Landforms of the Yorkshire Dales: unresolved debates

Tony Waltham

Abstract: A presidential address is an opportunity to take a fresh look at the Yorkshire Dales, not to see what is known so well about them but to see what is still unknown. Still open to debate are processes concerning stratimorphs, limestone pavements, erratic plinths, sulphuric acid and sub-glacial caves, while classic sites at Malham Cove and Brimham Rocks continue to provoke discussion. Questions are posed, but not all have answers that are readily available.

Known for their spectacular geology and their landscapes of glaciation and karst, the Yorkshire Dales remain enigmatic in some aspects of their geomorphology.

Major features of the Dales geology are well known, well documented and summarised in Aitkenhead et al (2002). Further detail is in the Settle Memoir (Arthurton et al, 1988) and the Orefield Economic Memoir (Dunham & Wilson, 1985), but the Hawes Memoir, covering the heart of the Craven Dales, never made it to print. Geological map coverage is good except that the best version currently available for the Pateley Bridge Sheet dates from 1889. The karst geomorphology of the Yorkshire Dales is comprehensively described in Waltham & Lowe (2013), which includes an important chapter with the only recent overview of the Dales glaciations (Mitchell, 2013).

Now that the author is past any serious research or fieldwork, and well into his dotage, this presidential address is an opportunity to dwell upon questions that remain unanswered within the geomorphology of the Yorkshire Dales. Conflicting opinions are reviewed without pressure to provide answers, some beliefs are indicated, and debates are left open. These are the questions upon which the author so often ponders.

Stratimorphic benches

Early accounts of the Craven Dales (around Malham and Ingleborough) followed Davisian principles in ascribing the landscape evolution to successive rejuvenations of peneplains and erosion surfaces (Sweeting, 1950), but this has not stood the test of time. It was Trevor Ford (1951), a past president of our Society, who first suggested, in a little-known publication, that the great limestone benches around Ingleborough looked more like structural features than erosion surfaces. These are now known as stratimorphs, being topographical features defined by an individual strong bed within the sedimentary sequence (Fig. 1). A ‘1300-foot erosion surface’ was the core feature in Marjorie Sweeting’s paper, but re-assessment of its elements has invalidated its geomorphological origins as an erosion surface by recognising the geological controls of its landforms (Waltham & Long, 2013).

Wrapped around the Three Peaks, most noticeably Ingleborough, the great benches at the top of the Great Scar Limestone are truly spectacular stratimorphs, with their expanses of nearly horizontal limestone pavements, and also the inclined pavements that overlook parts of Chapel-le-Dale. However, the situation is not so clear in the high ground above Malham. Upland at altitudes around 400 metres (which is close to 1300 feet) extends over a large area that includes outcrops of multiple limestone beds along with greywackes of the Malham Tarn inlier, and also straddles the North Craven Fault. The nearly flat land on variable geology within the Malham Tarn basin was presented as key evidence for the 1300-foot erosion surface. Furthermore, the gently rising limestone block to its south, incised by Gordale and Watlowes, can be regarded as outcrops of stronger rock that were being eroded but had not yet reached the profile of a never-perfect peneplain.

Within the Dales landscape of conspicuous stratimorphs, the Malham Tarn basin therefore appears to be the exception in that it preserves elements of

__Figure 1__. The stratimorph that forms the wide bench on the top of the Great Scar Limestone round the northeastern side of Ingleborough.

erosional planation to a contemporary base-level, which was probably local and not at sea level. Such a feature can be expected in any terrain with a long history of denudation and isostatic uplift, but the challenge remains in recognising these early features of landscape evolution where so much of the topography is defined by the underlying geology.

Limestone pavements

The lunar landscapes of bare rock across many parts of the limestone benches within the Craven Dales are known around the world as magnificent landforms of glaciokarst, swept clean by Devensian ice and subsequently fretted by post-glacial dissolution (Fig. 2). But they present a problem in being either or neither rillenkarren or rundkarren, the two main types of fretted limestone surface originally defined by Bögli (1960).

Within the Dales pavements, the rounded edges of the blocks and fissures (locally known as clints and grikes) are clear evidence of sub-soil dissolution whereby the rock surfaces are attacked in all directions by groundwater held with the soil cover (Webb, 2013). Bare limestone that is exposed to direct rainfall develops sharp-edged rillenkarren, as originally described in the Alps, and can be seen in many places around the world (Fig. 3). The implication is that limestone in the Dales has previously had an almost complete soil cover, which could have been any of various types.

A cover of permeable loess, largely derived from glacio-fluvial sediments in the Irish Sea basin, was extensive and much of it still remains (Wilson et al, 2012). Large amounts of loess have been washed underground to form cave mud, suggesting that its cover was once more extensive over the pavements, though not matching the complete loess cover that formed over the Peak District karst while it was never covered by Devensian ice. Glacial till lies on much of the limestone outcrop, whereas other areas never had a till cover. Till removed by post-glacial erosion was impermeable where it had a clay groundmass, preventing any rockhead dissolution beneath it, as indicated by the glacial striae emerging from under the till cover at Long Kin East on Ingleborough; sandy till would have allowed dissolution of underlying limestone. Organic soils, like that now preserved in Colt Park Wood, on Ingleborough, were extensive before being lost to woodland clearance and sheep grazing since Neolithic times. Little peat has ever developed on the limestone, except where it was rooted in loess or till, but its acidic drainage would have contributed to limestone dissolution.

***Figure 2**. Typical Dales limestone pavement, on the Ingleborough bench, with its rounded features comparable to sub-soil rundkarren.*

***Figure 3**. Rillenkarren that are typical of rainwater erosion of bare limestone; these are in Brazil, where lichen growth is impeded by strong solar radiation.*

The pavements were stripped bare by glacial scour before deglaciation of the Dales' high ground took place at around 17 ka (Wilson & Lord, 2014), during or after which the various soils could accumulate on them. Subsequently, some of this soil cover has been removed by erosion (Fig. 4), but it is difficult to conceive soil cover over all of the huge areas of pavement. Which leads to the concept of some of the rounded karren developing beneath the lichen that is ubiquitous on the surfaces of the Dales' limestone. Lichen growth contributes to erosion by decomposing the skin of the rock, and it may also aid dissolution by retaining water against the rock surface, thereby acting as a micro-soil. It might be significant that pavements on similar limestone on Ireland's Aran Islands lack comparable rounding of the clint edges where lichen cover is absent, probably due to wind-blown saltwater spray (Waltham, 2020).

Figure 4*. The well-known limestone pavement above Malham Cove, with its retreating cover of a loessic soil. The emerging limestone is scored by classic sub-soil rundkarren, whereas the pavement farther from the camera is less deeply dissected because it had less time beneath a soil cover.*

Erratic pedestals and erosion rates

Well known is the spectacular train of glacial erratics at Norber, on the southern flank of Ingleborough. Many boulders of greywacke stand on low pedestals of limestone that have long been taken to be sheltered from rainfall, therefore indicating surface lowering on the adjacent limestone (Fig. 5). However, this simple idea is now seen as fraught with problems.

Some of the pedestals are wholly or partly the edges of small bedrock terraces, with heights varying with bed thickness (Goldie, 2005). Dissolution on the adjacent limestone depends on whether it was sub-soil or subaerial since deglaciation (Parry, 2007), and all inferred dissolution rates have to be adjusted from when they were based on deglaciation assumed to be at around 14 ka since emplacement of the boulders has now been dated at about 18 ka (Wilson et al, 2012).

Calculated rates for surface lowering of the limestone vary between 10 and 50 mm/ka, whether from pedestal heights or by other indirect methods (Waltham, 2013). Applicable to non-glacial erosion of upstanding limestone benches these are reasonably in proportion with overall denudation rates for the Dales estimated at 100–150 mm/ka; the latter include valley incision, shale erosion and glacial action, all of which exceed surface lowering that is likely to occur on a plateau of strong limestone.

There is still a good story in the Norber boulders and their pedestals: but there are no clear answers where there are so many complexities in the processes. The debates continue.

Evolution of Brimham Rocks

Away from the limestone, the overlying grit also poses unanswered questions. Notably as to why Brimham Rocks are broken and carved into their fanciful shapes so much more that the same gritstone on other nearby plateau edges. The everlasting debate over tors, whether of periglacial or deep sub-soil chemical weathering, is of little consequence at Brimham. The detailed fretting of those tors has often been described as aeolian, with sand-blasting at a maximum during deglaciation of the area to create landforms akin to zeugens. However, the profiles of many of the Rocks at Brimham are clearly related to the bedding within the grit, and can therefore be ascribed to normal weathering that picks out lithological differences.

Perhaps the greater debate should be as to why Brinham Rocks is distinguished by fractures that are wider between the remnant tors than at any other outcrop in the same or comparable gritstones (Fig. 6). It appears that fissures wider than elsewhere existed prior to any weathering and etching of what are essentially the walls of open fissures. Such widening of the fissures could be due to cambering of the grit over softer shales beneath, with an element of sliding south of westwards towards the Nidd Valley. Or it could be due to glacial drag where ice moved west of southwards over the site beneath the confluence of ice streams from the Nidd Valley and the Vale of York.

There has to have been something special to account for the spectacle, unequalled in Britain, but there is as yet no clear answer as to what that was.

Figure 5*. Glacial erratic standing on a limestone pedestal at Norber; the level of the surrounding limestone surface is not readily ascertained for the purpose of estimating a dissolution rate.*

***Figure 6**, Brimham Rocks, distinguished by so many wide fissures between its tor blocks.*

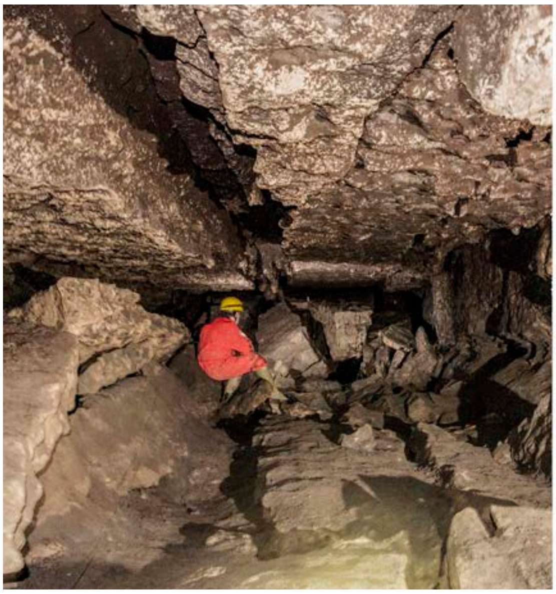
Caves developed by sulphuric acid

A remarkable series of maze caves has been found in the Yoredale limestones of the northern Dales, all but one of which are only reached through abandoned mine workings (Harrison, 2016). These are hypogene caves developed by slow flows of groundwater laterally though the limestones and constrained by impermeable beds above and below; they are distinguished by dense reticulate networks of joint-guided passages (Fig. 7). Sulphuric acid, derived by oxidation of sulphide minerals in the numerous hydrothermal veins of the orefield, has greatly aided dissolution of the limestone (Dale et al, 2015). Acid production has been largely ascribed to the change from the abundant galena to cerrusite, though its main source has been claimed as pyrite, even though this is much less common around the caves (Webb, 2021). The latter paper was a desk-study produced without the author visiting the caves; its comments on cave morphology have been largely discredited, and its theoretical considerations of the chemistry must be regarded with scepticism.

While debate continues over the details, sulphuric acid has clearly played some role in the formation of these Yoredale maze caves. This then raises the question of mineral acids flowing through micro-fissures on joint networks during the earliest stages of cave inception within the Great Scar Limestone of the Craven Dales. Though large passages (large enough for a man to enter) are now the conspicuous feature of the Dales caves, there is still much to learn about just how groundwater first found its way through large masses of very solid limestone.

The enigma of Malham Cove

It is slightly frustrating, indeed contrary, that Malham Cove is the best-known single site within the Yorkshire Dales glaciokarst, but cannot claim to be a karst landform (Fig. 8). For too many years, publications on



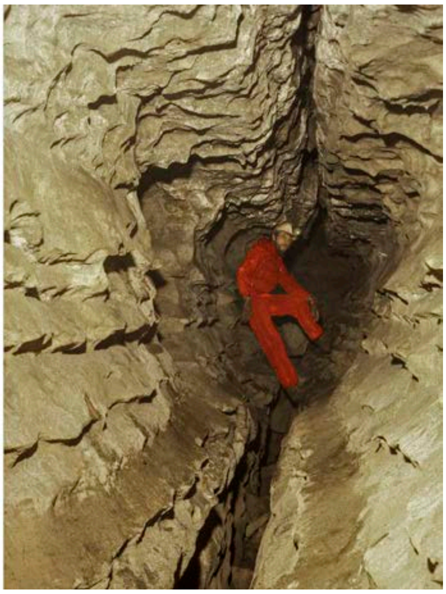


***Figure 7**. Joint-guided passages in the maze caves of the Northern Pennines, where sulphuric acid appears to have contributed to limestone dissolution. On the left in mineralised limestone at Hudgill Burn Mine Caverns, and on the right in Knock Fell Caverns where there are no adjacent mineral veins.*

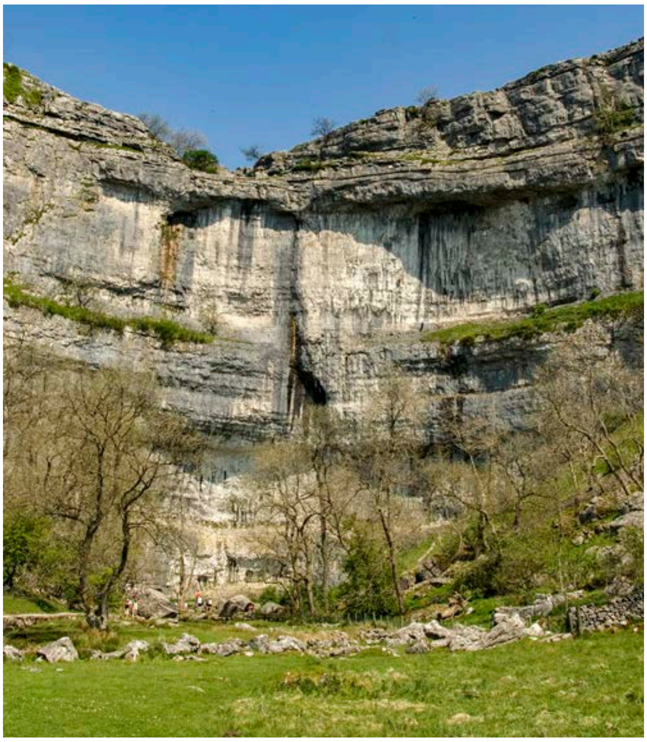


***Figure 8**. Malham Cove, still with no full story of its evolution.*

the geomorphology of the Malham area, too numerous to cite, have carefully avoided any explanation of the origins of that great white cliff that is the Cove. Its simple description as a 'dry waterfall' is escapist, even though it did have a short spell of activity in December 2015. The unresolved debate on whether Malham Cove is largely fluvial or glacial, and how much aided by fluvioglacial and karstic processes, has been outlined previously (Waltham, 2017a, and more briefly in 2017b), so will not be repeated here. But the question remains, research and fieldwork are required, and no answers are yet in sight.

Pre-Anglian terrains

It is not too difficult to conceive the pre-Devensian landscapes of the Yorkshire Dales. To be pedantic, the dales are glaciated valleys, and not glacial valleys, as they were largely excavated during long periods of fluvial erosion and were only modified during the much shorter interludes of ice cover (Fig. 9). Their lovely U-shaped profiles benefitted from only marginal trimming by the Devensian glaciation (Waltham et al, 2010). It is likely that the Anglian glaciation had a much larger impact on landscape evolution across the Dales.

Post-Anglian events are tied to an absolute chronology based on U-Th dating of stalagmites and cave rejuvenations, so the progress of valley incision can be roughly estimated (Waltham, 2013). However, pre-Anglian events are difficult to date. Improved laboratory techniques have pushed the limit of U-Th dating back from about 350 ka to nearly 600 ka (Lundberg et al, 2010), but any older dating relies on Be-Al dating of siliceous cave sediments, which has not yet been applied to Dales material. There are great banks of stratified sand in very old cave passages, notably in Lancaster Hole, Ireby Fell Cavern and the Gaping Gill Cave System, but their study awaits research funding.

Meanwhile, isostatic uplift in response to denudational unloading has been recognised as a process that parallels erosion, and reasonable estimates of uplift rates have been compiled (Westaway, 2009). But any chronology of pre-Anglian evolution of the Dales relies on extrapolations of processes and rates that verge on the tenuous. A very approximate conceptual model shows landscapes evolving while uplift brings older rocks to outcrop (Fig. 10).

Early exposures of limestone outcrops in valley floors can be recognised by cave passages that carried drainage beneath intervening outcrops of grit. One is

***Figure 9**. The near-perfect U-shaped glaciated trough of Wharfedale, with the village of Kettlewell on its floor.*

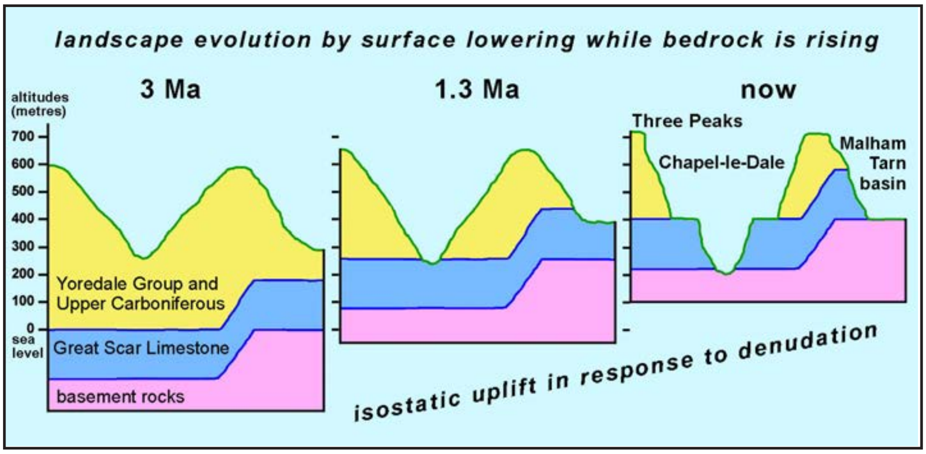


***Figure 10**. Evolution of the Dales landscapes, based on incision rates derived from stalagmite dates in drained caves, with summit denudation slower than valley floor incision and isostatic uplift due to denudation. The monocline between Chapel-le-Dale and the Malham Tarn basin is an artefact of the compressed drawing; the beds have a steady gentle dip. At about 1.3 Ma, limestone was first exposed in Chapel-le-Dale and doline karst formed above Malham. At around 3 Ma, the top of the limestone in Chapel-le-Dale was at sea level and far below the land surface.*

known for some length beneath the flank of Gragareth, while another is known only as a fragment at Victoria Cave (Fig. 11). These contribute to constructing a paleo-geography, and a paleo-geology, for the early Pleistocene in the Yorkshire Dales. That was a key period in the evolution of the landscapes, but further dating of cave sediments is required to establish a real chronology of these early events.

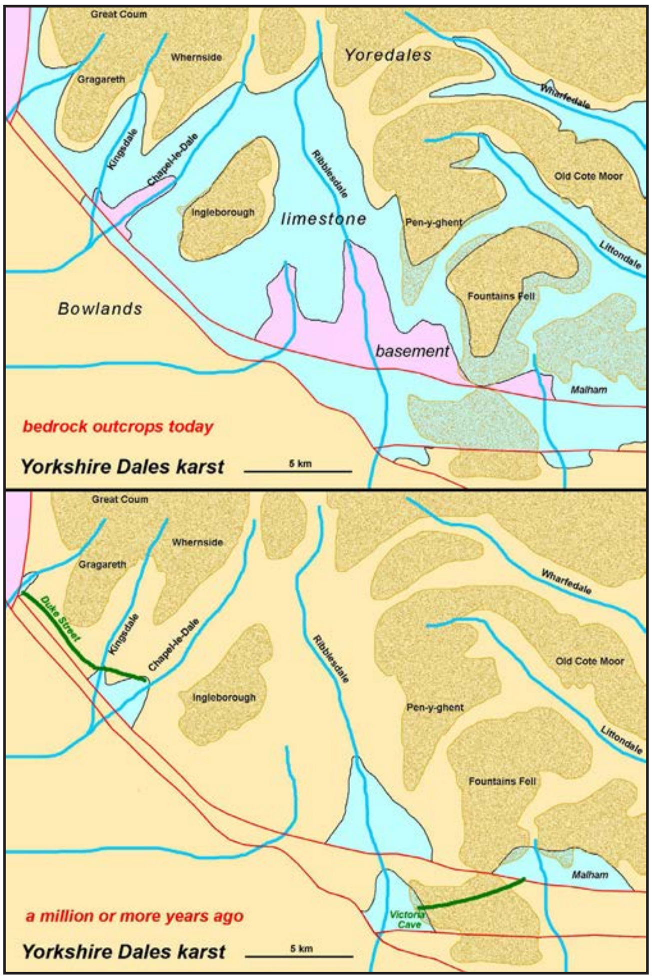


***Figure 11**. Above, an outline geology of the Craven Dales; and below, a conceptual outline of the same area more than a million years ago. Lower map is hugely simplified as it is based only on current topography with the geology at a lower level. Two cave drainage routes are shown in dark green.*

Caves beneath Pleistocene ice

Preglacial caves are known to exist in the Yorkshire Dales by way of the dated stalagmites within them (Latham & Ford, 2013). Caves existed beneath complete ice cover during both the Anglian and Devensian glacial maxima, though the extent of ice across the Dales during the intervening 'Wolstonian' cold stages remains open to speculation.

An interesting question hangs on the processes and situation within the caves during those periods of ice cover, especially with respect to their glacial rejuvenation (Fig. 12). The age distribution of dated stalagmites from the Dales caves indicates peaks of calcite deposition during the interglacial stages (Latham & Ford, 2013). This is to be expected, but U-Th dating is not precise enough to indicate any complete cessation of deposition during the glacial maxima.

Cryogenic cave calcite forms when water, draining from unfrozen ground, turns to ice in a cave that has freezing air draughting through it (Zak et al, 2004). As the water freezes, it becomes increasingly enriched in ions to the point of super-saturation and precipitation of calcite. Found on the floors of caves, crystals and loose grains of cryogenic calcite are generally only a few millimetres in size, though some up to 40 mm in diameter have been discovered in southern England. Cryogenic calcite is difficult to recognize, and none has yet been confirmed from Dales caves.

Appreciation of the past situations within the Dales caves can benefit from analogy with Castleguard Cave in Canada, which extends beneath the Columbia Icefield (Ford, 1983). Meltwater from the floor of the icefield does drain through the caves (Smart, 1983), but it has an available outlet at a large rising in an adjacent ice-free valley, whereas limestone in sub-glacial Yorkshire could not have drained out when the dales were occupied by glaciers. Castleguard's active conduits remain unseen, and it is likely that the water drains through old passages that formed under interglacial conditions. Both the main passage and various side passages in Castleguard Cave are sealed by ice plugs (Fig. 13) where they are truncated beneath the floor of the Columbia Icefield (Waltham, 1974).

***Figure 12**. A high-level passage in White Scar Cave; it was formed by pre-Anglian flow beneath Chapel-le-Dale, and was drained by Anglian glacial incision. It has probably looked much the same ever since, including when it lay beneath Devensian ice, except that the straw stalactites are post-glacial.*

Sub-glacial flows may distribute sediment within the caves, but, lacking in biogenic carbon dioxide, are unlikely to be forming new passages by dissolution. However, there are small active stalactites in Castleguard passages far from the margin of the ice-cap, so a minimal level of karstic dissolution and deposition does appear to occur beneath the ice.

***Figure 13**, The ice plug in Castleguard Cave, beneath Canada's Columbia Icefield, which bears comparison with ice that might have sealed off the Dales caves during the glaciations.*

From the available scraps of evidence, it appears likely that the Dales caves were largely or completely sealed off during the interludes of Pleistocene ice cover. They probably remained static (frozen in time would be the obvious pun) for some thousands of years, but there is still much to learn about how processes in the Dales karst slowly declined and then reactivated at the start and end of each cold stage.

Glacial meltwater can be a powerful agent of erosion, and it clearly had significant impact on landscape evolution in the Dales. There is still much to learn about processes during those critical periods of environmental change created by the climatic fluctuations of the Pleistocene. The glorious landscapes of the Yorkshire Dales can still provoke discussion among its geologist visitors (Fig. 14).

***Figure 14**. The view across the limestone benches towards Ingleborough.*

References

The author's publications are available as free downloads at www.geophotos.co.uk.

Aitkenhead, N. & 6 others 2002. The Pennines and adjacent areas. *BGS British Regional Geology*, 206 pp.

Arthurton, R. S., Johnson, E. W. & Mundy, D. J. C. 1988. Geology of the country around Settle. *British Geological Survey Sheet Memoir*, 60, 147 pp.

Bögli, A. 1960. Kalklosung und Karrenbildung. *Zeitscrift fur Geomorphologie*, Supplbd. 2, 4–21.

Dale, J., Harrison, T., Roe, P. & Ryder, P. 2015. Britain's longest maze cave: Hudgill Burn Mine Caverns, Cumbria, UK. *Cave Karst Science,* **42**, 20–41.

Dunham, K. C. & Wilson, A. A. 1985. Geology of the Northern Pennine Orefield: Volume 2, Stainmore to Craven. *British Geological Survey Economic Memoir*, 247pp.

Ford, D. C. (ed.) 1983. Castleguard cave and karst, Columbia Icefields area, Rocky Mountains of Canada; a symposium. *Arctic Alpine Research*, **15**, 423–554.

Ford, T. D. 1951. Northern Pennine karst: a postscript. *Cave Research Group Newsletter*, 35, 3–4.

Goldie, H. S. 2005. Erratic judgements: re-evaluating solutional erosion rates of limestones using erratic-pedestal sites, including Norber, Yorkshire. *Area*, **37**, 433–442.

Harrison, T. 2016. Maze caves of the Northern Pennines, UK. *Cave and Karst Science*, **43**, 21–36.

Latham, A. & Ford. D. 2013. Chronology of the caves [of the Yorkshire Dales]. 169–180 in Waltham & Lowe, *op. cit*.

Lundberg, J., Lord, T. C. & Murphy, P. J. 2010. Thermal ionization mass spectrometer U-Th dates on Pleistocene speleothems from Victoria Cave, North Yorkshire, UK: implications for palaeoenvironment and stratigraphy over multiple glacial cycles. *Geosphere*, **6**, 379–395.

Mitchell, W. A. 2013. Glaciation and Quaternary evolution [of the Yorkshire Dales]. 29–64 in Waltham & Lowe, *op. cit*.

Parry, B. 2007. Pedestal formation and surface lowering in the Carboniferous Limestone of Norber and Scales Moor, Yorkshire, UK. *Cave Karst Science*, **34**, 61–68.

Smart, C. C. 1983. The hydrology of the Castleguard karst, Columbia Icefields, Alberta, Canada. 471–486 in Ford, *op. cit*.

Sweeting, M. M. 1950. Erosion cycles and limestone caverns in the Ingleborough district. *Geographical Journal*, **115**, 63–78.

Waltham, T. 1974. Castleguard Cave, Canada. *British Cave Research Association Bulletin*, 5, 18–28.

Waltham, T. 2013. Karst geomorphology [of the Yorkshire Dales]. 65–92 in Waltham & Lowe, *op cit*.

Waltham, T. 2017a. Malham Cove: splendour and enigma. *Geology Today*, **33**, 32–40.

Waltham, T. 2017b. Malham Cove. *Mercian Geologist*, **19**, 116–120.

Waltham, T. 2020. Pavements of the Aran Islands. *Mercian Geologist*, **2**0, 63–65.

Waltham, T. & Long. H., 2011. Limestone plateaus of the Yorkshire Dales glaciokarst. *Cave Karst Science*, **38**, 65–70.

Waltham, T. & Lowe, D. (eds), 2013. *Caves and Karst of the Yorkshire Dales*. British Cave Research Association: Buxton, 255 pp.

Waltham, T., Murphy, P. & Batty, A. 2010. Kingsdale: the evolution of a Yorkshire dale. *Proceedings Yorkshire Geological Society*, **58**, 95–105.

Webb, J. A. 2021. Supergene sulphuric acid speleogenesis and the origin of hypogene caves: evidence from the Northern Pennines, UK. *Earth Surface Processes Landforms*, **46**, 455–464.

Webb, S. 2013. Limestone pavements [of the Yorkshire Dales]. 93–110 in Waltham & Lowe, *op. cit*.

Westaway, R. 2009. Quaternary uplift of northern England. *Global Planetary Change*, **68**, 357–382.

Wilson, P. & Lord, T. 2014. Towards a robust deglacial chronology for the northwest England sector of the last British-Irish Ice Sheet. *Northwest Geography*, **14**, 1–11.

Wilson, P., Lord, T. C. & Vincent, P. 2012. Origin of the limestone pedestals at Norber Brow, North Yorkshire, UK: a re-assessment and discussion. *Cave Karst Science*, **39**, 5–11.

Žák, K., Urban, J., Cílek, V. & Hercmand, H. 2004. Cryogenic cave calcite from several Central European caves: age, carbon and oxygen isotopes and a genetic model. *Chemical Geology*, **206**, 119–136.

Tony Waltham, tony@geophotos.co.uk
11 Selby Road, Nottingham NG2 7BP

Back cover photographs

Images of the Yorkshire Dales by Tony Waltham. Clockwise from the top: Scales Moor, above Chapel-le-Dale, a stratimorphic surface on the top of the Great Scar Limestone, with glacial erratics of Namurian gritstone; Idol Rock, at Brimham Rocks, formed of Namurian Brimham Grit undercut along a weaker, clay-rich horizon; the older part of Foredale Quarry in Ribblesdale exposing the basal unconformity of the Great Scar Limestone overlying Silurian Horton Flags; drumlins at Ribblehead; the glaciated trough of Wharfedale, upstream of Kettlewell; the meltwater gorge of Gordale, upstream of the Scar.