



The palynology of the Kimmeridge Clay and Carstone Formations (Upper Jurassic–Lower Cretaceous) at Middlegate Quarry, North Lincolnshire, UK, and its biostratigraphical and palaeoenvironmental significance

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Abstract: At Middlegate Quarry, the Carstone Formation is a c. 0.8 m thick unit of oolitic ferruginous sandstone. It rests unconformably on the lower Kimmeridge Clay Formation (KCF) and is overlain by the Hunstanton Formation (Red Chalk) with an apparently gradational junction. Marine dinoflagellate cysts (dinocysts) are present at a concentration of 9520 to 13 600 specimens per gram in the 0.15 m of KCF below the unconformity, and include taxa that confirm ammonite evidence for the intra-Lower Kimmeridgian Substage (Upper Jurassic, Cymodoce Ammonite Zone). A rich recovery of well-preserved Lower Cretaceous palynomorphs is reported for the first time from the overlying Carstone. Reworking of mudstone from the KCF into the formation appears to have provided a local argillaceous preservation matrix at Middlegate. The basal 0.15 m is dominated by palynomorphs derived from the KCF but the interval from 0.15 to 0.55 m above the unconformity mainly contains indigenous Lower Cretaceous palynomorphs. Dinoflagellate cysts are present in the Carstone at an average concentration of 454 specimens per gram, and include taxa that probably have stratigraphical range bases above the Aptian–Albian stage boundary: *Cyclonephelium compactum*, *Cyclonephelium intonsum*, *Endoscrinium heikeae*, *Leptodinium cancellatum* (consistent), *Stephodinium coronatum* and *Stephodinium spinulosum*. The additional presence of taxa with range tops/event tops in the Lower Albian Tardefurcata Ammonite Zone (common *Cauca parva*, frequent *Canninginopsis monile* and *Kleithriasphaeridium eoinodes*, and rare *Dingodinium albertii*, *Discorsia nannus* and *Kiokansium prolatum*) indicate probable assignment to this zone. The new palynological data support previous macrofossil (brachiopod) study of the Carstone at Middlegate and nearby Melton Bottom Quarry which tentatively assigns its highest part to the Tardefurcata Zone. The palynological and palynofacies assemblages are interpreted to confirm a relatively proximal to shoreline site of deposition, possibly inner to middle neritic.

Supplementary material: Quarry photographs and a palynological distribution chart are available at <https://doi.org/10.6084/m9.figshare.c.5538977>

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The extensive (>1 km wide) section at Middlegate Quarry, near the village of South Ferriby in North Lincolnshire (Figs 1 and 2), comprises the Upper Jurassic Ancholme Clay Group (upper Ampthill Clay Formation, Oxfordian, and lower Kimmeridge Clay Formation (KCF), Kimmeridgian), the Lower Cretaceous Carstone Formation, Lower to Upper Cretaceous Hunstanton Formation (formerly known as the Red Chalk, Albian–Cenomanian), and Upper Cretaceous Ferriby Chalk Formation type section (Cenomanian) and Welton Chalk Formation (Cenomanian–Turonian). Middlegate was designated a Site of Special Scientific Interest status for geology in 1987.

There has been a cement factory at South Ferriby since 1938 (Cox and Wright 2001); both chalk (limestone) and clay, the main raw materials used in cement manufacture, were supplied to it from the quarry via a 1.75 km long conveyor belt (Whitham 1992). The quarry was owned and operated by the Rugby Cement company (now Cemex) from 1993 to 1995 when our fieldwork was undertaken and samples collected. It was abandoned as a working quarry in 2020. The pumping of water from the quarry has ceased and it is estimated that an ingress of water will flood the lower

part of the quarry, submerging all of the Ancholme Clay and Carstone (Hildreth 2020a).

The quarry has afforded the opportunity to examine the contact between deposits of Late Jurassic age with those of Early Cretaceous age. In 1993, c. 17.2 m of grey mudstones belonging to the Ancholme Clay Group were exposed in the quarry bottom. Wignall (1990) provided a summary of the stratigraphy, palaeontology and palaeoecology of the Ancholme Clay succession at Middlegate. The contact with the overlying Carstone Formation is irregular, with the Carstone filling shallow hollows, troughs and burrows in the mudstones (Smart and Wood 1976).

The Carstone, as defined by Gaunt *et al.* (1992), is c. 0.8 m thick on average along the northern quarry face where we sampled it (Fig. 3). It is mainly composed of quartz sands, with limonite and calcite oolites, and sand-sized grains of degraded glauconite. Pebbles of phosphate, polished quartz and calcareous siltstone (Gaunt *et al.* 1992; Whitham 1992), along with grey-coloured argillaceous matrix material, occur at the base and throughout the lower c. 0.45 m of the formation at Middlegate. The Carstone is friable and can be dug out by spade but is cemented in patches. It is highly



Fig. 1. The Cretaceous outcrop in eastern England and Carstone Formation localities and boreholes mentioned in the text (modified from Hart 2019; Dodsworth *et al.* 2020).

porous and a significant aquifer (Gaunt *et al.* 1992). Above it, a 0.1 m unit of sandy marl with a burrowed-base (probably indicating a non-sequence; Hopson 2005), and overlying 0.15 m unit of banded red- and cream-coloured sandy marl, are interpreted to be Hunstanton Formation beds 1 and 2 of Gaunt *et al.* (1992). These layers are a lithological gradation between the sandstones of the Carstone and the more typical chalks and marls of the Hunstanton Formation (beds 3–11 of Gaunt *et al.* 1992). They have probably been included with the Carstone by earlier workers, such as Whitham (1992) who measured its thickness at Middlegate as about 1 m.

In this paper, Aptian and Albion chronostratigraphical substages and their corresponding ages are treated as formal units, using initial upper case letters, consistent with the

usual practice, although only the Lower Albion Substage has to date been ratified by the International Union of Geological Sciences (IUGS; see below). The palaeontology of the Carstone was summarized by Gaunt *et al.* (1992). It contains derived Jurassic and Lower Cretaceous *remanié* macrofossil suites, predominantly ammonites and bivalve molluscs. According to Casey (1961), the Carstone has not yielded indigenous ammonites in Norfolk or Lincolnshire. Indigenous brachiopods were reported from the top 0.15 m of Carstone at Melton Bottom Quarry near the village of Melton (Fig. 1; Owen *et al.* 1968) and the top 0.2 m at Middlegate Quarry (Smart and Wood 1976; Whitham 1992). Brachiopod faunas including *Burrirhynchia leightonensis* (Lamplugh and Walker) are comparable to those of the

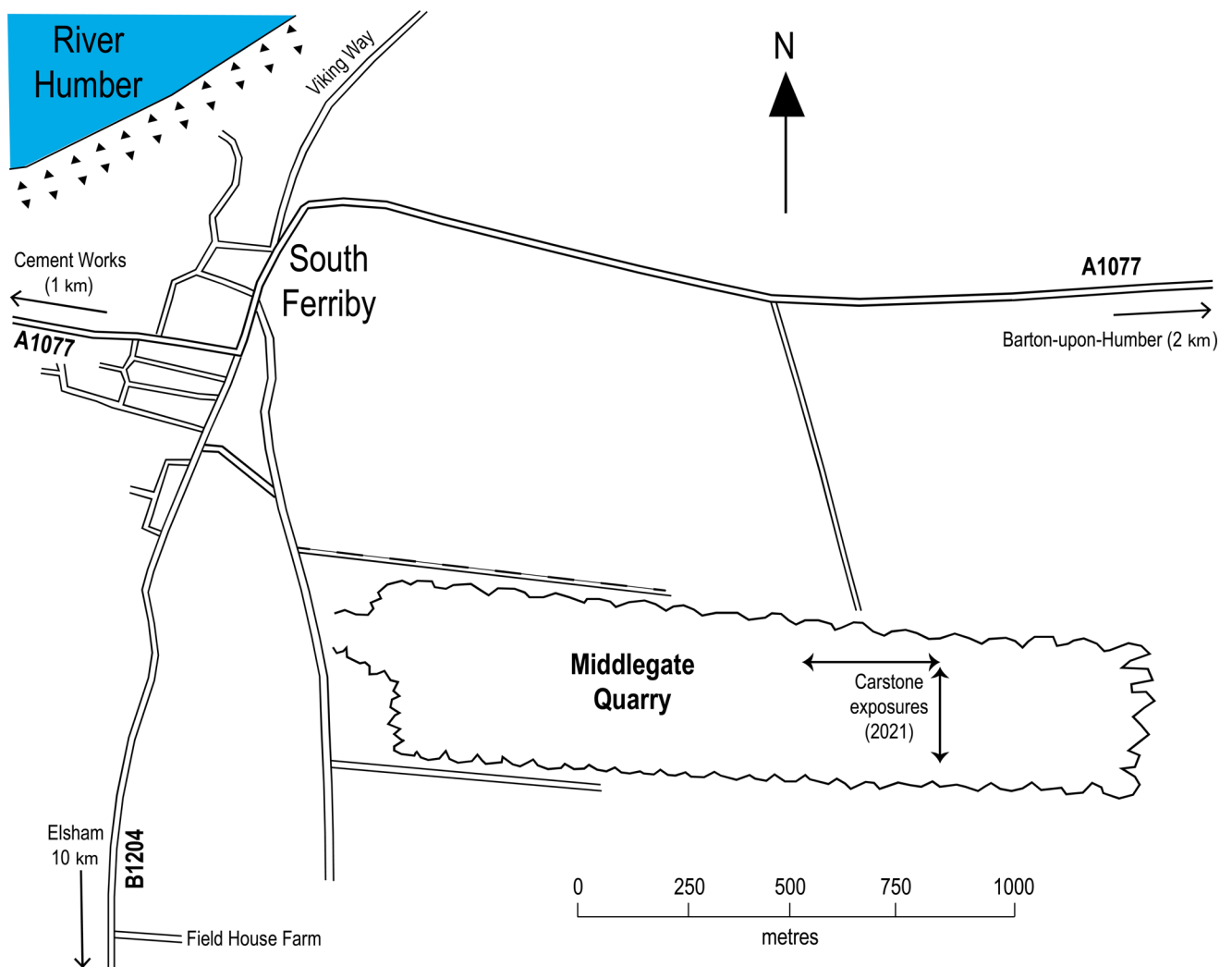


Fig. 2. Sketch map of Middlegate Quarry (O.S. National Grid Reference SE 993204), South Ferriby, showing the approximate position of current Carstone Formation exposures in the quarry bottom. The samples collected for this study in 1993 and 1995 were taken from around the westerly end of the current Carstone exposure, 53° 40' 13" N, 0° 29' 21" W.

Shenley Limestone in Bedfordshire, SE England, which is assigned to the Lower Albian Tardefurcata Ammonite Zone, named for *Leymeriella tardefurcata* (Leymerie). Dilley (1969) reported indigenous foraminifera from the top 0.15 m at Melton Bottom, including *Osangularia schloenbachii* (Reuss) which has an Upper Aptian to Middle Albian stratigraphical range in the North Sea region (Crittenden 1983; Crittenden and Price 1991). Gaunt *et al.* (1992) reported foraminifera and long-ranging Albian ostracods from the top part of the Carstone in a motorway excavation at Melton Gallows. The lower half of the Carstone has remained undated at these localities due to a lack of indigenous fossils. However, Kent and Dilley (1968) recorded Upper Aptian to possibly Lower Albian foraminiferal assemblages from a locally developed 3 m thick mudstone underlying the (0.6 m thick) Carstone at Elsham (Fig. 1).

The only previous palynological investigation of the Carstone in eastern England (localities undisclosed; Gaunt *et al.* 1992) reported that ‘dinoflagellate cysts are sparse, poorly preserved and dominated by the long-ranging *Odontochitina operculata*, many specimens of which are corroded’. Similarly, Hesselbo *et al.* (1990) reported ‘trace’ concentrations of dinoflagellate cysts in the Carstone of the Calne area, Wiltshire, southern England, but these offered no

control for its age. Although shown on lithological logs, the Carstone has not been sampled in some Cretaceous palynological studies, e.g. the Trunch borehole of Norfolk (Fig. 1; Pearce *et al.* 2020) and a Lower Greensand investigation of the Isle of Wight, southern England (Duxbury 1983), presumably due to its lithology appearing to be unsuitable, i.e. too coarse-grained, for palynological preservation.

During sampling of the Ancholme Clay at Middlegate in 1993 for a Master of Science palynology research dissertation (Black 1994), the grey colouration of the lower half of the Carstone was noted, potentially indicating reworking of Upper Jurassic mudstone into its matrix. Six samples were collected (RB10B to RB5B; Fig. 3) to check for reworked palynomorphs. After laboratory processing revealed rich palynological recovery of *in situ* and reworked taxa from the lower four samples, a further four infill samples were collected in 1995 from around the KCF–Carstone boundary (PD9503-1 to -4). While reworked Upper Jurassic taxa are prominent in samples from the lowest 0.15 m of the Carstone, they are only a minor component of assemblages from 0.15 to 0.55 m above the unconformity, in which indigenous Lower Cretaceous palynomorphs dominate.

This paper documents our Carstone samples, providing the first detailed palynological study of the formation and the

first account of well-preserved indigenous fossils from its lower half on the East Midlands Shelf. We discuss dinoflagellate cyst evidence for its age at Middlegate, and broader palynological and palynofacies implications for Carstone palaeoenvironments. Five samples from the uppermost 2.75 m of the KCF (Bed 12 of [Birkelund and Callomon 1985](#)) are also documented for comparison with reworked specimens in the Carstone.

The term Carstone was first formally applied by [Strahan \(1886\)](#), who described it as a coarse reddish-brown ferruginous grit with small phosphatic pebbles and flakes of iron ore. It was deposited during a phase of unconformable transgression ([Versey and Carter 1926](#); [BGS Lexicon of Named Rock Units 2021](#)): a lag deposit that is linked in terms of event stratigraphy to the subsequent deposition of the Chalk Group (Rawson, in the discussion of [Wood and Smith 1978](#)). In East Anglia, it forms an outcrop beneath the mudstones and siltstones of the Gault Formation in southern and central Norfolk, and beneath the limestones of the Hunstanton Formation in northern Norfolk. It is generally up to about 5 m thick, but reaches its maximum thickness

The Carstone has petrographic and mineralogical uniformity across Norfolk, Lincolnshire and Yorkshire, in contrast to the underlying Lower Cretaceous sandstones of

more local character (Versey and Carter 1926). However, there is some thickness and lithological variation across the region. Two distinct facies are recognized in the Carstone of southern Lincolnshire (Swinerton 1935): the Carstone sands and clays, and overlying Carstone grits. Only the upper ‘grit’ facies is developed between Clixby and Melton, where it is up to 1 m thick (Fig. 1; Kelly and Rawson 1983). To the north of Melton, over the Market Weighton Structure in Yorkshire (e.g. Kent 1955; Mitchell 1996, 2000), the Carstone is patchily developed (Versey 1931; Jeans 1973; Gaunt *et al.* 1992; Whitham 1994; Mitchell 1996), often only a few centimetres thick, but is 3.7 to 6.7 m in Painsthorpe Dale, where it may be an infilling of a channel or local fault trough in the eroded Jurassic surface (Jeans 1973). As at Middlegate Quarry (see above), Jeans (1973) noted considerable amounts of argillaceous material within the Carstone at some localities on the Market Weighton Structure, where it rests unconformably on Jurassic mudstones; the Carstone overlies the Upper Jurassic (Oxfordian) Ampthill Clay Formation at Melton Bottom (e.g. Sarjeant 1962), and the Lower Jurassic Lias Group at Goodmanham (De Boer *et al.* 1958).

The KCF is preserved to the north of the Market Weighton Structure in Yorkshire at thicknesses of up to 155 m (Gallois 2021). It is unconformably overlain by a relatively expanded Lower Cretaceous Series (Berriasian to Albian), represented by the Speeton Clay Formation (100–400 m thick; Rawson *et al.* 1978) and overlying Hunstanton Formation (24 m thick at Speeton; Fig. 1; Mitchell 1995). The Speeton Clay comprises mudstones, cement-stones and sporadic bentonites. It was divided by Lamplugh (1889, 1924), into five units (E to A from the base up) related to belemnite content, and these divisions are still maintained (Hildreth 2020b, p. 151; BGS Lexicon of Named Rock Units 2021). The Carstone is probably represented by a ‘Greensand Streak’ (Bed A4 of Wright and Wright 1955; Bed UA4 of Mitchell and Underwood 1999) at Speeton (Versey and Carter 1926; Casey 1961; Kaye 1964; Owen *et al.* 1968; Dilley 1969; Mitchell 1995, fig. 12). Bed UA4 and the immediately underlying *c.* 0.18 m of mudstone have yielded specimens of the ammonite *Epileymeriella* (*Epileymeriella*) cf. *hitzei* (Jacob), indicating probable assignment to the Lower Albian Tardefurcata Zone (Casey 1957; Mitchell and Underwood 1999). However, the only specimen recovered to date from Bed UA4, preserved as a phosphate mould (Lamplugh 1924, p. 21), may be reworked from the underlying Lower Albian mudstones at Speeton (Mitchell and Underwood 1999).

Material and methods

KCF samples (5 g) and up to 180 g of Carstone samples were prepared for palynology, using hydrochloric acid (35% HCl) and hydrofluoric acid (40% HF) to dissolve carbonate and silicate minerals, respectively. After daily stirring of the Carstone samples in HF for at least two weeks, however, the coarser-grained silicates were disaggregated but mostly undissolved. Only the fine fraction which settled out above the coarser grains was sieved for palynology, as this was presumed to contain most palynomorphs present. All preparations were sieved with a 10 µm mesh. Carstone preparations were swirled in a dish to separate any remaining

silicate grains and strewn on microscope coverslips after this stage. Post-HF kerogen slides were made for two of the KCF samples (PD9503-1 and -2). To improve the ratio of palynomorphs to amorphous organic matter (AOM; Table 1) for palynological study, KCF residues were oxidised with Schulze’s solution (70% nitric acid, HNO₃, supersaturated with potassium chlorate, KClO₃) for between five minutes and one hour, followed by one subsequent rinse with a 2% potassium hydroxide (KOH) solution. Some oxidized preparations were stained with Safanin O solution (red stain).

Where palynological recovery permitted, approximately equal portions of quantified organic residues from each sample were strewn over three to six 22 × 22 mm coverslips, dried, and mounted onto microscope slides using Petropoxy 154. Palynomorph counts were conducted with an initial 100 specimen count, to establish the ratio between terrestrial and marine palynomorphs (T/M ratio), as a proxy of terrigenous nutrient input (see the discussion below). Counting was continued until 250 terrestrial palynomorphs and 250 marine palynomorphs were reached. From the dinoflagellate cyst counts, the ratio of mainly heterotrophic peridinioids (‘P-cysts’) to phototrophic gonyaulacoids (‘G-cysts’) was calculated, as a proxy of palaeo-productivity (see McLachlan *et al.* 2018 for a recent review of the P/G ratio). The remaining strewn material was examined for rare taxa outside of the count. Selected dinoflagellate cysts are illustrated in Figures 4–6.

Semi-quantitative abundances are recorded as rare (1 specimen or outside the count), frequent (2–4 specimens), common (5–14 specimens), abundant (15–49 specimens) or super-abundant (50+ specimens). The volumetric method described in Dodsworth *et al.* (2020) was used to estimate ‘absolute abundance’, i.e. the concentration of palynomorphs in each sample (counts per gram, cpg; Table 1). Given the errors inherent in calculating absolute abundances, numbers are expressed to three significant figures (as recommended by Pearce *et al.* 2020). Separate counts of 100 kerogen particles (AOM, brown and black phytoclasts, palynomorphs and cuticle) were made from the un-oxidized KCF and Carstone kerogen slides.

The Middlegate Quarry palynological microscope slides are curated at the Centre for Palynology, University of Sheffield. A full range chart of palynological data is available in the Supplementary Material. Full author names and synonyms of dinoflagellate cysts, algae and acritarchs can be found in Fensome *et al.* (2019a). Corrections to the nomenclature of Fensome *et al.* (2019a) proposed by Dodsworth *et al.* (2020), with respect to *Pterodinium crassimuratum* (Davey and Williams) being a senior synonym, and Pearce *et al.* (2020) and Jarvis *et al.* (2021), with respect to *Sepispinula ambigua* (Deflandre) being a senior synonym and a confident generic assignment, are used in this paper. In addition, we informally retain *Cyclonephelium longispinatum* (Davey), as *C.* ‘longispinatum’ in the text below and in Figures 3 and 4. Fensome *et al.* (2019a, b) considered *C. longispinatum*, a species initially reported from Upper Cretaceous deposits of offshore southwestern Africa (Davey 1978), to be a heterotypic junior synonym of *Tenua anaphrissa* (Sarjeant), a Barremian (Lower Cretaceous) marker taxon in NW Europe (Costa and Davey 1992). The synonymy is based on the holotype photograph of

Table 1. Summary of palynomorph concentration (counts per gram, to three significant figures), >10 µm counts of 100 kerogen particles (AOM = amorphous organic matter; black and brown phytoclasts; cuticle; palynomorphs), gymnosperm pollen and pteridophyte/bryophyte spores as percentages of total terrigenous palynomorphs, and dinoflagellate cyst species richness ('diversity') of Cretaceous taxa in the Carstone and Jurassic taxa in the Kimmeridge Clay (obvious reworked specimens not included)

Locality: Middlegate Quarry, South Ferriby.															
(Not to scale.)															
Lithostrat.	Outcrop height (m)	Sample	Counts/g (total)	Kerogen					Terrigenous palynomorphs				Marine palynomorphs		
				AOM (%)	Phytoclasts (black)	Phytoclasts (brown)	Cuticle (%)	Palyn. (%)	Counts/g (terrest.)	Gymnosp. (%)	Pterido. (%)	T/M ratio	P/G ratio	Dinoflag. per g	Dinoflag. diversity
Carstone Formation	17.8–17.9	RB5B	0						0					0	0
	17.7–17.8	RB6B	<1						<1			0.30		<1	4
	17.6–17.7	RB7B	332	1	68	17	0	14	110	71.2	28.8	0.33	0.004	204	82
	17.5–17.6	RB8B	1,330	0	58	21	0	21	292	78.4	21.6	0.22	0.017	983	96
	17.4–17.5	RB9B	1,310	0	52	10	0	38	498	78.8	21.2	0.38	0.030	761	83
rw. KCF	17.3–17.4	RB10B	528	5	26	22	1	46	259	76.4	23.2	0.49	0.053	243	82
	17.2–17.3	PD9503-4	67 200	89	3	3	0	5	55 800	91.6	8	0.83	0	8,550	9
	17.15–17.2	PD9503-3	273	60	13	6	0	21	183	89.6	10.4	0.67	0.027	80	61
	17.1–17.15	PD9503-2	59 700	78	4	7	0	11	48 300	94	6	0.81	0	9,520	38
Kimmeridge Clay Formation	17.0–17.1	PD9503-1	119 000	82	4	7	0	7	103 000	94.4	5.6	0.86	0	13 600	49
	16.6–16.7	RB11B								96.4	3.6	0.71	0		41
	15.4–15.5	RB1C		No kerogen or concentration data for the lower three samples.						95.6	4.4	0.72	0		34
	14.4–14.5	RB4								91.6	8.4	0.81	0		34

T/M ratio, terrestrial/marine ratio. P/G ratio, the ratio between peridinioid (P) and gonyaulacoid (G) dinoflagellate cysts. rw., reworked.

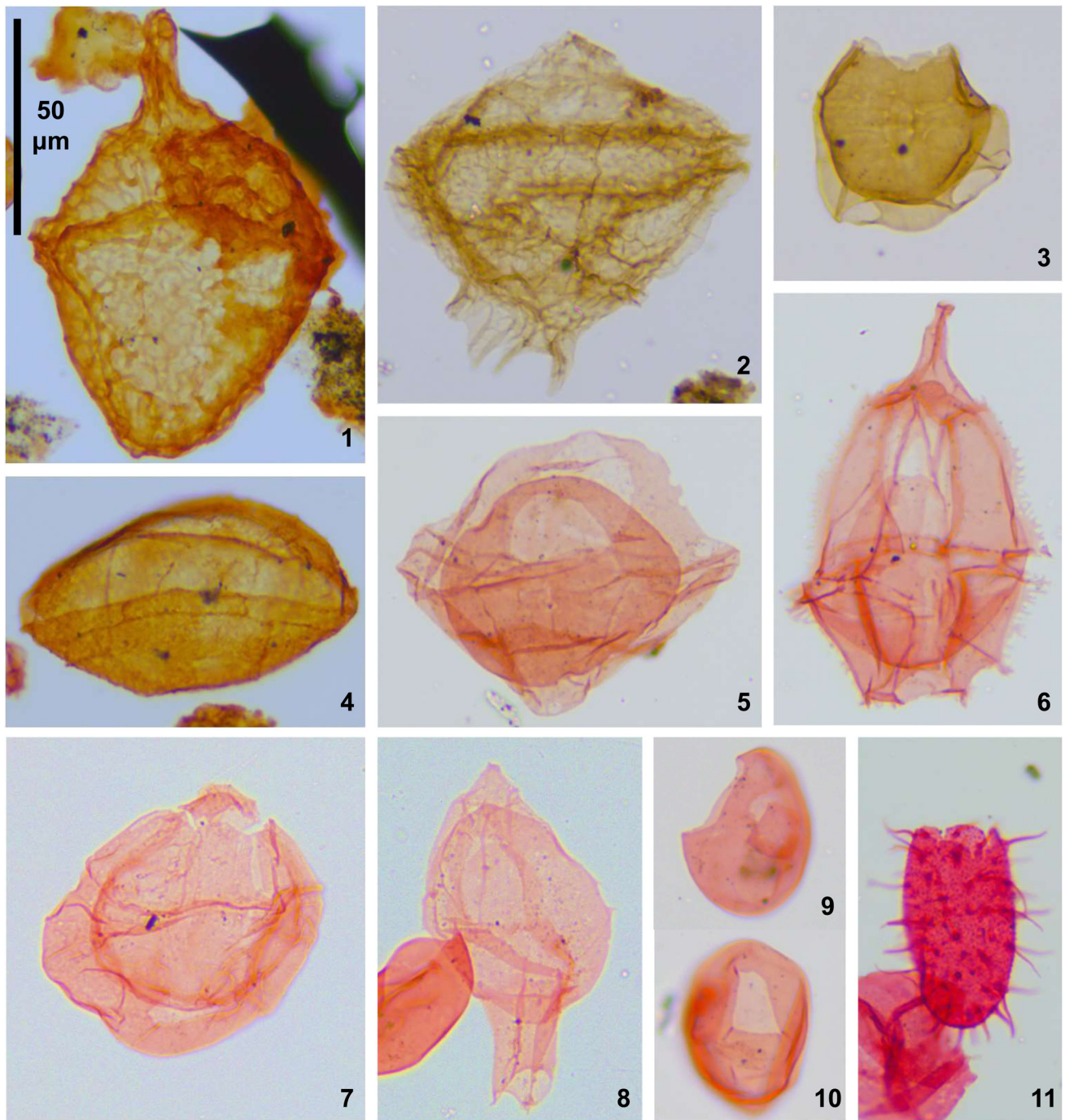


Fig. 4. Jurassic dinoflagellate cysts from the Kimmeridge Clay Formation (KCF) and Carstone Formation in Middlegate Quarry. All specimens were photographed at $\times 400$. Sample slide numbers and England Finder co-ordinates are given. 1. *Scrinioidinium dictyotum* subsp. *pyrum*, PD9503-1(C), O40/1 (KCF); 2. *Glossodinium dimorphum*, PD9503-3(kerogen slide), T37/1 (Carstone; reworked Middle Oxfordian to Volgian specimen); 3. *Sirmiodiniopsis orbis*, RB9B(4), O44/2 (Carstone; reworked Bajocian to Oxfordian specimen); 4. *Dichadogonyaulax chondra*, PD9503-4(A), G40/2 (Carstone; reworked Upper Oxfordian to Lower Kimmeridgian specimen); 5. *Endoscrinium luridum*, RB1C(1), R38/4 (KCF); 6. *Gonyaulacysta jurassica* subsp. *jurassica*, RB1C(2), T31/0 (KCF); 7. *Sirmiodinium grossii*, RB1C(2), Q34/4 (KCF); 8. *Tubotuberella apatela*, RB1C(2), H40/4 (KCF); 9. *Chytroeisphaeridium chytroeides*, RB1C(2), R31/1 (KCF); 10. *C. chytroeides*, RB1C(2), H45/0 (KCF); 11. *Prolixosphaeridium granulosum*, RB4(2), M42/1 (KCF).

C. longispinatum (Davey 1978, pl. 3, fig. 7) not displaying dorsoventral areas clearly devoid of ornament, and comparable thin processes on both taxa. However, *C. longispinatum* has a more symmetrical shape and less densely distributed processes than *T. anaphrissa*; its processes are longer, relative to central body diameter (*c.* one-eighth to one-fifth), than those on the holotype of *T. anaphrissa* (less than one-tenth; Sarjeant 1966, pl. 22, fig. 8). Dorsoventral areas devoid of processes were reported by Davey (1978) for *C. longispinatum* and are clearly visible on an illustrated specimen (Davey 1978, pl. 3,

fig. 4) that he considered to be possibly transitional with *Cyclonephelium compactum* Deflandre and Cookson.

Results

In the upper part of KCF Bed 12, high concentrations of palynomorphs were recovered (119 000 cpg in sample PD9503-1; 59 700 cpg in sample PD9503-2). The Carstone samples yielded much lower concentrations (273–1330; average 755 cpg, from samples PD9503-3, RB10B, RB9B, RB8B and RB7B). An

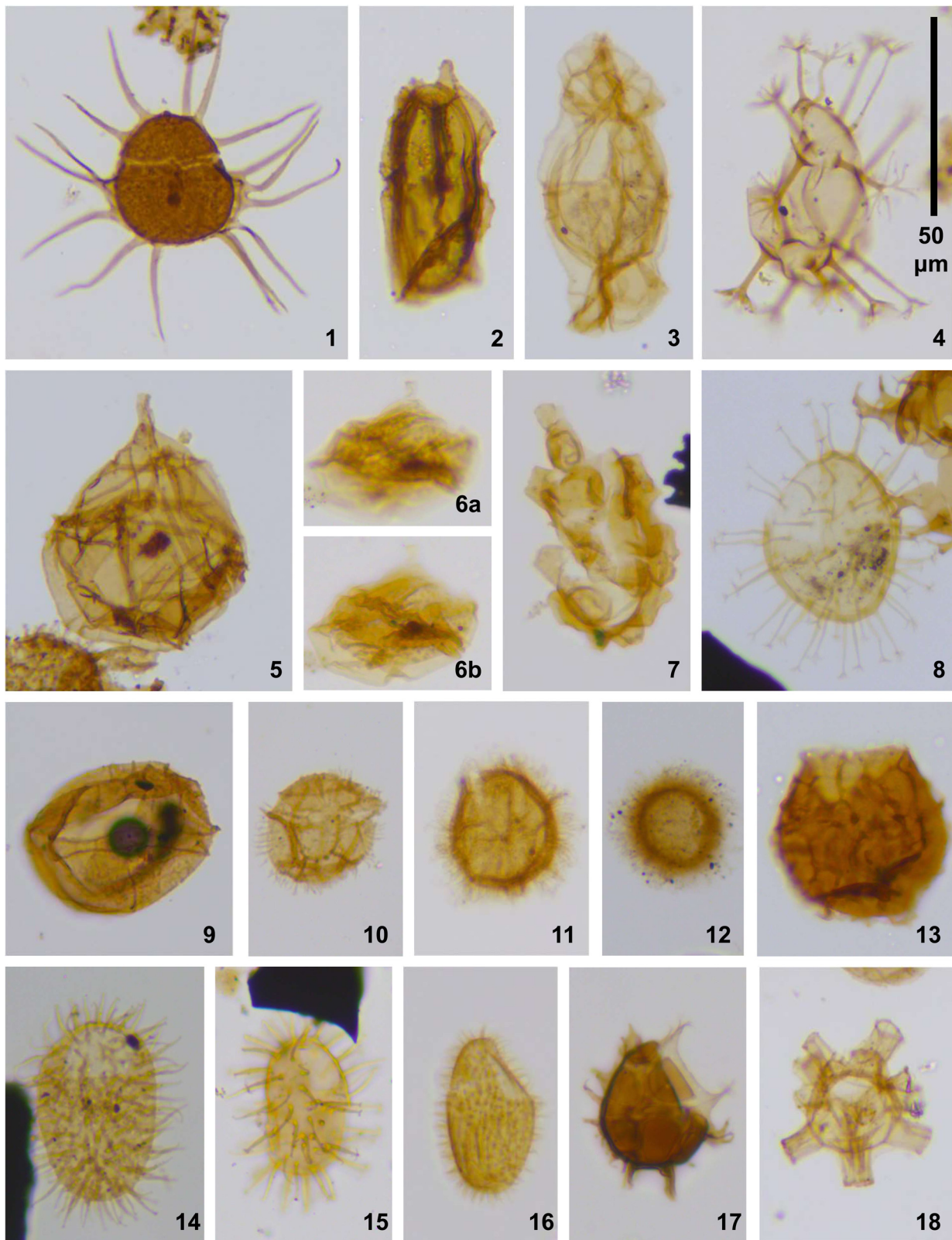


Fig. 5. Cretaceous dinoflagellate cysts from the Carstone Formation in Middlegate Quarry. All specimens were photographed at x400. Sample slide numbers and England Finder co-ordinates are given. 1. *Cauca parva*, RB10B(1), H44/4; 2. *Carpodinium granulatum*, RB10B(5), E31/1; 3. *Codoniella psygma*, RB8B(5), X47/3; 4. *Kiokansium prolatum*, RB10B(1), Q30/2; 5. *Leptodinium? hyalodermopse* sensu Davey (1982), RB9(B), O46/2; 6. *Dingodinium albertii*, RB7B(2), B42/0. (a) Focus on apical region, including periphragm horn. (b) Focus on antapical region and cavation; 7. *Litospaeridium?* sp., RB7B(2), M46/4. Broken specimen with c. 16 processes which are dome-shaped, typical of the genus (Stover and Evitt 1978; Lucas-Clark 1984); 8. *Kiokansium unituberculatum*, RB8B(3), Q42/3; 9. *Leptodinium cancellatum*, RB10B(1), H43/1; 10. *Microdinium setosum*, RB10B(2), C42/0; 11. *Microdinium? crinitum*, RB8B(6), X42/2; 12. *Cometodinium? comatum*, RB7B(3), H33/4; 13. *Ellipsoidictyum imperfectum* subsp. *imperfectum*, RB8B(3), X37/4; 14. *Protoellipsoidinium spinosum*, RB9B(2), U43/1; 15. *Protoellipsoidinium clavulus* subsp. *clavulus*, RB10B(2), U29/2; 16. *Protoellipsoidinium spinocristatum*, RB8B(3), M32/4; 17. *Spiniferites* cf. *jarvisii*, RB7B(2), H33/2. Note the thickened intra-plate areas. This morphotype is possibly transitional between *Pterodinium crassimuratum* and *Spiniferites jarvisii*; 18. *Discorsia nannus*, RB10B(5), T34/4.

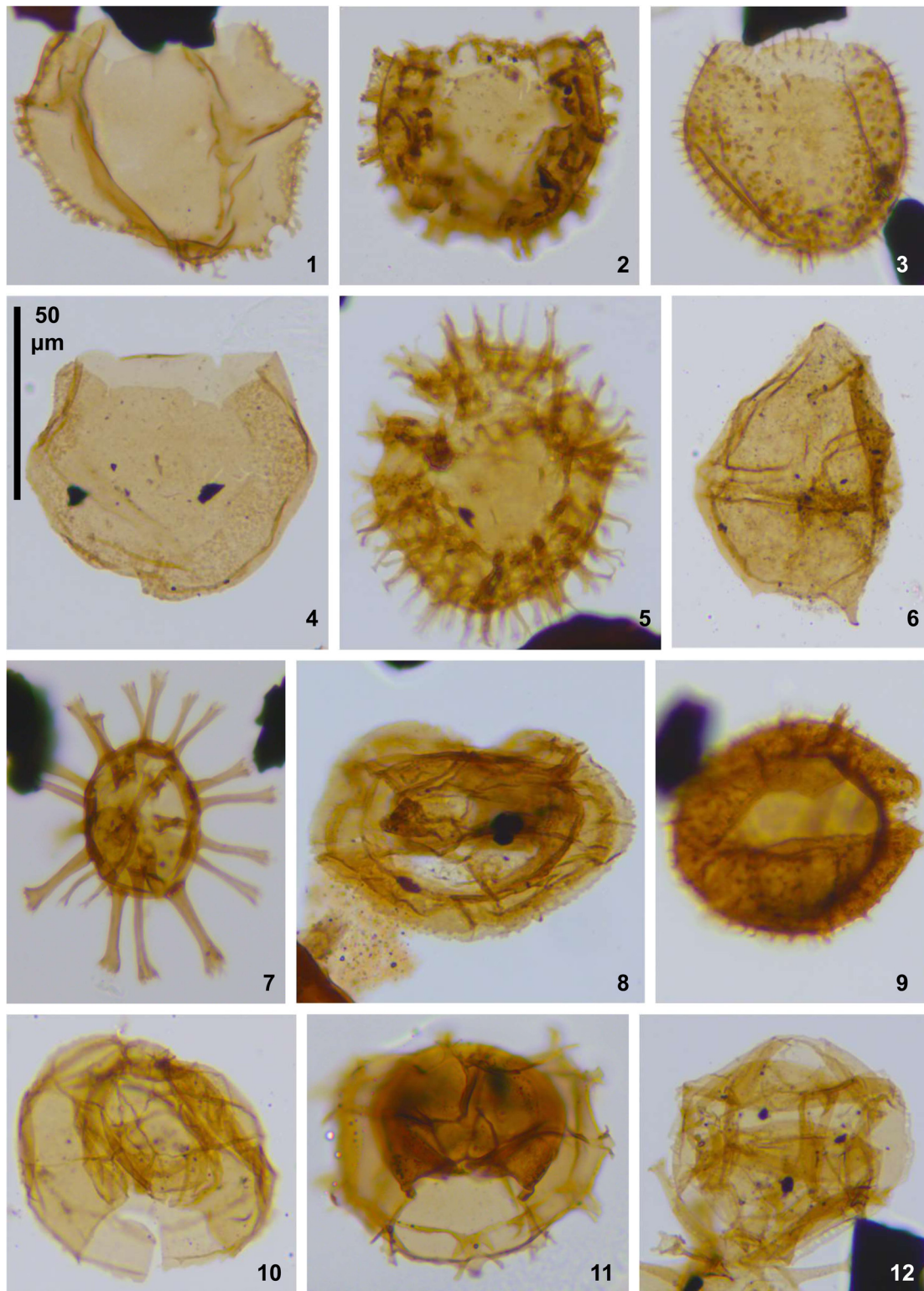


Fig. 6. Cretaceous dinoflagellate cysts from the Carstone Formation in Middlegate Quarry. All specimens were photographed at $\times 400$. Sample slide numbers and England Finder co-ordinates are given. 1. *Canninginopsis monile*, RB7B(1), M49/4; 2. *Cyclonephelium compactum*, RB10B(2), U43/4; 3. *Circulodinium distinctum*, RB7B(2), V37/4; 4. *Cyclonephelium intonsum*, RB9B(2), L34/3; 5. *Cyclonephelium 'longispinatum'*, RB8B(2), J37/4. This morphotype is typical of those observed at Middlegate. Note that its processes are significantly less membranous than '*Cyclonephelium compactum* (extreme)' of Duxbury (1983, 2001). 6. *Palaeoperidinium cretaceum*, RB10B(1), E41/3; 7. *Kleithriasphaeridium eoinodes*, RB8B(2), L46/4; 8. *Occiscysta tentorium*, RB9B(5), Q38/4; 9. *Cribroperidinium? tenuiceras*, RB8B(2), C39/3; 10. *Stephodinium coronatum*, RB10B(2), W29/1; 11. *Stephodinium spinulosum*, RB10B(5), R49/0; 12. *Endoscrinium heikeae*, RB9B(5), N42/2.

exception is the sample PD9503-4 which is almost entirely composed of reworked Upper Jurassic taxa and has a corresponding high concentration of palynomorphs (67 200 cpg). Samples from the upper part of the Carstone are impoverished of palynomorphs (sample RB6B, 11 specimens

only, <1 cpg) or barren (sample RB5B). Two additional samples were collected from the Hunstanton Formation (detailed positions not recorded) but these are also barren of palynomorphs.

The dinoflagellate cyst assemblages from the KCF contain between 34 and 49 (average 39) taxa. The Carstone

assemblages contain between 61 and 96 (average 81) *in situ* taxa from samples PD9503-3 and RB10B to RB7B. The KCF samples are dominated by G-cysts, occurring at a stratigraphically deeper level within the Lower Kimmeridgian than the widespread inception of P-cysts, including that of *Corculodinium inaffectum* in the Mutabilis Ammonite Zone (see below). In the Carstone, G-cysts are also prominent, with the *Spiniferites ramosus* 'group' and *Oligosphaeridium complex* being consistently abundant (Fig. 3). P-cysts are mainly represented by *Palaeoperidinium cretaceum* (Fig. 6.6), with subordinate *Ovoidinium* spp. and *Subtilisphaera* spp., but comprise no more than 5.3% of dinoflagellate cyst assemblages.

The prasinophyte algae *Pterospermella* and *Tasmanites* are frequent in most samples from the KCF and Carstone, while *Leiosphaeridia* is abundant in the KCF and rare in the Carstone. Acritarchs, mainly *Michrhystridium* (Acanthomorphytae), with subordinate *Veryhachium* (Polygonomorphytae), are common to abundant in the KCF and frequent to common in the Carstone. Fresh/brackish-water algae, mainly *Botryococcus braunii* Kützing and *Lecaniella foveata* Singh, are sporadically present but rare in both the KCF and Carstone.

In the KCF, terrigenous pollen and spores dominate over marine palynomorphs, with a T/M ratio of 0.71 to 0.86 (average 0.78; Table 1). Gymnosperm pollen are prominent, mainly represented by bisaccate pollen, associated with common *Araucariacites australis* Cookson, *Callialasporites* (including *C. dampieri* (Balme) and *C. turbatus* (Balme)), *Cerebropollenites macroverrucosus* Schulz and *Exesipollenites* (mainly *E. tumulus* Balme). A marked influx of the last occurs immediately below the Jurassic–Cretaceous boundary, comprising over one-half of the terrigenous assemblage in samples PD9503-1 and -2. Reworked *Exesipollenites* is also recorded in abundance immediately above the boundary, in samples PD9503-3 and -4. The remainder of the palynologically productive Carstone, overlying samples RB10B to RB7B, contain a T/M ratio of 0.22 to 0.49 (average 0.36) and relatively uniform terrigenous assemblages dominated by bisaccate pollen (average 72%) associated with smooth-walled trilete pteridophyte/bryophyte spores, mainly *Deltoidospora* and *Gleicheniidites* (average 18%).

In the >10 µm fraction of the kerogen, the KCF samples are dominated by AOM, a typical feature of the formation. In Carstone samples, phytoclasts and palynomorphs are prominent. The ratio of the former to the latter appears to increase up-section between samples RB10B and RB7B (Table 1) although, with just four samples considered, it is unclear whether this apparent trend is significant. The swirling stage of preparation of Carstone samples (see above) may have biased the Carstone residues, in terms of removal of larger relatively dense phytoclasts from the kerogen.

Biostratigraphy of Kimmeridge Clay Formation Bed 12

The Global Stratotype Section and Point (GSSP) for the base of the Kimmeridgian Stage and, by default, that of the Lower Kimmeridgian Substage, have recently (February 2021) been ratified by the IUGS. The boundary is dated as 157.3 ± 1.0 Ma (International Commission on Stratigraphy, ICS 2021) and placed in the upper part of Bed 35 of the Staffin

Shale Formation at Flodigarry, Staffin Bay, Isle of Skye, Scotland (<https://jurassic.stratigraphy.org>).

At Middlegate, the lowermost Kimmeridgian Baylei Ammonite Zone is present in beds 9–10 of Birkelund and Callomon (1985), 8.2–14.2 m above the base of the section in 1993. The overlying intra-Lower Kimmeridgian Cymodoce Ammonite Zone is present in Bed 11, 14.2–14.4 m, and Bed 12, 14.4–17.2 m, immediately below the Jurassic–Cretaceous unconformity (Wignall 1990). The remaining ammonite zones of the Kimmeridgian are eroded by the unconformity.

Research on the dinoflagellate cyst floras of the UK Kimmeridgian is extensive and well-established (e.g. Gitmez 1970; Gitmez and Sarjeant 1972; Riley 1974; Birkelund *et al.* 1983; Riding 1984, 1987, 2005; Nøhr-Hansen 1986; Riding and Thomas 1988, 1992, 1997; Thomas and Cox 1988; Bailey 1993; Bailey *et al.* 1997). Typical Lower Kimmeridgian dinoflagellate cyst assemblages are recovered from Bed 12 at Middlegate, including common to abundant occurrences of longer ranging taxa such as *Chytroesphaeridia chytrooides* (Figs 4.9 and 4.10), *Cribroperidinium globatum* 'group', *Dichadogonyaulax chondra* (Fig. 4.4), *Gonyaulacysta jurassica* subsp. *jurassica* (Fig. 4.6), *Mendicodinium groenlandicum*, *Pareodina ceratophora*, *Rhynchodiniopsis cladophora*, *Scriniodinium dictyotum* subsp. *pyrum* (Fig. 4.1), *Tubotuberella apatela* (Fig. 4.8) and *Valensiella ovulum*. The presence of *Senoniasphaera jurassica* (sample RB1C, 15.4–15.5 m) confirms an age no older than Early Kimmeridgian, while *Endoscrinium luridum* (Fig. 4.5), *S. dictyotum* subsp. *pyrum* and *Stephanelytron caytonense* (all present in the top 0.15 m of Bed 12) confirm an age no younger than Early Kimmeridgian. In addition, the presence of *Dingodinium tuberosum* (sample RB4, 14.4–14.5 m) is consistent with a broad latest Oxfordian to Early Kimmeridgian age (cf. Woollam and Riding 1983; Riding and Thomas 1992; Poulsen and Riding 2003).

The UK dinoflagellate cyst Zone Elu(a) of Riding and Thomas (1992), and corresponding NW Europe Zone DSJ28 of Poulsen and Riding (2003), have been calibrated to the Cymodoce Ammonite Zone by these authors. An absence of taxa with range bases in Zone Elu(b) (upper DSJ28–29), calibrated to the overlying Mutabilis Ammonite Zone of the Lower Kimmeridgian, namely *Corculodinium inaffectum* and *Perisseiasphaeridium pannosum*, confirms a stratigraphical position for Bed 12 below this level. Taxa with range tops in Zone Scr(d) (DSJ27), namely *Gonyaulacysta eisenackii*, *Nannoceratopsis pellucida* and *Scriniodinium crystallinum*, calibrated to the underlying Baylei Ammonite Zone are also absent, apart from isolated, possibly reworked specimens in sample RB11B (*N. pellucida*) and PD9503-2 (17.1–17.15 m; *S. crystallinum*). *Scriniodinium crystallinum* is a consistent component of assemblages in the (Oxfordian) Amphill Clay Formation at Middlegate (0–8.2 m above the base of the section in 1993; cf. Stancliffe 1984). Bed 12 is assigned on the basis of the above discussion to Zone Elu(a).

Biostratigraphy of the Carstone Formation

There is no direct ammonite evidence for the age of the Carstone on the East Midlands Shelf or Market Weighton Structure. The presence of indigenous Lower Cretaceous

dinoflagellate cysts allow deductions to be made about its age at Middlegate.

The base of the Albian Stage and Lower Albian Substage, dated as *c.* 113.0 Ma (ICS 2021), have a ratified GSSP at 37.4 m above the topmost limestone of the Faisceau Fromaget (the section's zero datum) at Col de Pré-Guittard in the Vocontian Trough, SE France (Kennedy *et al.* 2017). The boundary is denoted by the First Appearance Datum there of the planktonic foraminifer *Microhedbergella renilaevae* Huber and Leckie. This stratigraphical level is lower than previous placement of the Aptian–Albian stage boundary as determined by ammonites, at the base of the Tardefurcata Zone (see Kennedy *et al.* 2000 for a historical review) and assigned from 68.0 m at Col de Pré-Guittard. The GSSP at 37.4 m correlates with mid-levels of the underlying Jacobi Zone which is assigned between the zero datum and 68.0 m. The zone is named for the ammonite *Hypacanthoplites jacobi* (Collet). Although *H. plesiotypicus* (Fritzel) is now considered to be its senior synonym, the Jacobi zonal name is retained (Kennedy *et al.* 2000). The distributions of some of the Aptian–Albian dinoflagellate cyst marker taxa discussed below were documented by Davey, in Kennedy *et al.* (2000) at Col de Pré-Guittard and the nearby Tartonne section.

Dinoflagellate cyst range bases

Intra-Tardefurcata Zone range bases have been calibrated for the Albian-restricted marker taxa *Endoscrinium heikeae* (Fig. 6.12; Prössl 1990; Duxbury 2001), *Litosphaeridium arundum* (Davey and Verdier 1971; Costa and Davey 1992; Duxbury 2001) and *Odontochitina singhii* (Kennedy *et al.* 2000; Duxbury 2001). Only the first of these is recorded at Middlegate, in the RB10B to RB7B samples (Fig. 3). An isolated questionable specimen of *Litosphaeridium* (Fig. 5.7) in sample RB7B probably has too few processes (approximately one per paraplate area) to be assigned to *L. arundum* (cf. Lucas-Clark 1984).

At Middlegate, *Cyclonephelium intonsum* (Fig. 6.4) is rare but present in most Carstone samples. Its only previously published UK record may be from a relatively short stratigraphical interval, upper-Jacobi Zone to intra-Tardefurcata Zone on the Isle of Wight (Duxbury 1983). More widely distributed (NW Europe) taxa with known lowest occurrences either at the base of the Tardefurcata Zone or in the upper Jacobi Zone are *Cyclonephelium compactum* (Fig. 6.2), *Stephodinium coronatum* (Fig. 6.10) and *Stephodinium spinulosum* (Fig. 6.11; Davey 1982; Duxbury 1983, 2001; Costa and Davey 1992). Significantly, Kennedy *et al.* (2000) only recorded *C.* (cf.) *compactum* and *S. coronatum* from the Albian at Col de Pré-Guittard and Tartonne (*C. intonsum* and *S. spinulosum* were not recorded there). The presence of all four taxa in the lowermost Carstone sample at Middlegate (PD9503-3), a clast or lens of sandstone that is lighter-coloured than the encasing deposits, suggests an age probably not older than Albian.

Leptodinium cancellatum (Fig. 5.9) has a basal consistent occurrence around the Tardefurcata–Jacobi zonal boundary (Duxbury 2001) but can also occur sporadically throughout the Upper Aptian (Costa and Davey 1992). *Canninginopsis monile* (Fig. 6.1) has a range base in the Jacobi Zone (Duxbury 2002). *Ellipsoidictyum imperfectum* subsp.

imperfectum (Fig. 5.13) has a range base in intra-Upper Aptian deposits (pre-Jacobi Zone), as does *Kiokansium prolatum* (Fig. 5.4; Costa and Davey 1992; Duxbury 2001) and possibly *Microdinium setosum* (Fig. 5.10; Davey 1982). All five taxa are present in most Carstone samples, including consistent *L. cancellatum* in samples RB10B to RB7B, though only *E. imperfectum* subsp. *imperfectum* is recorded in the lowermost sample PD9503-3.

Dinoflagellate cyst range tops

The following taxa occur consistently in the Carstone at Middlegate and have range tops reported from the Tardefurcata Zone (Duxbury 1983, 2001, 2002; Costa and Davey 1992; Kennedy *et al.* 2000): frequent *Canninginopsis monile* and frequent *Kleithriasphaeridium eoinodes* (Fig. 6.7), rare *Discorsia nannus* (Fig. 5.18) and rare *Kiokansium prolatum*. Occasional specimens of *Dingodinium albertii* (Fig. 5.6) and *Occisucysta tentorium* (Fig. 6.8), along with common *Kiokansium unituberculatum* (Fig. 5.8) also indicate a stratigraphical position probably no higher than the Tardefurcata Zone (Costa and Davey 1992; Duxbury 2001). Common *Ellipsoidictyum imperfectum* subsp. *imperfectum* supports an age not younger than Early Albian (cf. Duxbury 2001). *Protoellipsodinium clavus* subsp. *clavus* (Fig. 5.15) is present in most of the Carstone samples. It has a range top in the Tardefurcata Zone on the Isle of Wight (Duxbury 1983) but has a deeper (Jacobi Zone) range top farther north in the Central North Sea (Duxbury 2001).

At Middlegate, *Cauca parva* (Fig. 5.1) is common to abundant in the lower part of the Carstone (samples PD9503-3, RB10B). It occurs throughout the Aptian and Albian stages in NW Europe (e.g. Costa and Davey 1992) and is abundant at some levels within the Aptian (e.g. Davey 1982; Duxbury 1983). It has a top common occurrence in the Tardefurcata Zone of the North Sea region (Duxbury 2001). At Col de Pré-Guittard and Tartonne, Kennedy *et al.* (2000) reported it to be relatively rare, apart from an isolated common occurrence in the Tardefurcata Zone at the former locality (their sample 15a, at *c.* 69 m above the zero datum).

Reworking in the Carstone

Isolated occurrences of dinoflagellate cysts that are typical of Aptian deposits (i.e. those with intra- or pre-Jacobi Zone range tops) are interpreted as reworked: *Aptea polymorpha* (sample RB10B) and questionable *Cerbia tabulata* (samples RB8B and RB9B). Other widely occurring Aptian forms (e.g. Davey and Verdier 1974; Duxbury 1983, 2001, 2019; Costa and Davey 1992) such as *Chlamydophorella trabeculosa*, *Circulodinium vectense*, *Spiculodinium neptuni* and (with the exception of a questionable specimen in sample RB10B) *Systematophora silyba*, were not recorded at Middlegate. Isolated specimens of *Callaiosphaeridium trycherium*, *Desmocysta plekta* and *Druggidium augustum* in sample RB10B, along with *Nexosispinum vetusculum* and questionable *Heslertonella heslertonensis* in sample RB7B, are probably reworked from pre-Upper Aptian, Lower Cretaceous deposits (cf. Duxbury 1977, 1980, 2001, 2018, 2019; Costa and Davey 1992).

Evidence from reworked macrofossils and mineralogy suggests that the Carstone in eastern England is mainly

derived from older Lower Cretaceous sandstones (Strahan 1886; Versey and Carter 1926; Swinnerton 1935; Casey 1961; Gaunt *et al.* 1992). The paucity of corresponding reworked Lower Cretaceous dinoflagellate cysts at Middlegate might be explained by oxidative destruction of palynomorphs in original coarse-grained host rocks or during subsequent transport.

The majority of reworked dinoflagellate cysts in the Carstone are derived from Upper Jurassic deposits. The same taxa that are recorded *in situ* in KCF Bed 12 compose the bulk of the reworked specimens (see the [supplementary](#) palynological range chart). They are abundant in the basal Carstone clast or lens sample PD9503-3 (possibly as encasing reworked mudstone contaminants) and dominate in the overlying sample PD9503-4. Although mainly represented outside of the 250 microplankton count, 10–20 reworked Upper Jurassic taxa are also present in each of the overlying RB10B to RB7B Carstone samples. Single specimens of *Perisseiasphaeridium pannosum* in samples RB8B and RB7B indicate an additional reworking component from stratigraphically higher levels of the KCF than those preserved at Middlegate (cf. Riding and Thomas 1992; Poulsen and Riding 2003). Amongst the terrigenous palynomorphs, prominent *Exesipollenites*, occurring *in situ* in the 0.15 m section below the Jurassic–Cretaceous unconformity, and reworked in the 0.15 m section above it, confirm mainly local derivation of mudstone matrix into the Carstone.

Dinoflagellate cyst zonation of the Carstone

The presence of dinoflagellate cysts with NW Europe range/event tops in the Tardefurcata Zone, and range bases in the Tardefurcata Zone or upper part of the underlying Jacobi Zone, suggest an Early Albian age for the Carstone at Middlegate (Fig. 3). The section from 0.15 m (sample RB10B) to 0.55 m (sample RB7B) above the basal unconformity is assigned to dinoflagellate cyst Zone LKP32 of Duxbury (2001, 2002). The prominence of reworked Upper Jurassic taxa between the unconformity and 0.15 m above it renders precise dating of that part of the section less well-constrained. The presence of comparable Lower Cretaceous dinoflagellate cyst assemblages immediately above the unconformity, including rare *C. intonsum*, *S. coronatum* and *S. spinulosum*, and common *C. compactum*, suggests assignment to Zone LKP32 or LKP31.2, respectively corresponding to the Tardefurcata and upper Jacobi ammonite zones. The base of the Carstone may correlate with the Central North Sea LK32.1 maximum flooding event proposed by Duxbury (2001).

Palaeoenvironments

Kimmeridge Clay Formation

The species composition of dinoflagellate cyst assemblages from Bed 12 at Middlegate is comparable to those from Early Kimmeridgian open marine settings elsewhere in the UK (e.g. Riding 1987, 2005; Riding and Thomas 1988, 1992). Their diversity, along with an abundance of ammonites in Bed 12 (Wignall 1990) suggests an open marine palaeoenvironment. The fine-grained organic-rich nature of the

rocks indicates sedimentation under low-energy, generally quiescent conditions, a setting likely to produce poor oxygenation of the water column. Work by Wignall (1990) on the benthic fauna of the Ancholme Clay at Middlegate (Bivalvia, Gastropoda, Scaphopoda, Brachiopoda, Crustacea, Echinodermata, Annelida and Bryozoa) indicates variations in the diversity of the macro-benthos that were attributed to corresponding variations in oxygen depletion of bottom waters. This may have been compounded by the absence of an effective oxygen-replenishment mechanism and the development of a temporary temperature/density barrier within the water column (Wignall 1990). The upper part of Bed 12 records a decline in ostracods (Ahmed 1987) and a rapid disappearance of previously diverse macro-benthos (Wignall 1990), possibly indicating relatively early onset of regional anoxic benthic conditions associated with the KCF (Wignall 1990). This is consistent with the preservation of high concentrations of AOM and palynomorphs, 59 700–119 000 cpg in the 0.15 m interval below the Jurassic–Cretaceous unconformity (Table 1). In the Mesozoic of eastern England, concentrations as high as this have only previously been reported from organic-rich deposits of the Cenomanian–Turonian boundary interval, which correlate with the global Cretaceous Oceanic Anoxic Event 2 (Dodsworth *et al.* 2020). Frequent prasinophyte algal genera *Pterospermella* and *Tasmanites* and abundant *Leiosphaeridia* in Bed 12 possibly indicate oxygen-deficient waters periodically encroaching the photic zone during its deposition (cf. Prauss 2007).

The large terrigenous component of palynological assemblages from Bed 12 (average T/M ratio of 0.78) would have been sourced by wind and run-off from adjacent landmasses such as a ‘Pennine Massif’ and ‘London-Brabant Massif’ (e.g. Brookfield 1973). Abbink *et al.* (2004) outlined a model using pollen and spore eco-groups as indicators for terrestrial palaeoenvironments during the Jurassic. The dominance of the ‘upland’ group in Bed 12, i.e. relatively buoyant bisaccate conifer pollen (Travis and Ginsburg 1966), is consistent with a low-energy, possibly distal to palaeo-coastline depositional setting (cf. Batten 1996). The secondmost numerically important group in Bed 12 are the gymnosperm genera *Araucariacites*, *Callialasporites*, *Cerebropollenites*, *Classopollis* and *Exesipollenites*. Their parent plants may have mainly grown along the coast (Abbink *et al.* 2004). The marked increase in the ratio of coastal to upland pollen in the 0.15 m interval below the Jurassic–Cretaceous unconformity at Middlegate (i.e. an influx of *Exesipollenites*) possibly reflects a local or regional fall in relative sea level.

Carstone Formation

Most of the indigenous dinoflagellate cysts in the Carstone are G-cysts (average P/G ratio of 0.026). Modern gonyaulacoid dinoflagellates are photosynthetic with high relative abundances occurring in areas of seas with lower productivity of heterotrophic phytoplankton, such as (proto-) peridinioid dinoflagellates (Harland 1988). Dinoflagellate cyst diversity is partly a function of environmental stress, with lower stress resulting in higher diversity (Wall *et al.* 1977). Generally, environmental stress decreases and species richness increases from near-shore to distal-shore areas (e.g.

Olde *et al.* 2015). The high diversity and low dominance (no taxa exceed 15% of assemblages) of G-cysts in the Carstone at Middlegate suggest a low-stress, open marine palaeo-environment, with relatively low nutrient input and associated palaeo-productivity of peridinioid dinoflagellates. Open marine conditions are also indicated by the nature of indigenous brachiopod assemblages in the upper part of the Carstone (Gaunt *et al.* 1992).

Apart from thick-bedding, sedimentary structures may not have been preserved in the Carstone of the East Midlands Shelf (e.g. Versey and Carter 1926; BGS Lexicon of Named Rock Units 2021). Gaunt *et al.* (1992) considered its lithologies to suggest an upper shore-face site of deposition. The prominence of phytoclasts in samples RB10B to RB7B, along with common pteridophyte/bryophyte trilete spores, support a relatively proximal to shoreline depositional setting and/or fluvial–deltaic influence (cf. Prauss 1993; Stead and Batten 2018). In addition, Prauss (2000) suggested that associations of increased numbers of *Cauca parva* and the P-cyst *Palaeoperidinium cretaceum* in Aptian–Lower Albian deposits of NW Europe, as seen to a limited extent in Carstone samples PD9503-3 and RB10B, may indicate an estuarine influence (see also Harding 1990). At Middlegate, however, the low T/M ratio (average 0.36), high diversity of G-cysts with low numbers of P-cysts, and sparsity of fresh/brackish-water algae, conversely indicate limited nutrient supply from land-derived run-off. The palynological data could be interpreted to indicate an ultimate site of deposition at Middlegate farther offshore than upper shore-face but still above storm wave base, such as inner to middle neritic.

Gaunt *et al.* (1992) reported that the genus *Odontochitina*, a relatively thick-walled dinoflagellate cyst, is the main palynomorph preserved in their eastern England Carstone samples. It is possible that local ‘sheltered’ conditions, such as a topographic trough in the seafloor of the Middlegate area, may have led to enhanced preservation due to reduced winnowing of clay- and silt-grade particles (including palynomorphs). Possible establishment of dysoxia within sediments could also have locally impeded oxidation of palynomorphs, particularly of the more delicate dinoflagellate cyst forms.

Frequent to common occurrences of the prasinophyte algae *Pterospermella* and *Tasmanites* in Carstone samples RB10B to RB7B may be reworked from the KCF. Alternatively, they may be contemporary with the Carstone, derived from lower salinity, possibly lagoonal areas (e.g. Tappan 1980; Vieira and Jolley 2020) or, unlikely given there is no other evidence for oceanic anoxia during deposition of the Carstone, reflect oxygen-deficient conditions in the water column (cf. the KCF discussion above).

The extinct areoligeracean group of G-cysts are mainly represented by the species *Circulodinium distinctum* (Fig. 6.3), *Cyclonephelium compactum* and *Cyclonephelium ‘longispinatum’* (Fig. 6.5) at Middlegate. They occur consistently in the Carstone samples, with the latter two showing an increase in relative abundance in samples RB9B and RB8B (Fig. 3). They are fairly ubiquitous in Lower Albian marine assemblages of NW Europe (Davey 1982; Duxbury 1983; Prössl 1990; Kennedy *et al.* 2000; Prauss 2000) but the increase may be significant in terms of a greater coastal/near-shore influence (cf. Brinkhuis and Zachariasse 1988;

Harker *et al.* 1990, p. 202–204; Li and Habib 1996; Olde *et al.* 2015). The areoligeracean species *Canninginopsis monile* has not previously been reported in NW Europe outcrops. It is documented from the Central North Sea, offshore of northern Scotland (Duxbury 2002), and its presence at Middlegate (Fig. 3) may therefore indicate sea palaeo-currents from the north. The non-areoligeracean, related genera *Palaeotetradinium* and *Rhombodella*, are frequent to common in the Carstone samples (see the supplementary palynological chart). Prauss (2000) noted that their presence in Aptian–Albian assemblages of NW Germany potentially indicates boreal to subboreal water masses, given that they are the dominant dinoflagellate cysts at some levels within the Albian of NE Greenland (Nøhr-Hansen 1993). *Cauca parva* may also occur in higher numbers in the more northerly areas of Europe (Prauss 2000).

Conclusions

Well-preserved palynomorph assemblages were retrieved from the grey mudstones of KCF Bed 12 at Middlegate. Dinoflagellate cyst species composition and diversity supports ammonite evidence for an open marine palaeo-environment. High concentrations of AOM and palynomorphs in upper Bed 12 are consistent with oxygen-deficient bottom waters, as indicated by lithology and the decline of benthic macrofauna. Zonal dinoflagellate cyst marker taxa present are in agreement with regional calibration of Zone Elu(a) to the Cymodoce Ammonite Zone.

Palynological assemblages from the lowermost 0.15 m above the sub-Carstone unconformity are dominated by reworked, mainly locally derived KCF palynofloras. This is reflected by the grey colouration of the basal Carstone matrix at Middlegate which is caused by an admixture of KCF mudstone. A clast or lens of relatively light-coloured sandstone, sampled immediately above the unconformity, is interpreted to be of earliest Albian age, based on the presence and absence of stratigraphically important Lower Cretaceous dinoflagellate cysts (Zone LKP31.2–LKP32; upper Jacobi or Tardefurcata Ammonite Zone). On the Isle of Wight, Duxbury (1983) recorded comparable assemblages from Lower Albian mudstones underlying the Carstone, but pre-Carstone deposits of this age are not widely preserved on the East Midlands Shelf.

Relatively grey colouration of the Carstone matrix is also observed in the interval from 0.15 to 0.45 m above the unconformity, where reworked KCF palynofloras are a relatively minor component of assemblages. Indigenous Lower Cretaceous dinoflagellate cysts are interpreted to indicate an Early Albian age (Zone LKP32; Tardefurcata Ammonite Zone) for the interval. This is also the case for a sample from 0.45 to 0.55 m above the unconformity which has relatively orange colouration. The uppermost Carstone samples analysed (0.55–0.75 m) have orange to red colouration and are impoverished or barren of palynomorphs.

The palynological and palynofacies assemblages from the Carstone are interpreted to indicate a relatively proximal to shoreline site of deposition, possibly inner to middle neritic, with an open marine palaeoenvironment and limited supply of terrigenous nutrients washed-in from fluvial–deltaic and estuarine/lagoonal sources. Northerly palaeo-currents or

water masses may have contributed to subtle phytoplankton provincialism relative to coeval deposits in southern England, France and, to a lesser extent, NW Germany.

Future palynological study of the Carstone is recommended at other localities, to further assess palaeoenvironments and the timing of onset of preservation of sediments above the sub-Carstone unconformity. While coarse-grained gritty sandstones are not generally conducive to palynological preservation, as seen at Middlegate, an argillaceous component to the matrix can support preservation. Successful palynological investigations have previously been carried out on Aptian–Albian sandstone-dominated formations in southern England (e.g. Cookson and Hughes 1964; Duxbury 1983; Hesselbo *et al.* 1990).

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