Kingsdale: the evolution of a Yorkshire dale

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SUMMARY: The glaciated trough of Kingsdale is a classic feature of the Yorkshire Dales, and is drained by a complex of cave systems. Within some cave passages, sediments and stalagmites have been dated to establish an absolute chronology for at least part of the dale's evolution. Much of the excavation of Kingsdale dates back to fluvial erosion early in the Pleistocene; the dale was then modified by pre-Devensian glaciers and excavated to almost its present depth. Devensian ice increased the depth profile by only a few metres, before leaving moraines that impounded a short-lived lake at the lower end of the dale. A post-Devensian channel now cuts through the main recessional moraine at Raven Ray, beneath which lies a deep buried valley.

Kingsdale is the most westerly of the classic Yorkshire Dales, lying between Whernside and Gragareth, near the southwestern tip of the Craven Uplands, almost due north of Ingleton (Fig. 1). Its magnificent U-shaped glaciated trough, alternatively described as parabolic in profile, is perfectly straight, some 6 km long and *c.* 700 m wide. It cuts through Carboniferous rocks belonging mainly to the Great Scar Limestone Group (Kilnsey and Malham formations) of the Askrigg Block, so that its walls feature a succession of limestone scars; wide limestone benches, largely covered with glacial deposits, stand above both its rims. The floor of the dale is perched, so that the River Twiss carries outlet drainage over Thornton Force and the other waterfalls in the Ingleton Glens, in a total descent of 150 m down to the Craven Lowlands.

The limestone of Kingsdale is *c.* 180 m thick. It largely comprises the Cove Limestone and overlying Gordale Limestone members of the Malham Formation (Arthurton *et al.* 1988), of Holkerian and Asbian ages respectively and formerly known as the Horton Limestone and Kingsdale Limestone (George *et al.* 1976); the lowest beds, exposed only below the mouth of the dale, include part of the Kilnsey Limestone, and the uppermost beds form part of the Hawes Limestone at the base of the Yoredale Group. Above the limestone, shales and other beds of the Yoredale Group have been stripped to the back of the limestone benches that flank the dale. Underlying basement rocks are exposed only at Thornton Force, below the mouth of the dale. The limestones dip northwards at *c.* 1°, though the dip varies across some very gentle folds. This means that the main limestone bench lies at an elevation of just over 400 m above the mouth of Kingsdale, but descends slowly up-valley, so that the outcrop is lost at *c.* 340 m just beyond Kingsdale Head. The limestone is a strong rock, though its mass strength is reduced by numerous bedding planes, some with significant shale partings and also by extensive sub-vertical jointing. At the mouth of Kingsdale, the flanking limestone benches and the Craven Uplands are truncated by the North Craven Fault, which defines the first steep step down to the Craven Lowlands (Fig. 1).

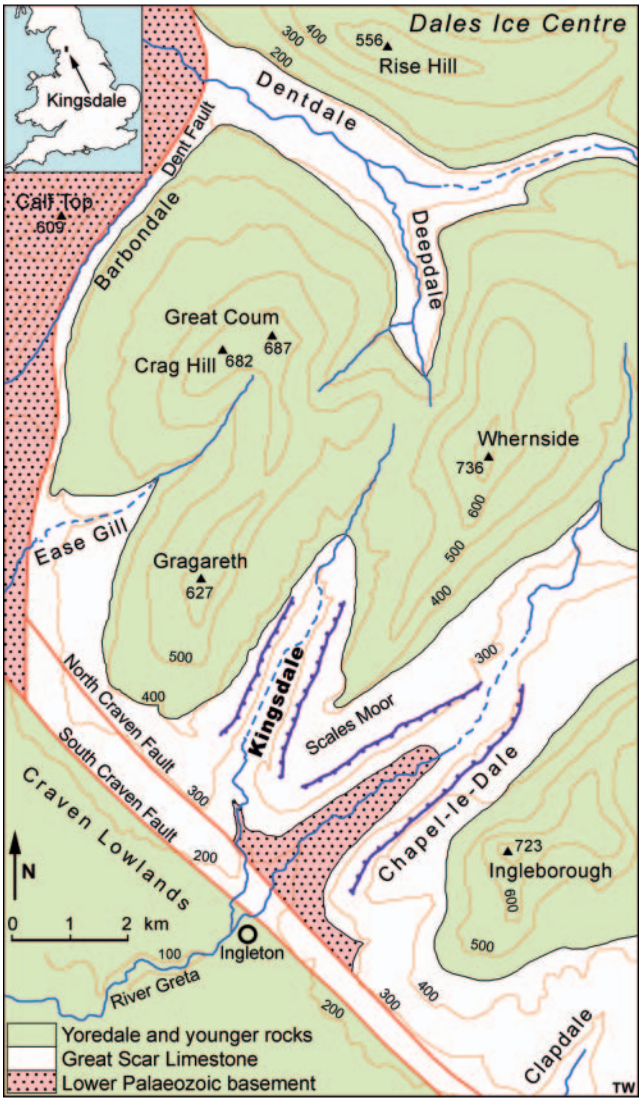

Fig. 1. Location of Kingsdale and adjacent dales, cut into the western corner of the Craven Uplands on the Askrigg Block. The rims of the glacial troughs are marked in Kingsdale and Chapel-le-Dale. Broken lines denote the river sections that are dry across the limestone except in flood conditions. Only the edge of the Pleistocene Dales Ice Centre is shown, as it extended further to the north.

1. GLACIAL FEATURES OF KINGSDALE

The glaciated trough of Kingsdale is a textbook landform, with its U-shaped profile only slightly modified by post-glacial

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Fig. 2. The view down Kingsdale from the slopes above Kingsdale Head. The Brown Hills recessional moraine lies between the trees in the foreground. The alluvial floor extends beyond, with the straight artificial flood channel of the beck on its right edge. The Raven Ray recessional moraine forms the barrier across the end of the dale, with its overflow channel heading to the left behind the large lateral moraine of Wackenburgh Hill.

alluviation (Fig. 2). It is perfectly straight, but there is no evidence of any fault guidance; its centreline is buried in drift, and there is no recognizable displacement between outcrops on each side. The splendid U-profile owes part of its origin and much of its preservation to the strength and stability of the limestone, especially with its slight increase in thicker and stronger beds near the top of the succession to define a sharp rim to the trough.

During the Devensian glaciation, a Kingsdale glacier was fed by ice from a Dales Ice Centre to the north (Mitchell 1994; Evans *et al*. 2005), with significant flow southwards from Dentdale, up Deepdale and over the saddle west of Whernside (Fig. 1). Through many of the Pleistocene cold stages, it is likely that all or most of the Askrigg Block was covered by ice and the dales occupied by thicker flows of ice that carried the significant flow within a broad ice sheet. Kingsdale was one such iceway, with an erosive stream of ice along its axis. This flowed between sheets of ice that were either cold-based or were moving but much more slowly across the high limestone benches and over the even higher hills such as Gragareth. Kingsdale was occupied by a valley glacier between its limestone walls only after and probably before these phases of total ice cover. Certainly this was the case in the retreat phases of the Devensian glaciation. With the ice surface altitude declining on the Dales Ice Centre, the flow of ice up Deepdale and over into Kingsdale would have eventually decreased, leaving a declining Kingsdale glacier with minimal flow and power.

The well-known glacial landforms of Kingsdale are all products of the retreat phase of the Devensian ice (Waltham 2007). Across the mouth of Kingsdale, the Raven Ray ridge is a textbook example of a terminal moraine forming a barrier, 700 m long and 30 m high, across the glaciated trough (Figs 2, 3). It is better described as a recessional moraine, as it was left behind during decay of the Kingsdale glacier. Lateral moraines continue down the valley from it on both sides (Fig. 3), with the eastern lateral moraine forming a conspicuous ridge over the lower limestone bench SW of Twistleton Scar End, before both lateral moraines merge into the till-mantled slopes that constitute the degraded scarp on the Craven Faults. Up-valley from the Raven Ray recessional moraine, the lateral moraine is more conspicuous on the eastern flank and forms most of the terrace either side of Braida Garth, though the farm itself stands on bedrock (Fig. 3). Wackenburgh Hill is a rock-cored lateral moraine with till overlying a shoulder of limestone, which is exposed in some of the dolines and caves that descend through the till. Within the hill, the limestone rises to a level close to 280 m, and only the rounded crest above that has the topographic expression of a lateral moraine. The dolines in a line along its western edge penetrate the till cover where it thins to *c*. 4 m over the limestone scar, and they rise gently to the south following up the dip of the scar. The west bank lateral moraine is a very modest feature, barely large enough to carry the minor road along most of the length of Kingsdale, though it widens at the upper end of the valley. Just below Kingsdale Head, a second recessional moraine survives as the uneven ridge of Brown Hills, which is lower and less conspicuous than its predecessor at Raven Ray (Figs 2, 3).

Between these pairs of lateral and recessional moraines, alluvial sediments form the broad valley floor with a low longitudinal gradient. Braided and meandering channels score the alluvium and have cut a cuspate margin into the upper end of the western lateral moraine; all these channels are normally dry since artificial straightening of the beck *c*. 200 years ago. Beneath the fields in front of Keld Head, depths to rockhead reach *c*. 15 m (as indicated by unpublished seismic refraction surveys in 1971 by N. G. Fox, a student at Lancaster University, and in 1982 by geologists from Trent Polytechnic), though these profiles could have missed a slightly deeper centreline of the valley.

A clear profile of the buried valley beneath the Raven Ray recessional moraine is visible to the left of Thornton Force, looking upstream, where the grassy slopes on till break the line of rock scars formed by the lowest beds of the limestone. The same buried valley has been traced back beneath the moraine by resistivity (Bruckshaw 1948) and seismic (Wilson 1980) surveys. The post-glacial channel cuts through the recessional moraine to the east of the old channel, and is entrenched into limestone for much of its line; the short cliff line overlooking the beck appears to be the original Raven Ray, though the name is now also applied more broadly to the moraine barrier.

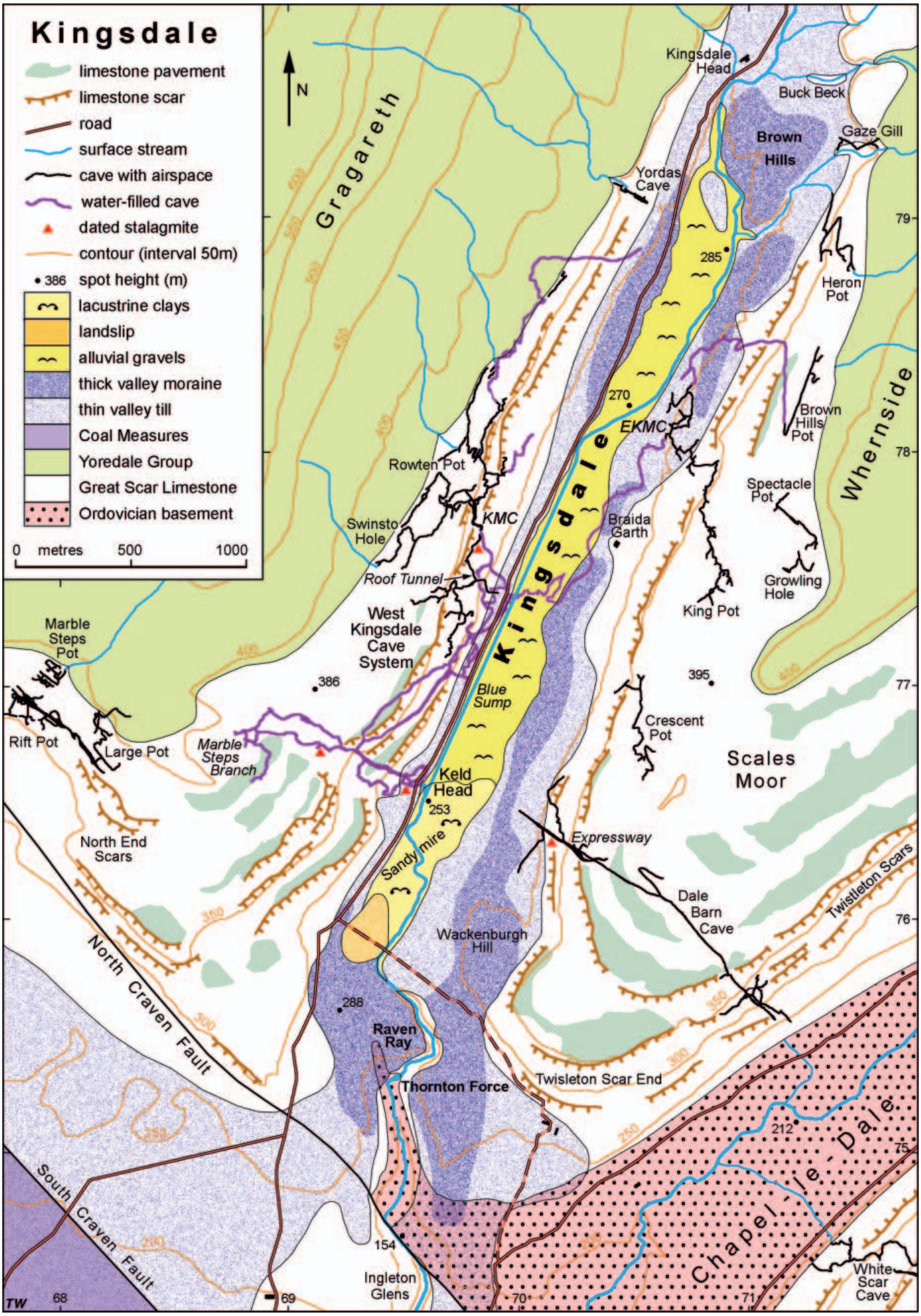

Fig. 3. The main features of the geology and geomorphology of Kingsdale and the known caves that lie beneath it. Minor faults within the limestone are not marked. Discontinuous veneers of thin till on the higher hillsides and within Chapel-le-Dale are not marked, and the extent of the thicker till of the moraines is approximate. For purposes of clarity, some minor cave passages have been omitted and scars and roads are not drawn where they pass over caves. The main cave passages, with air space inside them, include those that carry streams and those that are dry and abandoned; within their lengths there are short sections of flooded passage that are not distinguished. Water-filled caves are the long sections of conduit below the water table. KMC, Kingsdale Master Cave; EKMC, East Kingsdale Master Cave.

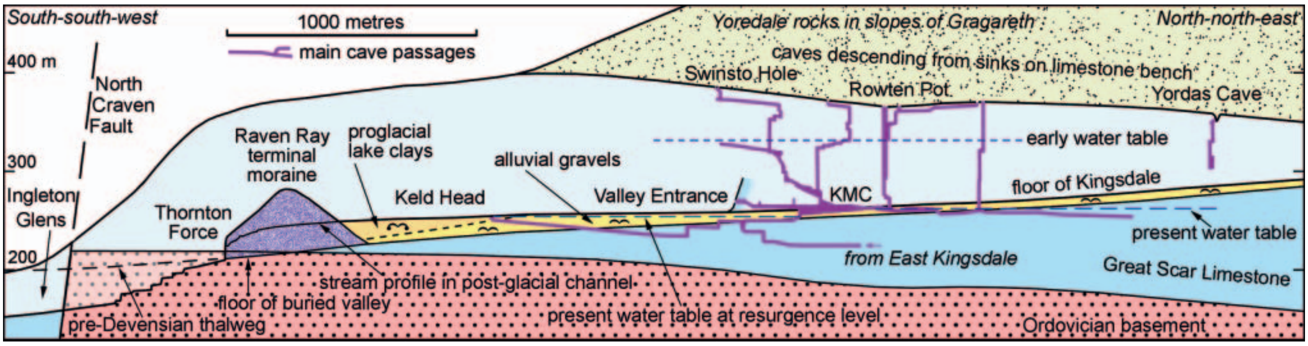

Fig. 4. Long profile of Kingsdale and the major caves beneath its western benches. The modern water table is stepped, with a higher elevation upstream of a section of vadose canyon in the Kingsdale Master Cave, which is the trunk drain. The paler tones on the rocks indicate positions in the hillside that is beyond the alluviated valley floor in this view. Roof Tunnel is the abandoned trunk cave passage truncated at the Valley Entrance. The landslip off the recessional moraine is not shown as its floor profile is unknown. Vertical scale is exaggerated by 4. KMC, Kingsdale Master Cave.

The new channel leads to the head of Thornton Force, where the modern stream rejoins its old valley; the waterfall has retreated back into bedrock, thereby famously exposing the basal unconformity of the limestone over the basement rocks of the Ordovician or older Ingleton Group.

2. CAVE DRAINAGE BENEATH KINGSDALE

The limestones of Kingsdale are drained by an extensive system of inter-connected cave passages (Brook 1974; Waltham *et al.* 1997). Many years of exploration and underground mapping by numerous teams of cavers and cave divers mean that the Kingsdale caves are now known more completely than most other cave systems in the Yorkshire Dales (Fig. 3); they are cited as the type example of cave development in the Dales (Waltham *et al.* 1981). Streams that drain off the shale-dominated Yoredale sequences, which form the higher slopes of both Whernside and Gragareth, all sink underground where they meet the top of the Great Scar Limestone (Fig. 3). The largest single input of water is from the head of the dale, feeding into various partly choked sinks in the reach below Kingsdale Head farm. The only significant surface flow across the limestone is in the flood channel along the axis of the valley, which is frequently active when flood flows are too large to enter the sinks at Kingsdale Head.

Streams that sink on the high limestone benches have utilized the bedding planes, shale beds, joints and small faults to establish underground routes through to the single resurgence of Keld Head on the valley floor. The dominant cave pattern is to drop down a joint to reach one of the many shale beds in the upper part of the limestone succession (Waltham 1970, 1971). There the cave heads north, therefore up-valley, as it drains down-dip in the vadose environment (Fig. 4). At some stage it encounters joints that allow it to descend to lower levels. Once a cave conduit passes beneath the contemporary water table and into the phreatic environment, it loses its gravitational constraint. It therefore doubles back to head south up the dip, and hence down-valley, to reach the contemporary resurgence at or close to the lowest outcrop of the limestone where it can drain out towards the Craven Lowlands. Repeated rejuvenations of the karst have left multiple cave levels within the limestone, where lines of underflow along lower bedding planes evolved into trunk conduits draining to newly available outlets at successively lower levels (Worthington 2004). The older high levels are now mostly dry and abandoned; some are truncated in the valley sides, and some are still occupied by younger streams. This pattern of sequential caves reflects the long-term slow uplift and subsequent denudation that is recognized across the north of England, besides being a worldwide phenomenon (Westaway 2009).

Beneath the limestone bench of Gragareth, the West Kingsdale Cave System is a classic of its type, with dendritic, vadose, tributary caves descending from multiple sinks to converge on the short section of large vadose canyon passage known as the Kingsdale Master Cave. This carries drainage into a long underwater passage, with various braids and loops, that reaches through to Keld Head (Fig. 3).

On the opposite side of the dale, similar stream caves descend northwards to converge on the East Kingsdale Master Cave. From there, the cave becomes a water-filled conduit that passes beneath the floor of Kingsdale to join the phreatic caves feeding out to Keld Head. It survives within only a thin thickness of limestone where it passes beneath the valley floor. The base of the limestone, resting unconformably on basement rocks, dips gently northwards from an altitude of *c.* 220 m where it is exposed at Thornton Force. The unconformity does have its own buried relief (Waltham 1977), but there is no indication that this is on a scale great enough to influence the karst drainage of Kingsdale. By inference from the structure of the exposed beds, the base of the limestone is probably at *c.* 212 m at Keld Head, and little above 200 m beneath Braida Garth (Fig. 4). It would appear that the flooded passage of the East Kingsdale Branch crosses beneath the valley with at least 10 m of solid rock above the cave roof and *c.* 18 m of limestone beneath the cave floor; divers have found neither outcrop nor pebbles of the basement rocks in the flooded caves. The sharp dogleg in this passage, beneath the floor of Kingsdale (Fig. 3), could indicate the crossing of a small fault, but divers have not been able to confirm this in the poor visibility of a very challenging environment.

Immediately north of the Craven Faults, limestone benches extend between the various dales and valleys (Fig. 1). Modern underground drainage on both sides of Kingsdale is towards the SE (Fig. 3), from Marble Steps Pot to Keld Head (though the long underwater section has not yet been fully explored), and through Dale Barn Cave to Chapel-le-Dale. Ultimately all drainage from the karst is across the Craven Faults and out onto the Craven Lowlands.

Table 1
Dated stalagmites from sediment sequences within the Kingsdale caves. The Marine Isotope Stages (MIS) are indicated, with options to place deposition in a warm stage where error bars make that possible and therefore likely

Sample	Location	Altitude	Age (BP)	Error bar (ka)	MIS	Reference
MS1	Keld Head, Marble Steps Inlet	248 m	87.8 ka	+/− 11.8	5b	Murphy *et al.* 2008
MS2		248 m	89.4 ka	+/− 1.0	5b	
KH1	Keld Head, First Airbell	252 m	2.5 ka	+/− 0.03	1	Murphy *et al.* 2004
KH2		252 m	4.5 ka	+/− 0.9	1	Murphy *et al.* 2008
DB1	Dale Barn Cave, Expressway	255 m	343.4 ka	+86.0, −47.7	9/10	Murphy *et al.* 2001
KM1	Roof Tunnel (Valley Entrance)	263 m	<400 ka		?	Atkinson *et al.* 1978
KM2		263 m	239 ka	+26, −20	7c	Waltham 1986
77240		263 m	324 ka	+/− >100	9	Gascoyne *et al.* 1983
77241		263 m	168 ka	+11, −10	6	
77242		263 m	300 ka	+ >70, −43	8/9	
77243		263 m	230 ka	+23, −19	7b/c	

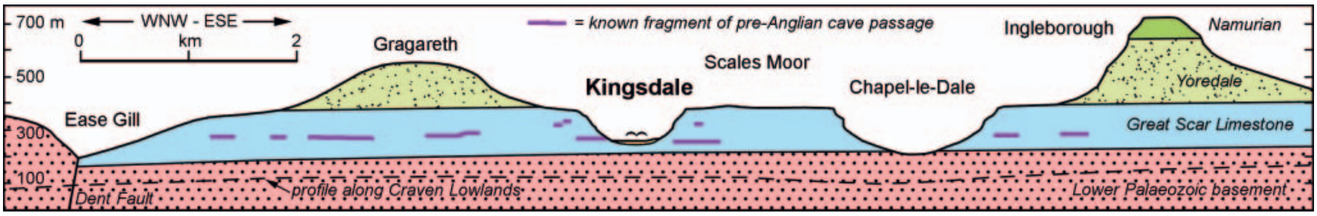

Fig. 5. Profile across Kingsdale, its flanking hills and the adjacent valleys, showing significant segments of the abandoned, phreatic, pre-Anglian, trunk cave passages. Vertical scale is exaggerated by 2.5.

2.1. Absolute ages of cave sediments

With all surface evidence eroded away by the last glaciation, absolute dating of cave sediments offers the only means of establishing a chronological framework for the evolution of Kingsdale. Stalagmites have been dated by decay of their uranium isotopes to thorium (Table 1), but these indicate only when the cave was above the water table; they therefore set a latest possible date for the formation of the stalagmite's host passage, which must be older and may be much older. They imply maximum levels of the contemporary local water table, and therefore the resurgence level, though stepped water tables through the karst aquifer may lie upstream of descending vadose canyons. A dated resurgence level then indicates a maximum altitude of the valley floor where outcrop patterns allow it to lie. However, karst drainage can cross beneath topographic divides, so water tables may relate to resurgences and floor levels in adjacent, deeper valleys. Declining levels of the radio-isotopes over time previously limited the U/Th dating of stalagmites to *c.* 350 ka (Gascoyne *et al.* 1984).

The largest programme of stalagmite dating in the Yorkshire Dales (Gascoyne *et al.* 1983) found peaks of stalagmite growth that broadly coincided with Marine Isotope Stages (MIS) 1, 3, 5a, 5e and 7–9, and conspicuous periods when carbonate precipitation ceased during MIS 2 and 6; these data included four samples from caves in Kingsdale (Table 1). Subsequent programmes have confirmed the pattern of activity through the later stages (Baker *et al.* 1995). Newer techniques with thermal ionisation mass spectrometers have extended the range back to 600 ka (Richards & Dorale 2003), and dating of quartz in clastic cave sediments by decay of their Al/Be isotopes can reach back to *c.* 2 Ma (Granger & Muzikar 2001); dates from these methods are not yet available for the Kingsdale caves.

2.2. Older cave passages beneath Kingsdale

Within the West Kingsdale Cave System, Roof Tunnel is an abandoned section of very old trunk passage; it is now truncated by the glaciated trough of Kingsdale, where it is partly obscured by glacial till at the Valley Entrance, at its eastern end and close to the dale floor. Calcite flowstones from within Roof Tunnel have yielded a range of ages, including four of >230 ka and two of >300 ka (Table 1). These indicate that the cave passage was essentially dry during the MIS 9 interglacial, almost certainly after rejuvenation by Anglian glaciers in MIS 12; it lay above a water table that stood at an altitude no higher than *c.* 260 m. Little should be inferred from the stalagmite date of >400 ka (Table 1), as this is at the interpretable limit of the primitive equipment used for U/Th dating in that very early analysis.

While the modern karst drainage of Kingsdale is largely mapped, little is clear about most of the earlier phases of drainage. Isolated segments of large, abandoned, phreatic trunk passage have been reached, via younger stream caves that intersect them, inside the limestone hills on both sides of Kingsdale; their continuations are choked with clastic sediment. These passages carried flow either to or from both Chapel-le-Dale and the Ease Gill valley when water tables and thalwegs lay at altitudes well above those of today (Fig. 5); precise ages of these ancient passages are unknown, but all those below 300 m in altitude are pre-Anglian. Beneath the eastern flank of Kingsdale, the large cave passage known as the Expressway was formed when it carried a major flow beneath a contemporary water table. Calcite flowstone dated to 343 ka (Table 1) coats the upper walls of the passage, and indicates the draining of the old phreatic route to Chapel-le-Dale prior to MIS 9.

Cave passages behind Keld Head (Fig. 3) are now flooded because they lie at levels below that of their resurgence onto the floor of Kingsdale. On the wall of a side passage off the trunk route in from Marble Steps Pot, calcite flowstone now 4 m below water level dates from *c.* 90 ka (Table 1). This indicates that the passages were at least partly drained, to a lower Kingsdale floor, at that time in MIS 5b (Early Devensian). Though there are still cave passages that await discovery, enough are known already to indicate that there is very little scope for the Keld Head passages to have drained at that time to either Chapel-le-Dale or the Ease Gill valley.

3. EVOLUTION OF KINGSDALE

Multiple glaciations have successively modified the geomorphology of Kingsdale during the various cold stages of the Pleistocene (see Gibbard & Cohen 2009 for Pleistocene chronostratigraphy, including correlation between the Marine Isotope Stages (MIS) and British Stages referred to below). Though that much is beyond debate, there is doubt over the exact role of each ice occupation and the amounts of valley deepening within each glaciation, and within each interglacial stage. The earliest history of Kingsdale dates back to fluvial erosion within the Neogene (Westaway 2009). With the evidence lost to erosion, the scale and depth of this ancestral valley cannot yet be determined, but the feature subsequently guided the more powerful and more erosive flows of ice within the over-riding Pleistocene ice sheets.

3.1. Anglian (MIS 12) and Hoxnian (MIS 11)

Though the early stages of this proto-Kingsdale were excavated within the Yoredale rocks, the Great Scar Limestone was eventually exposed across the valley floor, and much or all of the drainage then sank into newly developing caves. Most of these caves have since been destroyed by excavation of the glacial trough, but various fragments of high-level passages are known at altitudes *c.* 325 m under both benches (Figs 4, 6); these suggest a contemporary water table at a level not far above 325 m, but the contemporary dale morphology, the location of the resurgence and the absolute age are unknown.

At some early stage or stages the Kingsdale caves appear to have drained out to resurgences in either Ease Gill or Chapel-le-Dale, through the large trunk passages now known in segments under the intervening hills. The Ease Gill valley lies in the lee of Great Coum where deepening by subsequent glaciations has been minimal (Fig. 1); it also lies close to the line of the Devensian ice divide recognized further north (Mitchell 1994) and appears not to have carried any significant flow of erosive ice. The paucity of its post-Anglian deepening implies that it would have reached a level much lower than Kingsdale at these early times. Chapel-le-Dale is now, and probably always has been, at a lower level than Kingsdale, as it has a larger catchment to the north and also carried major ice flows from the Dales Ice Centre. Both Ease Gill and Chapel-le-Dale were well placed to receive early karstic drainage from a high-level Kingsdale. The remnants of trunk passage through Rift and Large Pots, towards Ease Gill, are at levels 20–50 m above that of Expressway, towards Chapel-le-Dale (Figs 3, 5). This implies, but does not prove, that the Ease Gill route is the older; there is, as yet, no further evidence of its age.

The drainage of Roof Tunnel by MIS 9, as confirmed by the stalagmite deposition within it (Table 1), indicates that the contemporary resurgence lay *c.* 100 m deep below the main limestone benches. If that resurgence was in Kingsdale, at or close to its floor level and somewhere near the present site of Raven Ray and Thornton Force, then the glaciated trough of Kingsdale was already *c.* 100 m deep by then. This was almost certainly a result of the Anglian glaciation in MIS 12, when Roof Tunnel had been truncated by Anglian ice (Fig. 6). But any link from Roof Tunnel to that resurgence has been removed by valley erosion, so there is an alternative situation, where the MIS 9 drainage of Kingsdale was out to Chapel-le-Dale, through Expressway in Dale Barn Cave (Fig. 3); it is unlikely to have been out towards Ease Gill as the known passages in that direction are at higher levels. The post-Anglian floor of Kingsdale could then have remained at a higher level, though this would imply that the floor of Chapel-le-Dale was already then entrenched to 100 m below the limestone benches. Either situation implies that the bounding scarp along the Craven Fault Zone already stood well above the Craven Lowlands to the south after the Anglian glaciation.

The Roof Tunnel cave passage lost its role as the West Kingsdale trunk drain when its flow was captured by a lower route towards Keld Head (Fig. 3). Cave drainage and passage development were minimal during the Anglian, and during each glaciation, when much of the ground was frozen (permafrost) and most cave entrances were blocked by ice plugs; analogy is drawn with the ice-plugged Castleguard Cave beneath Canada's Columbia Icefield today (Ford 1983). Enlargement of the passages southward towards Keld Head accelerated after the Anglian rejuvenation, so that Roof Tunnel was left dry by MIS 9. The position of the post-Anglian resurgence, in either Kingsdale or Chapel-le-Dale, is unknown, as the passage to it has been truncated at Keld Head. There may have been intermediate phases when the main drainage was out through passages from the Master Cave that are now choked and through the Blue Sump, an underwater distributary passage that was also later truncated (Murphy *et al.* 2008).

3.2. 'Wolstonian' (MIS 10-6) and Ipswichian (MIS 5e)

Whereas the altitude of the Hoxnian floor of Kingsdale remains uncertain, 'Wolstonian' ice appears to have excavated the dale to a level below 248 m, as stalagmite dated to *c.* 89 ka has been recorded at that level within the passages of Keld Head (Table 1). This glacial re-excavation of Kingsdale would appear to have been during MIS 6, when there was a marked cessation of stalagmite deposition within the caves (Gascoyne *et al.* 1983). However, there is sound evidence for glaciation of the Trent Valley during MIS 8 (White *et al.* 2010), to match the timing of a significant ice advance on mainland Europe, and it is unlikely that Kingsdale would have remained without an occupying glacier at the same time. Nevertheless, stalagmite deposition in the Yorkshire caves appears to have continued unabated through MIS 8 (Gascoyne *et al.* 1983), in a pattern confirmed by similar records from elsewhere in Europe (Lauritzen 1993). This would suggest that glacial occupation of the dale in MIS 8 was unlikely, unless an earlier cessation of calcite deposition is obscured by the low level of precision of these early age determinations. It therefore remains in doubt just when, and on how many occasions, Kingsdale was glaciated during the multiple cold stages of the 'Wolstonian'.

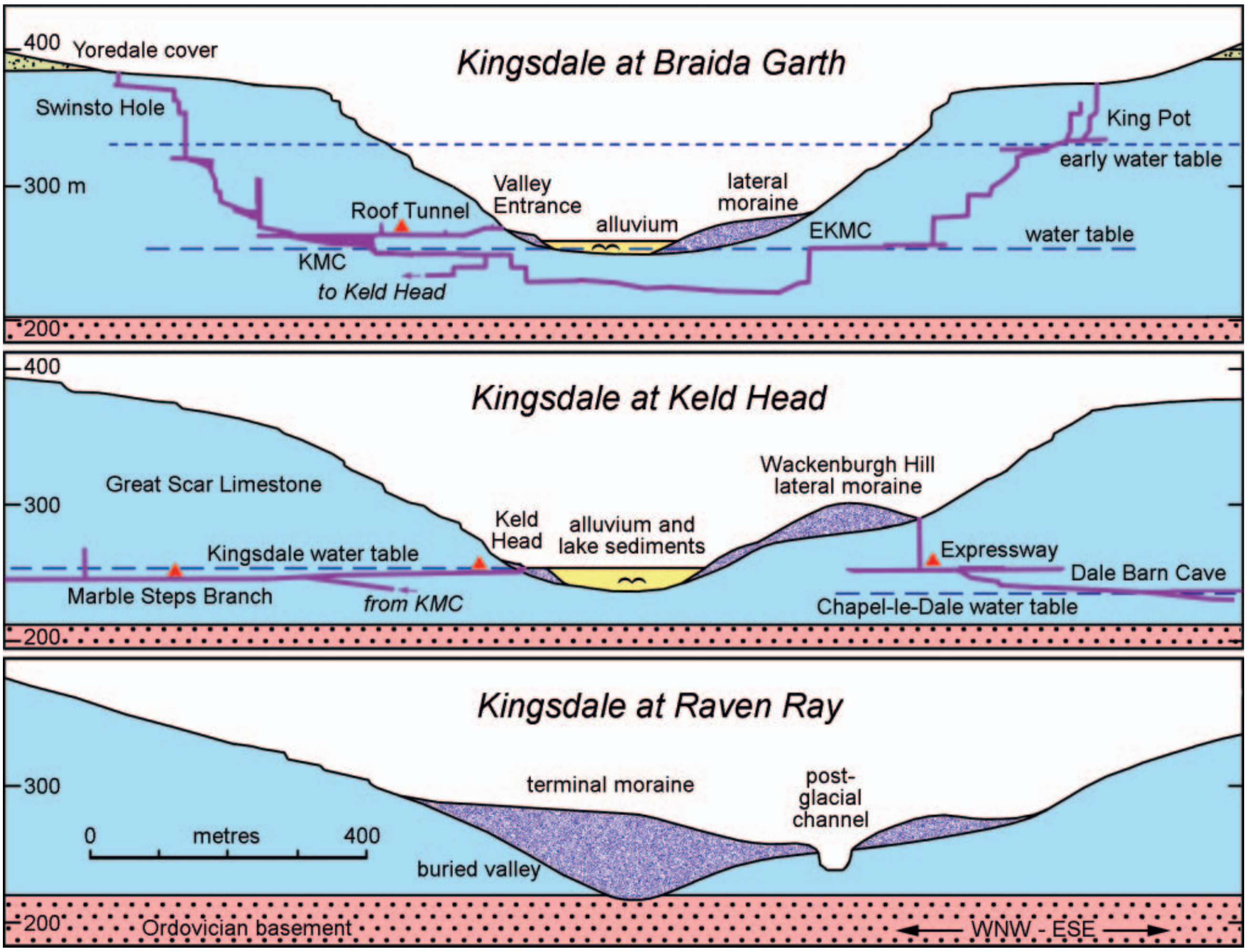

Fig. 6. Three profiles across Kingsdale, with projected positions of adjacent features. Locations are identifiable on Figure 3. Vertical scale is exaggerated by 2. KMC, Kingsdale Master Cave; EKMC, East Kingsdale Master Cave. Solid triangles are the dated stalagmite locations.

An additional 'Wolstonian' event in Kingsdale was the input of proglacial or subglacial water from Chapel-le-Dale. The large Expressway cave passage, at a level close to 255 m under Kingsdale's eastern flank (Fig. 3), contains thick banks of sediment that are conspicuous by their content of green, chloritized clasts (Murphy *et al.* 2001). These clasts were derived from the Ingleton Group basement forming the floor of Chapel-le-Dale, or just conceivably from the same rock at floor level in the intervening cave passages. There is no outcrop of these rocks up-valley in Kingsdale, and no realistic scope for any source beneath the sediments around Kingsdale Head. Much of the Expressway sediment is coarse diamicton of a type transported as sliding bed-load within a pipe-full conduit, which is characteristic of a sub-glacial tunnel (Saunderson 1977). This clast-laden drainage towards Kingsdale eroded the face of flowstone that is dated to 343 ka (Table 1). It is perceived as subglacial flow from a time when Chapel-le-Dale carried a glacier while Kingsdale was relatively free of ice (Murphy *et al.* 2001). The green clasts are absent from the Raven Ray recessional moraine, so this drainage beneath the Scales Moor interfluve is interpreted as a short-lived event within the 'Wolstonian', or possibly on the Devensian advance. As this flow was phreatic and driven by high water levels within the Chapel-le-Dale glacier, it offers no evidence of a contemporary Kingsdale at a lower level.

3.3. Devensian glaciation (MIS 2)

The early Devensian dates of the Keld Head stalagmite at the 248 m level (Table 1) suggest that Kingsdale had a depth profile during the Ipswichian interglacial that was very close to that of today. A subsequent exploration in Keld Head has revealed more calcite flowstone at a depth of 6.7 m below the current water level (John Cordingley, pers. comm., 2010). This indicates that the cave passage was drained to a resurgence below an altitude of 246 m, almost certainly on the floor of Kingsdale and probably also in Ipswichian times. Though the details await further exploration, and sampling and dating of the flowstone, this would appear to suggest an even lower Ipswichian valley floor and even less excavation by Devensian ice.

The modern rock floor, beneath the sediments of Kingsdale, appears to slope gently downstream from an altitude of *c.* 239 m at Keld Head, to *c.* 210 m where it is exposed immediately downstream of Thornton Force (Fig. 7); there the glacial fill within the buried valley reaches down to stream level *c.* 70 m west of the waterfall (Waltham 2007). Between these points, the buried valley has its floor at an altitude of *c.* 225 m beneath Raven Ray, as indicated by the geophysical profiling (Bruckshaw 1948; Wilson 1980).

The limited exposures indicate that the lower part of the old Kingsdale valley, buried beneath the moraine, has a narrower

Fig. 7. The end of the main buried valley beside Thornton Force, with its plug of till reaching from the crest of the Raven Ray recessional moraine down to beck level below the five hawthorn trees; the east sidewall of the buried valley is the end of the limestone scar behind the large yew tree beside the steps, and the west sidewall is the limestone scar in the left foreground.

profile that is more V-shaped in comparison with the wider U-shaped profile within the main dale (Fig. 6c). This may be due to ice cutting down into the weaker materials of the thinly bedded Kilnsey Limestone and the underlying slate, or it may reflect more entrenchment by proglacial or subglacial meltwater. The rock terrace beneath the lateral moraine of Wackenburgh Hill intrudes into the smooth U-profile of the glaciated trough.

Consequently, the Devensian glacier may have been responsible for as little as 9 m of dale floor deepening at Keld Head, though the exact figure remains unknown, because resurgence positions are unknown following glacial truncation of the caves. At the same time, the glacier trimmed the walls of Kingsdale to leave the lines of fresh scars along the stronger limestone beds. During the Last Glacial Maximum, the ice spread over the limestone benches on each side of Kingsdale, but there was minimal scour of the pavements, followed by widespread burial of them beneath veneers of till. Both features indicate a relatively weak flow of ice down Kingsdale when compared with the more powerful Chapel-le-Dale ice that left wide, scoured, bare, limestone benches on each side of its main trough. Just below Kingsdale Head, the rounded banks of the Brown Hills recessional moraine (Fig. 3) are followed up-valley by a spread of thicker till left by the wasting glacier, though Buck Beck cuts down into limestone just behind Brown Hills.

Current modelling suggests that the uplands of the Yorkshire Dales were probably clear of ice by *c.* 16.5 ka (Telfer *et al.* 2009) or even as early as 18 ka (Vincent *et al.* 2010), though some valley glaciers may have survived for slightly longer into the Windermere Interstadial. No glacier re-occupied Kingsdale during the Loch Lomond Stadial (Younger Dryas), when the nearest ice formed a small cirque glacier high on the northeast slopes of both Whernside and Great Coum (Mitchell 1996).

3.4. Devensian deglaciation

The conspicuous recessional moraine of Raven Ray was left as a barrier across the mouth of Kingsdale during the final retreat of the Devensian ice. The buried valley that was cut into bedrock remains beneath it. At that time, the Kingsdale ice was reduced to a valley glacier that did not fill the glaciated trough; on both banks and both upstream and downstream of Raven Ray, lateral moraines indicate the extent of the ice tongue. The main Kingsdale floor has a very distinct low gradient on the alluvial sediments that were deposited first as glacial outwash from the waning glacier and then by post-glacial streams. A recently excavated cable trench revealed about a metre of disturbed sediments and silty soils that consist largely of loessic material; these overlie alluvial gravels, whose base was not exposed, along the whole dale floor upstream of the small flat section known as Sandymire (Fig. 3).

Decay of the ice, and retreat of its front from its terminal moraine, left its outlet meltwater temporarily ponded as a lake behind the moraine; lacustrine sediments beneath the Sandymire flat confirm its past existence. The lake overflowed at the lowest point along the moraine crest, which was well to the east of the valley's centre line, and the new channel was entrenched though the till and into the buried limestone shoulder extending south from Wackenburgh Hill. Where it rejoined the pre-glacial valley at Thornton Force, a waterfall soon developed over the strong limestone lip above a plunge pool that was undercut into the weaker low-grade slates of the Ingleton Group basement. The waterfall has subsequently retreated *c.* 50 m to its current position. While the valley downstream was deepened by Devensian meltwater and by postglacial drainage, much of it dates from earlier stages as it is partly filled by the Devensian lateral moraine where it steps SE along the North Craven Fault.

The proglacial lake behind the Raven Ray recessional moraine was soon lost to lowering of its outlet where a channel was cut into the till, but the period of the lake's life is unknown. Its maximum level was probably close to 265 m, and its outlet gorge is entrenched into the limestone bedrock of the old valley side below 260 m east of the remaining ridge of recessional moraine. Initially, the lake was only small, when the ice wall was still close to the moraine. Patches of beach sand at elevations of just under 260 m on the slopes of the recessional moraine appear to be relicts of the lake at its highest level. Retreat of the glacier front saw the lake expand

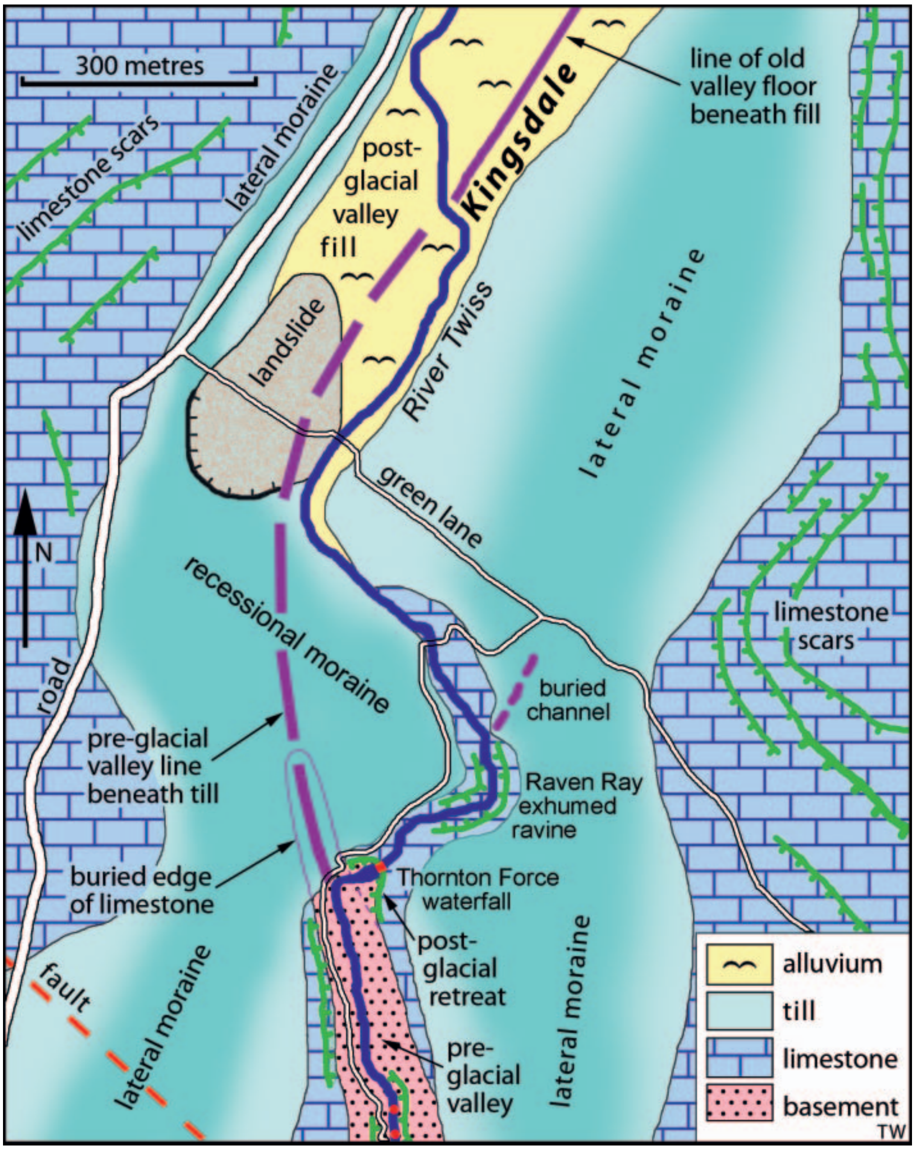

Fig. 8. The geomorphology of the Raven Ray area in Kingsdale. The line of the old channel exhumed within the Raven Ray ravine has its upstream extension into the small buried valley beneath the till. The alluvial fill on the main dale floor includes an upper layer of lacustrine sediment.

upstream, while its level declined and it was also being filled by the front of the gravel outwash from upstream. The lake clays that overlie the alluvial gravel reach more than 6 m thick under Sandymire, but extend only as far up valley as Keld Head, where they thin to nothing at close to the 253 m level (Fig. 3). A broad scoop in the moraine face, with a matching terrace of debris below, appears to be an old landslip originating from unstable conditions when the lake level was high; this awaits confirmation, as the terrace material is till and shear surfaces have not been found in shallow excavations within it.

Within the lake, dark lacustrine silts and clays accumulated to survive as the small flat area of Sandymire, between Raven Ray and Keld Head (the name Sandymire derives from sand banks within the modern river channel). Underwater exposures in the deepest pool in Kingsdale Beck show that these lacustrine sediments are at least 6 m deep, but their base on a deltaic front of gravels is not seen. Fragments of *Chara* are abundant in these lacustrine clays, except that they are almost completely absent from a layer 3.6–4.1 m below the main surface, as revealed in a core taken from the bed of the beck. This barren middle layer may represent a cessation of plant growth during the colder conditions of the Loch Lomond Stadial, but the sediments have not yet been dated.

3.5. Holocene (MIS 1)

Within the clay profile at Sandymire, and one metre above the barren layer, a cluster of beaver-chewed willow branches was exposed in the beck channel, and subsequently lost to erosion (Batty 2008). Whether this was a beaver dam, a lodge or just a channel log jam is unclear, but the wood has been dated to 7.7 ka and implies a contemporary wetland environment, with its surface at *c*. 251 m, and with all or most of the lake already gone.

A lifetime for the Kingsdale lake of less than *c*. 9000 years, between retreat of the valley glacier at *c*. 16.5 ka and confirmation of the wetland at 7.7 ka, indicates incision of its outflow gorge within the same time frame. This might be a rather short time to entrench the outflow through more than 10 m of limestone in the rocky ravine that is the true Raven Ray on the east side of the recessional moraine, even though this may include significant meltwater flood events. Such incision must be compared with only about a metre of channel lowering in nearly as long a time since the beavers chewed and placed their wood. It therefore appears likely that some ancestral feature was breached through the Raven Ray gorge. This may have been a left-bank marginal overflow channel that was exhumed, or could have been an older cave passage that was unroofed. The upstream continuation of either feature lies in the buried valley revealed by the rockhead profile on the east bank just north of Raven Ray; it is now plugged by till of the lateral moraine (Fig. 8).

Stalagmites that are now *c*. 300 mm below water level inside Keld Head and dated to both 2.49 and 4.5 ka (Table 1), indicate that the Sandymire alluvial flat, onto which the cave drains, was then marginally lower than it is today (Fig. 6b). Holocene alluviation on the flat may have been aided by the dam-building efforts of beavers, and also by sporadic flood events. A huge flood in 1941, one of a number to have washed away all the field walls across the valley floor, dumped a mass of debris into what had been a deep pool in front of Keld Head, though this had no lasting impact on the water level through the caves.

Cut timbers exposed by the river at Sandymire, 0.5 m above the beaver-chewed wood, date from the Bronze Age at *c*. 3.5 ka and indicate man's increasing activity in Kingsdale (Batty 2008). In the early 1800s, the river channel was straightened for much of the length of Kingsdale upstream of Keld Head, and the section down the western edge of the alluvium has been maintained since by periodic re-excavation. The almost flat section across Sandymire was partially straightened but has since developed new braids and meanders. These artificial changes have had no recognizable impact on the caves or on the wider surface geomorphology.

4. CONCLUSION

The geomorphology of Kingsdale reflects a long and complex evolution. Dated cave sediments reveal traces of the dale's chronology through post-Anglian times, and suggest that many of the karst features, the mature underground drainage and the glaciated trough are all older than had previously been accepted. Kingsdale is a textbook example of a glaciated valley, and has some of the clearest glacial features to be found within the many Yorkshire dales, but its considerable age confirms that it is essentially a fluvial valley that was only modified and trimmed by Pleistocene glaciers. Though Anglian ice must have had considerable impact upon all the Yorkshire Dales, the relative roles of Anglian glaciation, earlier glaciations and interglacial fluvial activity are currently unknown with respect to the earlier stages of entrenchment of Kingsdale and its neighbouring dales. Further evidence for the evolutionary history lies preserved within the caves, and a more complete understanding of Kingsdale (and the neighbouring dales) awaits the exploration of yet more caves and the sampling of their sediments by new techniques that improve resolution and accuracy and also extend the determinable time range. The main effect of the Devensian ice was to create the moraines and temporary proglacial lake that left the conspicuous landforms within the Kingsdale of today.

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