Middle Pleistocene palaeokarst in the buried chalk landscape of northwest Essex

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Abstract: Chalk palaeokarst structures, though widespread across Cretaceous outcrops of southern and eastern England, are largely hidden from view, and consequently unreported, in areas buried by glacial cover deposits. Well-preserved sinkhole subsidence features in northwestern Essex were first seen in the early 1970s. Close to the retreating Palaeogene feather edge, they owe their existence partly to a thick cover of Kesgrave Sands and Gravels (deposits of the former proto-Thames in Lower Pleistocene times) and partly to the protective mantle of Anglian glacial till (Middle Pleistocene). In more exposed locations, unprotected chalk that was deeply brecciated by permafrost degradation was unsuitable for the preservation of such sinkhole features. A multi-phase model for palaeokarst development within southern East Anglia spans the 2.5 million years of the Quaternary period.

Karstic features developed on chalk, though less spectacular than those of hard limestones, have been widely recognised across extensive Cretaceous Chalk outcrops in southern and eastern England (Fig. 1). Greater hazard awareness and meeting the challenge of engineering solutions to ground subsidence have driven much of this research initiative (Higginbottom & Fookes, 1971; Edmonds, 2008; McDowell et al, 2008). The North Downs, South Downs, Dorset Downs and Chilterns display a range of features associated with solutionally-enlarged fissures, typical of karstification, including caves, dolines (sinkholes), swallow holes, solution pipes, dry valleys and springs (Murton & Ballantyne, 2017). Karst hydrogeology has been tracked and monitored closely, and national databases have been compiled (Edmonds, 2008; Cooper et al, 2011). Little is known however of comparable features in the buried chalk plateau of southern East Anglia, largely because glaciation not only stripped away considerable volumes of surface chalk (Clayton, 2000) but also concealed the weathered landscape under widespread glacigenic sediments. Solution pipes and sinkholes are densely distributed in west Hertfordshire; but northeastern Hertfordshire and northwestern Essex have fewer such features because many were removed by subglacial erosion, and have been lost, mainly from buried valley sites (Catt et al, 2010). Relict subsidence sinkholes, previously undescribed, are preserved beneath glacial till in the upper Cam valley and around the Cam-Stort watershed, and are notable for the clarity of their infills, enabling a tentative chronology to be established.

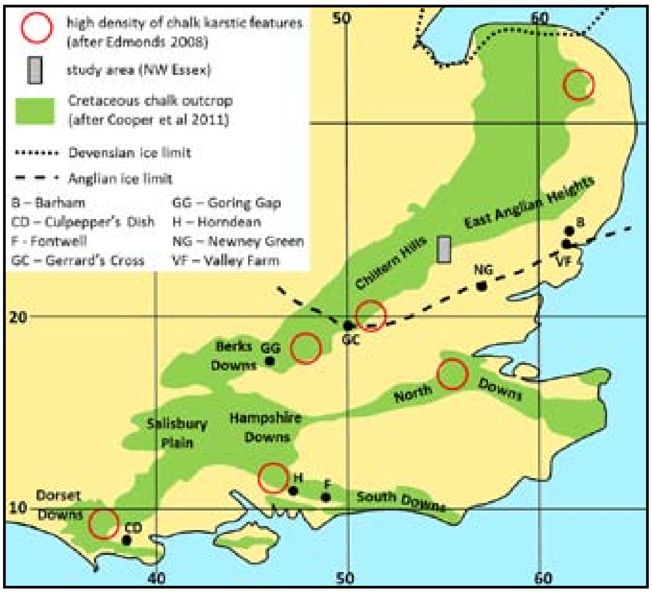


Figure 1. The chalk outcrop across southeastern England, with glacial limits and density of karstic features (after Edmonds, 2008 and Cooper et al, 2011).

In northwest Essex, a cluster of karstic features (Fig. 2) is located at and just north of the Chalk-Palaeogene boundary, drawing inevitable parallels with similar distributions noted elsewhere in southern England (McDowell & Poulson, 2008). The Palaeogene feather edge acted as an aquitard (Cooper et al, 2011) concentrating aggressive runoff onto soluble chalk beneath, and its southwards retreat to its

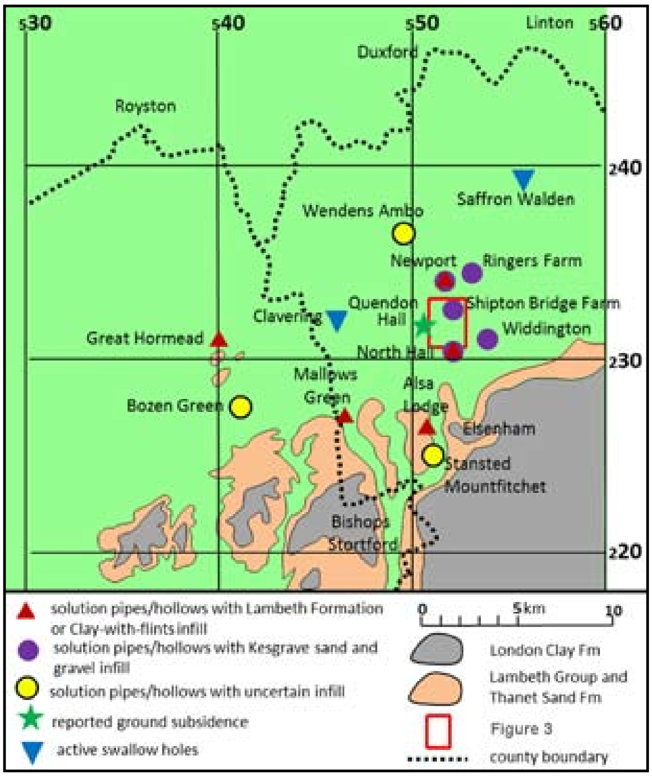


Figure 2. Distribution of chalk dissolutional features in northwest Essex and the Palaeogene feather edge.

Chrono-stratigraphy	*Sedimentary events*	*Probable age*	*MIOS*	*age BP*	*Formal stratigraphy (Bowen 1999)*	
					Member	*Formation*
Holocene	17. Alluvial infills	Holocene	1	12ka		Fenland
Late Pleistocene	16. Chalky diamictons	Devensian	2	15ka		Cam Valley
	15. Valley gravels	Ipswichian/ Devensian	5-2	117ka	3rd Terrace?	
	14. (erosional interval)	"Wolstonian"	(10-6)	360ka	4th Terrace?	
Middle Pleistocene	13. Organic channel infills	Hoxnian	11	425ka	North Hall (*repositioned*)	Hitchin
	12. Glacial buried channel infills	Anglian	12	480ka	Wicken Bonhunt, Henham and Observatory	Lowestoft
	11. Upper till				Lowestoft Till	
	10. Proximal glaciofluvial outwash				Ugley Green	
	9. Glaciolacustrine silts and clays				Newport	
	8. Lower till complex with deep brecciation, and coombe rock				Quendon	
	7. Coversand				Broomfield (including Barham Coversand)	
	6. (pedogenic interval)	early Middle Pleistocene	19-13	774ka	Valley Farm Soil	Kesgrave (Sudbury)
Early Pleistocene	5. Widdington Sands	Early Pleistocene	64	1.8Ma	Widdington (*repositioned*)	
	4. Chillesford Sands		74-71	2.0Ma	Chillesford (Chillesford Church)	Norwich Crag
Pliocene	3. Red Crag Sands	Plio-Pleistocene	98-95	2.5Ma	Red Crag	Red Crag
Palaeogene	(Lambeth Group)	Palaeogene	-	57-56Ma		
	2. Thanet Sand Formation			58-57Ma		
Cretaceous	1. Lewes Nodular and Seaford Fms (White Chalk Sub-Group)	Cretaceous	-	94-84Ma		

Table 1*. A proposed stratigraphy for the upper Cam valley.*

present position has left relict palaeokarst behind it. Differential fracture density within the Upper Chalk provides the network through which aggressive water has penetrated the rock. Lake and Wilson (1990) report up to 20 metres of fractured Upper Chalk, but see no particular pattern of fissuring: 'Water-bearing fissures tend to be distributed at random in the Upper and Middle Chalk'. However, Catt et al (2010) suggest that fissure enlargement is localised beneath valley floors where rock is more densely fractured, and where there is increased groundwater flow towards streams. Fissure enlargement also increases beneath and adjacent to buried valleys formed beneath the Anglian glaciers.

Cooper et al (2011) make a 3-fold subdivision of karstic distribution in Britain: (a) northern Britain, with its glaciokarst landscape (after Waltham et al, 1997), (b) southern Britain, never glaciated, but strongly influenced by periglacial processes, and (c) an intermediate zone of palaeokarst buried beneath covering formations. The upper Cam catchment lies in this third zone. In addition to deep dissolutional features, shallow periglacial karst (or epikarst) is recognised (Murton & Ballantyne, 2017). Small pocket structures (involutions), solution-pitted bedrock (karren) and brecciated chalk are all attributable to growth and melting of ground ice under periglacial conditions. Subsurface data in the upper Cam provide some indication of the intensity and dating of brecciation, and its relationship to the subsidence sinkholes.

The focus of interest centres on an area of about 4 by 8 km (Fig. 3) between Newport and Elsenham. The Palaeogene-Chalk feather edge lies at a height of about 80–95 m OD, north of which emerges chalk of the Lewes Nodular and Seaford Formations (White Chalk Subgroup, formerly Upper Chalk); locally about 140 metres thick, this is a fine-grained chalk of low density but with high porosity, and it has numerous flint nodule horizons. Surface exposures of bedrock are limited, as the chalk is widely and thickly mantled by superficial sediments. Formal stratigraphic names for Quaternary sediments were proposed by Boreham (in Bowen, 1999) (Table 1). Other investigations have focussed on the Crag deposits (Mathers & Zalasiewicz, 1988), the proto-Thames terrace sequence (Rose et al, 1999; Baker, in press), the glacial sequence (Allen et al, 1991) and post-Anglian valley development (Boreham & Rolfe, 2009).

A schematic cross-section across the upper Cam valley is shown in Figure 4, illustrating likely interrelationships within the local Quaternary succession. Stratigraphic boundaries are particularly complex (Lake & Wilson, 1990), but careful re-examination of all available subsurface data has been undertaken. These data (Fig. 3) include the original M11 motorway site investigations conducted by W.S.Atkins (1966), and further cores (also by W.S.Atkins) drilled in 1993 in connection with road widening; all these borehole logs are available in the BGS onshore borehole database. Other surveys (not in BGS records) were undertaken by W. &. C. French (now Kier Group) in 1969–1971 and J. Dillon-Robinson (Widdington) in 1970. Detailed field mapping, augering and stratigraphic logging were conducted in 1972–1974 (Baker 1976), and by the BGS in 1975–1985 (Hopson, 1981; Wilson & Lake, 1981; Lake & Wilson, 1990).

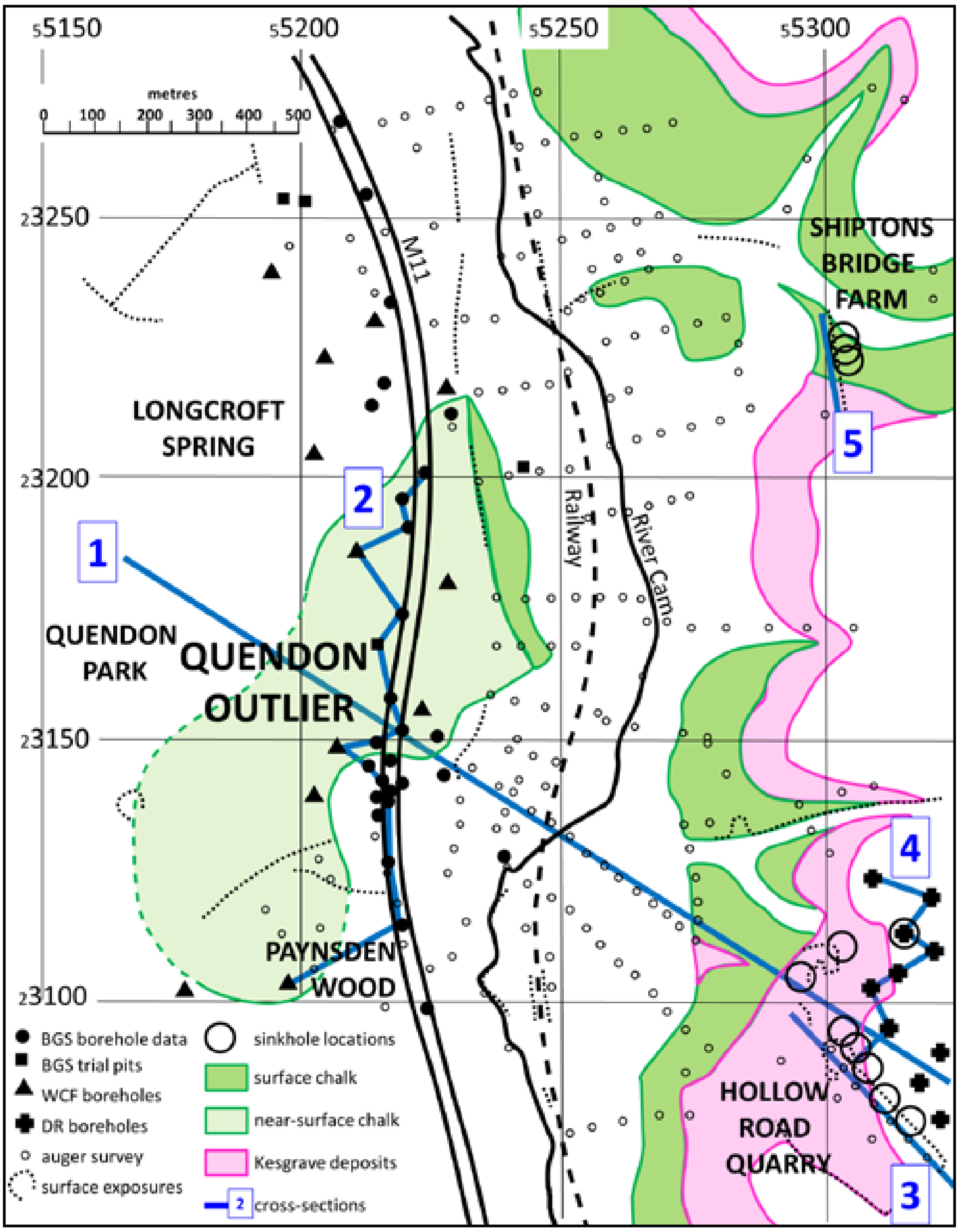
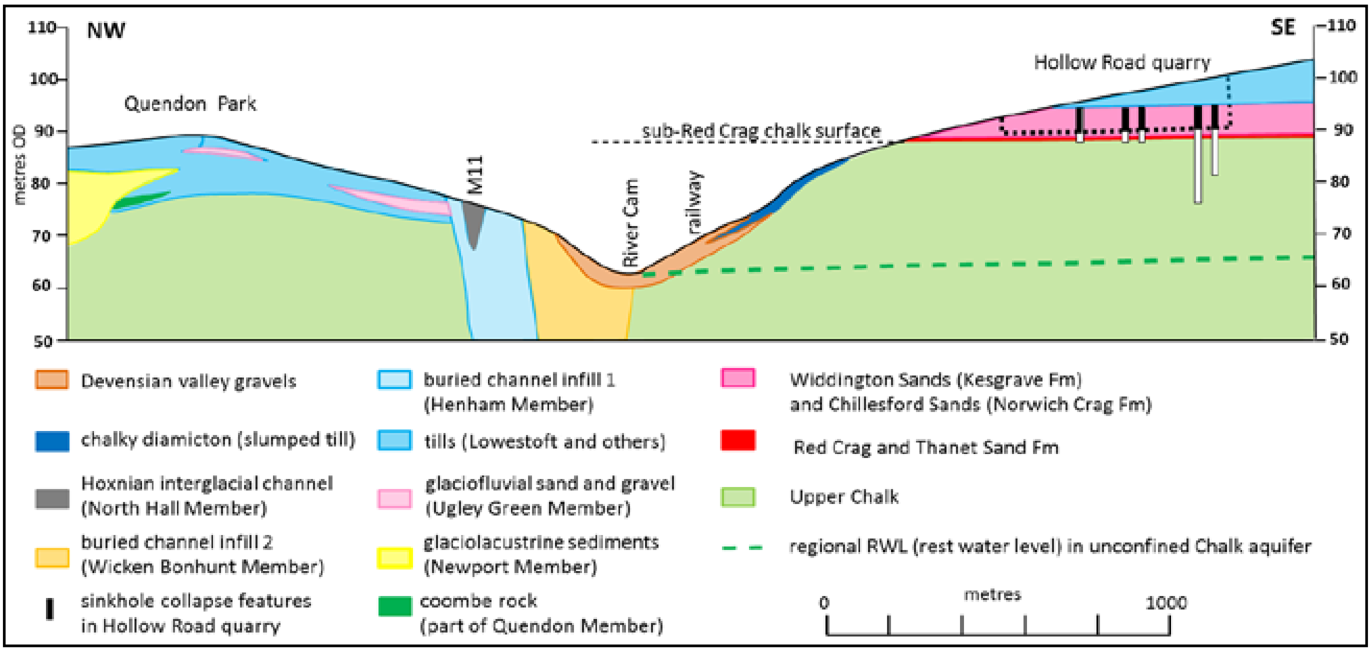


Figure 3. The upper Cam valley north of Bishop's Stortford, with the sources of data, selected outcrops and positions of the five cross-sections. WCF = W&C French boreholes, 1969-71; DR = Dillon-Robinson boreholes, 1970. (Stratigraphic boundaries based on BGS mapping)

Figure 4. Schematic NW-SE section (# 1) illustrating Anglian glacigenic sediments to the west, and Kesgrave fluvial sediments to the east.



West and east sides of the upper Cam valley differ in both lithology and topography (Fig. 4); the east side is dominated by well-sorted, fine–medium sands similar to the Kesgrave Sands and Gravels (Lower Pleistocene), whereas the west (Quendon Park Estate) is underlain by various glacigenic sediments, mainly Anglian in age.

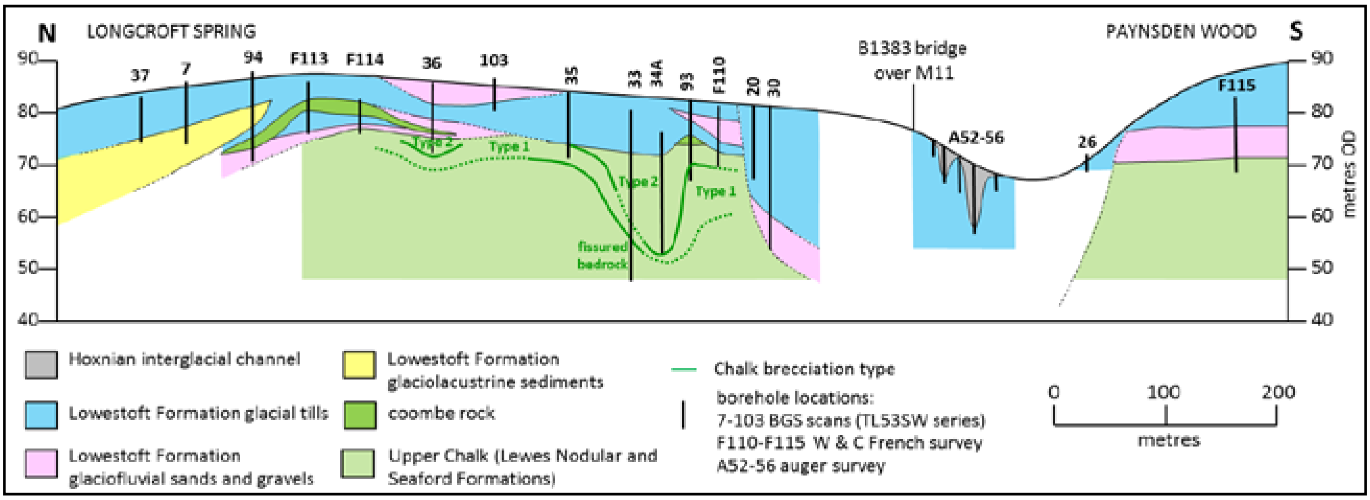
Chalk weathered profiles at Quendon

A localised and buried bedrock ridge, about 0.4 by 1.0 km, survives below Quendon Park Estate (Fig. 5) rising to 74–79 m OD. Subsurface chalk is deeply brecciated. The first indications of deep frost weathering of chalk came in 1966 with two boreholes (BGS TL53SW33 and 34a) drilled to depths of 33 and 23 metres. Core 34a (surface 75.6 m) passed through 3.6 m of glacial till, before encountering 19 m of brecciated and putty chalk with very weak penetration values throughout. Core 33 recorded similar results, then a further 8 m (below 54.6 m) of fissured chalk with strong penetration values. Water table stood at 59 m OD. This brecciated chalk matches Mundford Grade IV or III, with underlying fissured chalk matching Grade II (Ward et al, 1968). In 1993, further boreholes relating to road widening (BGS TL53SW93 and 94) confirmed the presence of deep frost-weathered chalk on the Quendon outlier (Fig. 5; Table 2). Where brecciation exceeds maximum depth of seasonal freezing (2–3 m), former permafrost is indicated. Murton & Ballantyne (2017) propose a subdivision of Grade IV weathered chalk into Type 1 and 2 brecciation, depending on fissure width and infilling.

In core 93 the description of unit **e** is consistent with widespread till of Anglian age. Unit **d**, a chalk gravel in a matrix of pulverised chalk, is indicative of Type 2 brecciation; however, a content of flint gravel suggests that lateral displacement may have occurred to develop a coombe rock (mobilised chalk breccia typical of periglacially-weathered chalk). This would have been linked to multiple freeze-thaw cycles in an active layer. Units **c**, **b** and **a** are partially weathered layers (clast-supported with some or no infilling of widened fissures); these would conform to Type 1 brecciation, associated with perennial or seasonal freezing, a transition between the active layer and permafrost (Murton and Ballantyne 2017). Rockhead of fissured chalk does not appear to have been reached in core 93.

Some 400 metres north, core TL53SW94 recorded 3.2 m of stratified coombe rock, underlying 11.4 m of glacial sediments (Fig. 5). This is logged as highly-

***Figure 5**. The Quendon chalk outlier (Section 2), with the multi-layered till complex and stratified coombe rock unit over deeply brecciated chalk bedrock.*



unit	thick. m	height m OD	description	Mundford Grade, brecciation type
		82.9	Ground level	
e	6.8	76.1	Variations of flint and chalk gravel, chalk cobbles and sand pockets in a matrix of firm to stiff brown silty clay	Glacial till truncating top of d
d	2.2	73.9	Off white chalk recovered as white comminuted material with scattered subangular chalk gravel in a matrix of very weak chalk. Upper 63cm with 5% fine flint gravel.	Grade V chalk Type 2 brecciation or coombe rock
c	4.0	69.9	Slightly to moderately weathered weak to very weak white rubbly to blocky chalk. Fractures very closely spaced with some infill of silt-sized comminuted material, and sparse infill of brown silty clay. Sparse flint nodules in lower 2 m.	Grade IV chalk Type 1 brecciation
b	2.0	67.9	Slightly to moderately weathered weak to very weak white rubbly to blocky chalk with closely spaced fractures and no infill; sparse flint nodules	Grade IV chalk Type 1 brecciation
a	0.5	67.4	Moderately weathered rubbly to blocky chalk; fractures extremely closely spaced but with some infill of comminuted chalk, and some brown speckling	Grade IV chalk Type 1 brecciation

***Table 2**. BGS core scan TL53SW93 (adapted).*

weathered white or off-white, weak, mixed putty chalk mud and rubble, with various inclusions of flint gravel, chalk gravel and sand, and is underlain by 0.8 m of dense, fine–coarse sand. This is interpreted as Grade V chalk (Type 2 brecciation, or coombe rock) similar to that observed in core 93. Five adjacent boreholes confirm the presence of this pulverised chalk layer (0.6–3.2 m thick) extending over a distance of 150 m, which would preclude the presence of an ice-rafted chalk erratic. Sourced from brecciated bedrock nearby, this has all the appearance of an unconsolidated periglacial sludge, derived by short-distance transport (Giles et al, 2017). The Quendon outlier is overlain by up to 11.4 m of glacigenic sediments, and at one point coombe rock is overlapped by laminated silts and clays of the Newport Member (of the Anglian Formation). Both brecciation and solifluction therefore are constrained to an early phase of the Anglian glaciation (~480ka).

Subsidence sinkholes at Hollow Road

Buried sinkhole structures within Kesgrave deposits at the Hollow Road sand quarry, Widdington, are roughly contemporary with the Quendon brecciation, dating to the early Anglian stage (Fig. 6). Sedimentology of the sands is given in Mathers and Zalasiewicz (1988) and Baker (in press). Palaeokarst structures were first visible in the early 1970s in the quarry face, which was then 350 m long and 13 m deep. Four sand bodies exist: (1) thin veneer of glauconitic Thanet Sands (0.6 m); (2) marine, Red Crag, ferruginous sands (1.5 m); (3) estuarine sands (Chillesford Sands, also known as Chillesford Church Sands) of the Norwich Crag Formation (up to 4 m thick); (4) fluviatile sands of the Kesgrave Sands and Gravels Formation (up to 6 m thick where undisturbed, but perhaps as much as 17 m before glacial truncation). The latter is divisible into 10 units (# 4–13). Eight subsidence sinkholes deform these sands (Fig. 6, A-H). Glacial till of the Lowestoft Formation truncates and overlies the sequence.

Although Upper Chalk is nowhere exposed at Hollow Road, augering and borehole data confirm the presence of a consistent chalk platform at 88–89 m OD, but pitted with a number of dissolutional pipes. Maximum pipe depths appear to be >5.5 m (Fig. 6, structure G) and 13 m (Fig. 7, borehole D8). Total estimated subsidence at D8 is 30 m, consisting of 13 m below chalk level, and 17 m above it, where cover deposits may have risen to the former proto-Thames terrace surface of 106 m OD before glaciation (Baker, in press). Presently the till-sand interface at Widdington lies at about 94 m OD suggesting that glacial truncation has removed at least 12 m of cover deposits. There is no direct evidence for solution pipe diameters, but infill widths give some indication of the cavity size into which they foundered; these vary from 1.1 to 3.0 m. A cluster of nine structures is confirmed within an area of 8 ha, and it is not immediately clear what factors are operating to develop such a high local density. Densities of 4/ha have been recorded at Gerrards Cross (McGregor & Green, 1983) and 55/km^2 at Horndean (McDowell et al, 2008), but, as Matthews et al (2000) point out, these can be two orders of magnitude greater than the regional distribution (15 per 100 km^2 in the South Downs), so due caution needs to be exercised in interpreting sinkhole density.

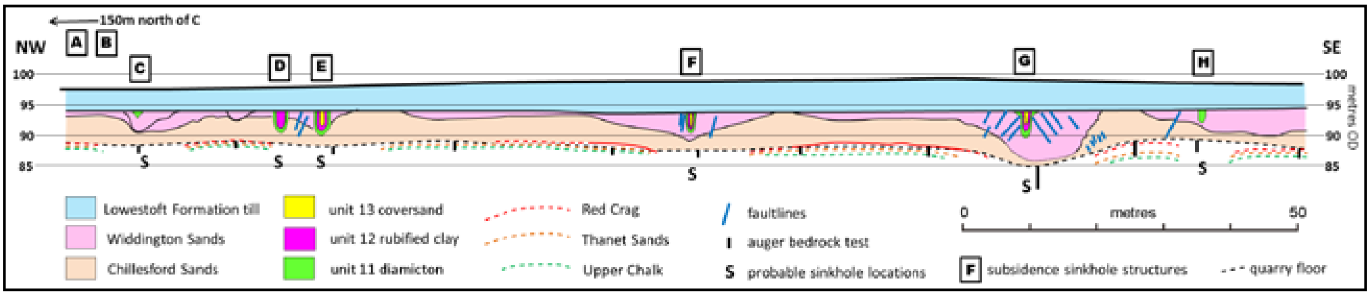
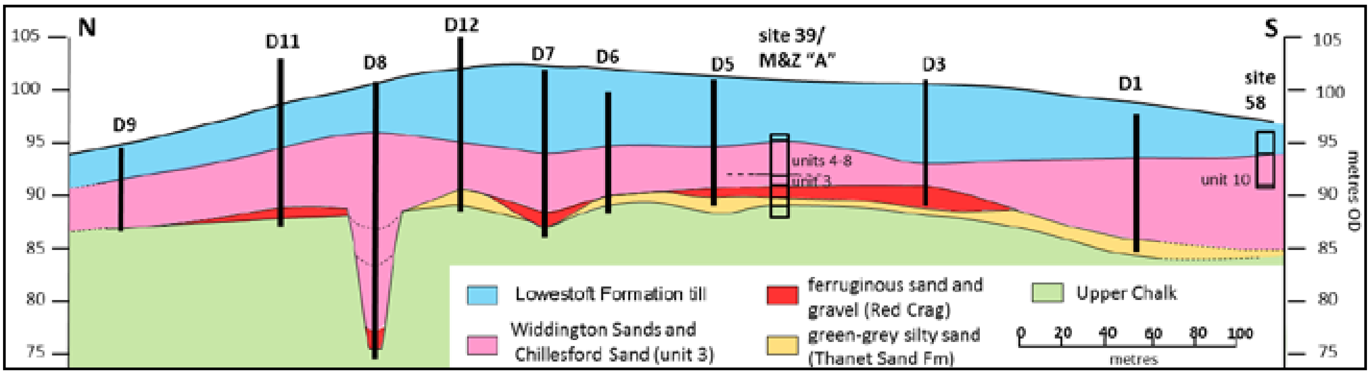


***Figure 6**. Hollow Road, Widdington (Section 3). Part of the exposed quarry face visible in March 1972, with six sinkhole structures (C-H). Sinkholes A and B lie 150 m north of C; a further sinkhole was revealed in borehole D8, 250m NNE of C.*

***Figure 7**. Hollow Road, Widdington (Section 4). Exploratory boreholes in 1970 confirm the continuation of sands north of the quarry face (now worked out). M&Z "A" refers to the sedimentary log described by Mathers and Zalasiewicz (1988).*



Infill stratigraphy

The features at Hollow Road, Widdington, are believed to be subsidence sinkholes, with infills that suggest either dropout or suffosion development (cavity collapse within cohesive cover, or slow subsidence of non-cohesive cover: Waltham & Fookes, 2003), rather than collapse (caprock) sinkholes or cave infills. They match Type 5 solution pipes as described by McDowell et al (2008), with metastable ground over solution pipes, and no surface expression. These would have required major water input at depth to trigger a chain of events, with cover deposits descending by staged suffosion into enlarged fissures (Edmonds, 2008). The preservation and coherence of infill material at Hollow Road is unusually good, allowing more precise reconstruction of palaeokarst history than is usually the case where infill material is mixed or was subsequently disturbed. After a short period of rapid sinkhole development and ground failure, the land surface was glaciated and the resultant till created an impervious resistant capping, insulating the buried structures from postglacial disturbance or modification. The planar nature of the till/sand interface indicates that no further subsidence occurred after glacial truncation.

Key to reconstructing infill history is a central column or wedge consisting of three distinct sedimentary units making up the core. Unit 11 is a clay-flint pebble diamicton, unit 12 is a reddened massive clay, and unit 13 is a banded coversand 4.0 m thick. Outer core units (11–13) occupy narrow vertical structures, columns and wedges (1.1–2.0 m wide), penetrating about 7 m into the upper sands. Structure B (Fig. 8) is a cylindrical feature with a tubular annulus of reddened clay enclosing an inner core of unit 13 coversand. Its smeared surface is suggestive of liquefaction, when mobile wet clay acted as a lubricant enabling dropout of a central rigid column. It is reminiscent of collapsed Lambeth Group beds piped into the irregular chalk at Gerrard's Cross (McGregor & Green, 1983) where many pipe walls have smooth, polished or fluted surfaces. Some clay structures are more wedge-shaped (Fig 9). All reddened deposits are assumed to relate to a period of temperate soil formation, indicated by the Valley Farm Soil horizon of presumed early Middle Pleistocene age, prior to the Anglian glaciation (Baker, in press).

Figure 8*. Structure B in November 1972, consisting of a vertical, clay-lined cylinder, about 2 m in diameter, with an outer wall of smoothed, deconstructed reddened clay (pebbly in places, units 11 and 12), enclosing an inner column of unit 13 coversand (not visible).*

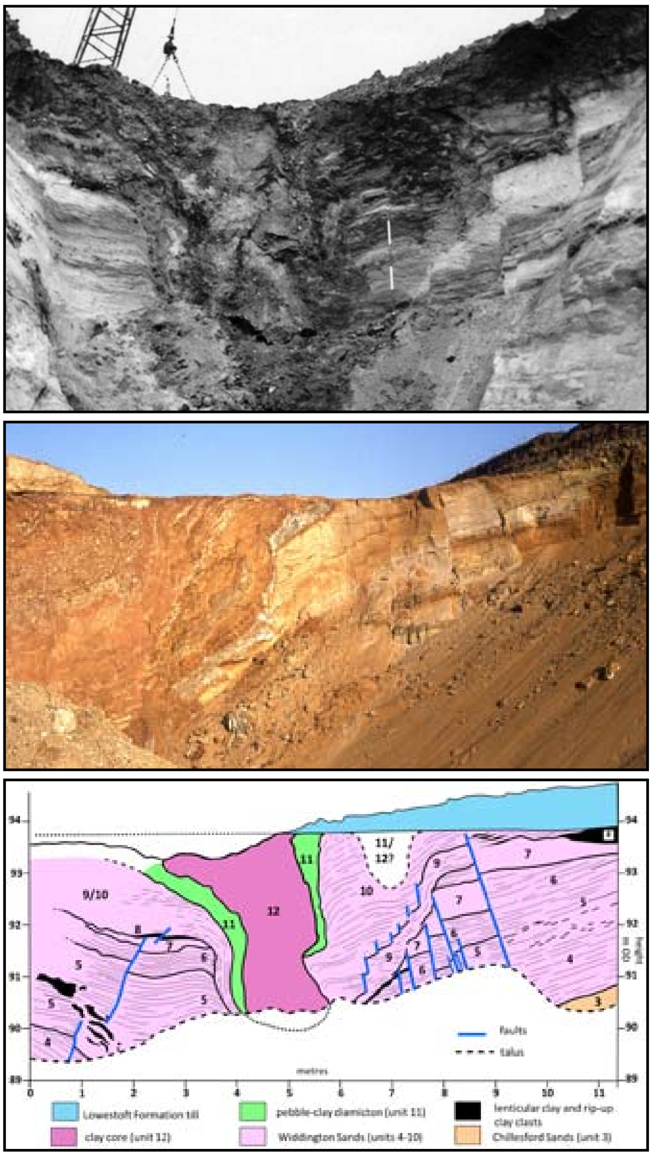


Figure 9*. Top: Structure A (at site 34) in March 1972, with a large wedge of massive reddened clay (unit 12), surrounded by a thin sheath of diamicton (unit 11). Middle: Northeast margin of the deformed and faulted doline fill in Structure A in November 1972. Lower: Interpretation of structure A, with a clay core, 3 m wide, tapers downwards to a depth of 4 m, inside a doline fill 12m in diameter; a cluster of small faults fracture units 4-9 on the right, and suffosed units 9-10 are downfolded on both sides.*

In three structures (E, F and G) the inner core of unit 13 coversand is a bedded sequence of ash-white and buff layers (Figs 10, 11). At least 4.0 m thick, this coversand was the final sedimentary unit that overlay Kesgrave deposits, the result of aeolian deposition (the Barham Coversand) in a cold, dry periglacial environment just prior to the arrival of the Anglian ice sheet. Sinkhole activity must have occurred towards the end of the periglacial interlude. A dropout mechanism is envisaged since the granular sand has behaved as a rigid mass; such brittle response might best be explained by permafrost rigidity, at the same time as partial thaw (in discontinuous permafrost) was reducing the integrity of other layers.

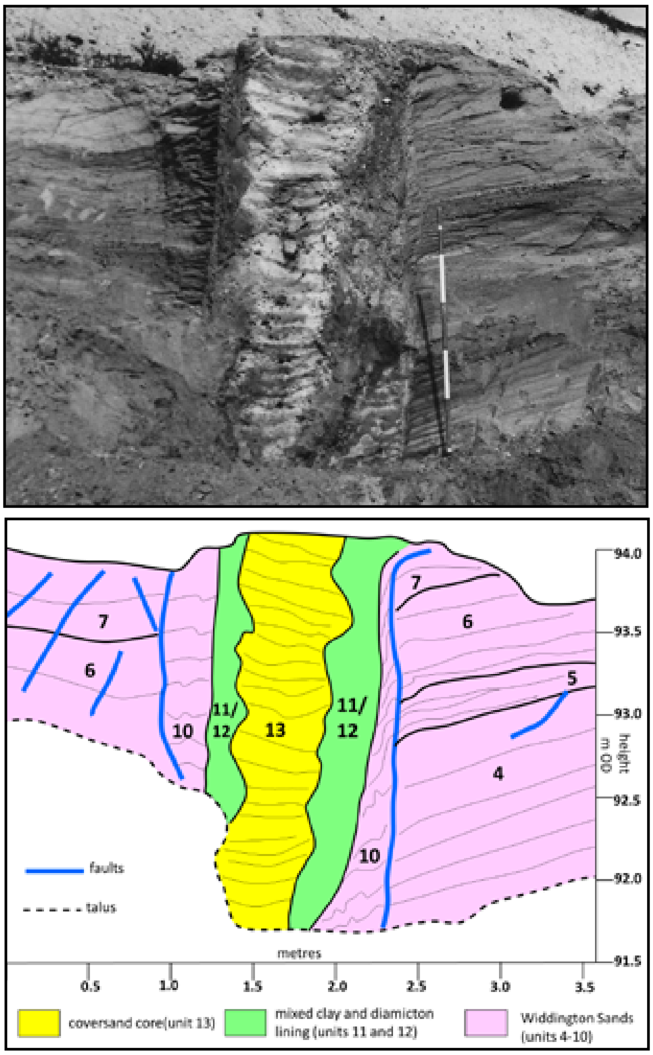


Figure 10. Structure F (at site 46) in November 1972, and its interpretation. A banded coversand core (unit 13), 2.5 m tall and 0.5 m across, with a the narrow zone of sheared faulted sand (unit 10) around the pipe wall, penetrating units 4-7, which are slightly down-folded into a shallow depression.

Doline subsidence around column dropout

At most sites subsidence generated a collapsed funnel around the central column. Structure A (Fig. 9) appears to have deformed surrounding sands across a diameter of 12 m, and structure G (Fig. 11) over a diameter of 22 m. These, and other, sinkholes developed in a sequence of events involving both suffosion and dropout processes. Sand beds have behaved with both brittle fracture and ductile response within the deepening and widening dolines. Stepped reverse faults are assumed to encircle the features concentrically, although none has been seen in plan. In structure A, units 4–10 are deformed asymmetrically: on one side they are largely folded, indicating flexible suffosional descent; on the other side, merely 5 m distant, similar strata show brittle response with multiple faults. In structure G the fault pattern is more symmetrical; a wall of unit 3

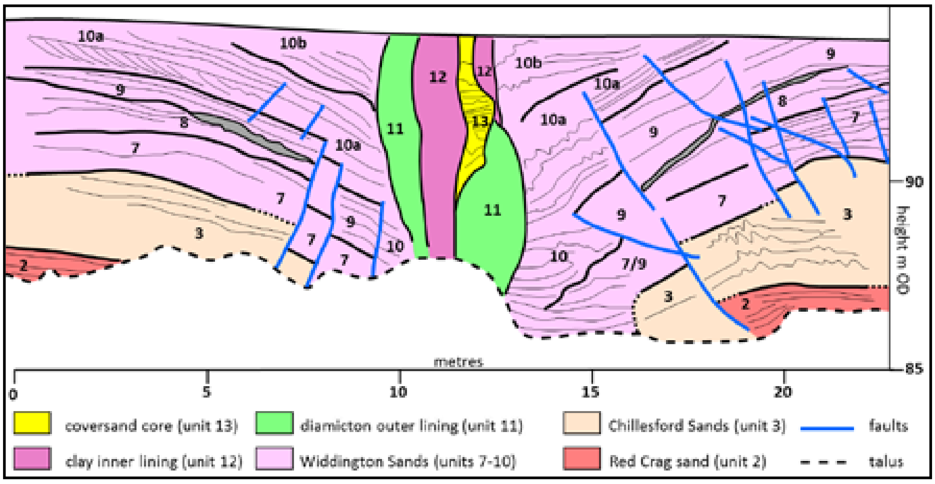


***Figure 11**. Structure G (at site 49) in November 1972. Above: the largest feature at Hollow Road, with 7 m of infill above a 5.5 m-wide pipe penetrating the underlying chalk platform at 87 m OD; a central core of coversand, clay and diamicton, 3 m across, is ringed by highly deformed sand units, downfolded and faulted within a broad doline 22 m in diameter. Left: an interpretation, with the coversand core, about 4m deep, inside a column of reddened clay and diamicton at least 7 m deep; both Widdington Sands and Chillesford Sands are steeply inclined, with step-faults inside a wide and deep doline; the two sets of faults suggest two episodes of subsidence.*

(Chillesford Sands) is brecciated and faulted on the right side, and higher units (7–10) are downfolded and faulted on both sides; units 11 and 12 comprise the central column wall enclosing a core of unit 13. The structures appear to indicate that contrasting water retention, by cohesive and granular units, may have caused different responses to temporary thaw.

If funnel geometry is projected upwards to a theoretical Kesgrave terrace surface at 106 m OD, a doline of considerable size could be envisaged, not unlike that of Culpepper's Dish, Dorset (86 m across and 21 m deep). Large dolines can develop over small fissures by evacuation of suffosed sediment into underlying voids (Edmonds, 2008). However, unlike Edmonds' model, it is thought that the full process of subsidence at Widdington was achieved rapidly, and was not spread over a prolonged period.

Pipes at Shipton Bridge Farm

A new ditch exposed chalk at Shipton Bridge Farm [TL531322] in 1973 (Fig. 12). This site lies midway between Hollow Road and the Newport chalk pit (see below), along the lower boundary of the Kesgrave outcrop (Fig. 3). A fissured chalk platform at 80 m OD, with a surface dissolutionally pitted with karren, is broken by three closely-spaced, sand-filled, solution pipes. Upslope, the ditch exposed 5 m of Widdington Sands, truncated by till at 85 m OD. Ferruginous sands (Red Crag) lie at the chalk-sand interface. The solution pipes (about 1.5 m in diameter) are infilled with well-sorted Widdington Sand (unit 10 in two pipes) and penetrate at least as far as 77 m OD, which is similar to pipe depth at D8 at Hollow Road (Fig. 7). Downslope, the infilled pipes are truncated by a shallow layer of chalky diamicton, identified as a slumped till remnant (Baker, 1976); similar chalky diamictons have been described down-valley (Boreham & Rolfe, 2009). These could represent paraglacial adjustment immediately following Anglian deglaciation, or (more likely) mass movement at a much later stage.

It is postulated that three subsidence sinkholes developed through 5 m of sands which descended at least 3 m into enlarged chalk fissures (Fig. 12). Glaciation then truncated and sealed the features, as at the Hollow Road sites. After an erosional interval, the till edge foundered to form a chalky diamicton that further buried the chalk platform, before erosion re-exposed the sand-chalk interface. It is not clear whether the karren were formed prior to deposition of the Red Crag as a precursor to the sinkhole formation, or developed subsequently at rockhead. Either way, the solution pipes appear to be the remnant roots of larger structures, as visible at Hollow Road.

Pipes at the Newport chalk pit

Infilled dissolution features are well documented at the Newport chalk quarry, located 2 km north of Hollow Road, and 1 km north of Shipton Bridge Farm (Fig. 13). Chalk has been worked here intermittently for 140 years; the present owners are Needham Chalks (HAM) Ltd. Whitaker et al (1878) recorded two large gravel-filled pipes above a persistent tabular flint layer, and C. J. Jeffery photographed a number of structures in January 1980 for the BGS. Lake and Wilson (1990) reported 20 m of fractured Upper Chalk with several solution pipes, typically 1–2 m wide and 2–3 m deep, lined with remanié, dark brown, sandy clay and infilled with reworked Kesgrave material.

In March 1973, the quarry face exposed a variety of dissolutional cavities (Fig. 14). Depressions, pipes, funnels and wedges, some with bulbous extensions, create a very irregular rockhead where dissolution appears to be an on-going process and several features may have coalesced. Clay linings contained many large, unworn, flint nodules set in a matrix of reddish brown clay, in the manner of Clay-with-flints (Catt, 2010). Green and McGregor (1999) analysed a sample of infill, finding an unusually large proportion of far-travelled clasts thought to belong to the Kesgrave Formation. At 80 m OD this would lie some 26 m lower than the putative altitude (106 m) of the proto-Thames terrace elevation at that stage.

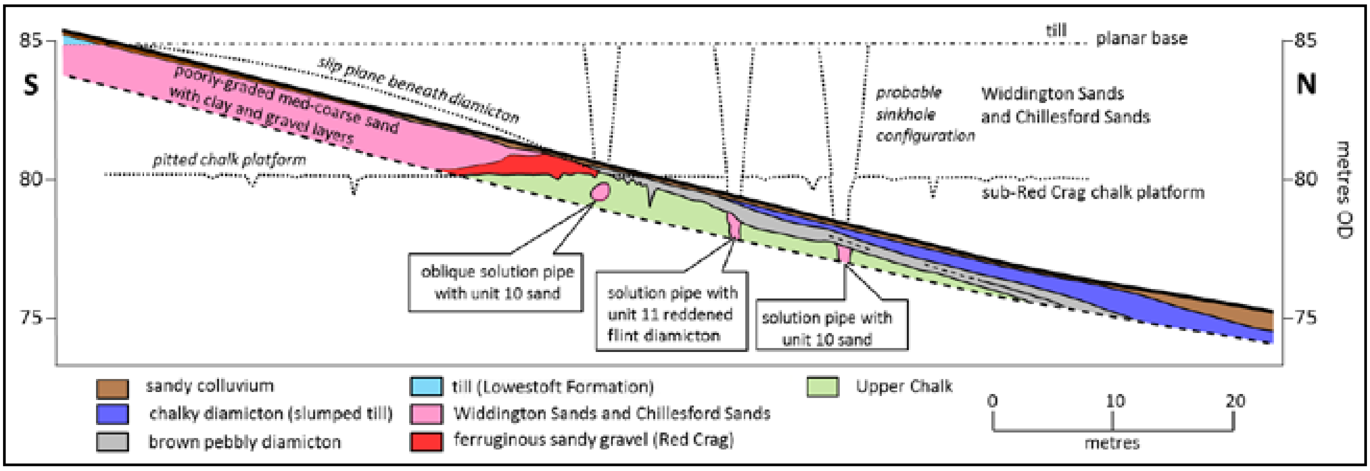


***Figure 12**. Shipton Bridge Farm (Section 5). A shallow ditch section exposing a group of three sinkholes, infilled with characteristic Widdington Sands, penetrating about 3 m below a pitted chalk platform at 80 m OD.*

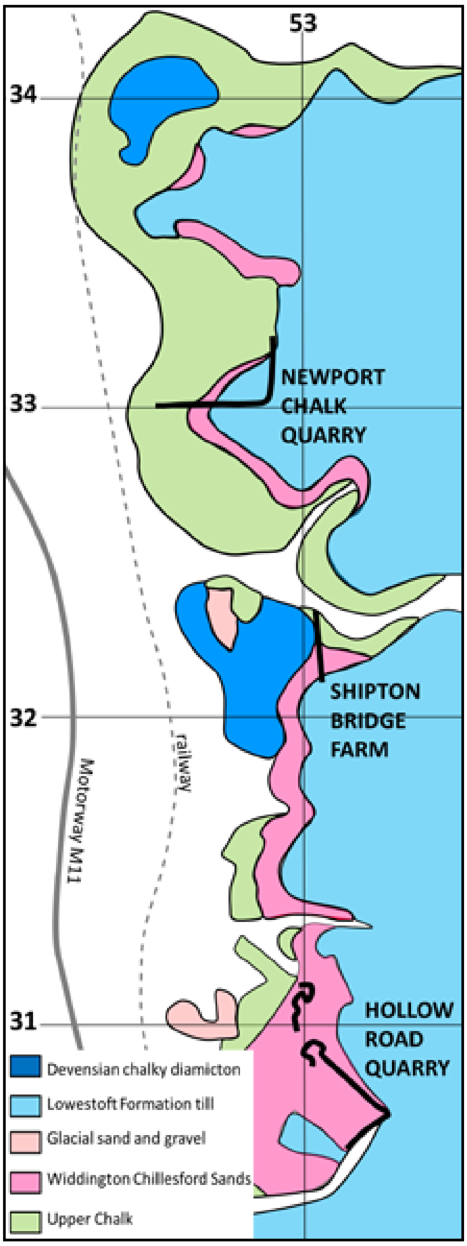


Figure 13 *[top left]. Location of the Newport chalk pit in relation to Hollow Road and Shipton Bridge Farm. (Stratigraphic boundaries based on BGS mapping)*

Figure 14 *[top right]. Newport chalk pit in March 1973, showing a variety of solution features between 72 and 75 m OD in highly fractured Upper Chalk. An undeformed tabular flint band extends beneath the features, and shallow brecciated chalk about 0.5 m thick gives a convex cliff profile (top right).*

Figure 15 *[above]. Newport chalk pit in January 1980, with pipe infills, each 1–2 m across, truncated in the quarry floor. View from TL526330 looking northwest towards Newport (photo: C J Jeffery, BGS).*

Figure 16 *[left]. Newport chalk pit, January 1980. Section of a dissolution hollow, infilled with reworked Kesgrave sands, rimmed with unworn flint nodules in a brown sandy clay matrix, in brecciated Upper Chalk. Section is 1.5 m high; ground level is at 80 m OD. Beneath the thin cap of quarry rubble, flow of the Late Pleistocene coombe rock (about 0.2 m thick) has laterally distorted the infill downslope (photo: C J Jeffery, BGS).*

Figure 17*. Newport chalk pit, January 1980. A large inclined solution pipe about 1 m wide and 2 m deep, descending to <78 m OD, filled with reworked Kesgrave sands, and rimmed with dark brown sandy clay containing unworn flint nodules (photo: C J Jeffery, BGS).*

In 1980, a newly-scraped surface at about 80 m OD revealed about a dozen cylindrical pipe infills, each about 1–2 m in diameter, within an area of about 300 m^2 (Fig. 15), and a total of 28 solution pipe features were observed in plan across this scraped surface. Cut quarry faces revealed solution pipes in profile (Figs 16, 17), and also a thin layer of mobilised coombe rock that truncates the tops and displaces them laterally in flame-like extensions downslope. Late Pleistocene brecciation is implied, in contrast to Anglian brecciation beneath Quendon Estate. Contemporary dissolutional lowering may also have removed as much as 0.6 m from exposed chalk surfaces in the Holocene period alone (applying a South Downs rate of 60 mm per 1000 years, as suggested by Williams and Robinson, 1983).

In the light of the new evidence from Widdington, it is possible to re-evaluate these Newport structures. Separated by only 2 km, it is likely that the two sites share a common origin, but occupy different stages in a single evolutionary process. In this scenario, the more complex forms at Newport are interpreted as enlarged bulbous roots of longer and narrower subsidence sinkholes. Shipton Bridge Farm represents an intermediate phase of sinkhole exposure and modification, whereas Newport represents a more advanced state of denudation, in which both till capping and Kesgrave cover deposits are now absent. Exposed to subaerial denudation, dissolutional enlargement has generated a variety of cavities. Surface lowering by dissolution (at perhaps 60 mm/ka) has truncated much of the original structures; infills have been mixed and compacted by the effects of bioturbation, illuviation, decalcification and cryoturbation. Some vestiges of Kesgrave sediments remain in the structures, albeit greatly modified, and shallow Late Pleistocene coombe rock truncates and distorts their upper surface. A final extinction stage in this 500 ka evolution is probably reached in the subdued chalk plateau of South Cambridgeshire, immediately to the north, and well beyond the influence of the retreating Palaeogene feather edge and the protective cover of proto-Thames terraces. Karst processes continue to the present day in the open, exposed landscape.

Chronology of the palaeokarst

The sub-Kesgrave palaeokarst identified at Hollow Road resembles those at Gerrard's Cross (McGregor & Green, 1983) and Goring Gap (Worsley 2016). Protected by its till cover, the Widdington stratigraphy is well defined and places sinkhole subsidence within the Early Anglian stage (~480ka). More specifically, subsidence is constrained to a brief interlude between deposition of the Barham Coversand and the full Anglian glaciation. This coincided with a time of cold, dry, periglacial conditions. In principle permafrost should be unfavourable for karst development (Murton & Ballantyne, 2017), and near-surface chalk karstification would have been more active during warmer climatic conditions. Groundwater percolation throughout the British Pleistocene record occurred readily during interglacials and interstadials, but karstic systems shut off when limestone was frozen in glacial and stadial stages, as indicated by high-resolution flowstone dating (Lundberg & McFarlane, 2007). However, concentrated flows of meltwater could be more effective under periglacial conditions (Higginbottom & Fookes, 1971), and deep penetration of meltwater might have been channelled down ice wedge casts (Rhodes & Marychurch, 1998). Spektor and Spektor (2009) describe infiltration of summer rainfall that actively promotes widespread contemporary karstification within the continuous permafrost zone of the Lena valley in Siberia.

These apparently conflicting views might be resolved in two ways with respect to the upper Cam valley. Firstly, it is suggested that the main period of dissolution and fissure widening was achieved during the early Middle Pleistocene period (0.77–0.48 Ma), with karstification continuing beneath a thick cover of permeable sediments. Widdington Sands and Chillesford Sands (which together might have reached 17 m thick) remained intact, spanning any cavities that were developing beneath. The thick cover material also acted as an insulating layer, shielding underlying chalk from the worst effects of brecciation and solifluction that affected the Quendon outlier, less than 2 km to the northwest (Fig. 4). Secondly, collapse and infilling can be assigned to a later event, triggered by a temporary amelioration in the Early Anglian cooling, which introduced large amounts of meltwater to the system. Subsequently, continuous permafrost was re-established; palaeokarstic structures and host sands, now both rigid with permafrost, were then overridden by glacial ice, truncated, and sealed beneath a substantial layer of till. This provided the necessary protection, in post-Anglian times, to prevent further subsidence or modification.

Evolution of the palaeokarst

A multi-phased model for palaeokarst development within southern East Anglia (Fig. 18), draws on the evolutionary perspectives of Edmonds (2008), McDowell et al (2008) and Cooper et al (2011). The full sequence of karstification is envisaged in eleven stages.

1. Prior to about 2.5 Ma the Palaeogene feather edge, retreating southwards, provided aggressive runoff from a London Clay surface.

2. In the period roughly 2.5–1.7 Ma, after removal of most of the Palaeogene cover, marine transgression (Red Crag) and regression (Chillesford Sands) contributed about 5 m of sandy sediment, which, with 12 m of proto-Thames aggradation reburied the chalk beneath 17 m of cover deposits.

3. During the early Middle Pleistocene (0.77–0.48 Ma), the proto-Thames migrated southwards. This was the main period of fissure enlargement and sinkhole formation within the chalk, and overlying sediments spanned the growing cavities.

4. Around 480 ka, the onset of the Anglian glaciation was heralded by severe, cold, dry, continental, periglacial conditions. Coversand buried the abandoned terrace surface to a depth of 4 m (to about 106 m OD). The ground was cemented by perennial permafrost.

5. Short periods of amelioration in this cooling phase were responsible for partial thawing of the permafrost, leaving discontinuous ground ice. Sinkhole dissolution could have resumed briefly with further fissure enlargement, extending sinkhole depths to 13 m (75 m OD). Meanwhile, frost degradation was responsible for deep-seated brecciation and the development of coombe rock in unprotected chalk areas such as the Quendon outlier.

6. At some time, immediately prior to the arrival of ice, snow and permafrost thawed, releasing meltwater and triggering the formation of subsidence sinkholes. This involved liquefaction, sand suffosion and dropout collapses when the permeable capping of sediment was no longer supportable. Progressive upward migration of cavities through the disturbed pipe infills (Edmonds, 2008) created surface depressions, increasing in size, to form funnelled dolines at least 22m in diameter.

7. During full glacial conditions (~450 ka) continuous permafrost was re-established. Rigid beds of ice-cemented sand were overrun and truncated to about 94 m OD. Sand beds were sealed beneath till as much as 14 m deep that formed a resistant, cohesive capping, preserving underlying structures and isolating them from further subsidence.

8. During post-Anglian adjustment (after 420ka) the till overburden was reduced in thickness. There is no surface expression of sinkhole sites, and little or no additional dissolution appears to have taken place.

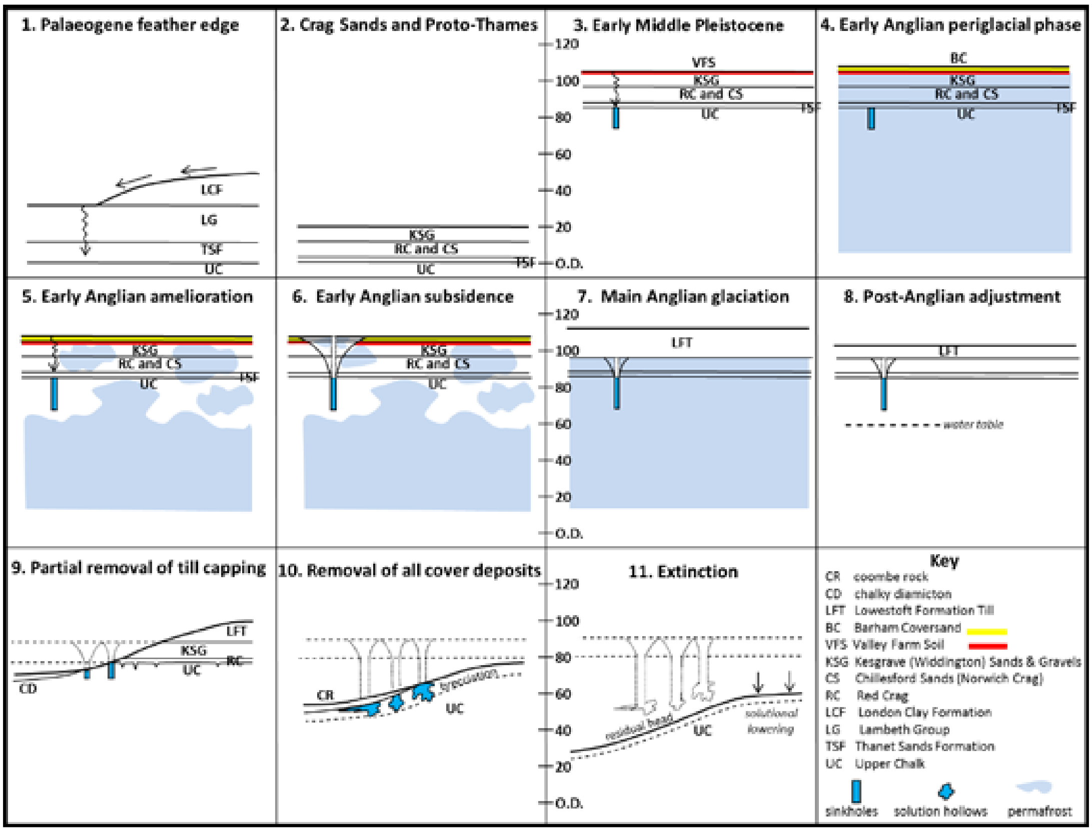


Figure 18. *A multi-phase model of palaeokarst development for the buried chalk surface of northwest Essex.*

9. A lengthy interlude of erosion ensued (spanning glacials and interglacials of 420–117 ka), during which the till overburden was dissected; the unprotected Kesgrave outcrop then receded, partially exposing the sub-Palaeogene chalk surface. A solution-pitted chalk surface may represent exhumed micro-karst or more recent (Holocene) surface weathering. The roots of sinkhole fills survive, but most of the higher structures are lost.

10. Further erosional development, removing both till capping and Kesgrave sands, exposed the chalk to Late Pleistocene periglacial activity. Reactivation of dissolution is identifiable in the Newport chalk pit. Vestigial remnants of reworked Palaeogene material survive in doline linings that have the character of Clay-with-flints. Original sinkhole geometry has been lost, and dissolutional enlargement has converted cylindrical roots into a variety of cavity shapes. Shallow brecciated chalk has solifluted downslope as coombe rock, distorting the tops of infills into flame-like extensions.

11. The ultimate stage in this evolutionary model is reached in the subdued chalk plateau farther north, where continued dissolutional lowering and colluvial processes during the Holocene (last 12 ka) are removing all traces of the palaeokarst and its sinkholes.

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