Classic localities explained 19

Malham Cove: splendour and enigma

A dry waterfall that recently came to life, a landform that is not karstic in the middle of a great karst terrain, underground drainage that is not as simple as it seems, and on-going debate about how it was formed: Malham Cove is more than just a spectacular sight.

Tony Waltham
Nottingham, UK
tony@geophotos.co.uk

The great, white, limestone cliff of Malham Cove is one of the landmarks of the Yorkshire Dales of northern England. Along with its neighbouring Gordale Scar, the cove has drawn visitors since popular tourism began in the early 1700s. Today it makes Malham one of the honeypot destinations within the National Park, and is also an essential stop during innumerable field excursions from schools and colleges. Whereas both Malham and Gordale lie within Britain's finest karst landscape, they are not essentially karst features, and although the cove is at the centre of a classic teaching example of karst morphology, there is still considerable debate as to just how it was formed.

In simple terms, Malham Cove is a dry waterfall (Fig. 1); that is, normally dry, but just occasionally becoming active. It has certainly been a much more active waterfall in the past, but its sheer dimensions hint at more complex origins. By whatever means it was formed, it is now a grand feature of the Yorkshire Dales landscape. It is 70 metres high, and widely quoted larger numbers are incorrect. To be precise, it is 70.06 metres from the lip of the waterfall notch down to the pool of water at its foot. The top of the cliff rises on each side of the central notch, and the well-known limestone pavements at the top of the cove stand 12 metres above the waterfall lip, and therefore 82 metres above the resurgence pool. So the popular quotes of 80 metres high do reflect the visual impact when it is seen on the approach from Malham village. The cove cliff is more than 200 metres long, although it loses height on each flank where the valley sides rise against it, and it is curved to form a grand amphitheatre.

Malham Cove is formed of strong Carboniferous Limestone that is massively bedded and almost horizontal. This rock is pale grey when fresh, but develops a white patina on weathered faces. Most of the cliff's height is formed of the Cove Limestone Member, Holkerian in age, of the Malham Limestone Formation, though it is capped by the Gordale Limestone Member, which forms the well-known limestone pavements above the rim. The two members are normally separated by the thin Porcellanous Bed, but this is locally absent. The upper boundary of the Cove Limestone Member is defined by the bedding plane at the overhang that is conspicuous across most of the cliff, just 2 metres above the lip of the dry waterfall. The lower boundary is only exposed inside the cave that is 2 metres below water level at the foot of the cliff. So the Cove Limestone Member is 74 metres thick at its type locality.

Above the cove, Watlowes is a classic, karstic, dry valley entrenched 30 metres into the limestone plateau for nearly a kilometre downstream of another dry waterfall at Comb Scar (Fig. 2). Flood events bring the Comb Scar waterfall to life, perhaps once every few years, but its water sinks into limestone fissures at its foot, and the Watlowes valley and cove are now almost permanently dry (Fig. 3). Upstream of Comb Scar, a shallower valley is dry as far as the Water Sinks that swallow the outflow from Malham Tarn, that lovely, shallow lake that appears to lie on

Fig. 1. The great white cliff of Malham Cove, formed in nearly horizontal Great Scar Limestone.

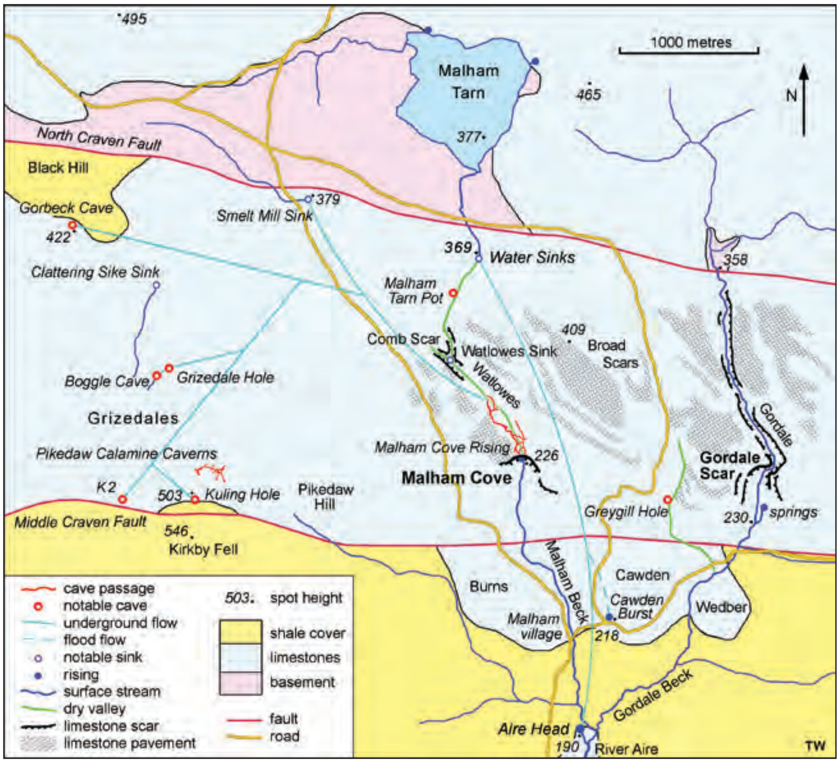

Fig. 2. The main features of the geology and karst geomorphology around Malham Cove. Except for the two caves of Malham Cove Rising and Pikedaw Calamine Caverns, the known cave passages are so short that they barely extend beyond the rims of the circles that show their locations. The underground flows that are marked, from Water Sinks to Aire Head and from the Grizedales sinks to Malham Cove Rising are active in all conditions; not shown are the complex and multiple links whereby water from all or most of the sinks emerges at all the risings in flood conditions (modified from Murphy, 2016.)

a limestone plateau but actually sits on an inlier of impermeable rock beneath the limestone. The stream from the tarn crosses the North Craven Fault and almost immediately sinks into down-faulted limestone, though the details are masked by a blanket of glacial till. Downstream of the cove, the valley is occupied by the stream that emerges from an underwater cave at the foot of the great cliff. The limestone plateau continues on each side until it falls away steeply at the Middle Craven Fault, south of which the main karstic limestone is buried beneath a cover of down-faulted shales.

The underground drainage between and beyond the Tarn's Water Sinks and the Malham Cove Rising is a classic of karst hydrology, as recounted below. But the surface hydrology is also notable for its stream and waterfall that have almost, but not quite, ceased to flow.

The Malham Cove waterfall

In historical times, Malham Cove frequently came alive with a splendid waterfall, but this is an evolving landscape, and changes have been recorded. Written descriptions from the eighteenth century describe a waterfall cascading over the cove after heavy rainfall. Later accounts report the last waterfall event during the wet winter of 1824. Subsequently, water only reached the Watlowes Sink at the foot of Comb Scar during the highest floods that averaged a 5-year return period. And the cove remained dry, except for occasional showers of dripping water that emerged from bedding planes just below the rim during major rainstorms.

That was until 2015, when a temporary waterfall developed for most of the day of 6 December (Fig. 4) and again for most of the night of 26–27 December. On each occasion, an exceptionally large floodwater flow from the tarn overcame the normal Water Sinks and formed a torrent onwards down the valley to Comb Scar. This became a powerful waterfall. Part of its water then sank through the debris into the Watlowes Sink, which lay beneath a large pool at the foot of the cascade, but a major flow continued along the normally dry Watlowes valley. It then formed the cove waterfall, with a perfect free drop about 4 metres wide and 70 metres high, though it was sometimes blown about by the wind. As the floods declined, the cove waterfall ceased to flow, but for a little longer after each event a stream continued to flow along Watlowes as far as a conspicuous sink about 150 metres back from the lip of the cove.

Each waterfall event followed exceptionally heavy rainfalls totalling around 90 mm within about 48 hours, although the rain had stopped for most of 6 December when the waterfall was actually flowing. Perhaps of greater significance, both events were late within a period of two months, starting on 5 November, when the tarn catchment had been saturated with more than double the normal rainfall.

The waterfall event on 6 December drew in local photographers and featured widely in the national media, besides providing a memorable interlude for Sunday hikers who happened to have chosen Malham for their day out. But the subsequent event, on Boxing Day, was barely recorded, as it was seen by few and was photographed by no-one during the night.

Underground waters at Malham

With the cove normally dry, underground drainage in the karst around Malham was one of the first in

Fig. 3. The dry valley of Watlowes, which extends from Comb Scar to the lip of Malham Cove.

Britain to have been subjected to systematic water tracing. The stream from Malham Tarn (Fig. 5) normally sinks at various points close enough to be regarded as a single site, and collectively known as the Water Sinks (Fig. 6). But there are two significant risings in the valley below. Malham Cove rising, directly at the foot of the cove cliff, lies about 1.5 km south of the tarn sinks. A larger rising forms Aire Head another 2 km to the south, downstream of the village, and just beyond a synclinal outcrop of the cover shales.

Down the valley from Malham Tarn, and just south of the North Craven Fault, no cave is accessible because all the sites at Water Sinks are completely choked with cobbles and boulders within and from the glacial till cover; the active sinks vary with stage and also over time. Similarly without any accessible cave and lying just south of the fault, Smelt Mill Sink swallows a separate small stream just a kilometre west of Water Sinks. There is also no open cave at Aire Head where the water emerges from two gravel-floored pools; the resurgence is actually from the Limestone Conglomerate, which lies within the Bowland Shales succession of the Craven Basin, but is in hydrological continuity across the Middle Craven Fault with the Great Scar Limestone to the north.

There is a cave at the Malham Cove rising, but it is entirely underwater. Low passages from both the main and flood risings lead into the large, underwater conduit of Aire River Passage. This follows the bedding with a cross-section mostly around 5 metres wide and about a metre high; its water flows up the gentle dip, which means that the deepest parts so far explored are at the farthest limits, nearly 15 metres below resurgence level. The main passage continues beyond a boulder blockage on the line of a suspected fault 650 metres from the entrance, and directly beneath the dry valley of Watlowes; it is still being explored by cave divers.

A connection from the tarn sinks to Aire Head was proven in the 1870s by the Malham Tarn Estate owner, Walter Morrison, when artificial flood pulses were created by lowering the sluice gate at the tarn exit and monitored the flow at Aire Head. Then in 1899 the Yorkshire Geological and Polytechnic Society repeated the pulse tests and also poured ammonium sulphate into the Water Sinks; this was recorded strongly at Aire Head, but also as a trace at the cove rising. They also used fluorescein dye to prove the link from Smelt Mill Sink to the cove rising. From these tests grew the popular concept of crossing flow-paths at Malham, as Aire Head lies west of the stream from the cove. In the 1970s, tests with dyed *Lycopodium* spores, together with more pulse tests, confirmed connections from both sinks to both springs under various stages of flood flow. Subsequently, a number of small sinks on Pikedaw Hill and Grizedales, west of Watlowes, have been dye-tested, proving that

Fig. 4. The waterfall that flowed over Malham Cove on 6 December 2015 (photo by Ian Wray, Rossparry.co.uk).

Fig. 5. Malham Tarn viewed from the south, with the limestone scars in the foreground lying south of the North Craven Fault.

Fig. 6. Water Sinks, where the outflow from Malham Tarn sinks through coarse sediment into the limestone south of the North Craven Fault.

they combine with the flow from Smelt Mill Sink to supply most of the water resurging at Malham Cove rising during normal conditions.

During flood events, the flow at Aire Head increases only slightly, indicating a restricted size to the conduits that feed it. However, Malham Cove rising can emit massive flood flows, and it is clear that under flood conditions more of the flow from Water Sinks resurges at the foot of the cove. Major rainfall events also bring Cawden Burst to life. This is an intermittent spring on the western side of the hill of the same name, at the top end of Malham village. After exceptionally heavy rain a powerful stream emerges from a scree slope and flows down the road to join Malham Beck in the centre of the village. Typically this happens just once or twice a year, with each event lasting for about a day. A dye test has shown that at least some of its water derives from flood sinks down-valley from Water Sinks. Cawden Burst flowed during the cove waterfall events of December 2015, but with timing that did not match the cove waterfall. This suggests that the burst is not entirely linked to the tarn's floodwaters, but may also be an overflow of drainage from the Grizedale area to the cove rising.

Fig. 7. Gordale Scar, with the narrow fluvial gorge in deep shadow beyond its breach of the headwall of the wider rock amphitheatre.

Whereas the underground hydrology at Malham is relatively simple at low stage, the complexities of ephemeral underground connections and overflows under flood conditions are still only partly understood. A programme of dye and pulse tests in May 2016 revealed more details of flows to the three inlet passages in the underwater cave behind the Cove Rising. With a high degree of maturity in its conduit network, and with individual channels becoming active as stage increases, the karst aquifer at Malham is considerably more complex than just having crossing flow-paths.

Gordale Scar

Gordale Scar includes another great natural amphitheatre of limestone cliffs (Fig. 7), less than two kilometres east of Malham Cove. Its overall scale is comparable to that of the cove, except that it is more deeply recessed, has taller and more broken cliffs reaching to 100 metres high, and its rear wall is breached by a deep gorge. Within the gorge, the stream pours through the Hole in the Wall, which was formed in 1730 when water broke through a

Fig. 8. The perfect example of a meltwater ravine cut into limestone, in the shape of Gordale, upstream of its steeper and narrower descent through Gordale Scar.

Fig. 9. Malham Cove seen from a drone on 6 December 2015, when floodwaters flowed along the length of the Watlowes valley and then over the cove; the cove waterfall was already losing strength when this photo was taken, and was being blown from vertical by a strong cross-wind (photo by Ian Wray, Rossparry.co.uk).

thin blade of rock between two deep fault-guided gullies. Prior to that, the eastern gully had been choked with sediment and the stream dropped into the head of the western gully. The narrow gorge is the real Gordale Scar, and above it the rocky valley of Gordale (Fig. 8) is comparable to Watlowes, except that it is more than a kilometre long and still carries an underfit stream for its entire length. This drains from the basin that contains Great Close Mire and includes a tiny inlier of basement rock just north of the North Craven Fault.

Gordale is notable for its travertine deposits, which lie along much of the valley, form conspicuous cascades within the inner recesses of the Scar and form Janet's Foss further downstream. This abundance of travertine may be enhanced by Gordale's southerly aspect, which leads to soil temperatures being higher than in most other streams in the Dales karst. The largest travertine deposits are in the deepest part of the Gordale Scar gorge. These have been carbon-dated to 4850–1910 BP, and contain well-marked fossil fabrics of algal origin. Only one cascade is now depositing travertine, and that is the one from the Hole in the Wall. The entire bank of travertine beneath it has formed since 1730, when the stream broke through the thin limestone wall above. The pre-1730 travertine survives just to the west of its successor, as the relict bank at the foot of the earlier waterfall.

Fig. 10. Niagara's Horseshoe Falls dropping over a limestone cliff similar to Malham Cove in height and width, but fed by a river that is much larger and wider that any that could have flowed down Watlowes.

The origins of Malham Cove

Malham Cove and Gordale Scar can both be described as steps in their respective valleys, formed where they pass off the edge of the limestone plateau. That edge is defined by the Middle Craven Fault, which separates the limestone of the Craven Uplands in the north from the softer sedimentary sequence beneath the Craven Lowlands to their south. Each valley-floor step has retreated about 600 metres from the fault outcrop.

There has long been debate and discussion on the origins of the spectacular landforms of the Malham area. The morphologies of the two valleys, Watlowes and Gordale, are clear enough to demonstrate that they are essentially fluvial features. Furthermore, they are now recognized as meltwater channels, formed quite rapidly by powerful rivers, largely or entirely when the ground was frozen during cold stages of the Quaternary. That explains their development on the limestone, which is significantly less permeable when its fissures were all blocked by ice. But the cove and the scar are not so easily explained.

The old red herring of collapsed caverns was raised to explain Gordale Scar, rather too easily when the breakthrough Hole in the Wall was claimed to be a relic of the mythical cavern system. But it is now well known that collapsed caverns are extremely rare, and small-scale underground loops and rock arches are merely normal components of fluvial processes in limestone terrain. Modern science ascribes the deep, narrow gorge of Gordale Scar to fluvial erosion, albeit on a locally spectacular scale.

Early ideas had it that Malham Cove was a 'dry waterfall' but also that it was somehow associated with spring erosion along joints and cavern collapse. Much of the early literature on the Yorkshire Dales karst carefully avoided any attempts at explaining the origins of the cove, and still today there is no consensus on exactly how the cove was formed. Alternatives and combinations are acclaimed, each with some caution by its proponents. The story is complicated because four suites of processes (fluvial, glaciofluvial, glacial and karstic) have all been active during parts of the Quaternary evolution of the cove. It is almost inevitable that all four have left their marks, but debate continues over how much each process has been responsible for the rather splendid landform that we now know as Malham Cove.

Fluvial erosion

A simple history as a dry waterfall is supported by the dry, fluvial valley of Watlowes feeding to the head of the cove. The problem arises in the 200-metre-width of the cove, which far exceeds the 50-metre-width of the Watlowes valley (Fig. 9). Niagara-style waterfall retreat typically forms a gorge with a cliff at its head, with both gorge and cliff little wider than the river channel. At Niagara itself, the Canadian Falls form a horseshoe 250 metres across, so quite similar in size to Malham Cove (Fig. 10). However, the downstream gorge is little wider than the falls, and the upstream Niagara River is nearly a kilometre wide, both very different from the wide dale below the cove and the narrow Watlowes above it. Within the Yorkshire Dales, comparison may be made with Trow Gill (Fig. 11), the meltwater feature on the slopes of Ingleborough, where waterfall retreat cut a narrow gorge back into the cliff line in the same bed of limestone as at Malham Cove. Similarly, the narrow gorge of Gordale Scar is a fluvial feature with a shape totally unlike that of Malham Cove.

Undoubtedly, Watlowes and the cove have carried significant streams in the past. These could have been long-lived features active on the limestone plateau when underground drainage was inhibited by ground ice developed under periglacial conditions during phases of the Pleistocene. Or they might have been features of short-lived, pro-glacial drainage from remnants of Devensian ice on the Malham High Country. Either, any or all of such processes are likely to have contributed to the deepening of the valley and the shaping of the waterfall cliff, but simple fluvial erosion alone cannot account for all the morphological features of the cove.

Glaciofluvial erosion

Any consideration of fluvial erosion at Malham Cove has to rely heavily on Pleistocene flows of meltwater, from or beneath ice sheets, especially during their retreat phases. Surface flow over the limestone then occurred when cave flows were restricted or eliminated by permafrost, or when meltwater flows temporarily exceeded the capacity of the contemporary sinks. A variation on a meltwater origin for the cove is waterfall retreat during periodic, massive, sub-glacial floods, known as jökulhlaups, after their occurrences in Iceland.

Those massive floods emerging from the Icelandic ice sheets are generated by sub-glacial volcanic eruptions. Events only slightly smaller can develop where meltwater accumulates beneath warm-based glaciers to a point where the covering ice is floated and uplifted enough to allow the water to escape laterally between a rock floor and an ice roof. Waters from limestone springs around Malham Tarn currently have temperatures around 7 °C. A typical Devensian temperature decline of around 6 °C then suggests that these karst springs could have continued to flow during at least parts of the Last Glaciation.

Fig. 11. Trow Gill, the meltwater gorge cut into the limestone 15 km west of Malham with a plan-shape very different from that of the Cove.

Karstic spring water could then accumulate within the Malham Tarn basin, until it lifted the ice and escaped southwards down a sub-glacial or pro-glacial Watlowes. Such self-dumping of an ice-dammed or sub-glacial pond within the tarn basin could produce flows of 25–50 cubic metres per second over periods of a few days, with a scale and profile comparable to many jökulhlaups observed elsewhere.

Very large, short-lived flows of this style could more easily account for the scale of the Watlowes valley than could steady stream flows from the modestly sized, potential catchment of the tarn area. But they are still a long way short of the scale of floods that could be expected to create Malham Cove as an ephemeral waterfall. Probably the best-known landscapes produced by glacier burst floods are the coulees and scablands in America's Washington state. Dry Falls and the amphitheatre containing the underfit Palouse Falls (Fig. 12) bear comparison with Malham Cove, but both were formed by multiple flood events, each with flows that were thousands of times

Fig. 12. Palouse Falls, in Washington, USA. The underfit waterfall drops into a basalt amphitheatre about as deep and wide as Malham Cove, which was formed by truly massive, glacier-burst, meltwater floods that also carved an upstream valley far larger than Watlowes.

greater than any that could have been generated from ice-ponded waters in the Malham Tarn basin.

Although meltwater erosion in some form, either sub-glacial or pro-glacial, and probably enhanced by jökulhlaup events, has more potential power than simple fluvial erosion within the Malham environment, there are still problems of scale. Not only is Watlowes much narrower than the cove, but its upstream section, above Comb Scar, is even narrower. Furthermore, there is minimal evidence of tributary channels contributing to a single large flow over the cove; it is possible for water to flow through conduits entirely within the ice, thereby eroding no valley in the bedrock, but these are unlikely to be large or long-lived. Glaciofluvial processes could have been significant at Malham, but they cannot account for all the landforms that survive today.

Ice action

The site of Malham Cove lay beneath the ice during each of the Pleistocene glaciations. The well-known limestone pavements around the crest of the cove, and their more extensive counterparts across Broad Scars are the clearest indicators of ice erosion (Fig. 13). Pavements are truly features of glaciokarst. Their bare rock surfaces were scraped, scoured, plucked and swept clean by over-riding glaciers, before the diagnostic runnels and karren features were formed by karstic dissolution without any formation of soil cover. There is no specific evidence of ice action on the walls of the cove itself, but the valley below the cove has been over-deepened, and that was most probably by glacial excavation (Fig. 14). For 600 metres downstream from the cove, Malham Beck runs across an alluviated valley floor. It then drains through a post-glacial trench cut into limestone bedrock, immediately south of the Middle Craven Fault, and this forms the outer rim of the over-deepened basin (Fig. 15).

Significant support for the role of ice erosion comes from the cove's width of about 200 metres, being so much greater than that of the Watlowes valley feeding to its head. The gross imbalance between the features' sizes suggests that much of the cove's morphology could derive from origins as a sub-glacial step, where a Quaternary ice sheet moving southwards from Fountains Fell, Darnbrook Fell and Littondale descended to the Airedale lowlands over the fault scarp along the Middle Craven Fault. Through much of the Quaternary glacial episodes, ice was probably cold-based and therefore had little impact

Fig. 13. The well-known limestone pavements on the rim of Malham Cove, which are clear evidence that Quaternary ice flowed over the cove.

Fig. 14. The glacially over-deepened valley downstream of Malham Cove, seen from the bedrock rise at the downstream end, with the beck draining through a post-glacial trench off to the right.

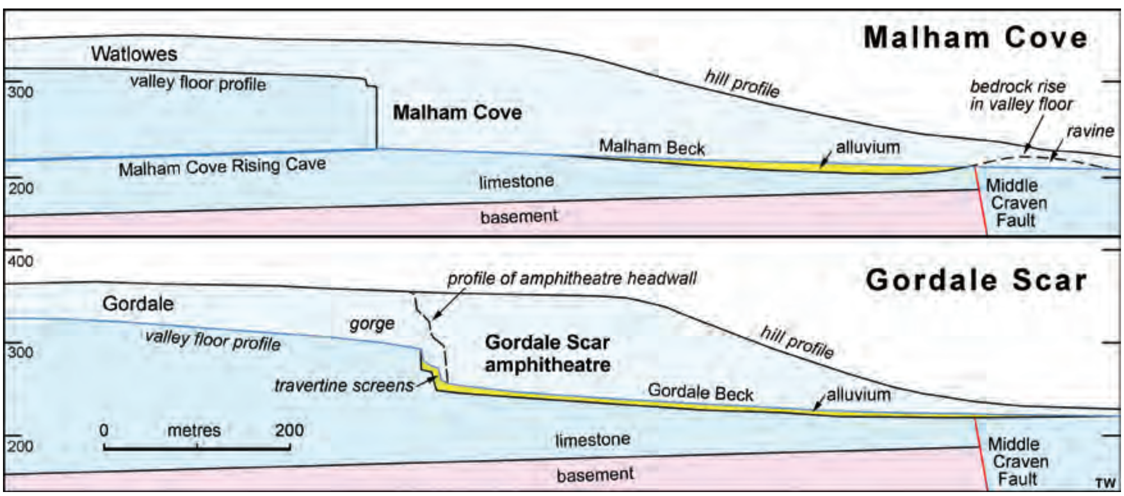

Fig. 15. Long profiles through Malham Cove and Gordale Scar together with their respective upstream meltwater channels of Watlowes and Gordale and their wider downstream valleys (after Waltham & Lowe, 2013).

on the landscape of the high fells. But, at critical times during the climatic oscillations, a change to warm-based conditions at lower altitudes would have given the ice significant erosive power at Malham Cove.

As the main source of ice would have been from the Littondale ice stream, it is likely to have moved almost due south across Broad Scars and then symmetrically over the cove amphitheatre. There is no reason to expect that ice was aligned along Watlowes, which is largely a younger, fluvial feature. Vertical joints within the limestone, and the weakness of the bedding plane (and the caves along it) at the foot of the cove would have facilitated the development of a steep back-wall by glacial plucking (a.k.a. quarrying).

Glacial quarrying and wall retreat beneath an ice sheet can exacerbate a small topographic feature, and can leave a vertical wall in strong, massive rock. Malham Cove can be compared with Vernal Falls in the Yosemite region of California. Those falls have a clear drop of 90 metres over the middle of a granite wall that is just slightly curved into a broad amphitheatre; this is the lower of two glacial steps along the Tenaya Valley, which still carries an underfit river (Fig. 16). Both steps are entirely within the granite, and their positions were largely influenced by a convergence of ice flows, as is the case with most steps in Alpine glaciated valleys. But the wide, vertical cliff at Vernal Falls is very similar to the topography of Malham Cove.

The rock-walled amphitheatre that is the lower, outer part of Gordale Scar is a landform of comparable size to that of Malham Cove, except that is more deeply recessed into the limestone plateau (Fig. 17). It too has retreated about 600 metres from the edge of the high ground marked by the Middle Craven Fault. Its origins are probably similar to those of Malham Cove, and are likewise open to debate regarding the processes involved. The one big difference at Gordale is the narrow gorge that forms the inner section of the scar, but it is clear that meltwater carved all or most of this into the headwall of the larger and older amphitheatre. Any assessment of the geomorphology of Malham Cove has to recognize its similarity with the Gordale amphitheatre (Fig. 18). Transplanted to an Alpine terrain, either feature could, and probably would, be described as a corrie headwall; but that is not exclusive, and many landforms are undeniably polygenetic.

Fig. 16. The waterfalls over two glacial steps along the Tenaya Valley in California; the downstream Vernal Falls is comparable in size to Malham Cove.

Karstic processes

The cove has been described as a pocket or headless valley, drawing on comparison with some of the cliff-bound headless valleys in the Causses and limestone plateaus of France. Concepts of their evolution are poorly defined, but are based on some combination of spring sapping, cavern collapse and river erosion. They do however involve very long timescales of development, without interruption by Quaternary glaciations, and are associated with rivers and cave

Fig. 17. The wide rock amphitheatre immediately downstream of Gordale Scar, formed by erosional retreat from the scarp of the Middle Craven Fault, which passes just behind the camera position.

systems of scales much larger than those at Malham.

Water emerging from the cave at the foot of Malham Cove does contribute to shaping of the cliff by dissolutional erosion, removal of rock debris and some undercutting of the limestone wall. The major bedding plane just below water level at the foot of the cove is scored by multiple, braided cave passages, each no more than about 5 metres wide. The caves have guided and aided surface retreat of the cove wall, but they are orders of magnitude smaller than the cove, and their role in its evolution was only minor. There is no cave at the back of the Gordale amphitheatre, so the foot of its cliff is a combination of rock buttresses and talus ramps.

There is the possibility that the main cave at Malham could have once been a vauclusian rising with an ascending passage where the face of the cove now lies. But that would have contributed to the formation of a narrow gorge as opposed to a wide amphitheatre. The entrance gorge at Peak Cavern, in the Derbyshire karst, developed from such a rising passage, and its dimensions are now very different from those of Malham Cove.

It is also possible that the over-deepened basin in front of the cove developed as a karstic feature, as a broad closed basin with an underground exit for its drainage. There is however, no sign of, nor evidence for, any cave outlet buried beneath the sediment, and the concept of glacial over-deepening better fits the overall morphology of the valley.

The debate continues

Even the age of Malham Cove is unknown. A stalagmite that is now below water level inside the cave passage behind the Cove Rising is dated to at least 27 000 years ago. This indicates that the valley in front of the cove had been eroded to close to its present profile prior to the main Devensian glaciation that shaped the details of so much of today's Yorkshire Dales landscape. The scale and morphology of any ancestral landform that pre-dated the Devensian is therefore yet another aspect of Malham Cove that remains unknown.

It is likely that all four of the above processes have contributed to the distinctive and unusual morphology of Malham Cove, but it is far from certain as to which processes were dominant. Whether or not enhanced by proglacial or subglacial meltwater, with or without jökulhlaup floods, fluvial erosion was largely responsible for developing the Watlowes and Gordale valleys; the same water must have contributed to shaping the cove at critical stages through the glaciation cycles. There is no doubt that Malham Cove was occupied and covered by ice during the Quaternary cold stages, and it remains difficult to explain the width of the cove without some element of glacial erosion. Karstic processes cannot have played a major role.

Fig. 18. The comparable erosional amphitheatres in front of Malham Cove (on the left) and Gordale Scar (on the right), with the main cliff lines picked out in red (satellite imagery from Infoterra).

Short of detailed mapping revealing more evidence, the origins of Malham Cove remain unresolved. There is no consensus among geomorphologists familiar with the site, most of whom steer clear of offering opinion. Though Malham Cove is one of the best known features of the Yorkshire Dales, it remains one of the least understood.

Suggestions for further reading

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