GULLS, GULL-CAVES AND CAMBERING IN THE SOUTHERN COTSWOLD HILLS, ENGLAND

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The study of fissures and caves formed by mass movement is important not only because they are a significant geohazard, but because such caves can be repositories for palaeogeographic information. In southern Britain, such open joints in solid strata are known as *gulls*. In the southern Cotswold Hills, a sequence of interbedded limestones and mudstones has been deeply dissected by the River Avon and its tributaries. Mass-movement and cambering has opened up narrow gulls and larger gull-caves to a far greater extent than had previously been realized. Surveys made inside the extensive abandoned Box Freestone Mine have allowed the spatial distribution of these features to be mapped. We found that the direction of extension is not always in the direction of topographic gradient; locally it can be influenced by the stratal dip direction. In some areas, abrupt changes in the orientation of valley sides have allowed mass movement in two directions, creating rectilinear networks of gull-caves. A quantitative assessment of the valley-ward extension of the strata caused by gulling was made in Box stone mines. Extension may often exceed 5%, and locally may reach 10% in discrete zones. Evidence of preferential dissolution along the NW-SE joint set in these gull-caves suggests former groundwater flow to the northwest, and not to the present River Avon valley. This indicates that the River Avon has subsequently captured the dip slope streams that fed the River Thames headstreams. The greatly enhanced flow of the River Avon after this capture caused rapid over-deepening of the valley, which triggered the original cambering and thus formation of the gull-caves themselves.

1. Introduction

The Cotswold Hills, located in the south-western part of the English Midlands, forms a significant escarpment about 100 km long and generally 20 km wide, reaching a maximum elevation of just over 300 m near Cheltenham. They comprise a sequence of interbedded limestones and mudstones of Middle Jurassic (Bathonian) age, with a steep scarp slope facing to the west and a shallow dip slope to the east (Barron et al 2011). Rivers rising on the dip slope flow towards the River Thames and the North Sea, scarp streams flow west to the River Severn and the Atlantic Ocean. The exception to this is the (Bristol) River Avon which rises on the dip slope of the southern part of the Cotswold Hills, then cuts through the escarpment via the Claverton Gorge near Bath; it continues west, picking up scarp stream tributaries, and passes through the cities of Bath and Bristol before reaching the River Severn.

This paper describes part of the southern Cotswold Hills to the east of Bath which has been deeply dissected by the River Avon and the By Brook, a major tributary which joins from the east (Figure 1). In the valley floor, the rivers have incised through the Middle Jurassic sequence into Lower Jurassic strata of the Lias Group, which are mainly mudstones with subordinate limestones. The lower part of the valley sides are cut in the Inferior Oolite Formation, a rubbly oolitic limestone up to 23 metres thick.

Above this is the Fuller's Earth Formation, a series of calcareous mudstones with occasional beds of flaggy limestone, approximately 46 metres thick. The Fuller's Earth mudstones are over-consolidated, highly plastic clays prone to mass movement. Capping the interfluves is the Chalfield Oolite; a succession of largely matrix-free oolitic limestones 35 – 40 m thick. Succeeding these limestones on the dip slope is the Forest Marble Formation, a sequence of coarse bioclastic limestones and mudstones. The regional dip is about 2° to the south-east. These Jurassic mudstones and limestones are prone to mass movement. The valley sides of the River Avon and its tributaries have extensively foundered, with significant land slipping in and around the city of Bath. These mass-movements include both rotational landslips and extensive cambering. Gulls are common in the more competent oolitic limestones, The term *gull* (derived from gully) is an old quarryman's term, used to describe open joints in solid strata (Fitton, 1836). They are particularly well developed in the Chalfield Oolite where the major joints have opened as the stata has extended valley-ward. When large enough to be explored by cavers, they are termed gull-caves; the anthropomorphological element of this definition is important because it means that they are accessible to direct study. Gull-caves are different from normal dissolutionally widened fissures and caves, and can be identified by their distinct morphology. Gulls are typically narrow, parallel-sided, joint orientated rifts, often with symmetrically opposing wall morphologies ('fit features' of Self, 1986), but where there has been vertical as well as lateral movement, bedding planes or other discontinuities may also have parted.

In the Bath area, the Jurassic oolitic limestones are excellent building stones, as they can be cut as 'freestones' which then harden on exposure to air. Consequently they have been extensively mined. Several large abandoned pillar and stall workings, with several hundred kilometres of surveyed passages occur in the Bath area. The effects of cambering can be seen in many of these mines. Gulls are common and there are also gull-caves large enough to be accessible for direct study. Moreover, these extensive stone mines enable the spatial extent of the gulls to be mapped out over wide areas, and can be used to identify zones of maximum extension.

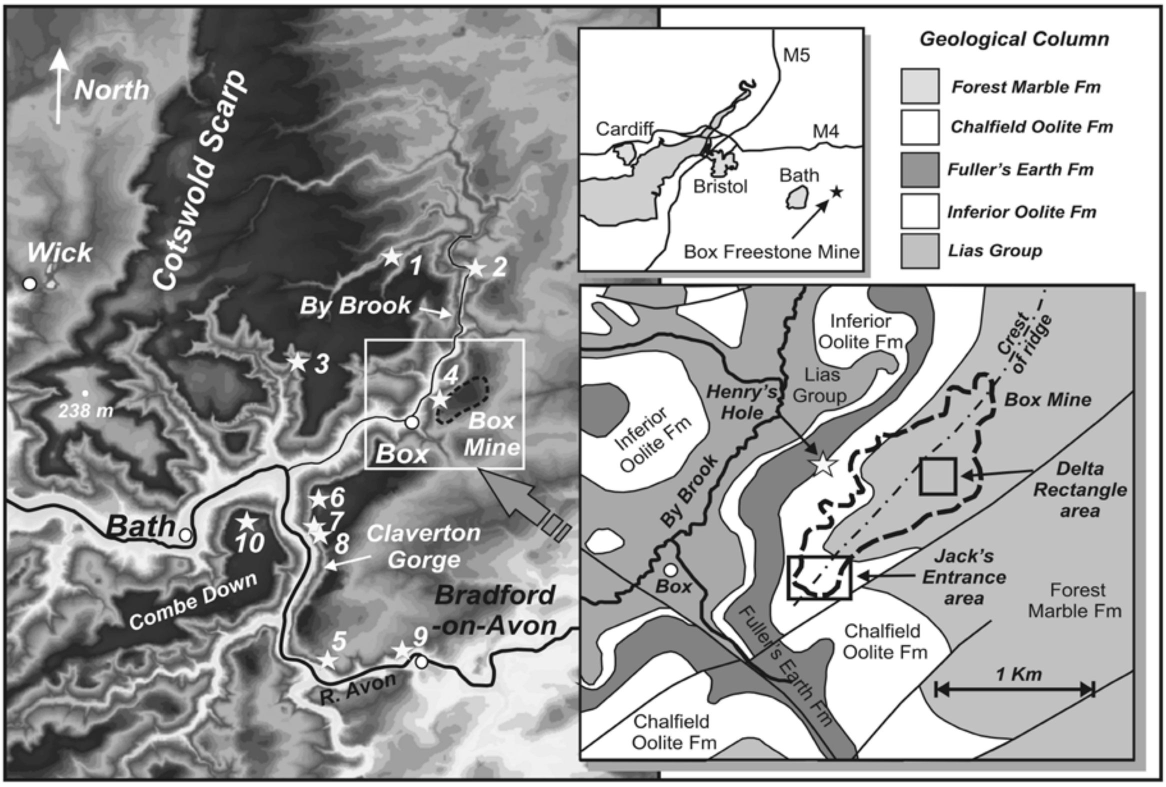

Figure 1. Map of the Avon valley around Bath. The topography is based on a NextMap digital terrain model, with a 5 m spacing greyscale ramp. The inset map is a geological map of the Box area (based on the British Geological Survey digital geological 1:50,000 scale data). Gull caves are marked with a star and numbered: 1. Bury Wood Camp [ST 8162 7397]. 2. Guy's Rift [ST 8450 7372]. 3. The Rock's Rift [ST 7896 7057]. 4. Henry's Hole [ST 8360 6944]. 5. Murhill Rift [ST 7956 6073]. 6. Gully Wood Cave No. 5 [ST 7937 6600]. 7. Gully Wood Cave No. 4. [ST 7946 6500] 8. Sally's Rift [ST 7941 6506]. 9. Gorton's Rift. 10. Bathampton Down and Bath University. Detailed descriptions of the gull caves are in Self and Boycott, (2000).

2. The formation of cambers and gull caves

Gulls form on steep hillsides as a result of mass movement, when well-jointed strata are unsupported on their downhill side. In sedimentary rocks, extension takes place along bedding planes with bed-over-bed sliding and the opening of joints (Hawkins and Privett, 1981). Gulls are particularly common in flat-lying or gently inclined strata affected by cambering. *Cambers* are caused by the gravitational lowering of outcropping or near-surface strata towards an adjacent valley. They occur where competent and permeable rocks overlie incompetent and impermeable beds such as clays. The competent beds develop a local dip towards the valleys, swathing the hill-tops and draping the valley sides (Hollingworth et al., 1944). The incompetent material is extruded from beneath the cap-rock, initially as a result of stress relief.

Parks (1991) has suggested that as a camber develops, the competent cap-rock breaks up into joint-bounded blocks above a basal shear plane in the underlying material. A Quaternary cold stage with permafrost conditions is then required, since the underlying strata (if it is mudstone) is much more susceptible to creep when frozen. Thawing at the end of the glacial cycle increases the water content of the mudstone, potentially saturating it and drastically reducing its shear strength. This causes it to behave as a plastic fluid and the competent cap-rock migrates in the direction of slope, opening the joints to form gulls.

The Parks model shows how gulls that are open to the surface can form in a thin cap-rock. In the Cotswold Hills, the limestone cap-rock is much more substantial and the gulls and gull caves generally have intact roofs. They have formed in the lower part of the limestone strata, with little or no mass movement having taken place in the upper part. This requires not only a basal shear plane, but also an upper parting/ sliding plane within the limestone sequence. A possible mechanism, involving the sequential unloading of joint-bounded blocks, was suggested by Self (1986). As extension occurred, individual blocks were able to settle slightly and then move laterally over the mudstone. The blocks move in the same direction but independently of each other, with neighbouring blocks supporting the overlying strata in turn, creating a gull network that propagates away from the valley.

Other features seen in the caves and mines of the southern Cotswolds appear to contradict the Parks model. Significant camber angles are limited in extent, only affecting the strata closest to the hillside margins, whereas gulls continue to occur deep within the stone mines. A possible contributing factor is pyrite oxidation in the upper horizons of the Fuller's Earth mudstone, with chemical leaching of the calcite cement greatly reducing its shear strength (Brown, 1991) and allowing mass movement at very shallow camber angles. Mass movement in the study area seems to have been triggered by the rapid over-deepening of the valley system resulting from the capture by the River Avon of dip slope streams of the palaeo- Thames drainage. High pore pressures in the mudstone need not have been caused by permafrost, but could have been a result of groundwater percolation from above. The stability of the gulls since their creation (with the growth of speleothem deposits) suggests that there was only one major episode of mass movement. A possible explanation is that mass movement ended when the valleys cut down into the more competent Inferior Oolite limestone, which gave stability to the hillsides above.

3. The gull caves

Typically, cave entrances in the southern Cotswolds are found in the cliff faces of abandoned small valley-side quarries (Self and Boycott, 2000). Some are single fissures a few metres long, while others form more extensive systems. The main jointing directions are NW-SE and NE-SW, so the more complex gull caves tend to be rectilinear networks. N-S and E-W joints are also present in the study area, but they generally have not been opened by mass movement. The known caves all occur on north- or west-facing (up-dip) slopes, probably because such slopes are less prone to rotational failure. Many more caves certainly exist, but these either do not intersect the surface or are buried under colluvium.

Two main groups of gull-caves occur (Figure 1). In the By Brook valley, Guy's Rift has 42 metres of surveyed passages. Archaeological material in the cave includes the remains of four human adults, three children and pottery of early Iron Age. Downstream, Henry's Hole is a narrow gull which gives access to a small area of independent mine workings, close to the vast Box Freestone Mine complex. The mine intersects other gulls, but one mined passage crosses (with an intact roof) beneath a substantial gull cave, 4 m tall and 40 cm wide. This is evidence for a high-level disturbance within the Chalfield Oolite. In the neighbouring valley, the Rocks Rift is entirely filled with sediment, including calcite flowstone fragments and limestone boulders; it had been previously excavated for 36 metres to create a garden folly.

The largest gull caves occur in the Claverton Gorge where the River Avon cuts through the Cotswolds escarpment (locations 5-10 on Figure 1). Gorton's Rift is a very deep gull accessed from within a small stone mine. The rift is 24 m deep from the mine level and must reach almost to the lithological boundary with the underlying Fuller's Earth mudstones. Several caves can be found on the east side of the gorge. Gully Wood Cave No. 5 is a network of 50 metres, developed on several levels whilst Gully Wood Cave No 4 is a 90 metres long contour-aligned gull with impressive passage dimensions (Figure 2). Murhill Rift comprises a major passage 80 m long linked to a complex network of rifts and passages on three levels close to the hillside, giving a total length of over 300 metres.

The largest cave in the region is Sally's Rift (Figure 2). It has three entrances and is 365 metres long. The passages are typically over 10 metres tall and between 20 cm and 50 cm wide; the largest passage lies closest to the hillside and is 15 metres tall and 2 metres wide. The cave is a series of contour-aligned gulls linked by gulls aligned along a camber spreading axis (marked A – B on Figure 2) which runs directly into the hill side.

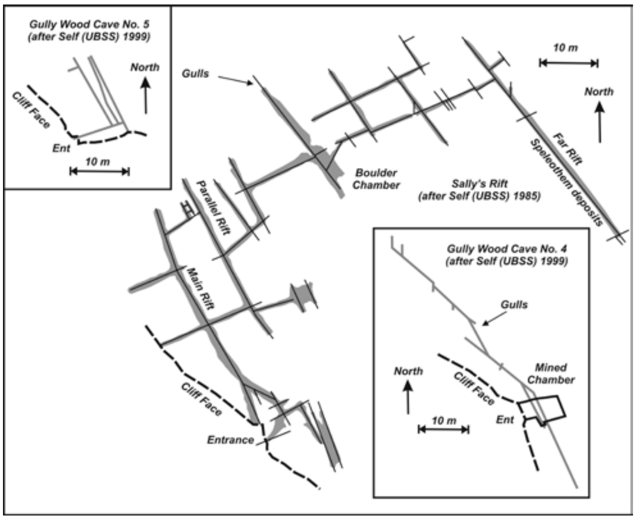

Figure 2. The Gully Wood gull-caves, including Sally's Rift.

This zone of lateral extension is the result of an abrupt change of direction of the River Avon valley just north of the cave, resulting in mass movement in two different directions (Self, 2008). The cave has several examples of "fit features", whereby a ledge on one wall matches an overhang at the same level on the opposite wall. In both Sally's Rift and Gully Wood Cave No. 4, there are localized deposits of gravel containing Cretaceous flints with occasional clasts of Carboniferous rocks; these are identical to local superficial deposits preserved on the plateau above the cave, identified by Donovan (1995) as an early Quaternary deposit.

4. Gulls in Box Freestone Mine

The Box Freestone Mine complex was worked mostly during the late 19th century using cranes and a network of horse drawn tramways. Over 60 km of passages are still accessible in an area of less than one square kilometre. Gull fissures are pervasive throughout the system and reach into the remotest parts, more than 600 m from the escarpment. The fissures range in width from a few centimetres up to gull caves over a metre wide and many tens of metres long. Locally they can extend up to 10 m above the level of the mine floor. These larger gulls are sometimes passable, but many have been used for storage of waste stone. A detailed survey of the gull fissures was made in two separate parts of the mine, around Jack's Entrance and in the Delta Rectangle area (see Figure 1), in an attempt to determine their spatial extent. In the Jack's Entrance area, the majority of gulls are aligned on the 150° joint set and are fairly regularly spaced around 3-8 m apart (Figure 3). Thirty-five gulls were recorded along a 200 metre transect due east from the entrance, showing an average extension of the strata of just over 5% along the length of the passage (Figure 4). However, in the middle part of the transect, there is a zone with much larger gulls, which give an extension value of 9% for this part of the

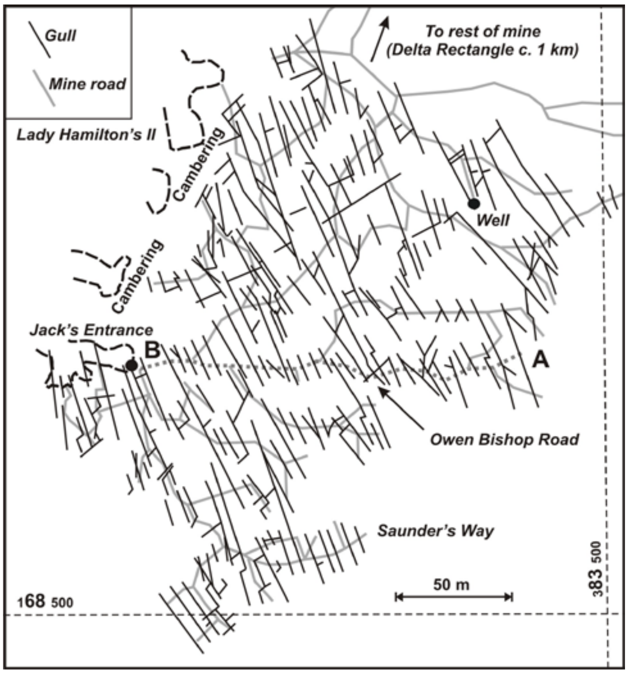

Figure 3. Gulls in the Jack's Entrance area of the Box Freestone Mine.

survey. These *zones of extension* were first reported by Hawkins and Privett (1981) on a building site in cambered lower Jurassic strata. Cambering is obvious along the western edge of the mine, reaching a maximum of 11° close to a collapsed former entrance. However, the camber angle decreases sharply a short distance into the mine and within 200 m the bedding becomes essentially horizontal.

In the Jack's Entrance area, the nearby hillside is aligned approximately north-south. Ordinarily, this valley orientation might cause both the NW and NE joint sets to have opened. However, the regional dip of the strata, around 2° to the southeast prevents this. Opening of the NE joint set would require cambering up-dip, whereas for the NW joint set cambering is in the much easier direction of strike of the strata. Figure 3 shows that the measured camber directions are not in the direction of slope, but consistently have a dip component, which explains the dominance of NW aligned gulls.

The Delta Rectangle area lies almost directly beneath the summit of Box Hill, about 400 m from the nearest escarpment edge. Numerous gull fissures are present but they are more widely spaced than those seen in the southern part of the mine. The gulls are typically 5 to 20 cm wide and both joint sets have opened, with no clear direction of extension (Figure 5). A 200 m east-west transect recorded 16 gulls with c. 1% extension of the strata along the length of the passage. Throughout the mine, the NW joint set is heavily corroded with extensive dissolutional fretting while the walls of the NE joint set are smooth. This suggests that preferred orientation of groundwater flow was in a NW-SE direction.

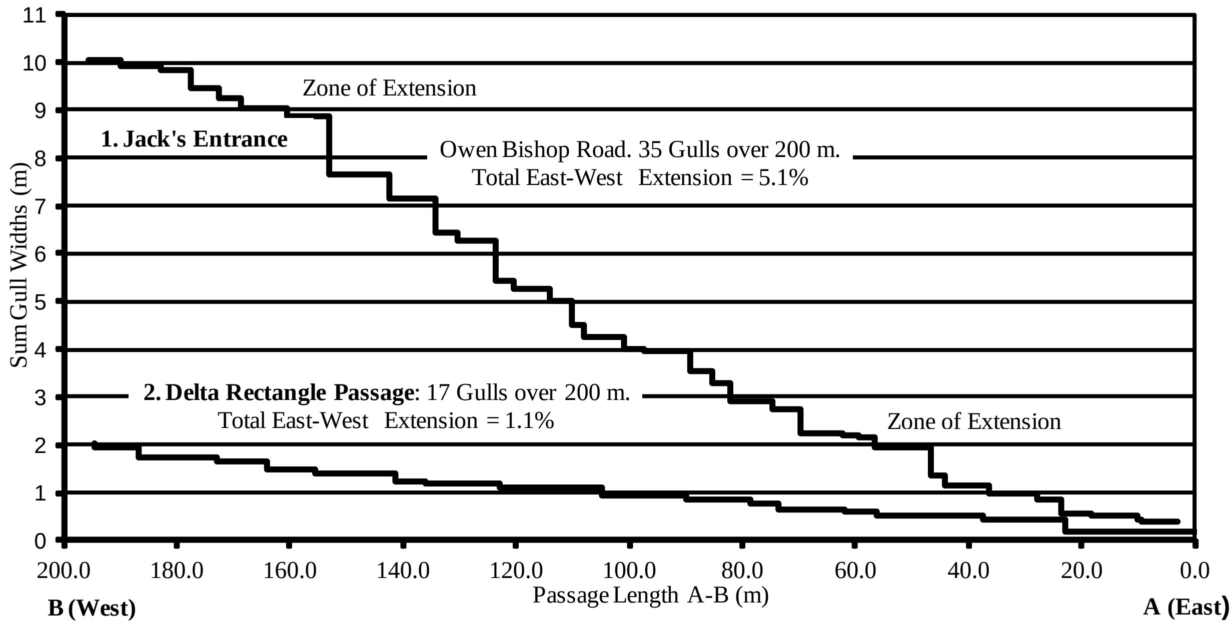

Figure 4. Transects through Box Freestone Mine: 1. Owen Bishop Road close to Jack's Entrance and the hillside (Jack's Entrance to the west); and 2. Delta Rectangle Passage in the interior of the mine beneath the interfluve. Two zones of extension are apparent on Owen Bishop Road in the Jack's Entrance area.

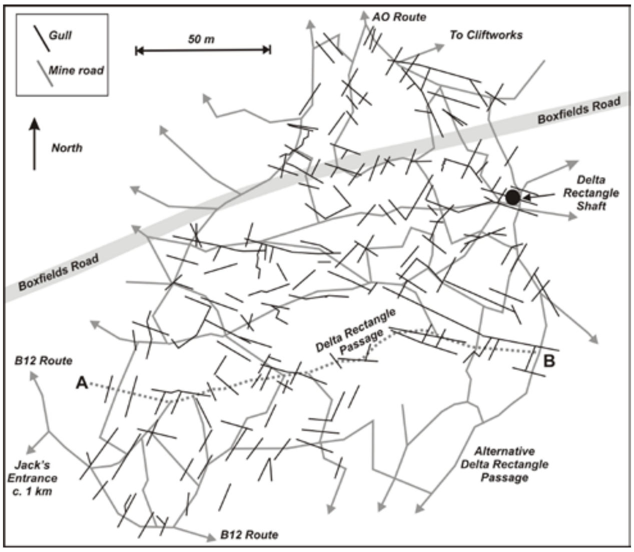

Figure 5. Gulls in the Delta rectangle area of the Box Freestone Mine.

5. The development of the Claverton Gorge

The Chalfield Oolite is an important aquifer, but it is only weakly karstic and groundwater travels freely along the joints. On the south side of the By Brook and the east side of the Claverton gorge of the River Avon, dissolutional etching is very pronounced in the NW/SE joint set (Self, 1995). This etching of the joint walls is the result of slow groundwater movement which pre-dates the onset of cambering (and de-watering of the strata). Drainage could not have been down-dip to the south-east because the Forest Marble forms an impermeable cap-rock. The outlet was therefore up-dip. Up-dip springs contribute to the present drainage of the By Brook valley.

The significance of the up-dip palaeodrainage of the NW joints in Sally's Rift is that the nearby River Avon flows in this direction. The Claverton Gorge (and the entire River Avon valley system upstream) could not have existed at this time; otherwise the groundwater movement would have been towards this valley using the conjugate joint set. This suggests that the proto- River Avon was an aggressive scarp stream tributary to the By Brook, while the Cotswold dip slope drainage was to the headwaters of the River Thames (Figure 6). Eventually, head-ward erosion by the River Avon allowed it to break through into dip-slope territory and capture these former Thames headstreams. With a greatly enhanced flow, the River Avon rapidly over-deepened its valley and formed the steep-sided Claverton Gorge. The tributary valleys also cut down to this new base level and the entire valley system was primed for cambering.

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