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## **Gordale Scar versus Malham Cove – further observations on these iconic landforms**

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The origins of Malham Cove have been a subject of debate for many years, with variety of possibilities having been proposed, recently summarised by Waltham (2017). The sheer scale of the feature has ensured its popularity ever since the early years of tourism (Halliwell, 1979) and the recent appearance of a temporary waterfall in December 2015 brought debate on the origins of the site to the attention of the popular press. Gordale Scar, however (Fig 1), has received less attention over the years but attempts to explain the origins of Malham Cove commonly pivot on the similarities and differences of the two sites (e.g. Murphy 2016). The two landforms have much in common, each having a fault-aligned valley leading to a deep, natural amphitheatre upstream of the Middle Craven Fault. Their positions relative to the Middle Craven Fault suggest that the amphitheatres are retreat features that originated on the fault line and then migrated northwards due to headward erosion. They differ in that Gordale Scar now has its stream incised through the height of the amphitheatre.

Four possible explanations have been proposed to account for this difference between the two landforms. Firstly, Gordale Beck has maintained a surface flow, whereas the Watlowes valley above Malham Cove has lost its drainage underground (Gunn and Kelly 2017). The underground flow in part resurges at the base of the Cove where an extensive submerged cave system has been explored (Cordingley 2017). There are, however also springs at Gordale Scar; these emit a considerable amount of water (Hill and Hall 2015 p.119) and during an exceptional drought in 1899 surface flow ceased through the scar and “disappeared in the stream bed about a quarter of a mile above the scar waterfall” (Howarth 1900 p20). A dye trace undertaken using approximately 360 kg (seven hundredweight) of ammonium sulfate added to Gordale beck where it is crossed by Mastilles Lane (SD 91106555). This showed that the springs were sourced from the upper reaches of Gordale Beck (Howarth 1900) suggesting that the conduit behind the springs is immature but can accommodate all the available flow during times of severe drought. This shows that there is some conduit development associated with Gordale Scar as well as that behind Malham Cove.

Secondly, a suite of minor faults exposed within the confines of Gordale Scar (Fig 2) might have aided more rapid incision and no comparable features are present at the Cove.

Thirdly, it may be that Malham Tarn has acted as a settling tank, removing much potential abrasive material from water reaching the Cove (Pitty et al. 1986), whereas a constant supply of abrasive clastic material enhanced stream erosion by Gordale Beck.

The fourth suggestion proposed by Clayton (1981) is that during deglaciation the Malham Tarn basin drained subglacially via Gordale Beck before the Watlowes valley was deglaciated and while the underground drainage routes were still blocked, the enhanced flow resulting in the greater incision.

At both sites the natural amphitheatres appears to have an origin largely separate from that of the valleys upstream of them. The size of Malham Cove and the typically glaciated parabolic profile of the valley downstream of the cliff suggest an origin that owes much to glacial erosion. Quaternary ice sheets traversed the

limestone plateau from Littondale before descending the fault scarps around Malham, but their paths have no expression on the high ground, where the modern valleys are clearly fluvial features. The ice moved southwards over the Middle Craven Fault scarp, and either trimmed, modified or excavated the cliff. The valley below the Cove is over-deepened to produce a bedrock bowl that is now partly filled with sediment in front of the cliff. The present water level in the flooded passages behind Malham Cove is maintained by this sediment fill, and the age of a now-submerged speleothem from within the cave shows that  $27.3 \pm 5.6$  thousand years ago the level of the rising was at least 2.4m lower than it is now (Murphy and Latham, 2001). This confirms that the step in the landscape pre-dates the Devensian glaciation, even if it was not exactly the same shape as the modern Cove prior to modification by its subsequent phase of ice cover. A similar glacial origin therefore seems likely for the amphitheatre at Gordale Scar, which by analogy, probably also predates the last glaciation.

There is however a feature seen at Gordale Scar that is not seen at Malham Cove, in that the deeply incised valley dissecting the amphitheatre is sinuous whereas both the valley upstream from the scar at Gordale and Watlowes Valley upstream of Malham Cove are strikingly linear features. One possible explanation for this sinuosity may be an origin as an incised meander. The sinuous nature of the thalweg can clearly be seen in the photo of Figure 3 where the eastern wall of the scar appears to form a gooseneck-like feature. The sinuous nature of the channel may account for the asymmetry of the gorge profile at this point noted and illustrated by Clayton (1966 fig.2 and caption). The sinuous nature of the channel means that the waterfall where Gordale Beck pours through the Hole in the Wall and down an active tufa bank, and the now inactive tufa banks up which the public footpath climbs, are hidden from view when the amphitheatre is approached from the south (Fig. 1). An origin as an incised meander would require down cutting to have occurred rapidly enough to curtail lateral meander migration, a situation that could have arisen due to a large and rapid fall of base-level. Such a fall in base level could be due to a variety of mechanisms, perhaps being a result of rapid back-cutting from the Middle Craven Fault scarp by an ice stream. Any explanation proposed for the formation of Gordale Scar and by analogy Malham Cove must not only account for the incision of the channel through the Gordale amphitheatre but also explain the sinuosity of the channel thalweg while doing so. The presence of an underground drainage system at Gordale, though apparently much less well-developed than that behind Malham Cove, also needs to be considered.

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Figures:

Figure 1: Gordale Scar as viewed from the south. The waterfall and tufa banks are hidden from view.

Figure 2: A vertical fault exposed above the waterfall within Gordale Scar.

Figure 3: Looking down into Gordale Scar from the western flank. The sinuous nature of the channel thalweg can clearly be seen.