within the flowstone specimen show that calcite deposition was not continuous. The same specimen was re-tested by Farrant (1995), who confirmed its minimum age.

In the short passage north from Boulder Chamber, pure white flowstones are being actively deposited. 10 m further along this same short passage, the drips are not depositing flowstone but are eroding a mud bank, leaving behind a collection of mud towers. In other parts of the cave the flowstones are dry, even in periods of wet weather. The speleothems of Thornton's Grotto are brown and pitted, having suffered a partial re-erosion at some time. The percolation water entering the cave is obviously very variable, both in its chemistry and in the routes it takes.

Sample	U (ppm)	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	Age (ka)	Error
SR - E - 88	–	–	–	4.5	78.5	64.8-93.5
SR - D - 88	–	–	–	16.0	144	118-181
SR - B - 88	–	–	–	41.0	211	162-302
SR - A - 88	–	–	–	18.0	>350	–
SR - 01 - 93	0.07	0.968±0.020	1.088±0.027	32.1	>350	–

Table 1. *U/Th ages for a speleothem from Far Rift. (Corrected ages given)*

In two places in the cave there is a connection via joints direct to the surface. The evidence for this is a muddy clastic deposit containing pebbles of Carboniferous and Cretaceous rocks, of very similar nature to the plateau gravels of Farleigh and Bathampton Downs (the two hilltops flanking the Claverton Gorge). Clasts from these surface deposits are described by Varney (1921) and others (see Donovan, this issue). In the cave these deposits can be seen at the northern end of Boulder Chamber, and in Far Rift in the mud slope and nearby false-floor remnants (Figure 7). In Far Rift, the source of this material can be traced to an impassably narrow joint on the southern side of the passage. An analysis of the clasts from the cave deposits is made in Table 2.

The main infil material is rock fallen from the roof. Usually this infil is of angular cobbles, mixed with a small amount of gritty clay. Large boulders, up to several metres in length, have also fallen from the roof and in places these have become wedged across the passage, forming boulder bridges. Some of the smaller cobbles may have spalled from the walls, particularly near the entrances where frost action could have had a significant effect during climatic cold phases.

SR1		SR5	
2	irregular rounded red coarse polished sandstone	1	Coal Measures sandstone
		1	rounded red quartzite
3	rounded white quartzite	6	black patinated spongy limonite shale (?) of irregular shape
9	rounded buff brown mudstone		
9	speleothem and cemented sediment	3	speleothem
1	bone	3	Great Oolite
1	irregular haematite	2	broken red patinated chert (1 very well rounded)
1	grey mottled sub-rounded chert		
2	angular broken red patinated chert	4	broken white/orange brown patinated chert (1 very well rounded)
16	angular broken white patinated chert		
2	flattened rotted brown and black patinated chert	1	grey banded Carboniferous chert

Table 2. *Clasts from the cave deposits of "clay with flints".*

DISCUSSION

Sally's Rift is a gull network, as can clearly be seen from Figure 4. Major joints have been widened by mass movement, with abrupt changes of width at cross-joints. Solution features are present in all major joints oriented north-west/south-east, but this solution seems to have been of lesser importance, probably contributing no more than 10 cm to the width of any passage. Passage junctions have abrupt corners (Figure 6), which is a mass movement feature; there is no solutional "rounding off", as is seen in caves formed by flowing water.

The solution features seen in the cave are of the form associated with slow moving or ponded water. There are no scalloped rock walls (turbulent flow) or fluting (vertical vadose infiltration). The delicate etching of features such as cross-bedding indicates calm phreatic conditions and a high water table. This was groundwater movement rather than stream flow. The early phreatic cave was certainly not a group of underground oxbows of the River Avon (see Appendix).

The oolite limestones of the southern Cotswolds have a high fracture density and are very permeable. Hydraulic gradients are shallow (Smart, 1977a), so any nearby outlet for water from the cave must have been at least at the level of the roof of Boulder Chamber (160m

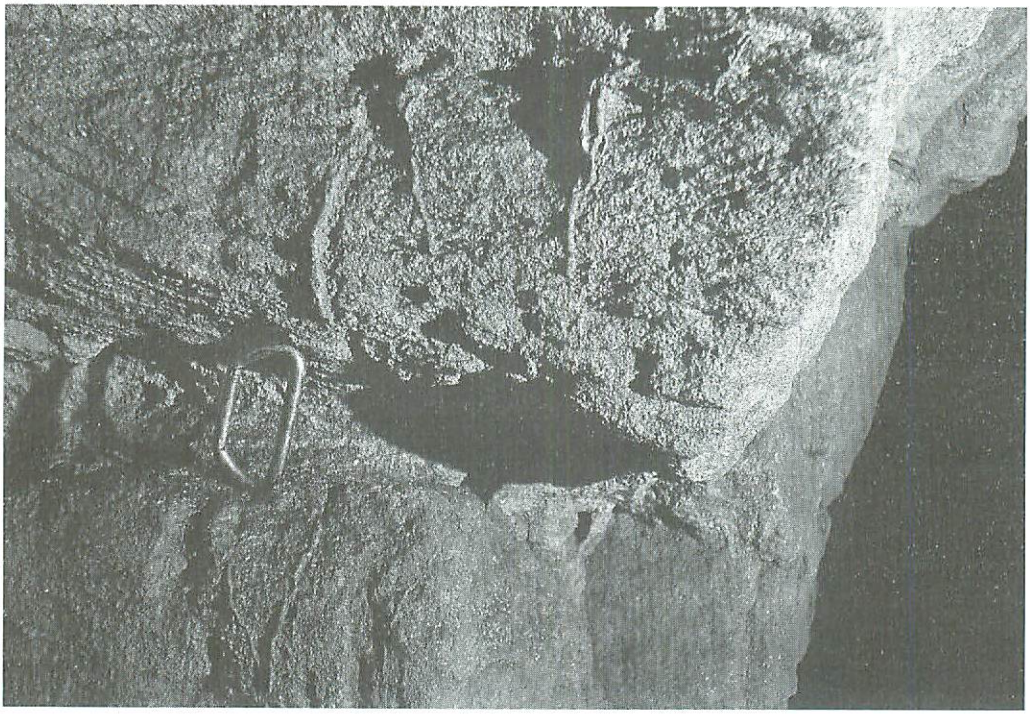

Figure 6. *Solutional etching of current bedding features in Parallel Rift. Note the abrupt junction with the conjugate gull where the bedding plane is not recessed. (karabiner for scale)*

AOD). With the present level of the nearby River Avon at 22m AOD, these features must predate the overdeepening of the Claverton Gorge.

The best developed solution features are all found in the north-west/south-east oriented passages and suggest groundwater movement in this direction. Drainage could not have been down-dip to the south-east, for the permeable oolite beds pass beneath the Forest Marble, which forms an impermeable caprock. The apparent outlet was up-dip to the north-west, emerging as springs in the vicinity of the present village of Bathford. (Similar up-dip springs can be seen in the present oolite drainage of the upper By Brook valley (Smart, 1977b)). If the major river, and deepest valley on the scarp side of the Cotswolds lay to the north of Sally's Rift, this river could not have been the Avon but must have been the By Brook. It may have been a combined Avon/By Brook whose head was a group of springs in the vicinity of Bathford.

If the River Avon had always flowed across the Cotswold escarpment (as envisioned in the superimposed drainage theory of Kellaway and Welch, (1948)) groundwater would have been drawn towards it. Clearly there was no nearby surface River Avon flowing north-west at a similar altitude to the cave, for solution features would have instead developed in the conjugate north-east/south-west joints. The pattern of this early phreatic "cave" also precludes formation by water from the River Avon (see Appendix). The solution features predate the present topography and may date from the middle part of the Pleistocene.

One unusual aspect of this groundwater flow is that obvious solution features are only found in the upper parts of the jointing. It may be that the open joint network of the oolite allowed muddy sediments to be washed down by percolation trickles. Sediments may even have had their origin within the oolite strata, which has thin clay horizons. If sediments did fill the lower parts of the jointing, they would shield them from corrosion. Subsequent mass movement would remove any trace of such material, burying it beneath a great mass of clastic infil. The apparently enhanced solution at the highest levels in the cave may indicate proximity to the palaeo- water table. The greatest transfer of water, both discharge and recharge, occurs near the water table.

With the development of the Avon valley by headward erosion, the water table lowered and the jointing became de-watered. The "cave" at this time was a series of parallel joints, each one opened perhaps no more than 5-10 cm. Major changes began when the River Avon captured new tributaries from the Cotswold dip slope. The river rapidly overdeepened its valley and formed the steep-sided Claverton Gorge. The Fuller's Earth clays that form the sides of the valley were unable to support the oolite beds above and cambering began. At this time the mass movement cave Sally's Rift was initiated, though it is not possible to determine the scale of this initial phase of gravity sliding. The evidence from the cave suggests that there have been several periods of movement, with relatively stable periods between. This may be due to climatic factors, with sliding occurring whenever conditions are suitable.

The most likely time for a major period of mass movement is during the melting of permafrost at the end of a climatic cold phase, when the strata are oversaturated with water and their shear strength is correspondingly reduced (Hawkins, *pers. comm.*). Melting takes place from both above and below, but the frozen middle ground inhibits rotational slides and favours cambering. Brown (1991) noted that a large number of superficial valley disturbances have been reported from Southern Britain; this is partly because of the suitability of the lithologies, particularly the Jurassic strata, and partly because of prolonged periglacial effects away from the centres of glaciation. In the particular case of the Great Oolite/Fullers Earth boundary in the Bath region, Brown found that pyrite oxidation in the upper horizons of the clays has caused chemical leaching of their calcite content; this greatly reduces their shear strength and allows mass movement at much shallower camber angles than in comparable Inferior Oolite valley slopes.

The allochthonous cherty mud deposit seen in Boulder Chamber and Far Rift could have been emplaced at any time after cambering. The presence of cherts in the Far Rift false floors proves that they have entered the cave over a period of time, and that Far Rift is part of a major fracture system that in places extends to the surface. The parent deposit on the plateau surface is a high level drift and was probably emplaced before significant solution of the jointing began (see Donovan, this issue). Hawkins and Kellaway (1971) found a similar cherty deposit re-sorted and stratified in solution cavities on Bathampton Down, the hilltop facing Sally's Rift across the Claverton Gorge; the deposits had been disturbed by subsequent cambering.

Figure 7. *Calcited false floors of "clay with flints", Far Rift.*

The speleothems of Far Rift are of particular interest and developed after the initial phase of gravity sliding. The flowstone boulders that now litter the floor are too massive to have formed in a de-watered solution joint. Some of the calcite blocks are 25 cm thick. The oldest radiometric date obtained from one of these broken speleothems (more than 350 ka) also gives a minimum age for the cave. The probability is that mass movement began much earlier.

Other radiometric dates (Table 1) for the Far Rift flowstone show that deposition continued until middle Devensian times. In some of the samples there is contamination from detrital thorium (shown by a ratio of less than 20 between the two thorium isotopes), and a correction factor must be applied to the calculated ages. Sample SR-01-93 has a reliable age of more than 350 ka; sample SR-E-88 has an approximate age of 78.5 ka. A number of hiatuses within the flowstone specimen indicate that deposition was irregular, so the roof collapse which destroyed these speleothems may have occurred some time after the youngest radiometric date. It is possible that this collapse occurred during another period of gravity sliding, due to widening of the passage. Flowstone deposition and minor roof falls continue to the present day.

The radiometric ages obtained from the speleothems in this cave are much greater than had been anticipated, so the cave must be older still, 350 ka being a minimum. The suggestion of Chandler *et al* (1976) of a Wolstonian (or older) age for the foundering of the Avon valley slopes is clearly an underestimate. If the major period of cambering was at the end of a cold stage of the Quaternary, as proposed by Hawkins, these disturbances will be of Anglian (or older) age. The stability of Sally's Rift for such a long period of time is of more than just local interest, and cambered strata in general may be more stable than previously thought.

Visitors to the cave sometimes think that Far Rift is part of a major karst conduit, now fragmented by mass movement. There is no evidence to support this view, except for the unusual beauty and "natural" appearance of the passage (in comparison with usual, sharply angular gull rifts). If examined in detail, the solution features in Far Rift are no different from other gulls of this orientation, and there are no similar passages of karstic origin elsewhere in the Cotswolds. Even if a karst origin had been proved it would make little difference to this study, since calcite flowstone can only form in air-filled caves. The radiometric minimum age is still valid for the de-watering of the limestone by the proto- River Avon, and the overdeepening of the valley with associated cambering probably occurred soon afterwards.

One reason for the apparent stability of some gull caves may be vertical displacement of the most valleyward blocks of the competent strata. Diagrams of cambered strata (e.g.. Hawkins, 1980) show the beds curving smoothly towards the direction of slope, where one would expect rotational slides in the underlying incompetent beds to soon disrupt the lithological boundary. This may happen on the most actively eroding hillsides, with boulders of the competent strata littering the slope, but in some cases the marginal blocks may sink and bed themselves into the substrate and act like bookends to the rest of the gulled strata. Unless the beds are loaded (by construction projects) or lubricated (by climate change), they may be stable for long periods of time.

Far Rift is a remarkably large passage, considering that it is 60 m from the side of the hill and at roof level perhaps 20 m below the ground surface. There are probably other gulls, as yet unseen, even further from the valley side. Such deep and hidden gulls could have implications for the construction industry.

This study supports the view that the River Avon is a scarp stream that cut through to the Cotswold dip slope by headward erosion. Once on the dip slope, the Avon captured streams from the Frome area of Eastern Mendip which were flowing north-east, perhaps to join the River Thames at the Swindon Gap. This greatly increased the flow of the proto- Avon and with soft clays now exposed in its overdeepened valley, nick points worked upstream to reverse the former drainage route and capture further dip slope tributaries. The cambering and gulling which followed this overdeepening may have occurred quite rapidly, so the 350 ka minimum age for the cave may also be taken as the minimum age of river capture. More probably, these events took place at the end of the Anglian cold stage, perhaps half a million years ago. The high level drift that overlies the cave is therefore at least of Anglian age and may be much older.

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APPENDIX – CAVES IN CAMBERED LIMESTONE

Caves in cambered limestone can pose some problems of interpretation. If the limestone is strongly jointed, gull networks and karstic maze caves can appear very similar. Usually there is enough internal evidence to distinguish between the two types (as described earlier in this report), but sometimes the situation is complicated by the presence of both solution and mass movement features. The relative importance of the two processes may be difficult to determine.

Solution can take several different forms. In many gull caves there is a simple solutional etching of the rock walls, produced by groundwater movement in the joints prior to cambering. It is also possible for a limestone massif containing long-abandoned phreatic (or even vadose) conduits to be dissected by later mass movement. The caves of Portland are a mixture of old bedding-controlled phreatic passages and young joint-controlled gulls. Problems of interpretation arise when the solution passages are also joint-controlled, particularly network mazes. Slip rift disruption of a maze cave gives the possibility for solution rifts, gulls and passages of mixed origin all to exist in the same cave.

The majority of karst caves are of dendritic (branchwork) pattern, with passages joining together in the downstream direction. A significant minority are quite different and are classed as mazes. In an extensive study, Palmer (1975) found that two processes suppressed the natural tendency of caves to form branchwork: diffuse infiltration and floodwater recharge.

Diffuse infiltration mazes form by the ingress of rainwater from the overlying land surface, or by the infiltration of groundwater from adjacent insoluble strata. Palmer's classic example is Clark's Cave (Virginia, USA), where permeable sandstone overlies the limestone. Solutionally aggressive water is supplied to all available fractures and, typically, all joints are enlarged to a similar extent. In strongly jointed limestone this produces the most perfect network mazes.

Floodwater recharge causes temporal variations in discharge and head. This encourages the development of diversion passages around constrictions in a cave caused by breakdown or sediments. If the jointing is prominent, network mazes may form but most are rudimentary and irregular. Similar mazes can form in the banks of surface streams.

A cambered limestone hillside may contain karstic caves from an earlier erosion period, but a comparison with uncambered limestone hillsides shows that such caves are only locally common. Large tracts of limestone have relatively few caves. When a cavernous hillside cambers, the older generation of caves are dissected by young gulls. The gulls may use the same structural controls as the earlier cave, but a karst rift widened by gulling should have significantly different solution features to other gull rifts of the same orientation. Floodwater recharge mazes are sufficiently irregular that some major joints should show opening by mass movement only. Diffuse infiltration mazes would be expected to show the opposite effect – occasional solutional passages not significantly widened by gulling. If very narrow fissures show solution features, this is normally the result of groundwater flow and all major joints so oriented should show these features. (Such fissure flow occurs in rock types that tend not to form major karst conduits, such as the oolitic limestones of the Cotswolds). It should therefore be possible to determine the extent of any original karst cave, provided that the gull network is sufficiently extensive.

Many gull caves are located on valley sides above surface rivers. If the cave has solution features it is tempting to think of them as being the result of infiltration from the river (underground oxbows) when it was at a higher level. There are two reasons why this is unlikely. When a surface river is cutting down through limestone, underground oxbows can be formed in any part of the strata. Gull caves are always located at the base of the limestone sequence. Secondly, with a steadily falling water table, a formerly phreatic passage developed in a single major joint should become wider towards its base as the cave stream becomes vadose (since in the vadose zone only the lower parts of the walls are available for solution). Low-level solution features should be more pronounced than those at high level. The solution features normally seen in gulls are not of this type and must pre-date the development of nearby rivers.

Phreatic solution pre-dates gulling. Karst caves of either phreatic or vadose form also pre-date gulling. Infiltration of surface water can produce vertical vadose (fluting) features in gulls, but cave streamways cannot form without provoking landslips.

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