CHAPTER 4

Karst geomorphology

Tony Waltham

The limestone terrains of the Yorkshire Dales provide spectacular examples of well developed glaciokarst. The broader landscapes and many of the individual landforms owe their origins to processes of both karstic dissolution and glacial erosion. Glaciokarst is defined as a karst that is actively being, or has recently been, glaciated (Fig. 4.1). In this context, 'recent' extends back into the Pleistocene, when the Yorkshire Dales region was glaciated during several of the cold stages and karst was developed on the limestone during the intervening warm stages. There is huge variation among the landforms of glaciokarst, depending largely on the altitude and aspect, on any inheritance of earlier features, and on the thickness, flow and erosional power of either warm-based or cold-based ice within each glaciation.

In a global perspective, the youngest glaciokarsts have been exposed for only a few hundred years since the Neoglacial retreat, and have extensive bare rock, small and immature sinks, and minimal dissolutional rounding of landforms (Fig. 4.2). Older glaciokarsts, which have been exposed for 10,000 to 15,000 years since retreat of the Devensian ice, retain the bare outcrops, though with dissolutional modification, and have a proportion of larger and more mature sinks. The Yorkshire Dales glaciokarst is of the latter type. Limestone pavements are diagnostic of glaciokarst, though their morphological details vary with the antiquity of the glaciation, as well as with lithology, joint densities and aspect. The pavements on the great limestone benches between the dales of Yorkshire are justifiably famous, and are the most conspicuous feature of the glaciokarst. They evolved from surfaces that were eroded and scoured by ice sheets, largely during the Devensian. Many or most pre-existing karst features are destroyed by a glaciation, but some relics can survive, and the landforms of the Dales karst still include some large dolines and open caves that have survived from before the Devensian glaciation.

The limestones of some alpine glaciokarsts have, or had, high-altitude glaciers feeding meltwater into them and resurging far below in valleys without glaciers. This was generally not the case in the Yorkshire Dales, where the ice cover was total during the Pleistocene glacial maxima, analogous to the ice cover now in Greenland. Valley glaciers existed in the Dales only during the phases of advance and retreat, and the prolonged retreat phase of the Devensian glaciation was largely responsible for trimming the distinctive U-shapes of the main dales (see Chapter 3). There is still debate about the extent and capability of underground drainage beneath the ice cover (see Chapter 7).

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Periglacial activity (in cold conditions but without ice cover) during those same marginal phases of ice advance and retreat further complicates detail in some of the sub-aerial and sub-surface landforms.

The terrain of the Yorkshire Dales is essentially one that has been greatly modified by ice action. Karst features are merely superimposed on the large-scale glaciated topography, though this does not imply that they are all later than the Devensian glaciation. The great glaciated troughs of the dales, which give their name to this part of Yorkshire, are the dominant landforms (Fig. 4.3). The karst largely fits around these, mainly in the form of the cave systems that lie beneath the flanks, and in some cases beneath the floors, of the dales and their ancestral valleys. Though the dales were modified and deepened by flows of ice directed along them, ice also swept over the limestone benches and over even the highest summits during each glacial maximum (see Chapter 3). Where this ice was moving enough to maintain some erosional power it left behind expanses of bare limestone pavement, but wasting of the ice, particularly where it slowed or stagnated in the lee of hills, left sheets of till that were later pocked by subsidence dolines. The landforms of the high benches combine with those along the glaciated troughs to produce an impressive glaciokarst within the Dales.

The limestone benches

A major element of the Yorkshire Dales landscape is the series of broad plateaus and benches formed roughly on the top of the strong, sub-horizontal Great Scar Limestone and standing 100–150m above the floors of the intervening dales. In the Craven Dales, they are all overlooked by residual masses of Yoredale rocks that form the main summits, including the Three Peaks, so are best described as benches, though they are also commonly referred to as plateaus. The best of these, notably around most of Ingleborough and along both flanks

***Figure 4.1**. Bare limestone, open pavements and rock scars are the elements of glaciokarst at Comb Scar above Malham (TW).*

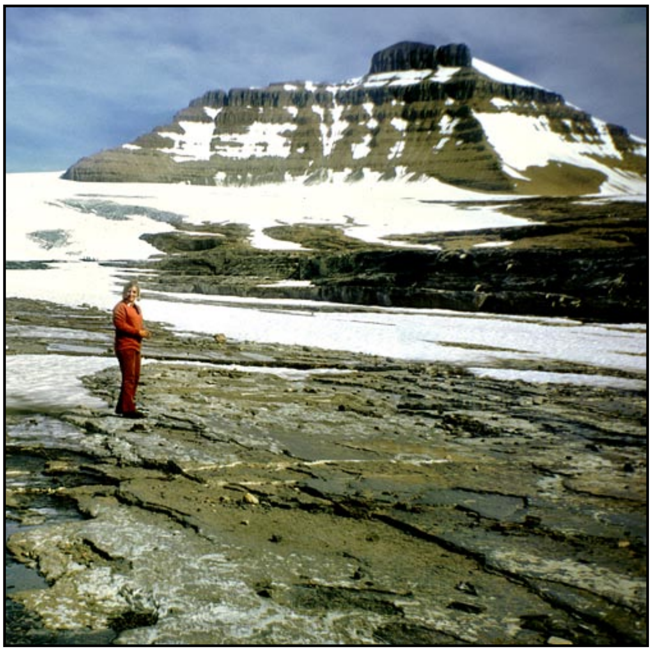


Figure 4.2. *An ice-scoured rock pavement of limestone in a young glaciokarst, only exposed for a few hundred years since Neoglacial ice retreat in the Canadian Rockies; much of the Dales pavement looked like this prior to evolution by post-glacial dissolution (TW).*

of Chapel-le-Dale, are great rock platforms surfaced with extensive limestone pavements (Fig. 4.4). At other locations, notably along the sides of Wharfedale and Ease Gill, the top of the Great Scar Limestone is marked by little more than gently rounded shoulders, with thin strips of pavements and limestone crags almost masked by blankets of glacial till.

Stratimorphs are topographical surfaces formed by individual beds of strong rock, where weaker cover material has been stripped away by erosion. It is clear that most of the great limestone plateau surfaces within the Dales karst are stratimorphs (Waltham and Long, 2012). They are developed on the top surfaces of just a few beds of strong limestone in the uppermost part of the Great Scar Limestone succession (Fig. 4.5). These are the same beds that now form the largest of the limestone pavements with the particularly extensive unbroken clints. The stratimorphs were developed by progressive stripping of overlying beds of weaker rock, largely by ice-quarrying (or plucking as it used to be known) from their down-glacier margins (Fig. 4.6).

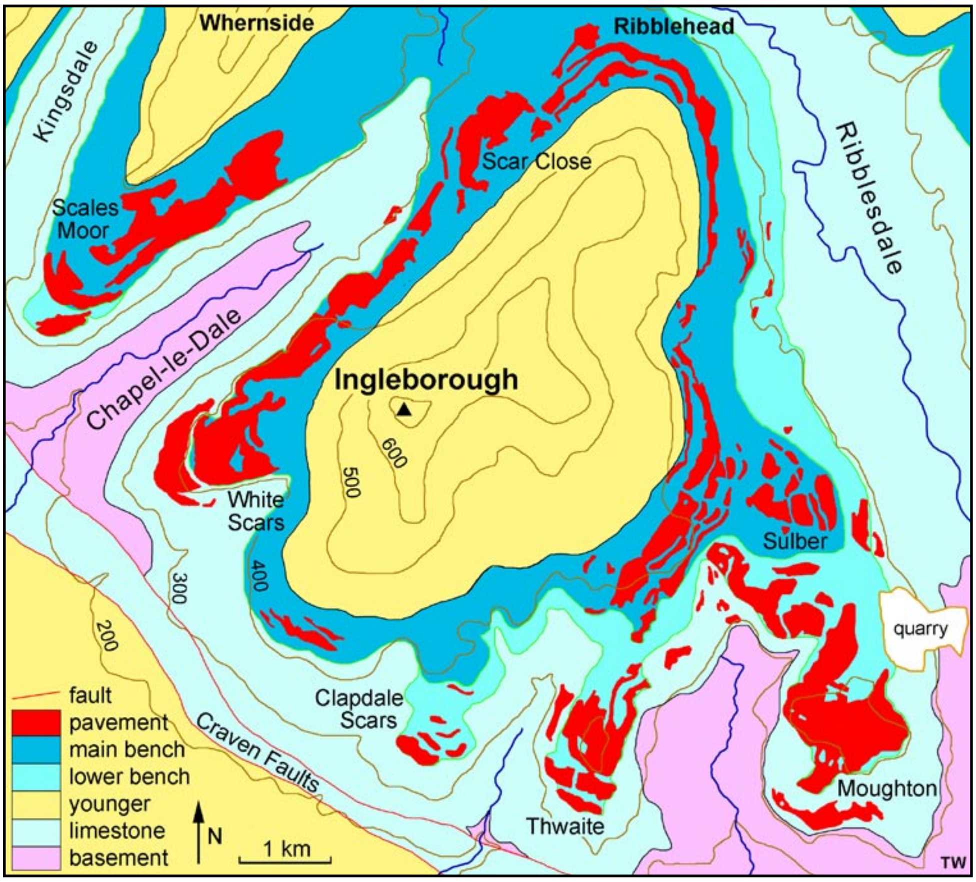
Figure 4.4. *The expanse of limestone pavement, a characteristic karst landform of the Yorkshire Dales, on the eastern bench of Ingleborough; Pen-y-ghent rises in the distance (TW).*

The stratigraphical control of these surfaces is most evident where they are inclined to follow the local dips. This is particularly conspicuous on the western flank of Chapel-le-Dale, where the great pavements of Scales Moor slope northwards from their horizontal expanse on the wide bench above Twisleton Scars, and descend more than 50m to where they are partially obscured by till between Weathercote and Bruntscar. Gently sloping pavements also follow the various gentle folds on Moughton Scar, above Crummack Dale. There, the large-scale feature that is the plateau surface is best described as a number of stratimorphic surfaces on a series of closely-spaced bedding planes.

The expanses of limestone pavement on the main benches are perhaps the highlight of the Dales glaciokarst (see Chapter 5). They are less jagged than most pavements

Figure 4.3. *The glaciated trough of Wharfedale, with the steeper parts of its flanks exposing almost the entire thickness of the Great Scar Limestone (TW).*

Figure 4.5. *The extents of the wide benches and pavements on the limestone plateaus west of Ribblesdale; the main bench is a stratimorph on the highest beds of the Great Scar Limestone, whereas the lower bench is less well-defined on beds at lower stratigraphical levels. The younger rocks on Ingleborough are largely the Yoredale Group with a summit cap of Millstone Grit, whereas those in the southwest are mainly Upper Carboniferous Coal Measures; the basement rocks are Lower Palaeozoic slates and greywackes; contours are in metres.*



Great Scar Limestone

Within this chapter the term 'Great Scar Limestone' is used informally to describe the main limestone unit within which the major karst landforms and caves are developed; it includes the Great Scar Limestone Group and also any of the limestones within the Yoredale Group that are locally continuous with it.

in the high alpine chains of Europe, as they are dominated by rundkarren and benefit hugely from being developed on the cleanly-defined bedding surfaces. Whether these are extensive horizontal expanses as along Chapel-le-Dale, steeply inclined slabs as at Hutton Roof, or across sequences of steps as on The Clouds, they are all stratimorphs. Pavements over ice-rounded hills, as in the Malham High Country (the high ground around Parson's Pulpit and High Mark, northeast of Malham Tarn), are broken into strips that roughly follow the contours and so lack clints more than a few metres across.

The outer edge of each pavement terrace is at the crest of a long and low limestone scar, many of which overlook another pavement on the bench below. Scar height is limited

Figure 4.6. *Erosion of the overlying beds and glacial stripping of the stratimorphic surface at Shining Stones on Great Asby Scar, Cumbria. Devensian ice moved towards the camera, and quarried the edge of the higher bed as it stepped down to the next strong bed. Most blocks from the upper bed were entrained within the ice and completely removed, but some were left close to their source. The net result was retreat of the scar on the upper bed, and evolution of the ground surface by the glacial stripping (photo: Simon Webb).*

by the thickness of the bed that supports the pavement above it, except where higher crags are cut through multiple beds. A bank of scree stands on the back of the bench below each scar, and commonly masks the bedding plane or shale bed that defined the level of that bench and its pavement (Fig. 4.7). At many sites, a strip of till or Holocene soil is preserved in the most sheltered position along the lower edge of the scree. The nature and extent of these screes are also influenced by the fracture patterns within the limestone scar (Sweeting, 1966), but the rates of scree formation are clearly lower than they were immediately after deglaciation of the Dales, as many are now stable enough to be masked, partly or wholly, by soil.

The margins of the limestone benches and their pavements are mostly defined by the broad topography of the valley sides, though in detail the local features are aligned on joints. Faults do influence the topography, notably in the hills east of Settle, but most limestone scars are eroded well back from any formative faults. The exception is Giggleswick Scar, a major feature on the South Craven Fault immediately west of Ribblesdale. This is a fault-line scarp where the topographical step is due to differential erosion, and is not just due to the fault displacement as in a true fault scarp. Over a length of more than 2 km, the limestone crags rise nearly 100m above the eroded Bowland Shales; known caves within the Scar are all short, and are most notable for their archaeological materials.

Though the rundkarren and grike fissures are dissolutional and therefore karstic, the main pavement surfaces clearly originated by glacial erosion. The wide pavements both west and east of Ingleborough lie where the limestone was swept clean beneath the margins of more powerful ice flows down Chapel-le-Dale and Ribblesdale, with that from the latter

Figure 4.7*. Limestone scars and screes above Thieves Moss, on Ingleborough's eastern plateau; Simon Fell forms the skyline (TW).*

also over-riding the low plateau of Moughton. In contrast, the slopes of Newby Moss are almost devoid of pavement and lie shrouded in till deposited in the lee of Ingleborough's summit mass (Fig. 4.8). As further evidence of erosion by ice moving southwards, glacial striations survive beneath till close to Long Kin East Pot on Ingleborough's Allotment (Fig. 4.9). So the pavements are glaciokarst. They have elements of biokarst, as their rundkarren formed largely beneath a soil or plant cover that was rich in biogenic carbon dioxide and through much of post-glacial time was more extensive than it is at present. Much of the soil is loessic, and was largely blown onto the limestone benches soon after retreat of the Devensian ice, though much of it was re-worked during the cold interlude at 8.2 ka BP (Wilson *et al*., 2012c). The pavements also have elements of 'anthropokarst', because they are now largely maintained as bare rock by the grazing activity of the sheep that were introduced by humans since Neolithic times; some were picked clean more recently by extractors of rockery stone. There is considerable variety within the morphologies of the Dales pavements (see Chapter 5), and they clearly have complex origins, including elements from pre-Devensian stages of development.

Most of the Dales limestone benches lie at altitudes very close to 400m. Consequently, they were described as the remnants of a peneplain, which was widely known by its historical name as the 1300-foot erosion surface (Sweeting, 1950, 1974). Its named altitude was an approximation and the mapped plateaus, benches and shoulders lie between 15m below and 25m above the 1300-foot (396m) level. Much of this mapped feature coincided with the main benches on top of the limestone around and west of Ingleborough, which were subsequently described as stratimorphs that are related to geological structure (Waltham, 1970).

The reality of such upland erosion surfaces has long been regarded with some scepticism (Clayton, 1981). Many parts of the 1300-foot surface were mapped across the outcrops of

Figure 4.9*. Glacial striations on limestone pavement immediately after clearance of the till blanket, near Long Kin East on eastern Ingleborough; the striae had survived because the till cover has a low permeability and probably a high content of limestone debris, both factors that would restrict dissolution of the buried limestone surface by percolation water (TW).*

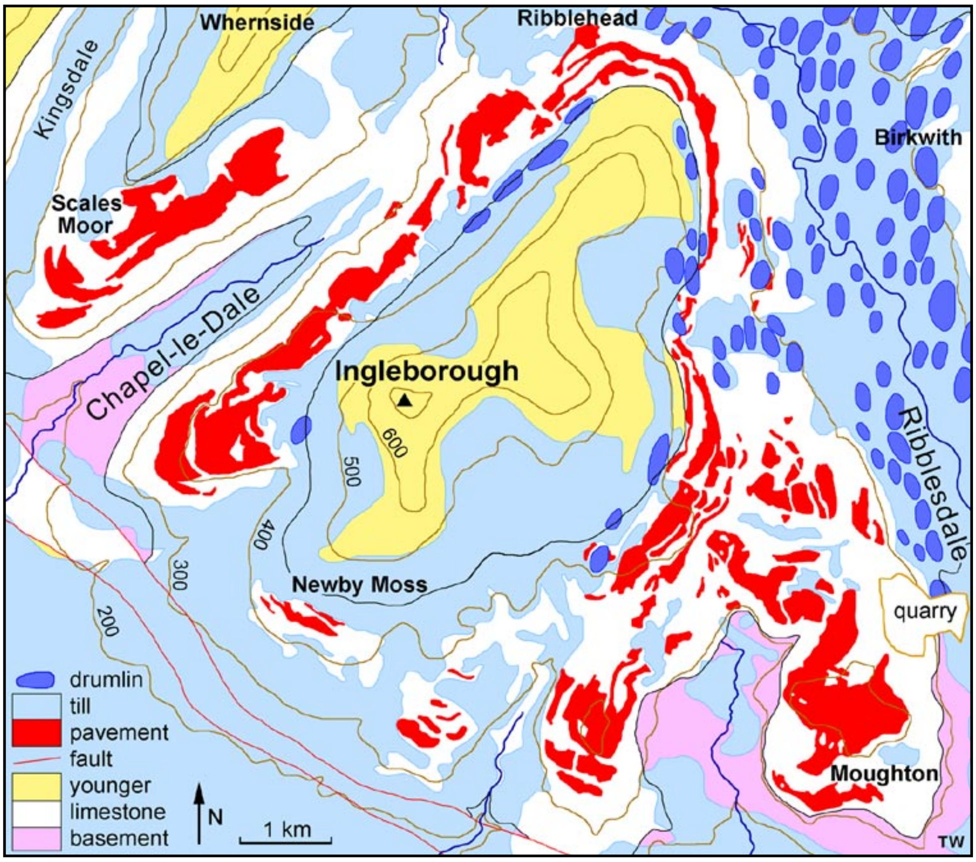


Figure 4.8*. Distribution of limestone pavements and glacial deposits around Ingleborough; the patterns of the till sheets and the drumlins reflect ice flow from the north with the Newby Moss shoulder in the lee of the summit (compiled from field mapping by Angus Tillotson and Tony Waltham and from various sources).*

Yoredale rocks (Sweeting, 1950), but a correlation of these with the recognisable breaks of slope at altitudes close to 396m reveals that many are at the transition from the shale-dominated Yoredale sequences downwards to the Great Scar Limestone (including any Yoredale limestones that are locally continuous with it). Though these hillside shoulders have not been stripped down to form stratimorphs, they appear to be features of the geology and are not purely the products of erosional processes (Waltham and Long, 2011). It is also significant that the surface was not mapped across the area of steeper dip around Bruntscar between Whernside and Chapel-le-Dale. A 1300-foot "erosion surface" across the Yorkshire Dales cannot now be regarded as tenable. There is no place for it within a credible model for the incision of the dales and the evolution of the limestone benches (see below). Similarly, any concept of an earlier and partly deformed erosion surface at about 600m, with the Three Peaks among the residuals that rose above it (King, 1969; Clayton, 1981), must be regarded with considerable caution.

One location with evidence of an erosion surface is between Malham and Malham Tarn (Fig. 4.51), where a platform cuts across both the limestone and the basement rocks on either side of the North Craven Fault (Sweeting, 1950). The northern half of this, north of the North Craven Fault and around Malham Tarn, is cut into both limestone and basement rocks, whereas the southern half rises gently as a slightly eroded stratimorph on the top of the Great Scar Limestone. There appears to have been erosional planation of the Malham Tarn basin, but this is purely a local feature, and it does not imply any wider occurrence of an erosion surface (Waltham and Long, 2011).

Incision of the dales

There has long been debate over the ages of the large-scale landforms of the Yorkshire Dales, but early estimates of late Tertiary origins, and a rather vague "pre-glacial" age for the perceived 1300-foot erosion surface, lacked any constraint from an absolute chronology. Radiometric dating has now provided some constraints, especially with pre-Devensian dates from analyses of cave stalagmites. These data have been used to indicate rates of valley incision (Atkinson *et al*., 1978; Gascoyne *et al*., 1983; Waltham, 1986; Waltham *et al*., 1997). As stalagmites can be deposited only in air-filled caves, their existence indicates that they were above the contemporary local water level. At most sites, this was at, or not far above, the resurgence level in the adjacent valley, and therefore indicates a maximum altitude for the contemporary floor of that particular valley, or dale. Any sections of perched phreas, forming sumps along the main cave conduits, would preclude local stalagmite deposition, and could be interpreted incorrectly as indicating a higher contemporary valley floor. Details are also slightly complicated because the positions of the earlier resurgences along the sloping dale floors are generally not known. However, most dale floors have only low gradients, and the first generations of resurgences are assumed to have been located close to the North Craven Fault where they were at the lowest local outlets from the karst aquifer. These were at high stratigraphical levels within the Great Scar Limestone, as the basement was still far below the contemporary valley floors.

Within these limitations, graphical correlation of ages and altitudes of stalagmites then produces very approximate time profiles of the dale floors (Fig. 4.10). Mean values for dale-floor incision, derived from the stalagmite data, have been estimated as <0.2 m/ka (Gascoyne *et al*., 1983) and 0.12 m/ka (Waltham, 1986), and overviewed as 0.2 m/ka (Waltham *et al*., 1997). A best estimate based on current data (Fig. 4.10) is probably closer to 0.15 m/ka, but this is still based on a very small data set where the critical few stalagmites are those of greatest age and lowest altitude.

Valley floor time profiles, for the valleys west of Ingleborough, are merely drawn around the clouds of points on a graph (Fig. 4.10). Any new stalagmite analysis that plots below or left of any clouds deflects its profile and indicates a lower incision rate. The rate of 0.15 m/ka for Chapel-le-Dale is probably most representative for incision of the major glaciated dales, though its rate may be as high as 0.22 m/ka if a single less reliable date of >350 ka is ignored. The rate of 0.09 m/ka for Ease Gill reflects the minimal ice action in its sheltered location. The comparably low rate for Kingsdale is clouded by large uncertainties in its older dates and by concealment of the dale's rock floor beneath sediment, but may also reflect the low power of its ice flow that lacked a major catchment. All these figures are mean rates that encompass both glacial and interglacial erosion; in reality they should probably be stepped to indicate increased rates of incision by ice erosion. Furthermore, most of the available data only reach back about 350 ka, so do not cover the erosional impact of the largest glaciation, the Anglian. This was in Marine Isotope Stage (MIS) 12, at around 450 ka, though there may have been a comparable or larger glaciation in MIS 16 at around 640 ka (see Chapter 3). There are no data on the activity of earlier glaciations that may well have impacted the Dales area (Lee, 2011; Lee *et al*., 2012).

Along the southern margin of the Askrigg Block, Kingsdale, Chapel-le-Dale and Wharfedale are each entrenched about 200m below the main limestone benches. The calculated incision rates therefore imply periods of

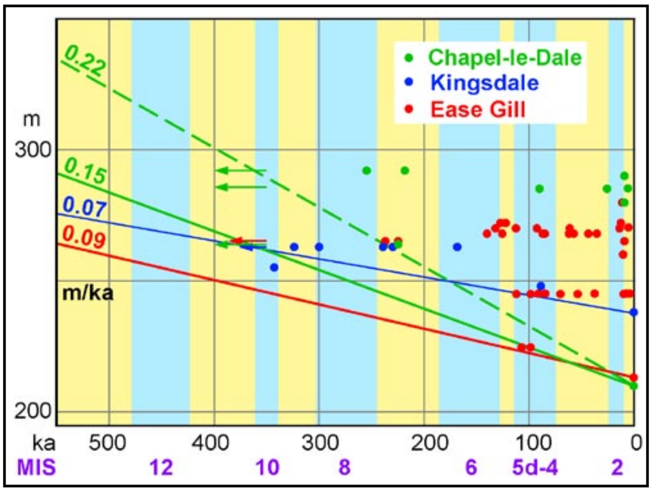


Figure 4.10. Ages and altitudes of dated stalagmites from caves beside the western valleys of Ease Gill, Kingsdale and Chapel-le-Dale, with mean incision rates interpreted for each valley (see text); the cold Marine Isotope Stages are shaded, but within these time intervals the glacial cover was not continuous in the Yorkshire Dales, as is apparent from some of the stalagmite deposition; arrows indicate ages determined only as >350 ka.

around 1.3 Ma for their excavation. Ribblesdale is wider than the three neighbouring dales, and traverses a structural high on the edge of the Askrigg Block (Arthurton *et al*., 1988). The top of the Great Scar limestone is exposed at an altitude of around 550m on Dick Close, high on the shoulder of Fountains Fell, and 370m above the floor of Ribblesdale at Stainforth. This might imply a first exposure of the limestone at about 2.5 Ma, though this concept figure could be reduced slightly if incision of Ribblesdale was more rapid under erosion by the most powerful sector of the southbound Pleistocene ice flow. Stalagmites from Victoria Cave date at least as far back as MIS 13, with finite age determinations of about 480 and 523 ka, and also estimated ages of >600 ka (Lundberg *et al*., 2010). However, these are from a truncated cave fragment at such high altitude that it is likely to have been drained long before those times, when the floor of Ribblesdale was already much lower by any estimate of its incision rate. Furthermore, Victoria Cave may not have been among the first generation of caves, as these may equally well have developed in the structurally higher limestone north of the North Craven Fault prior to their complete removal by subsequent surface lowering.

The limited available evidence suggests that an early exposure of the Great Scar Limestone in the Yorkshire Dales area took the form of an inlier surrounded by Yoredale outcrops in the floor of a proto-Ribblesdale more than two million years ago. Outcrops in the floors of the dales to the west probably followed at around 1.3 Ma. Valley incision through the weak Yoredale sequences created outcrops of the underlying limestone that initially were quite small on the floors of narrow valleys that were the proto-dales. The wide outcrops on the top of the Great Scar Limestone then developed by shale retreat as the weak Yoredale cover was eroded back more rapidly than the dales were entrenched, and widened, within the limestone (Fig. 4.11). These were

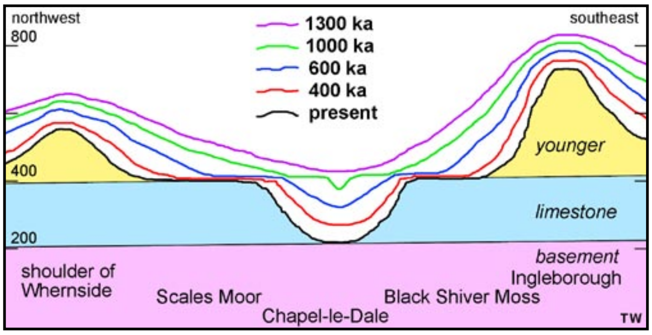


***Figure 4.11**. Concept sketch profiles across Chapel-le-Dale and Ingleborough, with an interpreted sequence of stages in the denudation of the area; profiles are drawn relative to the geology, and absolute altitudes increased over time with isostatic response to the erosional loss; the main bench surfaces are all on the top of the limestone, and are only separated for clarity; vertical scale is exaggerated by about 3. The drawn stages are: 1300 ka ago, when the Great Scar Limestone was only exposed further down the valley; 1000 ka ago, with a trench cut into the limestone while Yoredale rocks were stripped from adjacent benches; 600 ka ago, with limestone benches above a valley profile that may have been more rounded from previous glaciations; 400 ka ago, after the Anglian glaciation, with a rounded dale profile between wide benches; and at present, after the Devensian glaciation, with a deeper dale profile between benches that have retreated by erosion of the Yoredale rocks.*

subsequently left to become the main benches and plateaus, on each side of upper Ribblesdale and the other neighbouring dales. The oldest benches, adjacent to the lower reaches of Ribblesdale and Wharfedale, were not so well developed in the disturbed limestone of the Craven Fault Zone, and have been largely lost to subsequent slope retreat.

The plateau surfaces developed as the valleys widened more rapidly above the limestone. Retreat of the shale margin at the inner edges of the limestone benches is recognised by the occurrence of isolated large potholes that appear to be pre-Devensian and now lie well away from the shale catchments that fed streams into them. Features along the western and eastern flanks of Ingleborough suggest that the shale margin has retreated by a few hundred metres since just before the Anglian glaciation (Sweeting, 1974; Waltham, 1990), though there has been less retreat on the southern flank that was sheltered from strong ice action. By extrapolation, the shale margin might be expected to have retreated by about 600m since 1.3 Ma, thereby increasing the extent of the stratimorphic surfaces on top of the Great Scar Limestone.

It is important to recognise that the 1.3 Ma figure for initial exposure of the limestone in the western dales is approximate and is also only a minimum. Any new analyses that reveal greater ages of stalagmites at lower altitudes would reduce the interpreted valley incision rates and thereby extend the timescales of the limestone landscapes to well before 1.3 Ma. Any former existence of perched water levels could have a similar effect. The figure also assumes roughly steady denudation rates over time, but the mean rate may have been lower prior to the mid-Pleistocene climatic transition at 1.0–0.8 Ma that prompted accelerated glacial valley incision (Hauselmann *et al*., 2007). Extending the timescale to 2 Ma would allow for perhaps a kilometre of shale retreat, a figure that is more compatible with the widths of the main benches around the Three Peaks.

Through this period of 1.3 Ma or more, the dales were entrenched into the limestone to depths of around 200m (Fig. 4.12). Fluvial lowering of the dale floors across the limestone outcrop would have been seriously compromised by the development of underground drainage. An estimate of 46 mm/ka for dissolutional lowering beneath a soil cover (Parry, 2007) would produce significantly less than 50m of surface lowering in 1.3 Ma, after again discounting intervals of reduced activity during cold stages and also accepting that soil cover would not have been permanent through the warm stages. This would account for only a small fraction of the depth of the main dales, which confirms that a significant proportion of their excavation was by glaciers. The rounded, U-shaped valley profiles indicate that, even if they were not largely excavated by ice, the dales were significantly modified by glacial erosion. This may or may not have been entirely within 1.3 Ma, but that period does appear to have included the major glaciations in the Yorkshire Dales, notably after the mid-Pleistocene increase in the scale of glacial activity at around 0.8 Ma. Sound evidence relating to the evolution of the Dales region prior to 1.3 Ma is lacking, and will remain so unless and until appropriate clastic cave sediments are dated by their contents of cosmogenic aluminium-26 and beryllium-10 (see Chapter 10).

__Figure 4.12__. The broad U-shaped glaciated trough that is Chapel-le-Dale, entrenched nearly 200m below the level of the limestone benches on each side (TW).

A nation-wide survey of long-term uplift rates suggested a mean value of about 0.2 m/ka for the Askrigg Block (Westaway, 2009). However, many of the local data were derived from interpretations of cave stalagmite ages (largely from Waltham *et al*., 1997), and uplift rates are not the same as the denudation rates inferred from the stalagmite records. Models of crustal viscosity and deformation suggest that isostatic rebound in response to denudation generates uplift that is about 85% of the mean value of surface lowering by erosion (Burbank and Anderson, 2001). Fission track analysis of apatite crystals within Lake District rocks has indicated rock removal of about 700m from the summits and 1500m from glaciated valleys by surface erosion through the Cenozoic (Green, 2002). Application of that ratio to the Yorkshire Dales would imply that while the dale floors were eroded by about 200m, over a period of about 1.3 Ma, the surfaces of the summits and high ground between the dales were lowered by about 100m. This is, however, a tenuous line of evidence, and interfluve lowering could be less than half the valley incision. A value of about 150m for the mean denudation would then imply around 130m of uplift over the same period. A mean uplift rate of about 100m per million years places the top of the main limestone mass (now at altitudes of 400m to 500m across the heart of the karst) at sea level at around four to five million years ago. Such a time-scale is broadly compatible with that for the southern Pennines, where Neogene sediments of the Brassington Formation are preserved in collapse dolines and were uplifted from near sea level during and since Pliocene times (Walsh *et al*., 1999). Whatever the history of the region prior to about 2.5 Ma, the Great Scar Limestone was nowhere exposed through most of it.

A question remains as to the destination of all the rock material that has been eroded from the Dales region. On the Askrigg Block and within the Lune and Ribble catchments (which include the Dales' main karst), clastic material removed from the Yoredale sequences and from the overlying grits below the main summit levels amounted to about 60 km^3 (estimated from the modern geology and topography); this was within the last few million years. Initially this contributed to the alluvial flats towards Morecambe Bay and to the mantle of till across large areas to the south. Ultimately much of it was reworked into glacial outwash that now floors the Irish Sea and extends to and beyond the edge of the continental shelf, where it forms huge fans of sand and mud deep under the Bay of Biscay (Zaragosi *et al*., 2000). Largely within the last million years or so, since the limestone was widely exposed at outcrop, roughly another 15 km^3 of limestone was removed. While some of this was entrained in till after the glaciers deepened the dales and scoured the limestone stratimorphs, most was carried away in solution, and it ended up as part of the carbonate solute load of oceanic waters.

Initiation of the Dales karst

It is likely that the first exposures of the Great Scar Limestone were just north of the North Craven Fault, and probably in Ribblesdale, where its proto-valley crossed the structurally highest part of the Great Scar Limestone. An interpretation of the extent of the early karst landscapes can be created by correlating the structure and altitudes of the top of the limestone with estimated altitudes of the palaeo-topography based on inferred rates of surface lowering (Fig. 4.13). This reconstruction is only an approximation and an interpretation that is based on a series of assumptions, but it conforms to the fragments of evidence that are currently available. It is dated to around 1.3 Ma solely on the basis of the valley floor erosion rate determined for the dales west of Ingleborough. Altitudes relate to the present position of the limestone, with no account of uplift, and both the geology and the topography are likely to have been about 130m lower 1.3 M years ago.

An initial Ribblesdale inlier would have expanded towards the high ground north of Malham. It may also have extended eastwards beyond Malham, but with rather poorer karst development on the thinly bedded Yoredale limestones (which are locally almost continuous with the Great Scar). Palaeo-surface levels can only be estimated, but there may have been limestone outcrops in Wharfedale and Littondale and perhaps also in a proto-Darnbrook (Fig. 4.13) The main unit of limestone was probably also exposed in three small inliers between the North and Middle Craven Faults. It is difficult to correlate the earliest karst landscapes on the Malham High Country with those in lower Ribblesdale. The early limestone outcrop may have been broken by shale cover

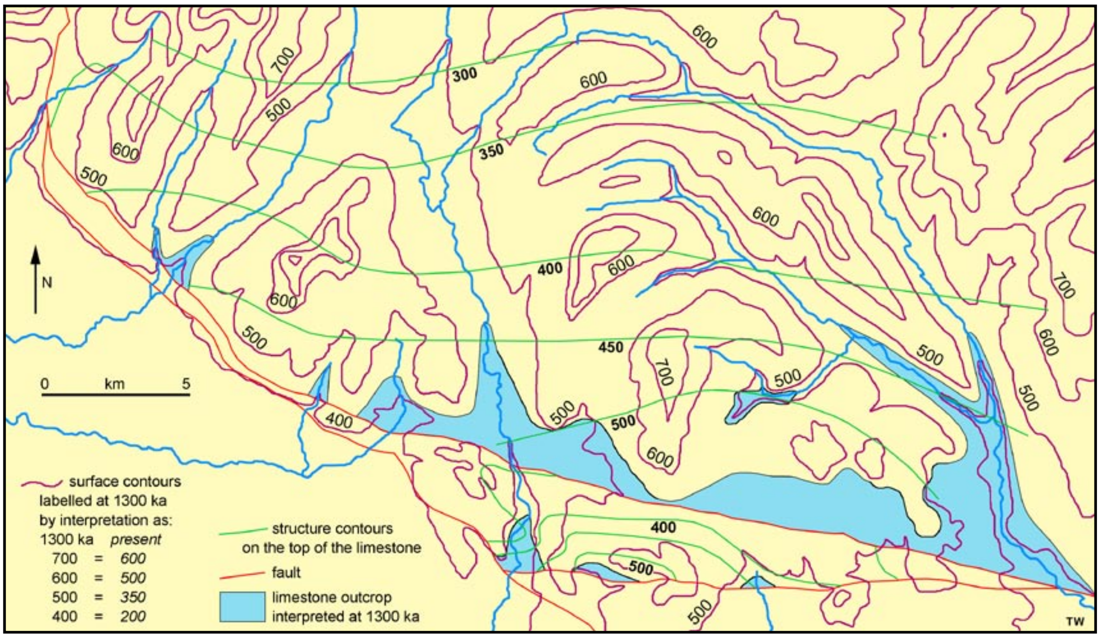


Figure 4.13*. An interpretation of the extent of karst on the southern Askrigg Block around 1.3 million years ago, soon after the limestone was first exposed by erosion of the younger rocks. Structure contours are drawn for the top of the integral karst unit; this is not definable by stratigraphy, as it extends only to the top of the Hawes Limestone in the west but includes the Gayle and Hardraw Scar limestones in the east. Structure contours north of the North Craven Fault are based on altitudes of stream sinks into the main limestone mass (thereby excluding sinks in the higher Yoredale limestones). Between the North and Middle Craven Faults structure contours are largely interpolated from those drawn on the base of the Gordale Limestone (Arthurton et al., 1988) and measured thicknesses of that limestone and the Yoredale Group (Dunham and Wilson, 1985). An approximation to the old topography is indicated by contours that are the present contours re-labelled as tabulated in the key; these are 200m higher than those at present along the dale floors, 100m higher over the interfluves and proportioned in between (see text). The old outcrops are interpreted from the structure contours and the re-valued topographical contours. Rivers are drawn in their present positions, and are only included to make the map easier to follow.*

south of Fountains Fell, but underground drainage from the Malham Tarn area to Ribblesdale could have been among the earliest to reach maturity within the Dales. Little is known of the geological structure and the extent of the early karst in a possibly similar situation between the Malham high ground and lower Wharfedale. Both dales were subsequently deepened and widened, thereby destroying any early suite of karst features on and beneath their flanks.

Karst also developed on smaller inliers of limestone where the other dales cross the upturned southern edge of the Askrigg Block (Fig. 4.13). The presence of an inlier in Chapel-le-Dale is inferred from the stalagmite chronology of the dale (Fig. 4.10). An early limestone outcrop in lower Ease Gill cannot be identified from this interpretation (Fig. 4.13), but probably did exist within the zone of folding against the Dent Fault at or very soon after this early stage. The early inlier in Clapdale may not have existed if the valley is a younger feature. There was a second inlier in Ribblesdale, in the more folded limestone against the Middle Craven Fault. This would have extended to the area of Attermire Scar, and would at some stage have overlain enlargement of the cave passage of which a remnant survives as Victoria Cave. This small inlier had no hydrological continuity across the North Craven Fault to the main area of karst at that time (Fig. 4.13) because the throw on the fault is greater than the limestone thickness, but it may have had an underground link with a small inlier just below the site where Malham Cove subsequently developed.

These early inliers developed as karst on benches and platforms of the limestone where and when the cover of weaker Yoredale shales was stripped away. It is likely that ice swept over these outcrops during pre-Anglian cold stages, and limestone pavements comparable to those on the modern benches existed at some subsequent times. All traces of these early karst landscapes were destroyed as the dales were widened and deepened, though some features survived on the high ground north of Malham. Alongside the main dales, the limestone benches retreated towards the high ridges. As they progressively shifted towards their present positions, many of them also became much wider, as the weak Yoredale cover rocks were stripped away from their inner edges more rapidly than their outer edges receded in the strong limestone. The main process of denudation on the limestone benches was probably a series of events of glacial quarrying of individual beds, alternating with dissolutional lowering during the interglacial and postglacial stages, and ultimately creating the stratimorphs within the modern landscape of the Dales.

On the main limestone benches, overall surface lowering, solely by dissolution, may be taken broadly to match estimated mean Holocene rates of 3–13 mm/ka (Goldie, 2005; see below). Discounting intervals of reduction or loss of dissolutional activity during cold stages, this could account for about 5–15m of limestone denudation since initial exposure at about 1.3 Ma. Dissolution rates may have been higher during periods of soil cover (Parry, 2007), but probably pertained only through limited intervals. However, these total figures were nowhere achieved, as the initial karst landscapes have since been removed by incision of the dales and by the denudation that has caused migration of the karst areas across the newly exposed limestone outcrops and towards the interfluves.

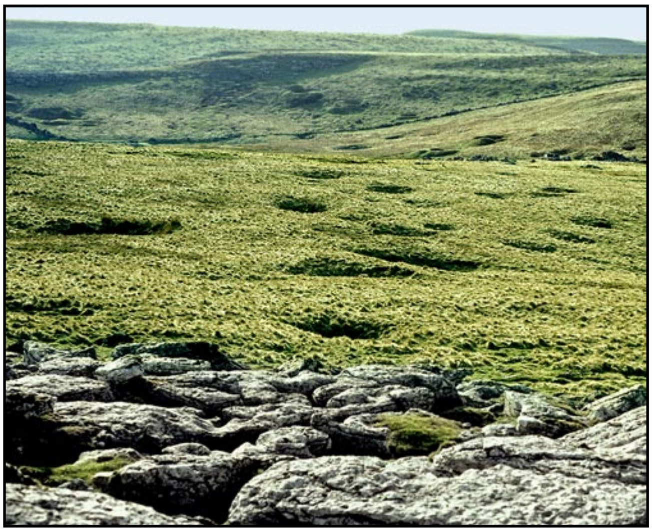


Figure 4.14. Broad shallow dolines and limestone scars that are typical of the very old karst on the Malham High Country (TW).

The karst north of Malham was initially developed over the area of the Tarn and eastwards across the Mastiles bench, and karst has only existed on High Mark and Parson's Pulpit for somewhat less than 1.3 Ma. Nevertheless, the oldest surviving karst landforms in the Yorkshire Dales are probably the large dolines within the polygonal karst on this area (Fig. 4.14). Some of the rounded karst features on the Malham High Country have been variously described as tors, towers or pinnacles, though they are essentially isolated clints and blocks that survive from a pavement that has since been largely eroded away. They have long been interpreted as very old (Goldie, 2006a, 2007), but suggestions that they are pre-Quaternary cannot be substantiated. Their location high on the interfluve between Ribblesdale and Wharfedale makes them difficult to date. Preservation of this polygonal karst does indicates how minimal was glacial erosion at its interfluve site, during at least the Devensian glaciation, in contrast to the rather more conspicuous ice quarrying and abrasion on the pavements that were over-run by more-active ice adjacent to the faster flows both east and west of Ingleborough.

Limestone dissolution

As in almost any karst, stream waters and percolation waters carry dissolved carbonate, both within the Dales caves and on the fells above (Table 4.1). Most percolation waters are enriched with biogenic carbon dioxide from their passage through the soil and plant cover. The concentration of carbon dioxide in the water is then a key factor, along with flow rates and temperature, in the dissolutional removal of limestone (Palmer, 1991; Dreybrodt, 2004; Faulkner, 2009). Concentrations of dissolved carbonate are merely a consequence of the dissolution kinetics, but, combined with records of rainfall or stream flows, can be useful indicators of the mean rates of removal of limestone where more detailed chemical data have not been recorded (Gabrovšek, 2009).

Typically in the Dales karst, percolation waters carry between 150 and 250 mg/L of solute (expressed as calcium carbonate, but generally including a small proportion of magnesium carbonate). Values show considerable variation between sites and over time, relating to the nature and extent of flow paths down through the limestone (Pitty, 1974). Standing pools on bare rock gain carbon dioxide from their lichens and mosses, and then dissolve the limestone; their solute concentrations increase further with evaporation losses, and may lead to re-precipitation, whereas they decrease after recharge from rainfall events that make the water aggressive again (Sweeting, 1966).

The aggressiveness of soil waters, and their potential capacity for limestone weathering, can be assessed by the weight losses of prepared limestone tablets placed within the soils. Significant chemical contrasts have been found in different soil types in the Malham area (Trudgill, 1985). Calcareous soils in slopes above Cowside Beck have developed over talus and soliflucted head, both composed of limestone debris, and showed minimal weight losses of tablet samples, except in a thin zone immediately below the surface. In contrast, acid soils in slopes above Darnbrook Beck have formed on till that mantles the limestone and is derived largely from the shales and sandstones of the Yoredale and Millstone Grit sequences. Large tablet losses throughout the thickness of the Darnbrook soils showed the capability of limestone weathering by percolation water in and beneath these acid soils that have developed on the glacial deposits.

Within the Dales karst, conduit flows through the limestone, in stream caves and at resurgences, typically carry between 100 and 200 mg/L of calcium and magnesium carbonates (Table 4.1). Allogenic streams that flow onto the Great Scar Limestone typically have carbonate solute levels of 30–50 mg/L, which are derived largely from the Yoredale limestones higher up their courses. The increases in solute concentrations as the streams flow through the limestone caves are almost entirely due to increments from fissures and tiny inlets of percolation waters that have gained high carbonate concentrations after their initial passage through the cover of soil and peat. Increments of 20 mg/L of solute per 800m length of flow-path have been recorded in streams on the limestone surface (Sweeting, 1966), but solute increases were immeasurably small along the 500m of the Long Churn streamway (Fig. 4.15) that lacks any significant inlets of peat water along its course to Alum Pot (Richardson, 1974). Solute concentrations at all resurgences show marked decreases at high stage due to dilution by flood

$CaCO_3$	locations	source
	autogenic waters	
156 – 227	seepages in Ingleborough Cave	Pitty, 1974
130 – 250	seepages in Alum Pot area	Richardson, 1974
175 – 275	percolation springs around Malham	Trudgill, 1985
78 – 342	pools on bare limestone	Sweeting, 1966
	allogenic streams	
36 – 64	Alum Pot Beck, at high and low stage	Richardson, 1974
48	Fell Beck	Pitty, 1974
30 – 36	typical sinking streams	Sweeting, 1966
	resurgent waters	
82	Clapham Beck Head	Pitty, 1974
137 – 200	Malham Cove and Aire Head	Trudgill, 1985
	Darnbrook Fell, 5 risings –	Ternan, 1974
111 – 174	mean values	
88 – 113	minima in flood	
148 – 217	maxima at low stage	
140	typical risings	Clayton, 1981
90 – 120	typical risings, at high and low stage	Sweeting, 1966

Table 4.1. Representative solute loads, in mg/L of calcium carbonate, carried in streams and from springs within the karst of the Yorkshire Dales.

pulses with short flow-through times (Table 4.1). However, the high flood flows account for greater total carbonate loads, and therefore cause the maximum rates of both chemical and mechanical erosion.

Karst denudation rates

Rates of dissolutional denudation, or mean surface lowering on the limestone, can be assessed by various methods: 1) from data on solute loads in stream waters, 2) by direct measurements on rock surfaces, 3) by weight losses of prepared limestone tablets, and 4) by inference from rock pedestal heights beneath boulders. Though each method measures a different component of the overall denudation, correlation of the data sets provides a broad picture of the total denudation process (Table 4.2). Dissolution is however only a part of the total denudation process in the Yorkshire Dales, which includes major glacial erosion, especially along the dale floors where surface lowering rates are significantly higher than on the main limestone benches.

Estimates of dissolutional denudation can be made by application of the Corbel formula (Trudgill, 2008). This indicates that D = 4ET/10,000, where D = denudation rate in mm/ka, E = annual precipitation less evapotranspiration in mm, T = mean solute concentration in mg/L, with the approximation that limestone density is 2.5 t/m^3. The main limitation with these estimates relates to the origins of the solute, which is derived from three distinct sources: dissolution on the ground surface or at rockhead beneath a cover of soil or drift, dissolution within fissures in the epikarst, and dissolution in cave passages deep within the karst.

Dissolution at the surface, or at the sub-soil rockhead, generally accounts for only about 30% of the total carbonate in karst waters (Gabrovšek, 2009); consequently denudation rates calculated in this way are generally higher than direct measurements unless sub-surface erosion is estimated and accounted for. Dissolution of rock within the few metres closest to the surface, in the zone known as epikarst, contributes to long-term denudation when voids in the fissure system coalesce to allow surface lowering. Calculated rates are only long-term means (on scales of at least 10 ka), and then involve inaccuracies through glacial removal of partially eroded epikarst. The dissolution in deep caves does not contribute to surface denudation, except in the very long term. Deductions from measured stream solute concentrations allow for solutes derived from allogenic input.

Despite these limitations, the Corbel formula does provide very rough estimates of mean dissolutional denudation on the limestone outcrops (Ford and Williams, 2007). An estimate of 41 mm/ka for the rate of surface lowering in the Dales excludes an almost equal contribution from underground dissolution (Sweeting, 1966), but it is unclear how much of the latter is in fissures and cave passages and how much is at rockhead beneath a soil cover. Comparable rates can be deduced from data on specific resurgences (Table 4.2), but also without distinction between surface lowering and underground losses.

Direct measurements of surface lowering on bare limestone pavements indicate only one component of denudation in a karst with any degree of soil cover. Rates of 12–74 mm/ka have been determined with a micro-erosion meter (Trudgill *et al*., 1981) on the Highfolds pavement above Malham Tarn. Maximum rates of cave stream entrenchment, deduced from dated stalagmites close to the floors of canyon passages in Lost John's, White Scar and Ingleborough Caves are 20–50 mm/ka (Gascoyne *et al*., 1983). These cave floor measurements are means over periods of 100 ka, which include cold stages of reduced flow and perhaps even phases of sediment accumulation, but cannot be related to external limestone surface lowering as the sites are all perched above local base-levels.

Erosion rates that are orders of magnitude higher have been deduced (only approximately) where acidic peat water has drained onto freshly exposed limestone pavement (Sweeting, 1966). Part of the glacially striated pavement on the Ingleborough Allotment was lowered by 30 mm or more between 1947 and 1960, after its clay-rich till was removed from a small area. When peat was cleared from a small area of pavement on Scales Moor, water draining from the adjacent remaining peat was reported to have carved runnels 70–150 mm deep, also within 13 years (Sweeting, 1966), but this is an extraordinarily high rate of channel incision that cannot be regarded as representative. Similar runnels, up to 30 mm wide and 90 mm deep, score a fresh limestone exposure in Meal Bank Quarry, Ingleton, having formed probably within about a hundred years since closure of the quarry in 1911. These originate at seepage from a shale bed and the associated deposition of yellow jarosite (hydrated iron sulphate) indicates the local role of strong acids derived from pyrite (iron sulphide) within the shale. All these high rates are created by concentrated flows of acidic water, and do

Figure 4.15. The streamway of Upper Long Churn Cave feeding to Alum Pot (TW).

mm/ka	method	location	source
83	solutes	Dales average (total denudation)	Sweeting, 1966
41	solutes	Dales average (surface dissolution)	Sweeting, 1966
62 – 97	solutes	Darnbrook Fell	this chapter
65	solutes	Malham	this chapter
12 – 74	direct (MEM)	Malham (pavement)	Trudgill *et al*., 1981
< 20 – 50	(stalagmite)	cave streamways (over >100 ka)	Gascoyne *et al*., 1983
2300	direct	Ingleborough (runnels in peat water)	Sweeting, 1966
20 – 40	tablets	Cowside (in calcareous soil)	Trudgill, 1985
100 – 600	tablets	Darnbrook (in acid soil)	Trudgill, 1985
26 – 33	pedestals	Norber (over 15 ka)	Sweeting, 1966
3 – 13	pedestals	Norber and Scar Close (over 15 ka)	Goldie, 2005
46	pedestals	Norber (sub-soil, over 10 ka)	Parry, 2007
10	pedestals	Scales Moor (sub-aerial, over 15 ka)	Parry, 2007
150	(dale incision)	(total erosion, for comparison)	this chapter

Table 4.2. Estimates of limestone denudation rates at sites within the Yorkshire Dales karst.

Figure 4.16. *Glacial erratic of strong grit standing on a high steep-sided limestone pedestal at Norber, on Ingleborough's flank; this erratic, the most photographed and iconic of the Norber boulders, toppled off its pedestal 2009; its demise was probably due to a shear failure that allowed the thin upper bed to detach, slide sideways and unbalance the main block before both fell to the grass surround (TW).*

not represent overall denudation rates. Rates of surface loss, calculated from weight losses, of buried limestone tablets are indicative of denudation rates beneath different soils (Table 4.2), and these results also show the importance of acid soil waters in dissolutional denudation (Trudgill, 1985).

Denudation rates estimated from pedestal heights

Limestone pedestals sheltered beneath large erratic boulders have long been used to infer denudation rates on the unprotected limestone; among the finest are those beneath large blocks of strong grit at Norber, on the southeastern flank of Ingleborough (Fig. 4.16). Numerous estimates of pedestal heights, and deductions of denudation rates (see listings in Goldie, 2005, and in Parry, 2007) remain questionable because they did not take full account of bedding-related steps in the limestone profiles. Many pedestal heights are unclear or debatable, and further doubts over deduced denudation rates are raised by the degree of real protection that the boulders provide.

Early estimates of the heights of the Norber pedestals centred around 400–500 mm, implying denudation rates of 26–33 mm/ka since retreat of the Devensian ice. Subsequently, re-assessment, particularly with regard to stepping of the limestone surface, has indicated heights of only 50–200 mm, and rates of only 3–13 mm/ka (Goldie, 2005, 2012). This contrasts with the claim for a mean height of 460 mm for steep-sided pedestals interpreted as developing due to sub-soil dissolution at Norber (Parry, 2007). These measurements were taken to imply a mean denudation rate of 46 mm/ka, subsequent to soil developing only with climatic amelioration at about 10 ka, whereas pedestals with sloping walls that averaged 150 mm high, on Scales Moor and elsewhere, were interpreted as forming under sub-aerial conditions with a denudation rate of 10 mm/ka (Fig. 4.17).

Figure 4.17. *A glacial erratic on a low pedestal with sloping sides, on Scales Moor (photo: Brian Parry).*

All these pedestal-deduced rates (Table 4.2) would decline slightly if re-calculated from an ice retreat that may have been as early as 16.5 ka (Telfer *et al*., 2009), or possibly even earlier at Norber (Vincent *et al*., 2010; Wilson *et al*., 2012b.). They are all only approximations as they span climatic variations through the Holocene; it is also unclear when processes stabilized following the main ice retreat (see Chapter 3) and whether dissolution was briefly interrupted by periglacial conditions during the Loch Lomond Stadial (Faulkner, 2009). An added complication is provided by the possibility of pedestal development being influenced by nivation processes localised within hollows in wind-blown snow that developed around the erratics in periglacial conditions (Wilson *et al*, 2012a). Some pedestal heights may also be a factor of bed thickness, and others may have been increased by artificial removal of limestone blocks. Denudation rates inferred from pedestal heights can only be simplifications regarding complex processes, and must be assessed with due caution.

Progress in karst geomorphology

Studies of the surface landforms of limestone karst evolved over the centuries in different parts of the world, but were commonly regarded as a mere variant within wider studies of geomorphology and surface processes. A breakthrough was the research by Jovan Cvijić on the Dinaric karst of his home country, which generated his two landmark publications (1893, 1918).

Since the initial work by Cvijić, karst science has evolved into a wide understanding of geomorphological processes backed up by the physics of hydrogeology and the chemistry of dissolution. The standard text on the subject is the comprehensive discourse by Derek Ford and Paul Williams (2007), while the most readable overview of karst landforms is still that by Joe Jennings (1985), a Yorkshireman who emigrated to the Australian karst.

Karst studies in the Yorkshire Dales were similarly relegated to incidental diversions from either geomorphology or geology, with the exception of works that focussed on the caves. Notable among the latter was the research by Marjorie Sweeting, who worked for many years on the Dales limestone country. Her papers are cited in this chapter, and her textbook (1972) on karst geomorphology includes numerous references to the Yorkshire Dales.

	sink	rising	underground flow			time in flood (2)	surface flow (3)		
(1)	altitude	altitude	distance	drop	gradient		distance	drop	gradient
Dentdale	220	148	3200	72	2.2	10%	4000 (4)	24	0.6
Ease Gill	349	213	2300	136	5.9	1%	---	---	---
Kingsdale	290	253	3100	37	1.2	20%	1200	33	2.7
Chapel-le-Dale	292	224	3300	68	2.1	<1% (5)	---	---	---
Ribblesdale	297	277	500	20	4.0	1%	2500	40	1.6
Malhamdale	366	188	3500	178	5.1	0	---	---	---
Littondale	268	230	3500	38	1.1	50%	11500 (6)	65	0.6
Wharfedale	---	---	---	---	---	---	22500 (7)	200	0.9
Nidderdale	222	160	3200	62	1.9	<1% (8)	---	---	---

***Table 4.3**. Underground flows of the trunk rivers along the main dales.*

Footnotes

1. Altitudes and distances are all in metres, and distances are straight-line; gradients are percentages.

2. Time in flood is a rough percentage of the total time that a parallel surface flood overflow channel is occupied.

3. Surface flow data apply to river lengths where flow is always above ground.

4. Surface flow in Dentdale is only that downstream of Popples.

5. Chapel-le-Dale has its top sinks near Ivescar, but flood time is only for the stretch downstream of Haws Gill Wheel.

6. Surface flow in Littondale is only that downstream of Litton, but includes the distance that flow is confluent with that of the Wharfe as far as Grassington.

7. Wharfedale has some stretches with partial underground flow, in Langstrothdale, which are not included.

8. Flood time in Nidderdale is only that for the channel downstream of Goyden Pot.

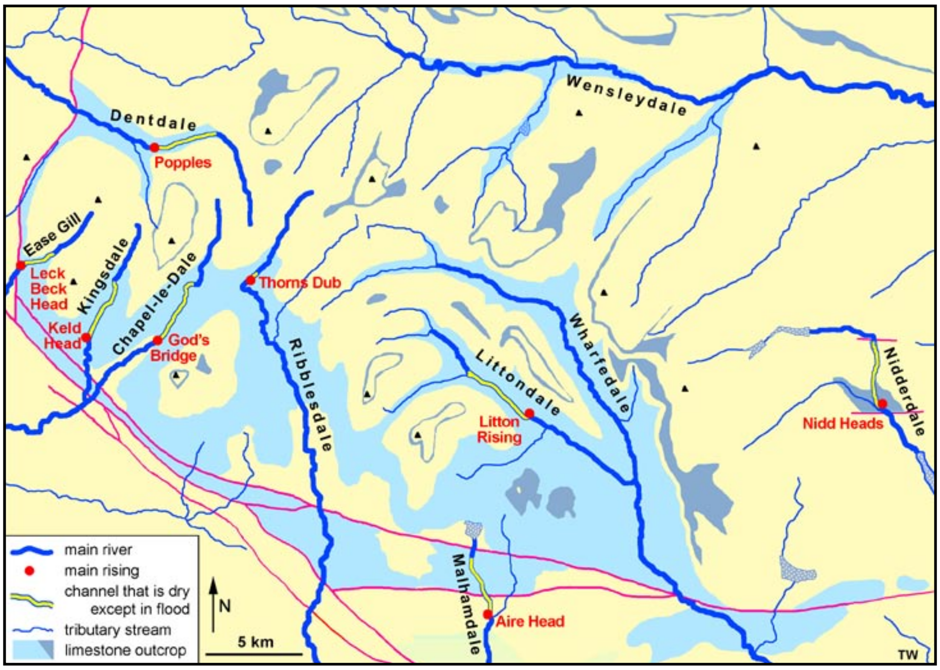


***Figure 4.18**. The surface courses of the main rivers, and their sections that are normally dry across the Great Scar Limestone in the southern Yorkshire Dales; the channel above Aire Head always carries a small flow from the Malham Cove Rising.*

Stream sinks, potholes and risings

The shale-dominated Yoredale sequence that overlies the Great Scar Limestone provides numerous sources of allogenic water that sink into the top of the limestone and resurge near its base, having travelled through the extensive cave systems that are a key component of the Dales karst. The sinks can be distinguished in two groups, those on the streams and rivers that flow along the main dale floors, and those on the smaller streams that flow from the high Yoredale outliers onto the main limestone benches. A third important component of water within the karst is the direct rainfall onto the limestone or onto its cover of soil or permeable drift. This enters either by percolation through the soil, by very small flows into individual fissures on the exposed karst, or by point recharge in doline floors (see Chapter 9).

The main river courses

Of the nine trunk rivers and streams along the floors of the dales through the main karst, all but two have long lengths with underground flow, where the stream courses are dry except in times of flood (Fig. 4.18 and Table 4.3).

Dentdale: The River Dee loses water into various sinks from Cassa Dub downstream, and its rocky channel is normally dry as far as the resurgence at The Popples, beyond which the river flows entirely in daylight except for two short sections with some parallel underground flow. Downstream of the underground section, the river flows on alluvium and till.

Ease Gill: This is the only main valley that is not a glaciated trough, though Pleistocene ice left extensive till and traces of a recessional moraine. The valley is in the lee of Great Coum, and was therefore sheltered from powerful glacial erosion. Its stream sinks at the shale margin, at Top Sink, and resurges at Leck Beck Head, with much of its underground course under the north bank known through the Ease Gill Cave System. The gill carries floodwater only after storm events. The resurgence is close to the Dent Fault, and Leck Beck shortly crosses onto impermeable basement rocks.

Kingsdale: The headwater stream normally disappears into choked sinks just downstream of Kingsdale Head, and flows through the West Kingsdale Cave System to the resurgence at Keld Head. Flows exceed the sink capacity for about 20% of the time, when the artificially straightened channel over the alluvium becomes active. The resurgence is from a truncated cave passage about 40m above the base of the limestone. Downstream, the River Twiss flows over alluvium and then descends over thinly bedded basal limestones to reach the basement at Thornton Force (Waltham *et al*., 2010).

Chapel-le-Dale: Winterscales Beck, the main headwater stream, is lost into choked sinks near Ivescar in dry weather, and flows as far as the Haws Gill Wheel sink in flood (Fig. 9.3). Only in major flood events is there any surface flow further downstream, where the underground course is known through flooded caves behind the God's Bridge resurgence, which is close to the base of the limestone.

Ribblesdale: The River Ribble flows above ground in a wide dale with a complete floor of till and alluvium, to and beyond the concealed base of the limestone just upstream of Horton. The main headwater, Gayle Beck, flows underground for just a short distance through the Katnot and Thorns Gill caves, but floodwaters also occupy a parallel surface ravine. Further downstream, an enlarged River Ribble flows for 4 km over limestone between its crossings of the North and South Craven Faults. This section has a gradient of 1.2%, but is largely on thinly bedded limestone that is covered with drift sediments; underflow leakage may exist, but no sinks or risings have been identified.

Malhamdale: The geology at Malham differs from the other dales, as its allogenic stream from Malham Tarn flows from the basement and across the North Craven Fault onto the limestone, before disappearing into choked sinks and resurging from the choked Aire Head risings and from the submerged cave at the foot of Malham Cove. Surface flow down the Watlowes valley and over the Cove has not occurred since the early 1800s (Howson, 1850; Halliwell, 1979.).

Littondale: The River Skirfare has surface flow largely over till and alluvium, as far as its underground section past Litton village where the rocky surface channel is occupied only for about half the time (Fig. 4.19). Below the main Litton risings, the river is on the surface, flowing over alluvium, to its junction with the Wharfe.

Wharfedale: The River Wharfe maintains surface flow across the entire limestone outcrop, though there are sections with

Figure 4.19. *The rocky bed of the River Skirfare close to Litton village in Littondale, when all flow is underground and when the channel becomes active in mild flood conditions.*

Figure 4.20. *Kingsdale Beck flowing over thinly bedded limestones in its final descent towards the head of Thornton Force (TW).*

components of underground flow beneath Langstrothdale upstream of Yockenthwaite. Downstream of that section, the dale is floored entirely by alluvium, and this may conceal a small inlier of basement rock near Kilnsey.

Nidderdale: The underground flow of the River Nidd is through caves that are largely within the Yoredale Middle and Three Yard limestones, from sinks near Manchester Hole to Nidd Heads. Beyond the choked sinks, surface flow is frequent as far as Goyden Pot, but is only rare beyond there, except for tributary streams that drain off the grit and create flows along sections of the main channel before sinking.

Wensleydale and its tributary dales, along with Swaledale, have no sections of underground flow along their trunk rivers, as outcrops of Great Scar Limestone are absent or minimal along their floors. In Wensleydale, the River Ure cascades over the low steps of Aysgarth Falls carved into the top of the Great Scar Limestone, but the water does not sink, and it flows off the valley-floor inlier not far below the falls. The smaller southern valleys of Crummack Dale and Clapdale were glaciated and do carry modern streams, but they are effectively elements of the drainage off the high benches, as described below.

Most of the data on the drainage along the main dales (Table 4.3) could be taken to imply that underground flow is achieved (except in flood conditions) where the hydraulic gradients across the limestone outcrop are steeper than about 1%, while surface flow is maintained over lower gradients. This may then be seen as an indication of the maturity of the karst, though its picture is simplified as the development of complete underground drainage is greatly dependent on the size of the allogenic flow, the scale of glacial or alluvial sediments masking the limestone and also on local details of the limestone stratigraphy and structure.

The two exceptions in the drainage regimes can be explained. In Kingsdale, the underground flow emerges onto the surface where its cave was truncated by Pleistocene glaciation. The conduit is now back-flooded by about 7m, partly by post-glacial sediments, and emerges in the pool at Keld Head. The surface stream's steep descent to the lip of Thornton Force is then over thinly bedded basal limestones (Fig. 4.20), where bedding planes effectively return to the surface any developing loops of underground flow; there is some leakage into fissures just behind the waterfall, feeding to a tiny resurgence cave near the base of the limestone half way down and just beside the waterfall. Along the great proportion of Ribblesdale, surface flow is maintained over a steeper gradient by a locally thick and extensive blanket of almost impermeable till, to the extent that the conduit from Alum Pot to Turn Dub passes beneath the surface channel without any hydrological link.

Some smaller streams do maintain surface flows across the limestone outcrops, mostly on valley floors of alluvium or till; these include many streams in upper Ribblesdale that emerge from caves at high level and continue in daylight down to the valley floor. Cowside Beck, a tributary to the Skirfare, has the longest surface course over limestone that is not in a glaciated dale. It is partly over thin alluvium, but owes much of its existence to its very low overall gradient and a lack of fissures that can swallow the stream, even though part of it has the cave carrying water from Darnbrook Fell at just a few metres depth and almost directly beneath it. Gordale Beck also maintains continuous surface flow, except in very dry conditions when all the water can sink into an immature route beneath the valley to springs downstream of the Scar. The Beck water is saturated with respect to calcite, so fractures and fissures along most of its bed are not opened by dissolution; instead, they are choked by deposition of travertine (see Chapter 6), and probably by clastic sediment derived from the till.

Sinks and risings of the limestone benches

Around the inside margins of the limestone benches, small streams arrive off higher slopes that are dominated by shales and mudstones within the Yoredale sequence. These sink into hundreds of caves and potholes; there are more than a hundred around Ingleborough alone (Carter and Dwerryhouse, 1904). The caves are described in Chapter 7, but their sinks are conspicuous features of the karst. One of the characteristic landforms of the Dales is the open pothole, where an allogenic stream falls anything from 5m to 50m

Figure 4.22. *The shaft of Jingling Pot, in Kingsdale, rounded and fluted by spray corrosion and widened along its initial fracture (photo: Jerry Wooldridge).*

into the depths. Most potholes are enlarged from vertical joints, though some are on minor faults. Many remain as elongate fissures (Fig. 4.21), others have developed into rounded shafts, commonly elliptical along a fracture (Fig. 4.22), and others have expanded by wall collapse on multiple joints (Fig. 4.23).

Alongside the pothole sinks, many allogenic streams flow into open cave entrances. Many of these are into quite low passages, with roofs along bedding planes that are only a bed or two down from the top of the limestone. The initial sink was down a joint through the top one or two beds, but this has been cut back into a short canyon that now ends at the cave.

Figure 4.21. *Hunt Pot, on the west side of Pen-y-ghent, a classic stream sink into a deep fissure (TW).*

Figure 4.23. *The quarry-like sink of Hull Pot, on the west side of Pen-y-ghent, which was enlarged by multiple wall failures along parallel fractures and takes a large stream in flood conditions (TW).*

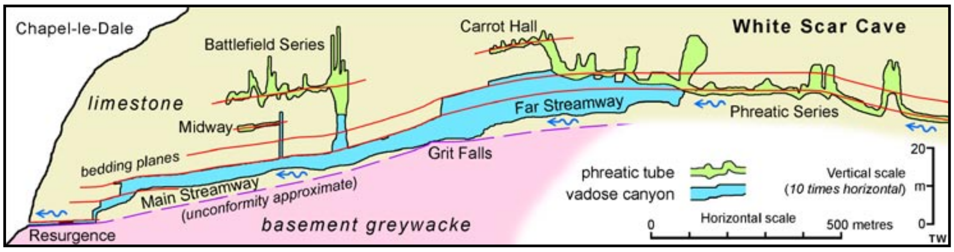


Figure 4.24. Extended profile through the outer part of White Scar Cave with its stream flowing for only a short distance on the base of the limestone out to the resurgence on the unconformity; basement rock is seen only at Grit Falls and at the resurgence; major bedding planes are only shown where recognised in the cave; minor faults are not shown.

Some streams continue in daylight beyond the shale margin, either by flowing over till that covers the limestone, or by flowing over bare limestone until they reach a vertical feature that can swallow their flow. But they too eventually sink, many at sites that are partially choked by coarse debris. Some older potholes have been left dry by retreat of the shale margin, though Alum and Rowten Pots are among those with younger stream caves opening into them at depth. Around Ingleborough, a former position of the shale margin may be indicated by the line of large old potholes (Fig. 7.42); originally considered only as "pre-glacial" (Sweeting, 1974), a pre-Anglian age may be inferred from the extent of the shale retreat (Waltham, 1990).

The large number of stream sinks on the Dales limestone benches drain through to a much smaller number of resurgences. Most underground streams converge with others in extensive, dendritic cave systems. Many caves descend 150–200m through almost the whole limestone thickness, and resurgences are commonly towards the base of the limestone. White Scar Cave is one of the very few that resurge in textbook fashion right on the base of the limestone. The lowest few metres in the Great Scar are commonly impure limestones, thinly bedded, with many shale beds and interrupted by rises in the local relief of the unconformable base of the limestone; all these are features of the patchy and uneven drowning of the pre-Carboniferous land surface. Consequently many of the low-level cave passages were initiated at inception horizons within the overlying, cleaner limestones, and feed resurgences that are above the basal unconformity. White Scar Cave would also do that if Pleistocene glaciers had cut Chapel-le-Dale a little wider, as its stream flows at a higher level for most of its length, and only descends to the base of the limestone in its last 160m out to daylight (Fig. 4.24).

White Scar Cave is one of the majority of Dales resurgences that pour water from cave passages initiated on bedding planes, though some do rise on joints. Many of the resurgence caves have been truncated by valley deepening (see Chapter 7). These include a significant number of smaller resurgences that lie at high stratigraphical levels within the Great Scar, notably Birkwith, Browgill and other caves in upper Ribblesdale (Fig. 4.25). These cave passages have developed on bedding planes, shale beds or other inception horizons high in the limestone sequence, and have then been truncated by valley incision to leave the resurgences perched well above the valley floors. Another reason that these caves and their drainage have not descended to the base of the limestone may relate to the relative scarcity of deep, open joints far from the Craven Faults (see Chapter 7). The deep shafts of Alum and Diccan Pots are on a single, major, north–south joint (which is probably a small fault); much of the passage in Red Moss Pot is also along a single joint, but is nearly horizontal as it stays at one bedding horizon.

Besides the sinks and risings in the Great Scar Limestone, the Yorkshire Dales also have large numbers of both in the various thin limestones of the Yoredale sequence. Across Wensleydale and the northern dales, and also on the higher slopes of the southern dales, the topography of the Yoredale outcrops is characterised by rock benches formed on each limestone and sandstone, separated by gentler slopes on the interbedded shales. It is not a karst landscape, except that each limestone bench creates a narrow strip of karst, with broken limestone scars, patches of pavement and short caves connecting sinks and risings respectively atop and beneath their own bench. Many sinks are choked with debris, and few of the open potholes are more than about 10m deep because they are limited by the limestone thickness. The Buttertubs, in Swaledale, are a group of beautifully fluted and unusually well-developed potholes about 15m deep in

Figure 4.26. The fluted potholes of the Buttertubs, high on the southern flank of Swaledale (TW).

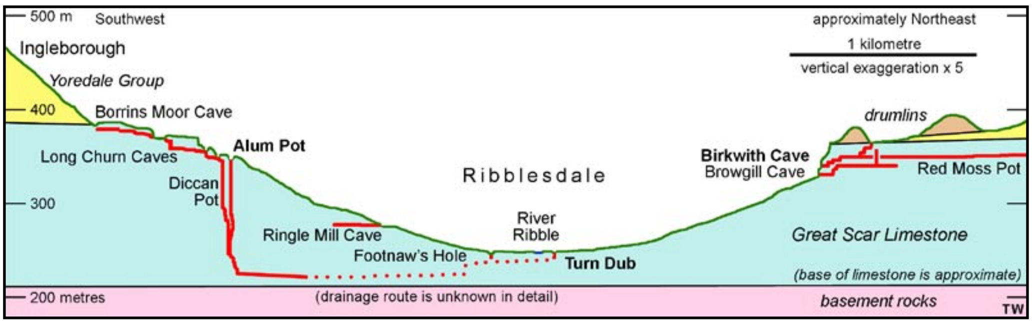


Figure 4.25. A simplified profile across the upper part of Ribblesdale, from the sinks and deep caves of Alum Pot on Ingleborough to the sinks and perched resurgences of the Browgill area.

the Main Limestone (Fig. 4.26). Many of the resurgences within the Yoredale succession are from small caves with sandstone floors at the base of the limestone units.

In the main karst of the southern Dales, the Lower Hawes Limestone (at the base of the Yoredale Group) is effectively continuous with the Great Scar Limestone, and consequently forms just a part of the Great Scar karst. The Middle Limestone is among those that thicken to the southeast, where it contains the caves and underground drainage of Nidderdale. Beneath and around Great Whernside, it is separated from the Great Scar Limestone by only a reduced thickness of non-carbonates, and the major stream sink at Mossdale Scar is also into the Middle Limestone, but has its resurgence at Black Keld low down in the Great Scar Limestone.

The third component of the Dales karst groundwater is the percolation flow supplied by dispersed recharge (see Chapter 9). A proportion of this emerges from small risings that are independent of flows from sinking streams. Many of these percolation risings are seepages with high solute loads, and they therefore precipitate carbonate when they reach open air, creating the localized travertine deposits that are yet another component of the Dales karst (see Chapter 6).

Dolines and shakeholes

The periodic glacial incursions of the Pleistocene ensured that the limestone terrain of the Yorkshire Dales never evolved into a fully mature karst, but remained as a glaciokarst. And whereas dolines are widely recognised as the diagnostic landforms of karst, they are little more than details in most of the overall landscape of the Dales.

Dolines include all types of closed depressions in karst (excluding poljes, which are much larger features and are not present in the Dales karst). Their common feature is underground drainage that prevents them filling with rainwater to create ponds; they can also be known as sinkholes (particularly in America and by engineering geologists). Within the Dales, the dolines fall into three groups (Fig. 4.28). Those in bedrock can be separated into solution dolines and collapse dolines, whereas those in the cover of soil or drift are described as subsidence dolines (Waltham *et al*., 2005); the latter are widely known within the Yorkshire Dales as shakeholes.

Figure 4.29. *A small and deeply fluted solution doline in strong and massive limestone on Scales Moor, above Chapel-le-Dale (TW).*

Figure 4.27. *One of the caprock dolines on Barden Fell, formed where Grassington Grit has collapsed into underlying limestone (TW).*

Caprock dolines are formed in non-karstic outcrops by collapse into underlying limestone. Within the Dales, these are only significant on some of the gritstone outcrops east of Wharfedale. Three caprock dolines up to 60m across and 10m deep, along with some smaller features, lie within the Grassington Grit high on Barden Fell, south of Stump Cross (Fig. 4.27). These may have developed through as much as 50m of the gritstone, but the structure of the underlying limestone is unknown, and a buried reef mass could be capped by a smaller thickness of non-carbonates. Above Black Edge, on Grassington Moor, another group of three caprock dolines, each up to 70m across, are formed entirely in the Grassington Grit where it lies above Yoredale limestones. These are floored by collapsed blocks of the gritstone, and have no known connections to passages in Mossdale Caverns, which lie obliquely beneath within the Middle Limestone.

Dolines in bedrock

Solution dolines develop by dissolution of rock on the surface, beneath the soil and within the epikarst, collectively lowering the surface around the central drainage outlet (Williams, 1983). In contrast, collapse dolines form largely or wholly by collapse into cave chambers or passages. In the Dales and elsewhere, most dolines in bedrock involve both processes, and therefore constitute a spectrum of morphologies that range from solution to collapse.

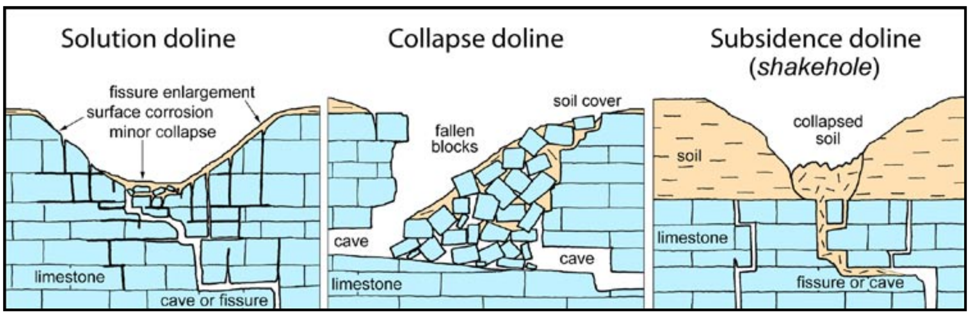


Figure 4.28. *Cross sections of the three main types of doline that occur in the Yorkshire Dales.*

Figure 4.30. *Bar Pot, on Ingleborough, a collapse doline with steep walls and fallen blocks of limestone (TW).*

Profiles of solution dolines vary from shallow bowls to vertical, cylindrical shafts. Whether the many open potholes that characterise the Dales karst are referred to or subdivided as dolines, shafts, stream sinks or potholes is a detail of terminology, as they cover a spectrum of morphologies. The smallest are just a metre or so across, and include some beautifully fluted conical depressions in clean rock (Fig. 4.29). Dissolution is a slow process, so solution dolines tens of metres across cannot have formed in the Dales karst since the Devensian ice cover. All the larger dolines have been over-run by ice. While some potholes have survived unscathed, all the wider and shallower dolines have been eroded or partially filled by glacial processes (see below).

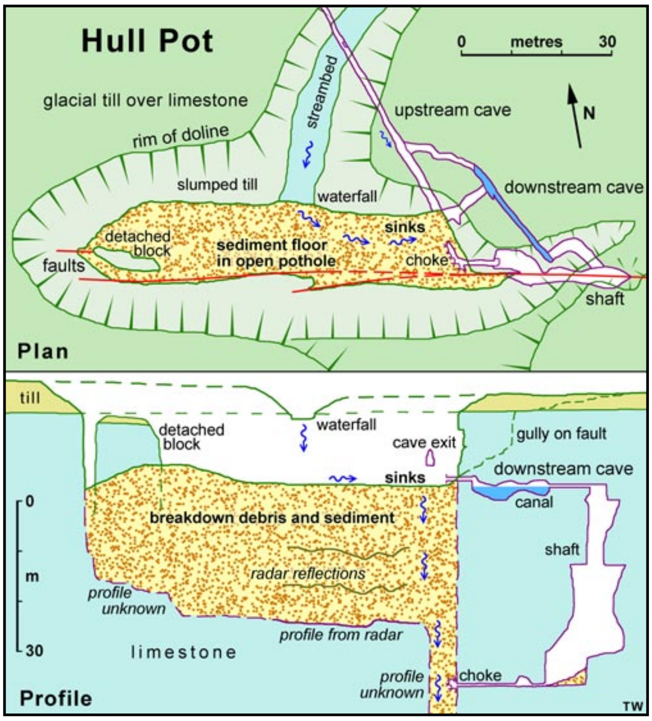


Figure 4.31. *Sketch profile through Hull Pot, with what is probably the lower part of a massive boulder pile reached through the adjacent shaft on the fault; the stream and waterfall are only active in flood conditions, and there is now leakage from the streambed into the upstream cave where it crosses beneath; the radar reflections are probably breaks on layering within the breakdown pile (after surveys by Arthur Gemmel and Phil Pappard, with ground radar data from Murphy et al., 2008).*

Rock collapse is largely a process that is only secondary to dissolutional cave development in karst terrains, and collapse features constitute only a minority of the dolines in the Yorkshire Dales. The Jingling Caves above Kingsdale, and many other stream caves that follow the highest bedding planes at shallow depths in the Great Scar Limestone, have their thin roof rocks penetrated by daylight windows. Some of these windows are just single fissures opened by dissolution on individual cross-joints, whereas others are longer stretches of open stream channel. Of these, some were cleanly unroofed by ice action, but some still contain the fallen blocks from roof collapse. The latter qualify as collapse dolines, but their sizes are limited to the few metres of the cave widths. There are a few larger collapse dolines, with Hull Pot (Fig. 4.23) and Bar Pot (Fig. 4.30) providing well known examples. Tempting though it is to ascribe these to "cavern collapse" there is scant evidence that there has ever been wholesale failure of roofs across wide cave chambers. It is just as likely that their first appearances as surface features were as single open fissures along joints, and these were then widened largely by wall collapse with progressive failure of adjacent joint-bound blocks of rock and subsequent dissolutional removal of the fallen blocks. There is ongoing wall failure at Hull Pot, but evidence of its early stages of collapse are now obscured by the breakdown blocks and stream debris that may be 60m deep (Fig. 4.31).

Large dolines cut into the bedrock of any karst involve both dissolution and collapse. Dissolution may well be the dominant process in most cases, but it works alongside the undercutting of joint-defined blocks of individual beds. These blocks are inevitable features along the internal slopes of large dolines, and their subsequent displacement, landsliding or collapse contributes to development of the doline, besides exposing further surfaces to sub-aerial or sub-soil dissolution. Morphologies of all the large bedrock dolines in the Dales karst have been complicated by the Pleistocene ice that intermittently covered them, partially filled most of them with till and perhaps modified their rock profiles.

An exhaustive survey identified 473 large karst depressions on the limestone outcrops of the southern Askrigg Block between Leck Fell and Grassington Moor (Marker and Goldie, 2007). Of these, 140 are on the Malham High Country, and another 82 lie on the southeastern benches of Ingleborough. Not included in that total are 32 large depressions on the wide bench of the Yoredale Main

Figure 4.32. *The largest of the ancient solution dolines on the Malham High Country (TW).*

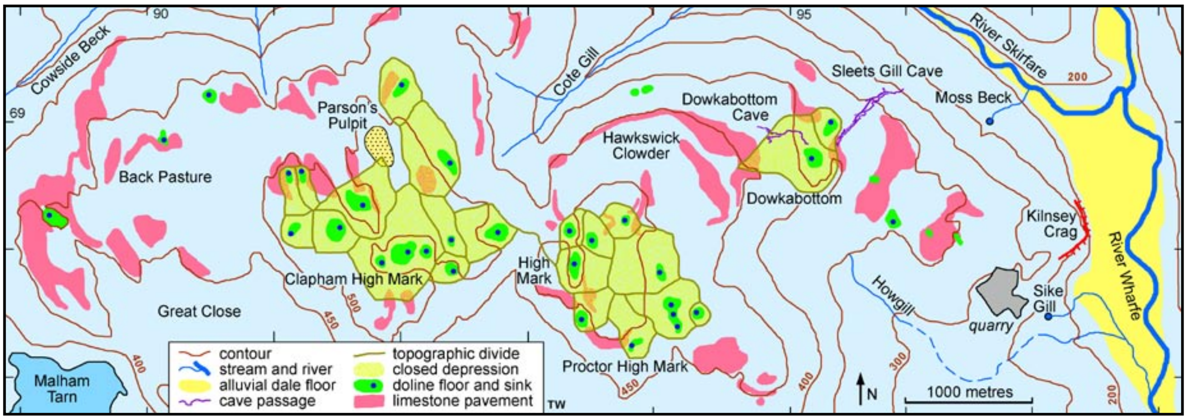


Figure 4.33. Major karst features on the Malham High Country; clusters of very large dolines combine to form the areas of polygonal karst; the top of Parson's Pulpit is an outlier of Yoredale sandstone.

Limestone above and west of Bishopdale. The largest of the depressions is that lying between Parson's Pulpit and Clapham High Mark (Fig. 4.32); it is nearly 800m in diameter, with an area of about 38 ha, and with most of its rim about 50m above its floor, though one saddle is only 20m above floor level (Fig. 4.33). Another 21 of the depressions each exceed 30 ha in area, and mean dimensions of the smallest 100 in the survey are 47m long and 27m wide; only 30 of the 473 are more than 7m deep. Nearly all of these depressions are true dolines, in that they have been created largely by dissolution of the limestone, with variable (but generally small) contributions from collapse processes during wall retreat. A few wide and shallow depressions on the north end of the Moughton plateau of Ingleborough are stratimorphic, as their floors largely follow the bedding across very gentle synclinal folds (Fig. 4.34). These could have been excavated solely by glacial stripping of the upper bed, but their profiles distinguish them even from the dolines with the widest and shallowest profiles.

The larger dolines on the Malham High Country combine to form limited areas of polygonal karst (Fig. 4.33), where the entire surface is formed by the dolines between nets of interdoline watershed ridges (Waltham *et al*., 1997). These may be regarded as a holokarst, and the only true karst, as opposed to glaciokarst, in the Yorkshire Dales. They are clearly the most mature karst features in the Dales, and are too large to have formed in post-Devensian time. They lie within

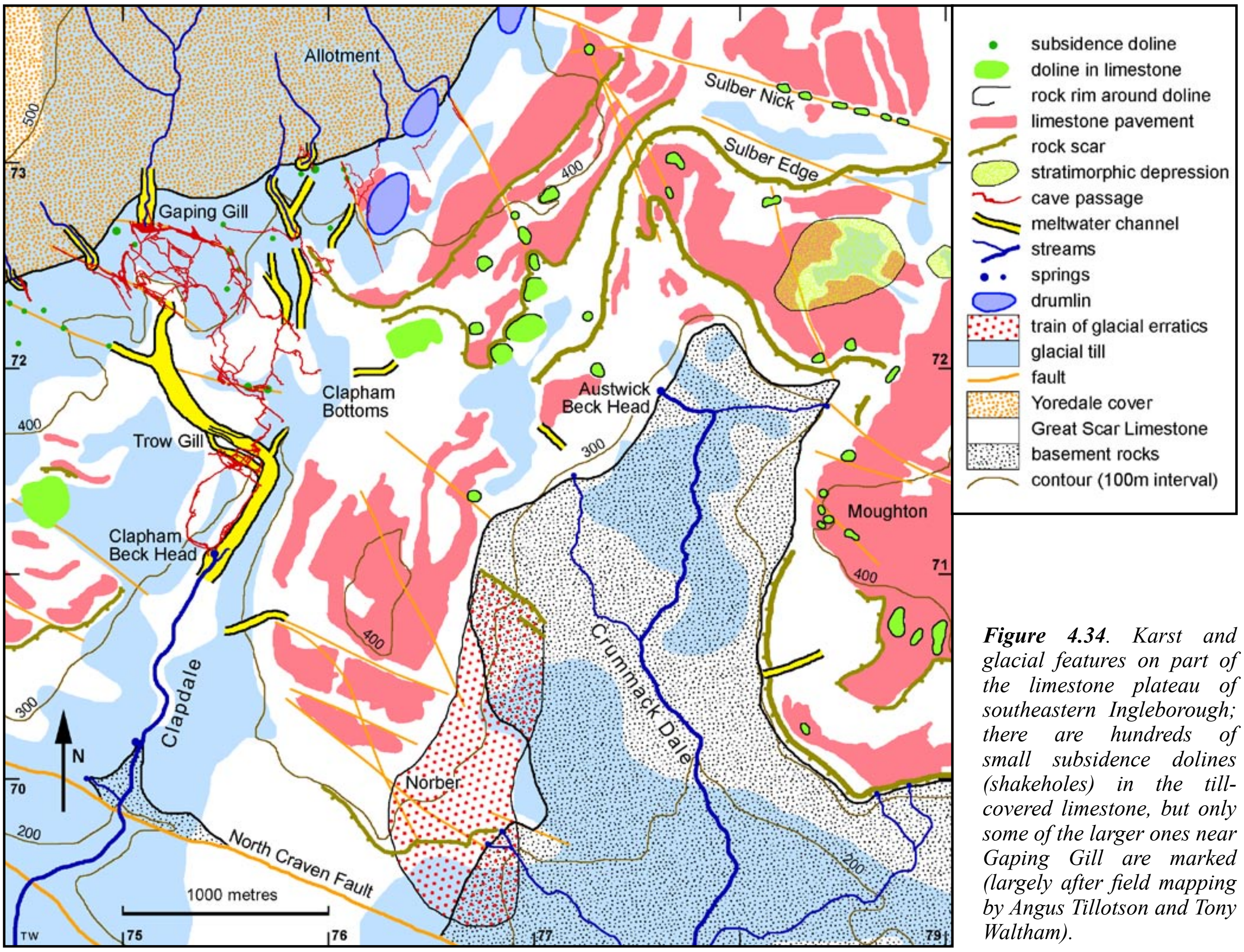


Figure 4.34. Karst and glacial features on part of the limestone plateau of southeastern Ingleborough; there are hundreds of small subsidence dolines (shakeholes) in the till-covered limestone, but only some of the larger ones near Gaping Gill are marked (largely after field mapping by Angus Tillotson and Tony Waltham).

Figure 4.35. One of the large old dolines with well-defined rock rims along the fault trace of Sulber Nick, eastern Ingleborough (TW).

an area distinguished by many boulders, clints, pavements and pinnacles of limestone all of which are so rounded that they are interpreted as being significantly older than much of the Dales karst (Goldie, 2006b). The Malham High Country appears to have spent long intervals beneath an ice cover, which was probably almost static, cold-based ice with little or no erosive power. This ice sat on the high ground along the upturned southern edge of the Askrigg Block, between a faster flow of ice down Wharfedale and a zone that moved a little more rapidly across the basin of Malham Tarn.

No evidence has been found of glacial erosion in the polygonal karst, but details within the dolines are largely obscured by extensive drift deposits. Parts of these have been mapped as till (Arthurton *et al*., 1988), though it may be that they are entirely loessic (Marker and Goldie, 2007). In the largest doline, augering has revealed a metre of clayey sand, and geophysical surveys indicate about 5m of underlying clays above well-fissured bedrock (Gullen, 1999). Deepening of the dolines may have been aided by sub-soil dissolution beneath the drift during interglacial stages (Clayton, 1981). Smaller shakeholes pock the drift floors within the dolines, but are irrelevant to the long-term doline genesis. That the large dolines and their polygonal karst above Malham are formed largely on the Gayle and Hawes limestones is incidental, as these are locally continuous with the Great Scar.

Large dolines on southeastern Ingleborough, around the head of Crummack Dale (Fig. 4.34), are very different from those at Malham, as they were over-run and modified by significant Pleistocene ice flows across the wide bench adjacent to Ribblesdale (Waltham, 1990; Goldie and Marker, 2001). Most of these dolines are 10–50m in diameter, and are characterised by low, well-defined, bedrock scars around their perimeters, with floors of grass-covered drift no more than a few metres below rim level. Their scar edges suggest glacial quarrying, or perhaps a greater component of collapse during their pre-glacial development, but many are notably close to circular in plan, indicating their evolution into mature dolines. Those along Sulber Nick are elongated parallel to the fault line that defines the feature, but are neverthless rounded in plan (Fig. 4.35). Coring of their soil floors has revealed loessic silts and clays (Goldie and Marker, 2001), which could include sediment from deglaciation lakes. Only two profiles came from dolines with the well-defined rock rims; one on the main upper bench revealed at least 2m of sediment fill, while one on the lower bench above Clapham Bottoms met bedrock, or a large boulder, beneath only 0.5m of sediment (Fig. 4.34). Geophysical surveys of the large doline, without a rock rim, at the head of Clapham Bottoms found sediments continuing to 4m deep (Gullen, 1999); between that unconsolidated fill and a bedrock floor, the same geophysics indicated about 13m of "altered" limestone, distinguished by its low seismic velocity, which could be interpreted as a pile of collapse blocks, or as heavily fissured bedrock, or conceivably as a block-rich till. Some of these Ingleborough dolines appear to have been deep and steep-walled features more like potholes than the wide and shallow depressions of Malham; they were formed at some time prior to the Devensian, or possibly by subglacial or proglacial meltwater, before being largely filled with clastic sediment.

A comparable feature on the opposite side of Ingleborough is Braithwaite Wife Hole, a conical doline 60m in diameter and 25m deep. Its southeastern side is broken by small scars and limestone outcrops, and once had an entrance into the cave chambers now only accessible from Sunset Hole. The other sides are ramps of till, mostly covered in grass. How much wider and deeper this doline might be remains unknown, but it is set into the limestone bench above Chapel-le-Dale so no more than a few metres can have been removed from its limestone rim by either dissolution or ice erosion. It stands as a fine example of a large and very old doline over-ridden by ice and partially filled by glacial debris.

Shakeholes within the soil cover

Subsidence dolines, or shakeholes, are those formed entirely within the soil profiles. In this context, the soil is any type of unconsolidated sediment that is alluvial or glacial, together with surface materials with an organic component, which are known as top-soil for their biological properties. Within the

Figure 4.36. Numerous small shakeholes in the remains of a thin sheet of till that covers part of the limestone pavements on Fell Close, on northern Ingleborough (TW).

Figure 4.37. A typical Dales shakehole, in Ribblesdale, in glacial till with sloping sides of grass-covered till and with bedrock limestone hidden beneath the slumped debris (TW).

Dales karst these materials include the glacial till and valley alluvium that may also be known as drift, as well as loess, lake sediments and hill peat, and soil is simply a convenient lithological term that includes all these loose materials that may overlie the limestone. These dolines have formed where the soil has been washed down into voids in the underlying limestone, in a process known as suffosion or ravelling, and can be separated into two broad types. Dropout dolines form rapidly by collapse of cohesive soils in arches over voids where soil had been washed out from beneath, whereas suffosion dolines form slowly as less cohesive soil slumps downwards as it is washed into the void beneath. These are only end-members of a series of landforms, and most of the dolines in the soils in the Dales have formed through a combination of slumping and collapse. They are therefore best described collectively as subsidence dolines, but locally they are generally known as shakeholes. There are thousands of shakeholes in the drift blanket of till and loess that lies across much of the Great Scar and Yoredale limestones (Fig. 4.36); about 3500 are recorded on Ingleborough alone (Waltham and Tillotson, 1989).

Figure 4.38. A newly formed shakehole on Newby Moss, Ingleborough, with sides of glacial till that have not yet slumped to a stable profile (TW).

The simplest form of a Dales shakehole is a conical depression with sides of grass-covered soil converging downwards to a narrow limestone fissure, through which the soil has been lost over time (Fig. 4.37). Any cohesion within a clay-rich soil allows voids to develop initially at the base of the soil profile and over the bedrock fissure, until the soil arches over them collapse; this can create new shakeholes with steep sides in the bare soil (Fig. 4.38), until they slump and degrade. Shakehole profiles therefore show considerable variation, which are further complicated by any choking of the outlet, whereupon a pond and its sediments may accumulate on the shakehole floor. Only some shakeholes have bedrock exposed on their floors. A typical shakehole has internal slopes of 10–40°, so its diameter is about two or three times its depth, and, if fully developed to expose bedrock on its floor, is up to about three times the soil thickness. Most Dales shakeholes are 2–10m across because they are limited by the 1–5m depth that is typical for the cover of till and loess.

Clusters of much larger shakeholes occur in areas of thicker till, notably in the lee of the hills that deflected southward-moving Pleistocene ice. The southwestern flank of Gragareth is notable for having more than a dozen shakeholes that are 20–40m across. Many of these are well choked with rock and soil debris, and one frequently contains a temporary lake (Fig. 4.39). Ashtree Hole is a large shakehole less than 10m deep, but the soil debris of its floor is exposed in the side of a cave passage (in Gavel Pot) 35m below (Fig. 4.40); this is clearly within a bedrock shaft, the width of which is unknown. Other shakeholes have open shafts on their floors, and many of the larger shafts were formed prior to the till being deposited over the limestone and locally slumping into the open voids. Death's Head Hole has slopes of slumped till that fall 5m to a rock lip, above a nearly cylindrical shaft 7m wide and 60m deep. Some shakeholes also have discrete streams draining into them, and are elongated where their small valleys have entrenched into the drift blanket. A depression 40m wide and 80m long, with a small stream entering at one end in wet weather, has the entrance to Ireby Fell Cavern in its floor, surrounded by soil slopes more than 10 m high. Whether this is described as a large shakehole or a small blind valley, or as a conspicuous stream sink, is immaterial, as all lie within a continuum of karst landforms created where water finds its way underground.

Figure 4.39. The very large shakehole that commonly contains a small lake near Notts Pot, on the southern flank of Gragareth (TW).

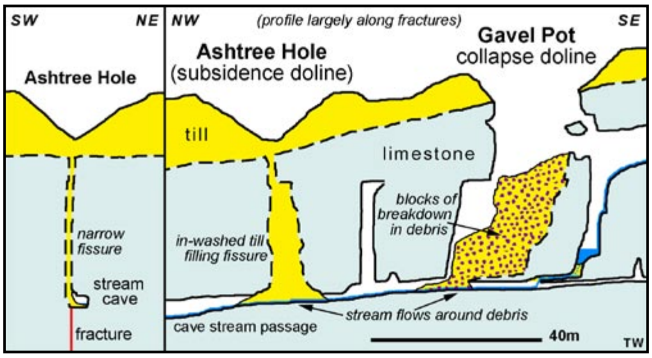


Figure 4.40. *Simplified profiles through the known and interpreted (broken lines) features of the large dolines of Ashtree Hole and Gavel Pot, on Leck Fell, related to the stream cave passage that lies beneath; the main fracture is probably a minor fault; the debris in Gavel Pot is a mix of limestone breakdown and glacial till.*

Because the mechanism behind shakehole enlargement is seepage water washing the finer components of the soil cover down into limestone voids, new shakeholes tend to appear, or old ones become larger, after rainstorm events or when a tiny surface stream happens to take a new course across the drift cover. In the winter of 1946, the floor dropped out of a shakehole originally less than 10m deep on Leck Fell; the event was unseen, but it revealed the entrance to Notts Pot. Also unseen, on Ingleborough during the winter of 1980, a whole side of the deep shakehole of Marble Pot sloughed into the chamber beneath (Fig. 4.41). Changes in stream courses have created new shakeholes on Newby Moss, and enlarged the existing shakehole now known as the entrance

Figure 4.41. *The deep shakehole at Marble Pot, on eastern Ingleborough, with a small stream flowing into it, and the scar left after 1980 by the massive slump in its sloping wall of till (TW).*

to Boxhead Pot on Leck Fell. Shakeholes are essentially post-glacial features, as they are set into Devensian drift, but they owe their existence to dissolutional widening of their underlying fissures in the limestone. At many, if not most, sites, that process started in pre-Devensian times, and only the soil loss is strictly post-glacial.

Patterns within the distribution of shakeholes are not generally recognisable, because a shakehole can develop over any of the myriad fissures that lie hidden in the limestone beneath the drift cover. Some larger joints, or faults, create lines of shakeholes, but there is normally no correlation between distributions of shakeholes, rock fractures and cave passages (Fig. 4.42). The exception is that there is commonly some concentration of shakeholes along the line of a shale margin buried beneath the drift, where seepage water within the drift flows downhill until it reaches the buried limestone. Similarly there is a better chance of enterable cave lying beneath the largest shakeholes. Conspicuous lines of shakeholes do lie over some narrow and buried outcrops of Yoredale limestones (Clayton, 1981), but locations of fractures and caves beneath cannot be inferred from distributions along the lines.

Valleys and gorges

Fluvial landforms within the Dales karst include a variety of valleys and gorges that all owe at least elements of their morphology to erosion by meltwater from the Pleistocene ice cover. There are dry valleys and gorges that are typical of karst landscapes, but there are also features that still carry surface water with significant flows that are either permanent or ephemeral.

Within the current karst environment of the Yorkshire Dales, most drainage across the limestone outcrop is underground, other than at flood stage when numerous flood

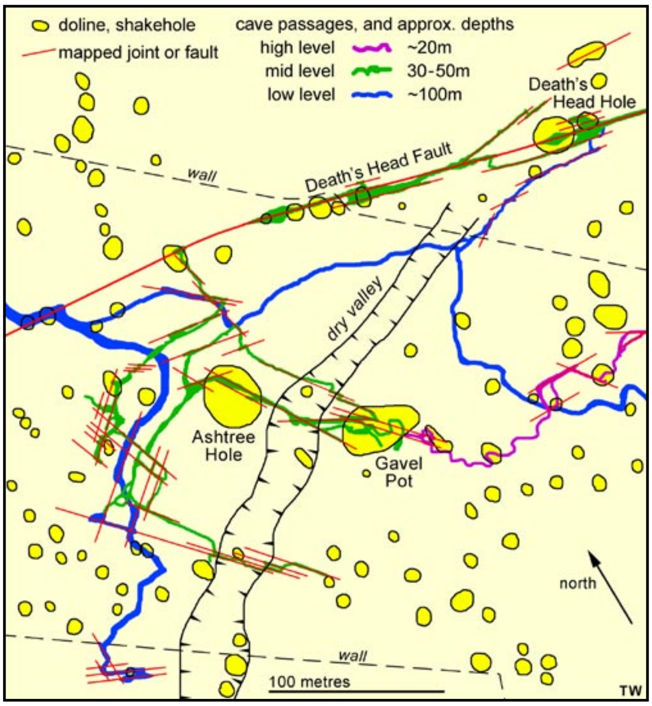


Figure 4.42. *Distribution of shakeholes within the till on part of Leck Fell, correlated with known cave passages and major bedrock fractures mapped within the caves; there are fewer shakeholes in the area of thick till around Gavel Pot and Ashtree Hole.*

channels become temporarily active. The notable exceptions are the larger allogenic rivers that flow through the glaciated dales with very low gradients and therefore have significant lengths of their flows above ground (Table 4.3). The flood channels themselves include some spectacular little canyons and gorges that are dry for most of the time. Short sections of Ease Gill are entrenched into clean and polished limestone, and the middle section of the Dee through Dentdale is along a small, rock-walled box canyon. Potts Beck and Crystal Beck both descend narrow valleys cut into the steep northern slope of upper Littondale, with flood channels that descend first over the Yoredale outcrop and then over the Great Scar Limestone. Both have their channels alternating between steep and narrow sections cut into thick beds of coarse sparry limestones and more open sections over more thinly bedded, fine-grained micritic limestones (Sweeting and Sweeting, 1969). In the northern dales, some of the larger streams flowing across narrow outcrops of Yoredale limestone have cut surface canyons faster than they can find underground routes. This down-cutting has been aided by steep descents over the terrace edges that characterise such sites, whereas many parallel and smaller streams cross the outcrops underground. Hell Gill (Fig. 4.43), at the top end of Mallerstang, has a narrow twisting gorge 500m long (Waltham *et al*., 1997), and the rather more accessible How Stean Gorge in Nidderdale is only slightly shorter.

Blind valleys develop where streams sink underground at fixed points for long enough to entrench their surface courses, but those in the Dales karst are limited to short features cut into areas of thicker till. The stream approaches to Gaping Gill Hole and Hurnel Moss Pot are two of the larger blind valleys on Ingleborough. Similarly, pocket valleys (or headless valleys) occur downstream of some resurgences in the Dales karst, but again are of very limited size. In Ribblesdale, Douk Gill Head is cut back into the basal limestone beds, and lies at the top end of one of the larger headless valleys, though this has an extension above and behind the scar as the dry valley reaching down from Hull Pot. Malham Cove is much larger, but has complex origins (see below).

The largest dry valleys and gorges in the Yorkshire Dales karst are those that were formed by meltwater from Pleistocene ice over largely frozen ground and have been left dry since climatic amelioration allowed drainage to return underground. Gordale and Watlowes are among the largest features, above Gordale Scar and Malham Cove respectively (see below). Trow Gill is a 300m-long, deeply entrenched section of a dry valley that descends from the Ingleborough bench into Clapdale (Waltham *et al*, 1997). Its steep and narrow upper part, just 70m long, has vertical walls indented by the remnants of breached moulins, and its lower part widens into a deep fluvial valley (Figs 4.44, 4.45). Though often referred to as a collapsed cave in the far past, later descriptions included or debated cavern collapse as just a part of its development, and it was subsequently described as a purely fluvial landform (Glover, 1974). The wide flare of Trow Gill below its upper fluvial slot, and the cave in its right wall that may extend beneath the debris slope, could indicate a role of headward erosion at a large old resurgence (Murphy, 1997). Two comparable meltwater features are Dib Scar and Conistone Dib, both of which are entrenched into the limestone slopes of Wharfedale below Conistone Old Pasture (Waltham *et al*., 1997). Dib Scar is a tapering gorge formed by waterfall retreat into a resistant, thick bed

Figure 4.43. *Hell Gill cut into the Yoredale Main Limestone at the top end of Mallerstang (photo: Mark Shinwell).*

Figure 4.44. *The narrow upper end of the Trow Gill meltwater gorge on Ingleborough (photo: John Cordingley).*

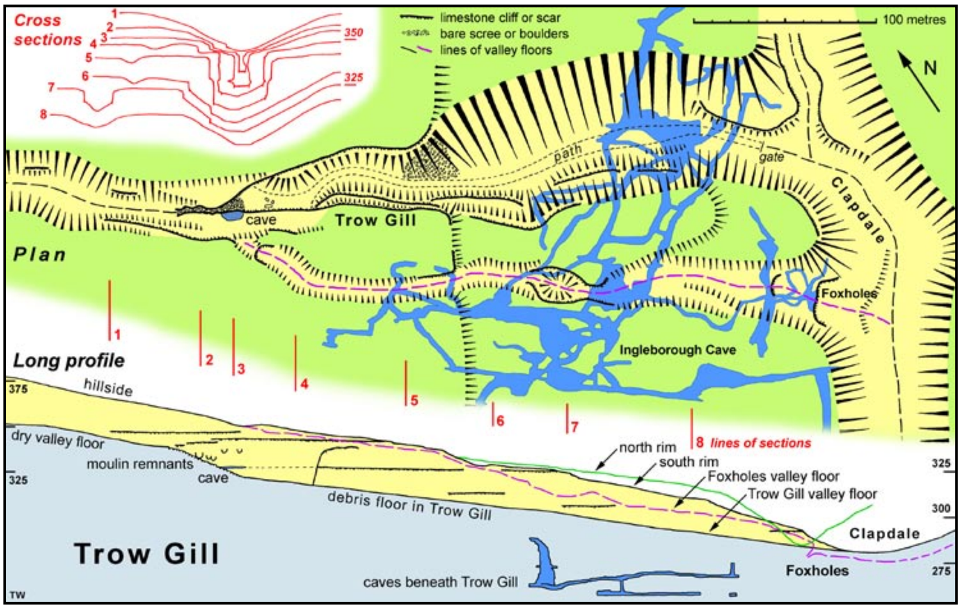


Figure 4.45. The Trow Gill meltwater gorge on Ingleborough, together with the adjacent Foxholes valley and an approximate outline, in blue, of the underlying cave passages (modified from Waltham, 1990).

of limestone, and strongly resembles the wider part of Trow Gill. Most of Conistone Dib is a broad dry valley, but its lower end closes in to a short narrow canyon that is very similar to the fluvial slot in Trow Gill.

Though cavern collapse has long been recognised as an untenable hypothesis for the formation of most gorges in karst, caves do play a role within the overall fluvial excavation of valleys and gorges, in the Yorkshire Dales karst and elsewhere. Beneath an active riverbed, underground loops develop wherever gradients and geological structure provide opportunity. The loops evolve into small caves, and are then unroofed by down-cutting, but thereby contribute to total erosional process. Such caves in the Dales include the various sites known as God's Bridge, of which the finest is that on the River Greta in Stainmore (Fig. 4.46), and the wide area of collapse on the bedding plane caves at Giant's Grave (Fig. 4.47), at the top end of Pen-y-ghent Gill (both in Waltham *et al*, 1997). The active Hell Gill gorge has both a remnant rock arch and a short abandoned loop in its wall.

While these dry valleys and gorges can be ascribed largely to excavation by Pleistocene meltwater, none can be dated to any particular glacial stage, except to note that the fresher features must have been created or re-occupied during the Devensian ice retreat for their clean rock walls to have survived until the present. Furthermore, there is variation within the environments of the meltwater streams. Proglacial erosion was restricted as glacier snouts were largely on the dale floors, below the limestone benches, and even those were short-lived during retreat phases. It has been suggested that Trow Gill could have been rapidly entrenched just below a tongue of ice that survived for some time on the Ingleborough benches (Sweeting, 1974), but the patterns of ice retreat are not known in detail. Subglacial meltwater was widespread and numerous channels have been mapped on the limestone uplands around Malham (Clayton, 1981; Arthurton *et al*, 1988); these include the channels that cross watersheds both north and west of Malham Tarn with reverse gradients that indicate flow under pressure beneath the ice. This water was derived from seasonal surface melt that descended through crevasses and moulins within the ice sheets. There may also have been a significant component from ice-dammed marginal lakes that could have been widespread around the Yoredale nunataks during stages of ice retreat (Faulkner, 2006); these temporary lakes would have fed water onto the limestone, but beneath the ice, in patterns broadly similar to those of today's hillside drainage.

Figure 4.46. God's Bridge in Stainmore, where the River Greta has a very short underground section in its path across the Namurian Great Limestone (known as the Main Limestone further south) (TW).

Figure 4.47. Collapsed ground at the head of Pen-y-ghent Gill with thick beds of limestone that have dropped just a few metres where they were undercut by the wide bedding plane passages of the Giant's Grave Caves (TW).

Figure 4.48. *The meltwater channel of Cowside Beck between Darnbrook Fell and the Malham High Country (TW).*

Cowside Beck (Fig. 4.48) and Pen-y-ghent Gill are both conspicuously large V-shaped valleys that drain into the south side of Littondale. Their morphologies are those of fluviokarst, with many similarities to dry valleys in the Derbyshire Peak District that were modified and enlarged under periglacial conditions. The same applies to some other dry valleys in the Dales, notably the wide section of Conistone Dib (Fig. 4.49). The Yorkshire Dales did not have the long period of Devensian periglacial conditions that distinguished the Derbyshire Peak, but these fluvial landforms may indicate similar conditions during any of the cold stages of the 'Wolstonian' (MIS 10, 8 and 6), or parts of them, when there was no ice cover on the high interfluves of the karst between the dales. They survived the Devensian and earlier glaciations because their orientation meant that ice moved across them, instead of along them. Also, the ice on the limestone high ground was slow-moving, with much of it cold-based so that it was frozen to the bedrock and therefore had minimal erosive power. This was in marked contrast to the main ice flows that were directed along, and thereby enlarged, the Littondale trough. Subglacial meltwater would have continued their excavation.

Figure 4.49. *The dry valley of Conistone Dib, cut by a meltwater stream that descended the steep eastern flank of the Wharfedale glaciated trough (TW).*

Both Cowside Beck and Pen-y-ghent Gill lack the steep cross-profiles of purely subglacial channels such as Gordale and Watlowes, and their relative contributions of periglacial and subglacial erosion remain open to debate. They are old features that were elements of the dendritic drainage pattern imprinted on the Yorkshire Pennines, of which most elements have since been glacially modified into the U-shape dales. Both are also distinctive in that they normally maintain surface flows along most of their lengths over the limestone outcrop, largely due to their low gradients. Ease Gill is a largely fluvial valley; it was occupied by Pleistocene ice, but this lacked erosive power in the lee of Great Coum. Subglacial meltwater is likely to have excavated much of the modern ravine that is entrenched through the till and into the limestone (Fig. 4.50), and also any ancestral valley features now obscured beneath the till.

Subglacial meltwater is a feature of warm-based ice, and its widespread influence on the landforms of the Dales' limestone uplands conflicts with the evidence for cold-based ice indicated by the preservation of the pavements on the high ground. It is likely that conditions varied beneath the Pleistocene ice on the Dales limestone benches, with both warm-based and cold-based ice existing in different areas at the same time, in addition to variations over time as conditions changed at any one place through a glacial phase; such a complex pattern has been recognised under other ice sheets (Faulkner, 2010). Clast-rich sediments in Dale Barn Cave, below Kingsdale, are interpreted as sliding bedload within a pipe-full, glacier tunnel (Murphy *et al*., 2001), but there is considerable variation in the environments and roles of old and contemporary cave passages beneath the Pleistocene ice (see Chapter 7). The lack of glacial erosion across many of the high-level limestone benches may be due in part just to the reduced speed of the ice. The slow-moving, thinner ice sheets had less erosive power than the faster flows of ice that followed the lines of existing valleys and contributed to deepening the glacial troughs of the major dales.

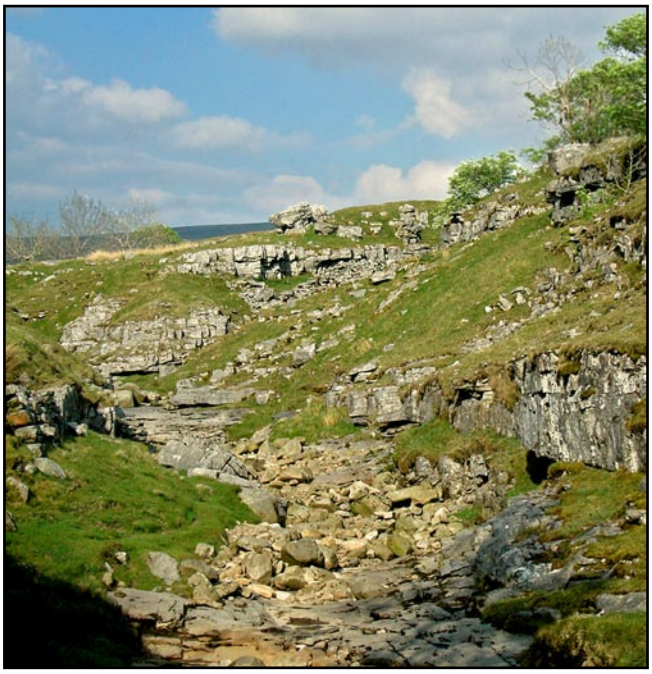


Figure 4.50. *The dry channel of Ease Gill entrenched about 15m into the floor of the wider valley (TW).*

Malham and Gordale

Above the village of Malham, Gordale Scar and Malham Cove are among the most spectacular landforms within the Yorkshire Dales. Each is a large step within the profile of its own drainage channel off the limestone high ground, and each has retreated about 600m from the bench margin along the Middle Craven Fault, which juxtaposes the limestone against weaker Bowland Shales to the south (Fig. 4.51).

The white limestone cliff of Malham Cove is 70m high and about 200m wide (Fig. 4.52). It lies at the lower end of Watlowes (Fig. 4.53), a dry valley entrenched 30m into the limestone surface for 850m downstream of its dry waterfall at Comb Scar. Upstream of the Scar, a shallower valley is dry as far as the Water Sinks that swallow the outflow from Malham Tarn. The hydrology between those sinks, the rising below the Cove and the Aire Head rising is complex (see Chapter 9). At the foot of the Cove a stream emerges from a cave that has been followed, entirely underwater, for 700m, following the bedding in a passage up to 9m wide and 3m high (Monico, 1995).

Figure 4.53. *The Watlowes dry valley, extending downstream from the cliffs of Comb Scar (TW).*

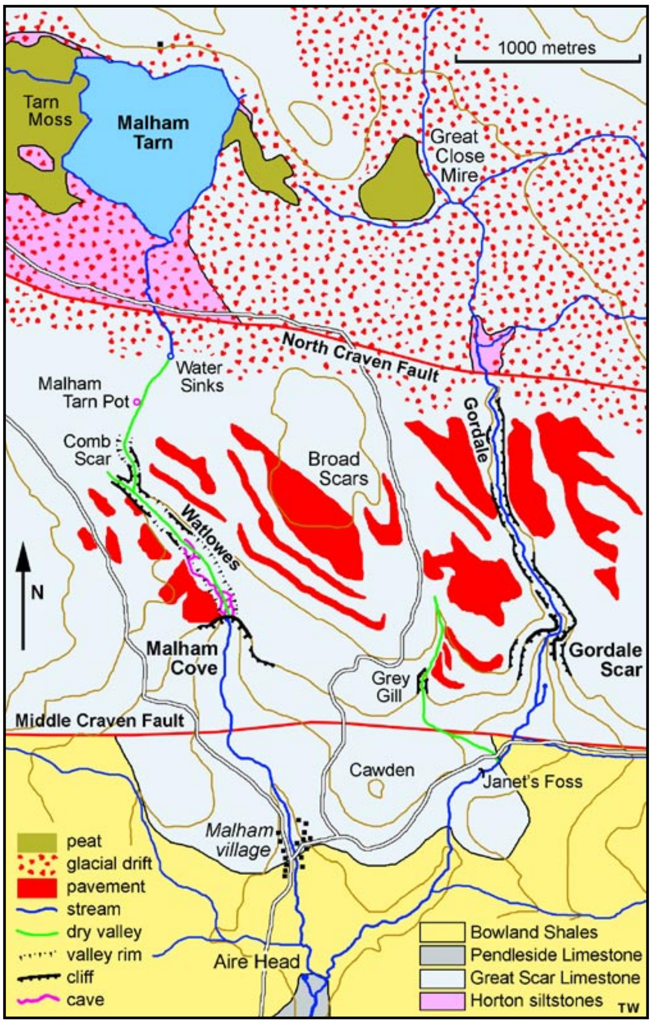


Figure 4.51. *Outline geology and the main karst features of Malham and Gordale; numerous small faults, mainly aligned NW–SE, are omitted for clarity, and both limestones include units of the reef facies that are not distinguished; only the main area of glacial drift around Malham Tarn is marked, and a thin mantle of till is extensive on the lowlands south of the South Craven Fault (geology mainly after Arthurton et al., 1988).*

Gordale Scar has an amphitheatre, also about 200m wide. Its scale is comparable to that of Malham Cove, except that it is more deeply recessed, has taller and more broken cliffs (reaching to 100m high) and has its rear wall breached by a deep gorge (Fig 4.54). Within the gorge, the stream pours through the Hole in the Wall, which was formed in 1730 when the water broke through a 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 where a large bank of travertine still marks the site of the former waterfall (Fig. 4.55).

Figure 4.52. *The limestone cliff of Malham Cove (TW).*

Figure 4.54. The equally wide erosional amphitheatres in front of Malham Cove (on the left) and Gordale Scar (on the right), with Gordale more deeply recessed and also scarred by the fluvial canyon incised into its back wall (satellite imagery from Infoterra).

Above the Scar's gorge, the rocky valley of Gordale is comparable to Watlowes, except that it is 1200m long and still carries an underfit stream for its entire length (Fig. 4.56). The water drains from the basin containing Great Close Mire, and is responsible for the various travertine deposits along and downstream of Gordale (see Chapter 6). Deposition of the travertine may be partially responsible for blocking bedrock fissures and preventing underground capture of Gordale Beck (Moisley, 1955); springs downstream of the Scar are fed by percolation water direct from the high ground.

Both Watlowes and Gordale are impressive meltwater channels. They were cut largely or entirely by subglacial streams, though components of their origins may lie in earlier fluvial or periglacial erosion, or in deepening by short-lived proglacial drainage from remnants of Devensian ice on the Malham High Country. The deeper of the two is Gordale, both in its upstream valley and its Scar gorge, where incision was more rapid on the weaknesses created by small faults.

The main debate concerns the origins of Malham Cove. Historically it was broadly accepted as a "dry waterfall" (Clayton, 1966), though early papers on the Dales karst avoided specific mention of the Cove (Sweeting, 1950; Moisley, 1955). Genesis of the Cove has to rely on some combination of four processes, all of which could have contributed to some extent.

Figure 4.55. Inside Gordale Scar, the beck pours through the Hole in the Wall, and the pre-1730 travertine lies to its left (TW).

Figure 4.56. The deeply entrenched meltwater channel of Gordale upstream of the Scar (TW).

Fluvial erosion. A simple history as a dry waterfall is supported by the dry fluvial valley of the Watlowes feeding to the head of the Cove. The problem arises in the 200m width of the Cove, which far exceeds the width of the Watlowes floor at less than 50m, as Niagara-style waterfall retreat typically forms a cliff little wider than the river channel.

Glaciofluvial erosion. Any consideration of fluvial erosion at the 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 the meltwater origin of the Cove is waterfall retreat during periodic massive subglacial floods, known as jökulhlaups after their occurrences in Iceland. Such floods are indicated by consideration of sub-ice water temperatures in the Malham Tarn basin that would have acted as their source, and their estimated flows of 25–50 m^3/sec could account for the large width of the Watlowes and perhaps that of the Cove (Pitty *et al*., 1986).

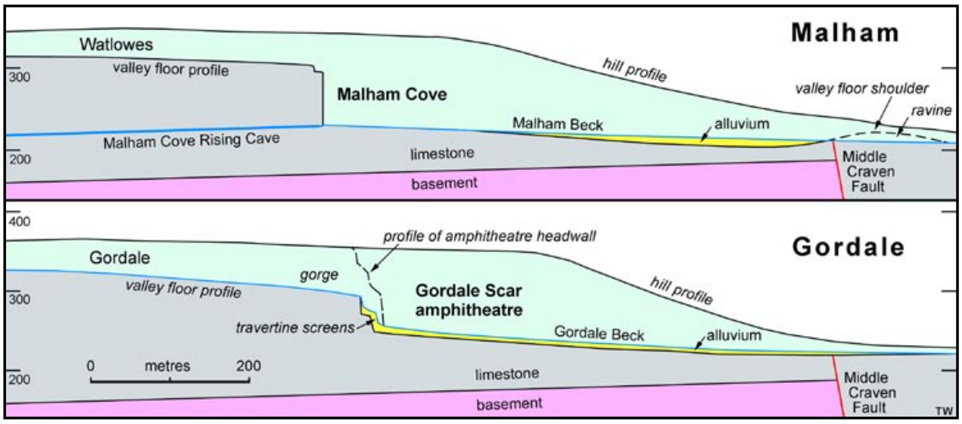


Figure 4.57. Profiles along the meltwater channels of Watlowes and Gordale and their wider sections downstream of Malham Cove and Gordale Scar.

Figure 4.58. Gordale Scar, with the deep and narrow gorge in the shadow that breaks the wall of the main amphitheatre of limestone cliffs (TW).

Ice action. The site of Malham Cove lay beneath the ice during each of the Pleistocene glaciations. Limestone pavements above the Cove indicate a level of ice erosion, but there is no specific evidence of ice action on the Cove itself. Support for the role of ice erosion comes from the Cove's width of about 200m being so much greater than that of the Watlowes valley feeding to its head (Clayton, 1981; Waltham *et al*., 1997). Much of the Cove's morphology could derive from origins as a subglacial step, excavated by glacial quarrying and wall retreat beneath a southward flow of ice that was channelled along a proto-valley roughly on the line of Watlowes and over the fault scarp. The basin below the Cove has been glacially over-deepened, with a post-glacial trench through bedrock at its outlet rim (Fig. 4.57).

Karstic processes. The Cove has been described as a pocket valley, created by a combination of spring sapping, cavern collapse and river erosion (Sweeting, 1972). Water emerging from the cave behind the rising would contribute to shaping of the Cove by dissolutional erosion, removal of rock debris and some undercutting of the cliff. However, the cave passage is less than 5m wide, and its impact can only be minor, even if it was once a vauclusian rising with an ascending passage where the face of the Cove now lies.

It is likely that all four processes have contributed to the distinctive and unusual morphology of Malham Cove, but it is far from certain as to which processes were dominant. Subglacial meltwater, with or without jökulhlaup floods, must have contributed to shaping the Cove at critical stages through the glaciation cycles. Karstic processes cannot have played a major role. And it is difficult to explain the width of the Cove without some element of ice action. The age of the Cove and the scale of its pre-Devensian ancestor are both unknown. Stalagmite from inside the Cove Rising is dated to at least 27 ka, and suggests that the valley in front of the Cove had been eroded to close to its present profile prior to the main Devensian glaciation (Murphy and Latham, 2001).

The rock-walled amphitheatre that is the lower, outer part of Gordale Scar is a landform similar in size to Malham Cove, except that is more deeply recessed into the limestone high ground (Fig. 4.58). Its origins are probably comparable to those of Malham Cove, and are likewise unknown in detail, though it is clear that the narrow gorge that forms the inner section of Gordale Scar was cut largely by meltwater.

Though the Yorkshire Dales karst is actually a glaciokarst, these two of its best known landmarks are fluvial features. Yet these apparent anomalies are perhaps appropriate, as they indicate the complexities of multiple processes that have combined to create the landscapes of the Dales karst.

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