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Boreham Cave, Littondale, North Yorkshire, UK: some geomorphological observations.

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Abstract: Observations made by the original explorers of Boreham Cave, a partly-submerged cave system on the northeastern flank of Littondale in the Yorkshire Dales, UK, have been augmented by recent studies of aspects such as overall cave morphology, geological and topographical setting, scallop geometry, sediment lithology, form and provenance, and speleothem ages. Consideration of the expanded dataset has enabled development of an interim cave development model for Boreham Cave itself, and supports speculation regarding its relationship to documented events during the Quaternary and with other cave systems in the wider area.
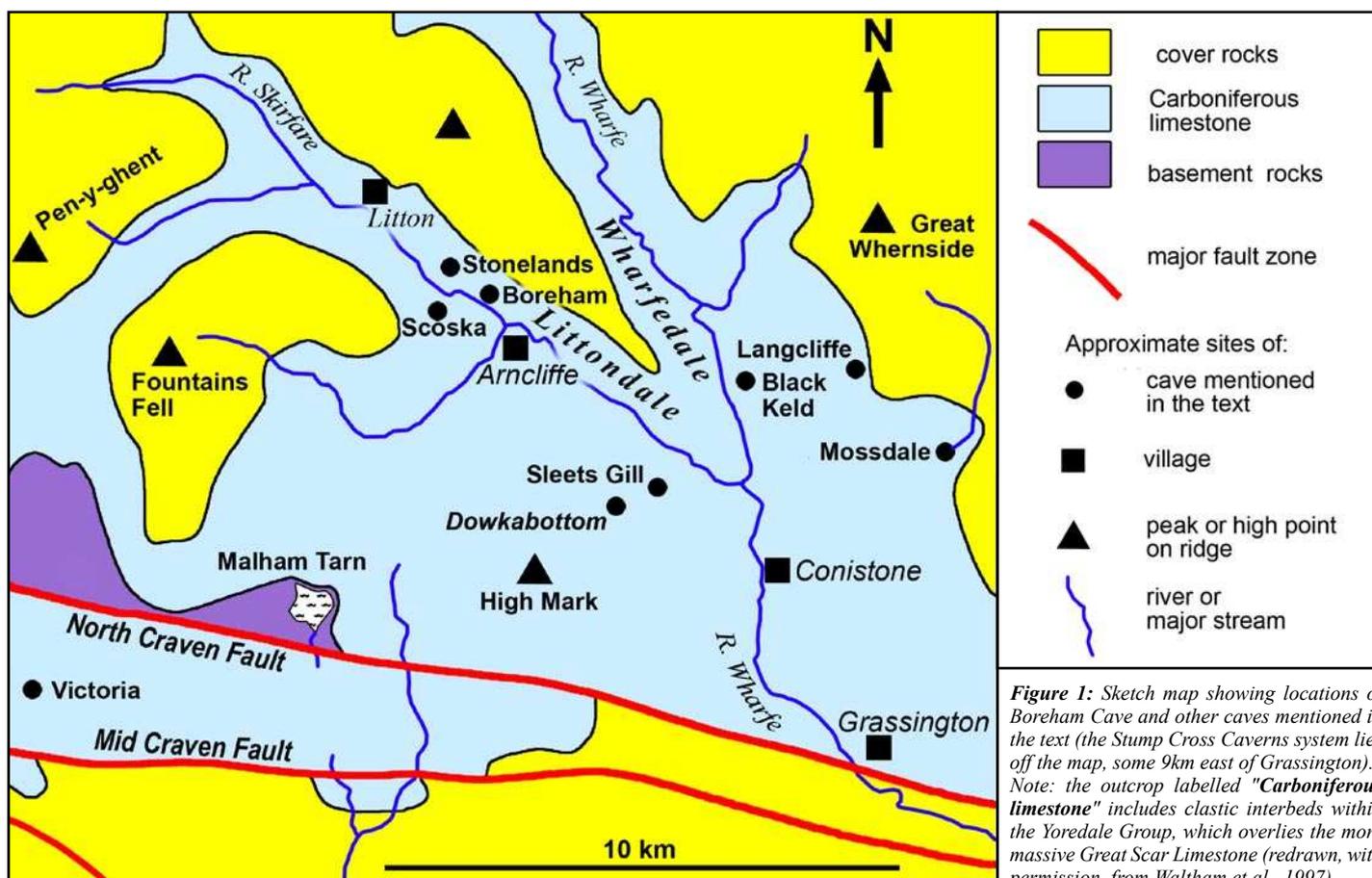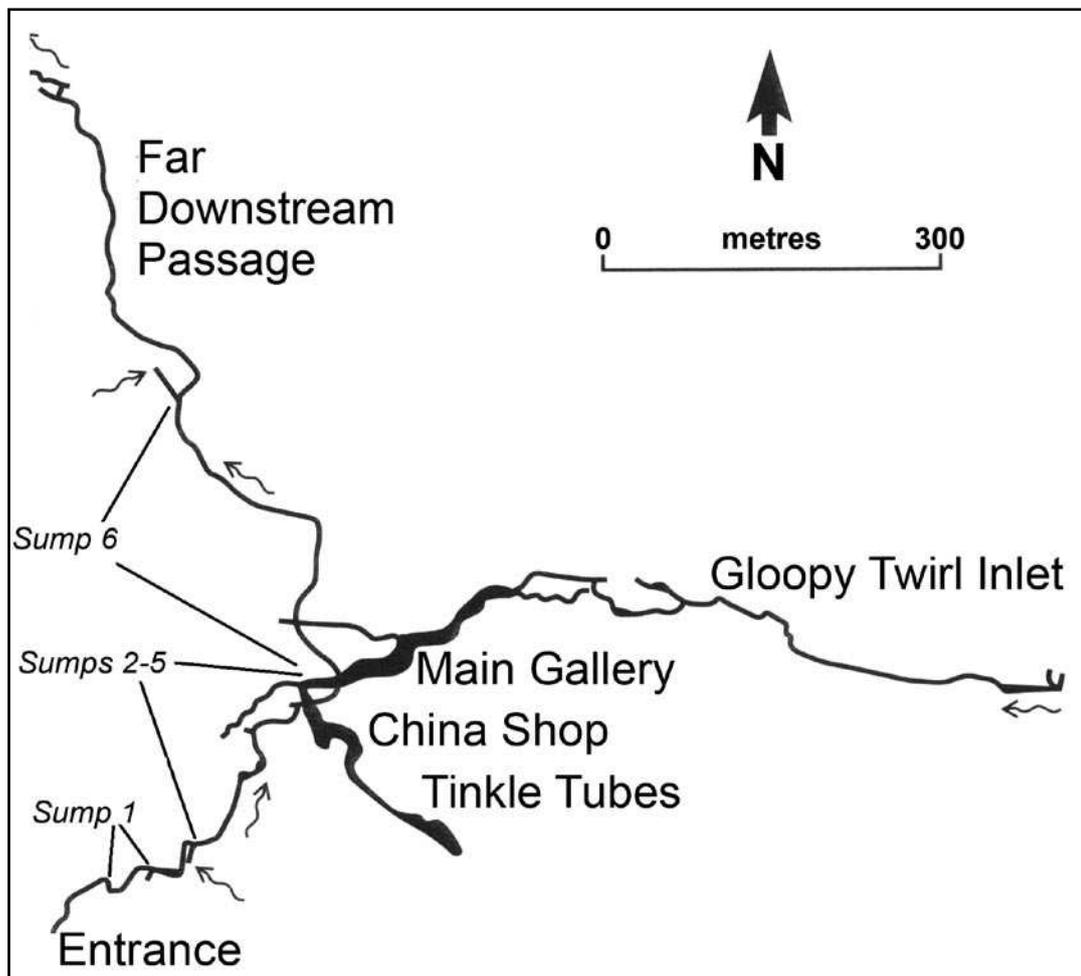
Boreham Cave is an extensive and complex, partly-submerged cave system on the northeastern flank of Littondale between Arncliffe and Litton in the Yorkshire Dales (Fig.1). Very little scientific work has been undertaken in the cave. This study set out to investigate how parts of the cave relate to aspects of the evolving regional cave inception model and to raise understanding of the timing and mode of deposition of the cave interior deposits.

The cave entrance is situated above the floor of Littondale, probably within the Cove Limestone Member of the Malham Formation (Arthurton *et al.,* 1988). This stratigraphical position possibly equates to the third major inception horizon proposed by Lowe (2000, p.72), which elsewhere is close to the Gordale Limestone–Cove Limestone boundary. This rock unit boundary also marks the approximate boundary between rocks of the Asbian and Holkerian substages (Waters and Lowe, 2013, Fig. 2.9) and is close to and locally coincident with

the expected horizon of the Porcellanous Bed (Garwood and Goodyear, 1924). This distinctive marker bed is well exposed at the nearby Stonelands Cave and at Scoska Cave on the western side of the valley (Fig.1). The related inception horizon, which was more recently referred to as Inception Horizon 2 (Lowe, 2013, Table 8.2), has guided significant lengths of bedding-related cave development within the southern part of the Yorkshire Dales.

Accounts of the cave's exploration are given by Brindle (1959), Anon (1974 and 1975), Yeadon (1974), Solari (1974), Watson (1989), with summary accounts provided by Farr (1991, p.136 and 1980, pp 129 and 131) and Yeadon (2007). An account of an early dive in the cave is given by Jessop (1998, pp 37–38). Details of the cave's submerged sections are given in Monico (1995). The cave is included in the karst section of the Geological Conservation Review (Waltham *et al.,*1997, pp 86–87).

*Figure 1: Sketch map showing locations of Boreham Cave and other caves mentioned in the text (the Stump Cross Caverns system lies off the map, some 9km east of Grassington). Note: the outcrop labelled **"Carboniferous limestone"** includes clastic interbeds within the Yoredale Group, which overlies the more massive Great Scar Limestone (redrawn, with permission, from Waltham et al., 1997).*

Description and observations

The passage leading to the first sump is a phreatic tube 1m wide by 2m high. In the past, the entrance (Fig.2) acted as a resurgence, but it is a long time since significant volumes of water resurged. An intact dry-stone wall crosses the stream bed a short distance from the cave mouth and an ash tree estimated to be 200 years old has grown in the dry stream bed. The first known account of this section of cave dates from 1751 (Cartwright, 1888) and interpretation of this description suggests that little has changed in the last 262 years. Though the visitor did not specify the name the cave, Craven (1999) argues convincingly that the cave described is Boreham Cave.

Beyond the first sump, the dry passage is much larger, estimated to be 4m high by 5m wide. This disparity in passage size between Sump 1 and the cave beyond was noted by Lister (1968). The passage between Sump 1 and Sump 2 contains an extensive sedimentary fill, which reduces the passage to stooping height in places (Fig.3). This deposit was described as unsorted glacial till by Long (1974). Brindle (1959) gave a more detailed account of the sediments but identified only a single unit of very poorly sorted material.

Re-examination of the deposits has revealed a much more complex stratigraphy. The fill sequence consists of a lower layer of brown silt overlain by diamict, an extremely poorly sorted deposit of boulders and cobbles in a sand/silt matrix. The diamict, which contains lithologies consistent with an origin from beds within the Yoredale Group and Millstone Grit Group, varies from 0.5m-thick at the inner end of the passage to 1m-thick at the exit from Sump 1. Overlying the diamict is a bed comprising finely laminated clays. The lamination is of the order of 2mm and grades upwards from pale to dark colour, with an abrupt upper limit. Such clays are commonly referred to as varved though use of this term in a cave environment is questionable because, strictly, it should be applied only to lake deposits. The non-genetic term rhythmite is preferred.

The fine and detailed layering is believed to be a result of a climatically-driven signal, and similar deposits are known to occur in Dowkabottom Cave, which is 3km to the south (Fig.1), and in Stump Cross Caverns, some 20km to the southeast (Sutcliffe *et al.,* 1985).

Parallel studies in Victoria Cave, approximately 12km to the west (Fig.1), have constrained the age of similar deposits to that of the Last Glacial Maximum and have proposed an origin due the inundation of the cave by glacial melt-waters while the area was covered by ice (Lundberg *et al.,* 2010). If this deposit is coeval with that from Victoria Cave the underlying deposits must pre-date the Last Glacial Maximum.

Very few speleothem deposits occur in the dry passages between Sump 1 and Sump 2, suggesting it is prone to periodic flooding. Two superimposed scallop populations are present on the ceiling of the passage – large scallops with a mean wavelength of 30cm have smaller scallops, with a mean wavelength of 6cm, superimposed upon them (Fig.4). The large scallops correspond to a mean flow velocity of 0.1 m/s and the smaller ones 0.6 m/s. This shows that since it was originally drained, the passage has been subjected to episodes of flooding, during which water flowed at a higher velocity than during the entirely phreatic stages of the passage's development. Both scallop populations indicate that water movement was towards the present cave entrance.

A short low crawl towards the southeast starting close to the divers' exit from Sump 1 leads via a squeeze into the base of a 10m by 3m joint-guided shaft. This was first entered in 1966 and revisited in 1974 (Anon, 1974). The scallop morphology on the shaft walls confirms that this was a phreatic lift – water flowed up the shaft. The possible presence of such a feature was inferred on the basis of observations of the sediment fill by the original explorer of the passage between Sump 1 and Sump 2 (Brindle 1959). This shaft has been ascended to reach 12m of passage leading to a choke (Brook *et al.,* 1998).

The very large sized inlet passage carrying the stream that enters Sump 2 was formerly filled with sediment, which is now being re-excavated by the underfit stream (Fig.5). Thus the passage between Sump 1 and Sump 2 appears to be the base of a major phreatic loop. Water entered from the choked inlet near Sump 2 and left via the phreatic riser near Sump 1. Flow in such a large passage might have developed the population of large scallops. The large scallops clearly pre-date the smaller scallops, so perhaps the latter post-date the development of Sump 1 and the entrance passages, which captured the flow as base level was lowered, and may relate to episodic flooding.

Figure 3: Sediment bank at the exit of Sump 1 in Boreham Cave (photo: David Ryall).

Figure 4: View towards Sump 2 in Boreham Cave, showing large and small scalloping on the passage ceiling (photo: David Ryall).

Figure 5: Clastic sedimentary infill, currently undergoing re-excavation by the underfit stream that enters near Sump 2 in Boreham Cave (photo: David Ryall).

Even during extreme flood events in the area very little water is observed emerging from the present cave entrance. Hence, the flood-liable appearance of the passage remains a puzzle: if it does fill with water under modern conditions, drainage does not pass through the cave entrance. The large volume of coarse-grained clastic sediment in the passage might date from when it functioned as the base of a major phreatic loop. Later, higher-velocity, flow might be responsible for the partial re-excavation of this fill.

The passage between Sump 2 and Sump 5 is of comfortable proportions but is smaller than the above-water passage between Sump 1 and Sump 2. Between Sump 3 and Sump 4 the inbound diver has to descend a 2m drop to reach Sump 4. Scallop morphology indicates that water has flowed up this climb, suggesting that this section of passage has acted to channel water towards the present-day entrance. Perhaps this scalloping is contemporaneous with the superimposed population of small scallops between Sump 1 and Sump 2 and both sets relate to a phase of development when the large phreatic loop had been abandoned due to readjustments in response to valley incision. If so, only the base of the loop remained submerged, perhaps intermittently, acting as part of a lower level of development feeding water from Sump 5 towards the present-day entrance.

Beyond Sump 5 a climb leads into the Main Gallery, from which the high-level development of Tinkle Tubes and the China Shop can be accessed. The Main Gallery has a classic phreatic roof tube, which can be seen to continue above the upward climb from the flooded level into the Tinkle Tubes. Scallop morphology shows that water flowed from the roof tube of the Main Gallery into the Tinkle Tubes, presumably towards a now-abandoned resurgence somewhere high on the valley side, perhaps at around 280m altitude.

The fine vadose canyon cut into the Main Gallery floor leads down to the still-submerged level of the cave system and appears to have formed in response to undercapture of the flow by passage development at the level of Sump 5. Upstream from the Tinkle Tubes the vadose canyon is partially blocked by angular breakdown material, which is overlain by fine-grained clastic sediment. Both the sediment and the breakdown are being eroded by the underfit stream that now occupies the passages.

To constrain the minimum age of the sedimentary fill in the Main Gallery, a stalagmite from immediately above the fine-grained clastic sediments was dated using uranium-series methods as described by Hoffmann *et al.* (2007). Top and bottom sub-samples (<100 mg) were drilled from the stalagmite sample to determine the period of growth, which appears continuous on the basis of internal morphology and structure. U–Th ages (Table 1) indicate that speleothem growth commenced at around 8.2 ka BP, just after a brief cold event (identified in Greenland ice cores; Rasmussen *et al.*, 2007) that was possibly caused by a large meltwater pulse into the North Atlantic from lakes associated with the final collapse of the Laurentide (North American) ice sheet. This cooling event has also been recognized in speleothems from White Scar Cave in North Yorkshire and Lancaster Hole in Cumbria (Atkinson and Hopley, 2013). Growth of the stalagmite ceased around 6.5 ka BP, indicating that prior to the mid-Holocene the gross morphology of the dry passages had reached a situation very similar to that now seen.

The cooling 8.2 ka BP cold event, which lasted less than a century, is believed to be one of the most severe climatic reversals experienced during the Holocene. It might have resulted in the destruction of ground vegetation, the accelerated erosion of superficial sediments, an increased frequency and intensity of frost-related processes, and subsequent meltwater run off. How these surface changes might have affected the karstic drainage awaits detailed investigation (Atherden, 2013; Wilson *et al.*, 2013).

Water-flow downstream from Sump 5 is currently northwestwards into the hillside. Near the limit of the Far Downstream Passage, a 6m-deep shaft can be descended, confirming that this is a perched submerged or still-phreatic passage section. At this point the main flow has been lost and an as yet un-passed slot marks the present end of exploration. This probably represents some form of off-route, parallel, shunt for flood-water, because the main flow must occupy a currently unknown parallel passage. A passable continuation might be explorable if the terminal constriction can be passed and the active flow regained. Alternatively, a search for the outlet in the submerged passage above the 6m-deep shaft might reveal additional undiscovered passages.

Interpretation

A proposed cave development sequence at Boreham Cave

1 Development of the Main Gallery (including inlets), feeding water to a resurgence via Tinkle Tubes;
2 Development of a phreatic loop close to the present valley side feeding to a high-level resurgence;
3 Passages of the present-day perched phreas developed (utilizing the base of the phreatic loop that developed during Stage 2) feeding water to the current cave entrance;
4 Capture of the water from the Main Gallery/Tinkle Tubes by the lower level of development of Sumps 1–5, and incision of the vadose canyon into the floor of the Main Gallery;
5 Breakdown deposits formed in the Main Gallery;
6 Development of an (as yet unexplored) lower-level passage, which captures the active flow and has resulted in flow reversal into the hillside and the abandonment of the present-day cave entrance by active stream flow. This flow might join with that using other conduits – possibly including passage development associated with Stonelands Cave.

The reversal of flow in the accessible sumps following valley rejuvenation and the development of a lower-level passage fits with a typical morphology described for many Yorkshire Dales cave systems, whereby drainage in the upper levels flows essentially down-dip away from the resurgence before reaching base level, where flow is reversed up-dip. A similar situation is exemplified by the cave system beneath Conistone Moor, where vadose flow from Langcliffe Pot and Mossdale Caverns is essentially down-valley away from the Black Keld resurgence and subsequent phreatic flow is up-dip towards Black Keld (Waltham *et al* 1997, p.92).

Such a hydrological system would also account for the results of a diffuse hydrological trace that was reported on Hawkswick Moor, on the northeastern flank of Littndale, several kilometres down-valley from Boreham Cave. Low concentrations of a chemical herbicide that was sprayed onto moorland to assist with bracken control were detected at a spring lying about 1km northwest of the limits of the herbicide application area (Knapp, 2005).

Following on from pertinent observations made by Brindle (1959), a number of broad similarities between Boreham Cave and Sleets Gill Cave, a hydrologically complex system on the southwestern flank of Littondale (Fig.1), are worthy of note. In both caves a second phreatic passage section has been identified, suggesting the existence of two previous resurgences at higher levels of development connected by intermittently flooded passages of typical phreatic morphology. In the case of Sleets Gill Cave the two phreatic risers of The Ramp, deep within the cave, and the present-day entrance slope both presumably fed towards separate resurgences when base-levels related to the floor of proto-Littondale were higher than today's valley floor (Waltham *et al.*, 1997, p.85).

Recognition of such a similarity of cave development history, mirrored within systems on both sides of the valley, should be a great help in deciphering the geomorphological history of this little-studied area, once a programme of absolute dating of interior deposits from the local cave systems is undertaken.

Conclusions

This study has confirmed many of the initial observations, made by the original explorers, regarding the complex speleogenetic history of Boreham Cave. It has also identified a second abandoned phreatic loop, of considerable size and hydrological complexity, that was previously unrecorded. New observations in the area of the downstream divers' limit suggest that the lower, and as yet unentered, phreatic level of development will be of explorable dimensions. The clastic deposits in the Main Gallery were deposited prior to about 8.2 ka BP. Observations during this study support conclusions drawn by Waltham *et al.* (1997, p.86) that the sedimentary deposits provide *"... important, but as yet unstudied, record of the Devensian glaciations of the eastern Dales"* and it truly is *"... a classic example of a phreatic system which has experienced rejuvenation and reversal of flow direction."*

Sample	Sample ID	^{238}U (ng g^{-1})	^{232}Th (ng g^{-1})	Measured activity ratios			Corrected age* (ka)	$(^{234}$U/^{238}U$)_{Ai}$ corrected
				$(^{230}$Th/^{232}Th$)_A$	$(^{230}$Th/^{238}U$)_A$	$(^{234}$U/^{238}U$)_A$		
BCMG-2012-01 (top)	BIG-UTh-P47	629 ± 2	3.4 ± 0.01	45 ± 0.2	0.079 ± 0.0003	1.341 ± 0.002	6.43 ± 0.07/0.06	1.348 ± 0.002
BCMG-2012-02 (bottom)	BIG-UTh-P48	426 ± 1	4.6 ± 0.01	28 ± 0.1	0.100 ± 0.0006	1.338 ± 0.002	8.17 ± 0.12/0.13	1.347 ± 0.002

Analytical errors are 2σ of the mean.

$(^{230}$Th/^{238}U$)_A = 1 - e^{-\lambda_{230}T} + (\delta^{234}U_{measured}/1000)[\lambda_{230}/(\lambda_{230} - \lambda_{234})](1 - e^{-(\lambda_{230} - \lambda_{234})T})$, where T is the age δ^{234}U $= ((^{234}$U/^{238}U$)_A - 1) \times 1000$. Ages in years before 1950.

Decay constants are 9.1577 x 10^{-6} yr^{-1} for ^{230}Th, 2.826 x 10^{-6} yr^{-1} for ^{234}U (Cheng *et al.*, 2000), and 1.55125 x 10^{-10} yr^{-1} for ^{238}U (Jaffey *et al.*, 1971).

* The degree of detrital ^{230}Th contamination is indicated by the measured $(^{230}$Th/^{232}Th$)_A$; an initial $(^{238}$U/^{232}Th$)_A$ of 0.8 ± 0.2 is used to obtain a corrected U–Th age.

Table 1: U and Th concentrations, isotopic activity ratios and U–Th ages for sub-samples of stalagmite BCMG-2012 from Boreham Cave, Littondale.

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