Rolling back the 'mudstone blanket': complex geometric and facies responses to basin architecture in the epicontinental Oxford Clay Formation (Jurassic, UK)

Mark A. Woods[a*], Jan A. I. Hennissen[a], Andrew J. Newell[b], Keith L. Duff[c], Philip R. Wilby[a]

[a]British Geological Survey, Keyworth, Nottingham, UK, NG12 5GG

[b]British Geological Survey, Maclean Building, Wallingford, UK, OX10 8BB

[c] 21 Bishops Walk, Barnack, Stamford, Lincs, UK, PE9 3EE

[*]Corresponding author: Email: maw@bgs.ac.uk

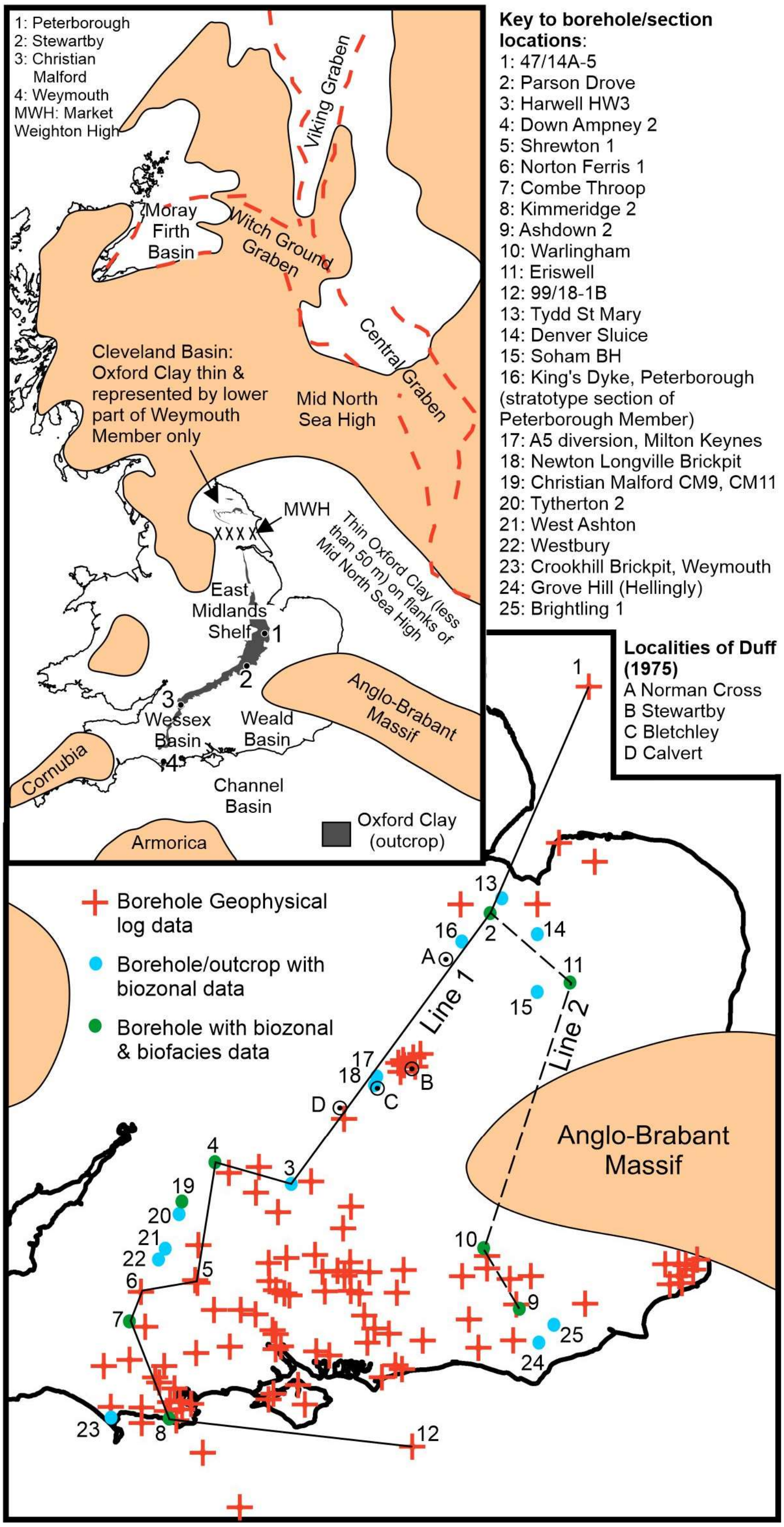
Abstract

Facies variability of mudstones is likely greater than generally perceived, with important implications for their behaviour in major civil engineering, energy and waste disposal applications. Here, we explore this variability for the UK Oxford Clay, a widely studied Middle/Upper Jurassic mudstone. Evidence from wire-line logs, geochemistry, sequence stratigraphy and biofacies analyses are combined to reveal heterogeneity within the Peterborough Member (Lower Oxford Clay) and to explore the extent to which it blanketed basin features or responded dynamically to them. Thickness modelling suggests that the Mid North Sea High, formed by Mid Jurassic thermal doming, likely influenced sediment pathways, favouring thick sediment accumulation in the Wessex Basin, thinner successions across the East Midlands Shelf, and sediment starvation in the Weald Basin. Biofacies patterns, determined using a novel combination of detrended correspondence and cluster analysis, vary significantly and suggest a complex patchwork of environments related to local basin setting. The Type Section of the Peterborough Member seems to represent only a narrow range of conditions that influenced its deposition, and cautions against developing basin-scale models based on a few well exposed and heavily researched outcrop successions.

Key Words: Callovian, mudstone, heterogeneity, sequence stratigraphy, XRFS chemostratigraphy, biofacies

1. Introduction

Recent research on the processes of mudstone deposition question the long-held view that these sediments can be understood as a 'mud-blanket' resulting from slow deposition from suspension in quiet water conditions (e.g. Scheiber et al. 2007, Macquaker and Bohacs 2007, Birgenheier et al. 2017). Earlier work on both the Oxford Clay (Hudson and Martill 1991) and the Kimmeridge Clay (Wignall, 1989) suggested that more episodic depositional events, including storms, may be important factors in mudstone accumulation. Temporal and spatial variability of facies in the lower part of the Oxford Clay were mentioned by Hudson and Martill (1991), and wider evidence of mudstone facies heterogeneity has emerged from outcrop and borehole studies (Macquaker 1994, Macquaker and Howell 1999, Birgenheier et al. 2017). Here, we adopt a multidisciplinary surface-to-subsurface approach to test the extent of facies variation at basin scale across a range of contrasting palaeogeographical settings for part of the Oxford Clay Formation (Peterborough Member) – a mud-dominated unit that has historically been regarded as generally uniform (Callomon 1968, Holloway 1985). Limited outcrop studies point to the presence of vertically stacked lithofacies that can be related to patterns of relative sea level change and sequence stratigraphy frameworks (Partington et al. 1993, Macquaker 1994, Norris and Hallam 1995, Macquaker and Howell 1999, Hesselbo 2008). Our work combines these localised outcrop data with an extensive subsurface data archive,


1: Peterborough
2: Stewartby
3: Christian Malford
4: Weymouth
MWH: Market Weighton High
Viking Graben
Moray Firth Basin
Witch Ground Graben
Central Graben
Cleveland Basin: Oxford Clay thin & represented by lower part of Weymouth Member only
Mid North Sea High
MWH
Thin Oxford Clay (less than 50 m) on flanks of Mid North Sea High
East Midlands Shelf
Wessex Basin
Weald Basin
Anglo-Brabant Massif
Cornubia
Channel Basin
Armorica
Oxford Clay (outcrop)
Key to borehole/section locations:
1: 47/14A-5
2: Parson Drove
3: Harwell HW3
4: Down Ampney 2
5: Shrewton 1
6: Norton Ferris 1
7: Combe Throop
8: Kimmeridge 2
9: Ashdown 2
10: Warlingham
11: Eriswell
12: 99/18-1B
13: Tydd St Mary
14: Denver Sluice
15: Soham BH
16: King's Dyke, Peterborough (stratotype section of Peterborough Member)
17: A5 diversion, Milton Keynes
18: Newton Longville Brickpit
19: Christian Malford CM9, CM11
20: Tytherton 2
21: West Ashton
22: Westbury
23: Crookhill Brickpit, Weymouth
24: Grove Hill (Hellingly)
25: Brightling 1
Localities of Duff (1975)
A Norman Cross
B Stewartby
C Bletchley
D Calvert
Borehole Geophysical log data
Borehole/outcrop with biozonal data
Borehole with biozonal & biofacies data
Line 1
Line 2
Anglo-Brabant Massif

43 **FIGURE 1**

providing a fully contextualised model-based understanding of the likely extent of facies variability across the entire preserved basin, allowing understanding of the role of structural/bathymetric features in controlling facies patterns.

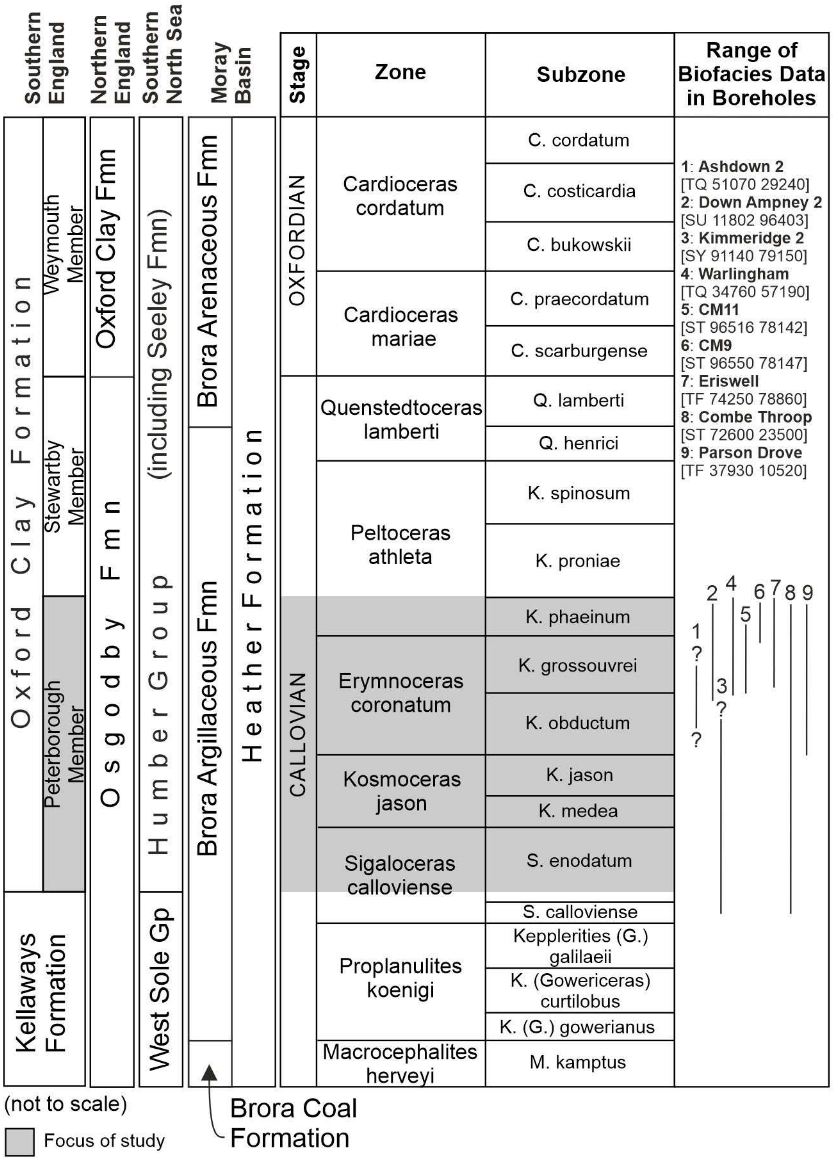
Current knowledge of the Oxford Clay is strongly influenced by a few well-exposed onshore sites distributed across its outcrop (particularly the type sections of the component members in Cambridgeshire (Peterborough Member), Bedfordshire (Stewartby Member) and Dorset (Weymouth Member); e.g. Hudson and Martill 1991, 1994, Kenig et al. 1994, Macquaker and Howell 1999, Page et al. 2009; Figs 1, 2). These outcrops, however, provide an incomplete picture of the Oxford Clay because much of the formation is concealed beneath a thick (up to 1km) cover of younger strata in areas such as the Wessex-Channel Basin in southern England. Fortunately, a long history of hydrocarbons exploration in these deep basins has left a rich source of borehole information. Here, we make use of this subsurface information to elucidate the extent of facies heterogeneity in the lower part of the Oxford Clay (Peterborough Member) and its relationship to basin architecture. To achieve this we: 1) use borehole geophysical logs and biostratigraphical data to understand patterns of sediment thickness with respect to major palaeogeographical and basin structural features; 2) combine new geochemical data with existing knowledge to refine understanding of the impact of relative sea level change; and 3) explore variability in biofacies data for a series of distinct basin settings (shallow platform, shallow shelf, shallow flooded massif, intra-basinal high, deep shelf, faulted basin margin, distal basin) in order to resolve the extent to which environmental signals are reflected in the gross lithological character of local successions.

Key objectives of this study are to: 1) understand basin-scale facies variability for the Peterborough Member, and the extent to which it behaves as a ‘mud blanket’; 2) develop conceptual understanding of how basin architecture might influence sediment fluxes and environments across the basin, and how these relate to facies variability; and 3) understand the extent to which any heterogeneity in the Peterborough Member might be replicated in other Jurassic mudstones. More broadly, our new digital model provides a resource for future assessment of regional physical property variation in mudstones like the Oxford Clay, of particular relevance to planned infrastructure development (National Infrastructure Commission 2018), and their suitability as a host rock for nuclear waste storage (Delay et al. 2007, Butler 2010; Norris 2017).

2. Geological Setting

Deposition of the Oxford Clay Formation (Callovian/Oxfordian) coincided with a period of marked crustal extension and fracturing associated with North Atlantic rifting (Wilhelm 2014). Mid Jurassic (Late Toarcian – Bathonian) thermal doming of the North Sea region began to subside in the Early Callovian (Underhill 1998), although the dome flanks persisted as a positive structural entity (Bradshaw et al. 1992). These features added to a complex palaeogeographical fabric in the UK region, where an epicontinental sea, dotted with emergent island massifs and cut by extensional basins controlled by reactivated Variscan structures, formed the environment for deposition of the Oxford Clay Formation (Fig. 1).

The Oxford Clay Formation is subdivided into three parts: the Peterborough, Stewartby and Weymouth members (Fig. 2). The lowermost Peterborough Member is the most organic-rich part of the formation, comprising brownish-grey mudstones and silty mudstones with typically 3 – 16 % TOC (Kenig et al. 1994), plus occasional sandstone and concretionary limestone units. Compositionally, it is a mixture of mica, illite, mixed illite/smectite, kaolinite and quartz, with calcite from shell beds, foramininifera and nannofossils, and amorphous organic matter derived from marine phytoplankton (Kenig et al. 1994; Macquaker 1994; Norry et al. 1994). The highest organic-rich mudstone unit defines the top of the Peterborough Member. Younger parts of the formation (Stewartby and Weymouth members; Fig. 2) typically comprise massive, paler grey silty mudstone (Cox et al. 1992)



Southern England
Northern England
Southern North Sea
Moray Basin
Stage
Zone
Subzone
Range of Biofacies Data in Boreholes
Oxford Clay Formation
Weymouth Member
Stewartby Member
Peterborough Member
Kellaways Formation
Oxford Clay Fmn
Osgodby Fmn
Humber Group (including Seeley Fmn)
West Sole Gp
Brora Arenaceous Fmn
Brora Argillaceous Fmn
Heather Formation
OXFORDIAN
CALLOVIAN
Cardioceras cordatum
Cardioceras mariae
Quenstedtoceras lamberti
Peltoceras athleta
Erymnoceras coronatum
Kosmoceras jason
Sigaloceras calloviense
Proplanulites koenigi
Macrocephalites herveyi
C. cordatum
C. costicardia
C. bukowskii
C. praecordatum
C. scarburgense
Q. lamberti
Q. henrici
K. spinosum
K. proniae
K. phaeinum
K. grossouvrei
K. obductum
K. jason
K. medea
S. enodatum
S. calloviense
Kepplerities (G.) galilaeii
K. (Gowericeras) curtilobus
K. (G.) gowerianus
M. kamptus
1: Ashdown 2 [TQ 51070 29240]
2: Down Ampney 2 [SU 11802 96403]
3: Kimmeridge 2 [SY 91140 79150]
4: Warlingham [TQ 34760 57190]
5: CM11 [ST 96516 78142]
6: CM9 [ST 96550 78147]
7: Eriswell [TF 74250 78860]
8: Combe Throop [ST 72600 23500]
9: Parson Drove [TF 37930 10520]
(not to scale)
Focus of study
Brora Coal Formation

91 **FIGURE 2**

and are less organic-rich, suggesting a more oxidizing depositional environment (Kenig et al. 1994). A thin limestone interval (Lamberti Limestone) or equivalent shell bed/siltstone separates the Stewartby and Weymouth members (Cox et al. 1992). In northern England (Yorkshire), deposition was strongly influenced by a shallow structural block (Market Weighton High; Fig. 1) and the Peterborough and Stewartby members are replaced by sandstones of the Osgodby Formation (Cope 2006, Powell et al. 2018, fig. 13; Fig. 2). This facies transition and thinning of the Oxford Clay across eastern England into the Cleveland Basin was documented by Penn et al. (1986). Across the rest of southern England, thickness data for the Peterborough Member indicate around 17 m at Peterborough on the East Midlands Shelf (Hudson and Martill 1994), ca. 10.5 m in the Eriswell Borehole (Bristow et al. 1989) on the flanks of the Anglo-Brabant Massif, ca. 15 – 18 m in boreholes in the Weald Basin (Lake et al. 1987), and about 22 m near Weymouth on the Dorset coast (Callomon and Cope 1995).

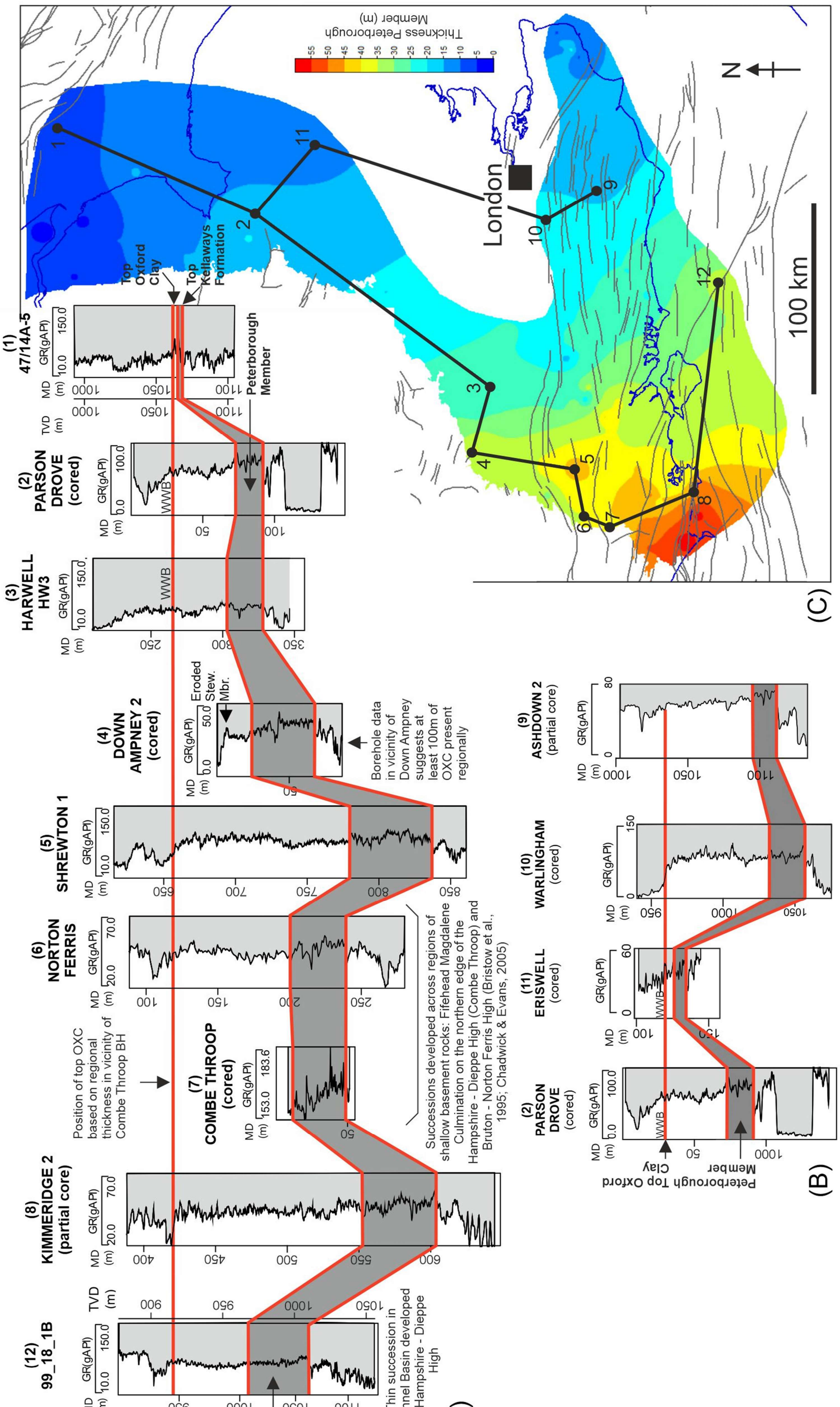
Offshore, strata equivalent to the Oxford Clay are sandy and silty in the Southern North Sea (Seeley Formation; Lott and Knox 1994; Fig. 2), become deltaic and coal-bearing in the Central Graben (Møller and Rasmussen 2003), and return to marine, mud and silt-dominated facies (Heather Formation; Fig. 2) in the Moray Firth and Viking Graben (Underhill and Partington 1993). Across southern England and the adjacent offshore regions the top of the Oxford Clay is widely conformable with the overlying Corallian Group, except where the West Walton Formation has eroded into the top of the Weymouth Member (Penn et al. 1986), or where the Corallian Group has been completely removed by later erosion.

3. Materials and Methodology

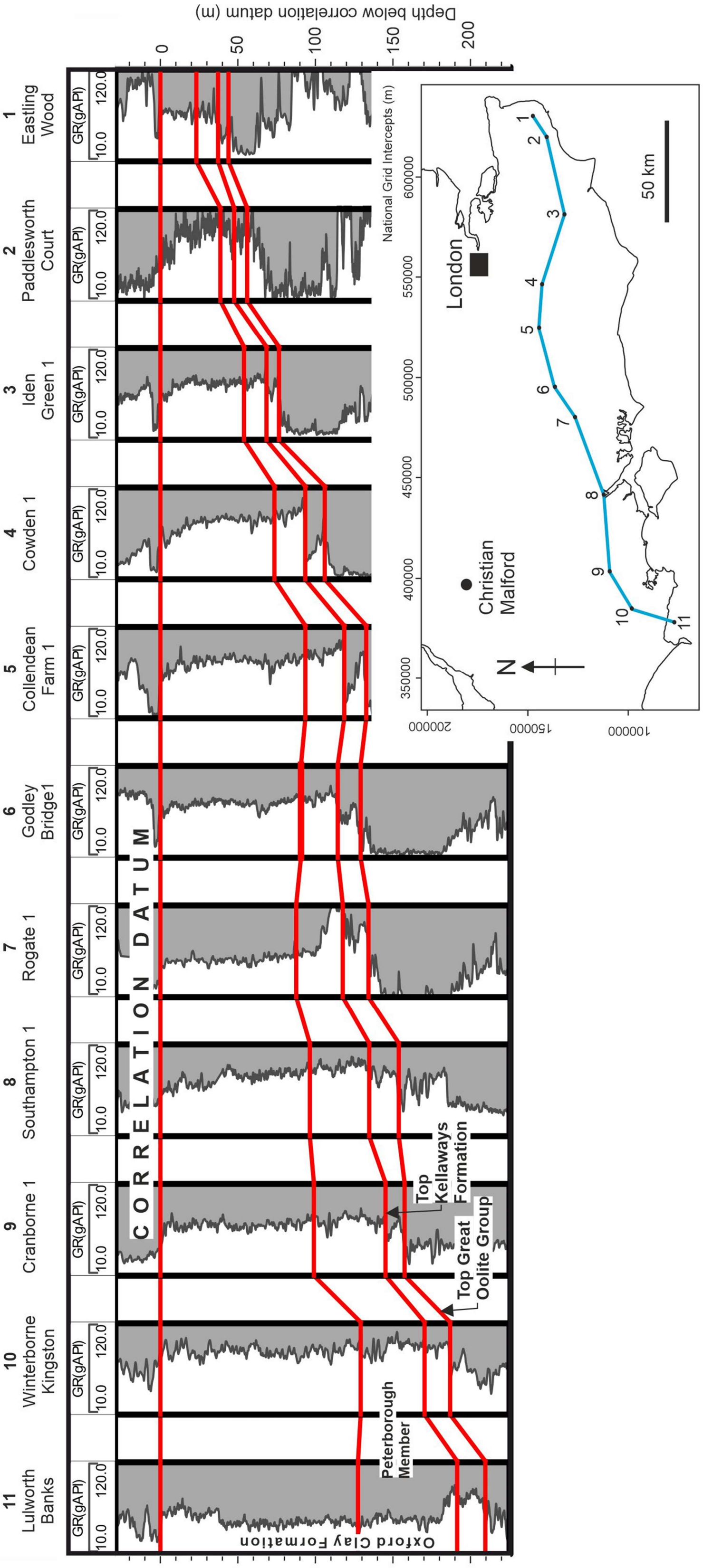
Determining the likely range and extent of basin-scale facies patterns in the Peterborough Member requires broader knowledge of the depositional system that influenced those patterns. Key factors are basin architecture, sea level fluctuation, and knowledge of environmental gradients (e.g. oxygenation, wave energy) at different locations across the depositional landscape. To meet these requirements our multidisciplinary approach uses borehole geophysical, lithological and biozonal data to understand stratigraphical patterns and model sediment geometry; geochemistry to interpret sea level fluctuation and its impact on the length of sediment pathways; and biofacies data to infer environmental signals across contrasting basin settings. The large archive of subsurface data (borehole core, geophysics, biostratigraphy) for the Peterborough Member held by the British Geological Survey (BGS) provides both the spatial extent and stratigraphical resolution required by the scale of this study.

3.1 Regional geophysical log interpretation

The inflection patterns of borehole geophysical logs in the Oxford Clay are usually sufficiently distinctive to allow recognition of its component formations (Whittaker et al. 1985, Penn et al. 1986), with the elevated organic content of the Peterborough Member typically corresponding with a higher gamma log response. Stratigraphic picks for the Oxford Clay were made mostly from gamma ray and sonic logs for ca. 127 boreholes across southern, central and eastern England and adjacent areas of the Channel and Southern North Sea basins (Figs 1, 3 and 4). Where present, stratigraphical picks were made for the top of the Great Oolite Group (Cornbrash Formation), Kellaways Formation, Peterborough Member, Stewartby Member and Weymouth Member, as well as associated unconformities and faulted contacts. An important first step in this process was calibrating log responses against known Oxford Clay stratigraphy in boreholes that, in addition to a suite of geophysical logs, had associated core (Callomon and Cope 1971, Whittaker et al. 1985, Penn et al. 1986, Bristow et al. 1989, 1995 fig. 36) and biostratigraphical data (Gallois 1979, Cox 1977, 1984,


(A)
(B)
(C)
(1) 47/14A-5
(2) PARSON DROVE (cored)
(3) HARWELL HW3
(4) DOWN AMPNEY 2 (cored)
(5) SHREWTON 1
(6) NORTON FERRIS
(7) COMBE THROOP (cored)
(8) KIMMERIDGE 2 (partial core)
(9) ASHDOWN 2 (partial core)
(10) WARLINGHAM (cored)
(11) ERISWELL (cored)
(12) 99_18_1B
Peterborough Member
Top Oxford Clay
Top Kellaways Formation
Eroded Stew. Mbr.
WWB
Borehole data in vicinity of Down Ampney suggests at least 100m of OXC present regionally
Position of top OXC based on regional thickness in vicinity of Combe Throop BH
Successions developed across regions of shallow basement rocks: Fifehead Magdalene Culmination on the northern edge of the Hampshire - Dieppe High (Combe Throop) and Bruton - Norton Ferris High (Bristow et al., 1995; Chadwick & Evans, 2005)
Thin succession in Channel Basin developed on Hampshire - Dieppe High
Thickness Peterborough Member (m)
London
100 km
N

138 **FIGURE 3**



1 Eastling Wood
2 Paddlesworth Court
3 Iden Green 1
4 Cowden 1
5 Collendean Farm 1
6 Godley Bridge1
7 Rogate 1
8 Southampton 1
9 Cranborne 1
10 Winterborne Kingston
11 Lulworth Banks
GR(gAPI)
10.0
120.0
CORRELATION DATUM
Top Kellaways Formation
Top Great Oolite Group
Peterborough Member
Oxford Clay Formation
Depth below correlation datum (m)
National Grid Intercepts (m)
London
Christian Malford
50 km
N

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1988, 1991, Gallois and Worssam 1983, Buckley et al. 1991). These reference boreholes provided an important constraint on extending stratigraphical interpretations into boreholes where only geophysical logs and cuttings information were available. Interpretations were checked for internal consistency using a grid of intersecting borehole correlation panels, and by flattening correlations on multiple horizons to explore stratigraphical and structural trends.

Stratigraphic picks were subsequently used to create a refined thickness model of the Peterborough Member and wider Oxford Clay Formation. Maps were interpolated using Discrete Smooth Interpolation (DSI) (Mallet 1989) in SKUA-GOCAD™ software from borehole thickness data that was corrected for both deviated borehole paths and variable structural dip.

3.2 Lithological data

Lithological information is provided by pre-existing boreholes in BGS archives, supplemented by two newly drilled boreholes near Christian Malford, Wiltshire (Fig. 1), as well as information collated from published records, BGS technical reports and unpublished borehole logs in BGS data archives. The boreholes at Christian Malford are continuously cored and provide an important record of the succession across the Coronatum/Athleta Zone boundary (Fig. 2) in an area where data are sparse. Pre-existing borehole data (boreholes 2, 4, 9 – 11 of Fig. 2) relate to historical BGS work on the Oxford Clay, and are represented by discontinuous core samples. These boreholes were selected from the BGS archive to optimise core sample density (typically 0.1 m or less) and provide representative stratigraphical and geographical coverage of the Peterborough Member. Lithological descriptions of discontinuous core samples were made using a binocular microscope during acquisition of biofacies data for these successions (see 3.4 below), and the observations used to construct synthetic graphical borehole logs, supplemented by information from pre-existing logs and reports where available and relevant.

3.3 Geochemistry

A newly drilled cored borehole (CM11; Fig. 1) in the higher part of the Peterborough Member (Coronatum & Athleta biozones; Fig. 2) at Christian Malford, Wiltshire, provided material for geochemical analysis (Fig. 5). Borehole CM9, drilled as part of a previous investigation at Christian Malford (Hart et al. 2016, 2019) and partially overlapping with CM11, provided material for analysis in the higher part of the Phaeinum Subzone.

Geochemical data were obtained from slabbed core lengths of CM11 using a portable Niton XLt 793 X-Ray Fluorescence Spectrometer (XRFS), fitted with a 40kV Ag anode X-ray tube and using the 'Standard Soil Mode'. Measurements were made at 10 mm intervals and for 30 seconds along the core length, with values checked for internal consistency against a designated standard reference sample. This procedure was repeated for the partially overlapping succession in CM9 using selected milled samples of core material, analysing for 120 seconds with the XRFS in a static semi-automated configuration.

3.4 Biofacies & biozonal data

Biofacies data (Figs 5 – 9) characterise stratigraphical intervals according to the types and abundances of fossil material, and use understanding of palaeoecological affinities of facies components to infer environmental signals. The technique can reveal patterns of environmental change that can be compared with variability in the lithological character of host sedimentary successions. Previous work on the Peterborough Member (Duff 1974, 1975) has used biofacies from outcrop data for a limited part of the depositional basin to understand stratigraphical shifts in depositional conditions. This work expands application of these data to a network of sites across the wider depositional basin in southern and eastern England, selected to capture responses in a probable diverse range of environmental settings in contrasting palaeogeographical and structural settings. We analyse the distribution of biofacies components in borehole core using correspondence analysis and clustering to explore their relationships and patterns in their stratigraphical distribution.

Biofacies data for the Peterborough Member, comprising more than 2200 observations of core samples, were compiled for the following 8 cored borehole sites (Fig. 1): Christian Malford CM9 and CM11 (distal shallow marine shelf), Down Ampney 2 (proximal shallow marine shelf), Combe Throop (intra-basinal high), Kimmeridge 2 (deep marine shelf), Warlingham (faulted epicontinental basin margin), Ashdown 2 (distal marine epicontinental basin), Parson Drove (shallow marine platform), and Eriswell (shallow flooded massif margin).

For the Christian Malford (CM11) Borehole, biofacies data were collected from half-core samples (10 cm diameter) at 10 mm intervals, examining part and counter-part bedding surfaces. Biofacies components (Appendix 1) assessed as part of this study cover a range of taxonomic groupings, mostly genera but including some broader categories (e.g. ammonites, foraminifera) where appropriate, and also include the occurrence of features like wood and coprolite. Relative frequency of key biofacies components (Appendix 1) was assessed using a semi-quantitative scale, based on threshold counts (present; common, 2 – 4 specimens; abundant, ≥5 specimens; plaster, with numerous specimens covering core surface). Biofacies data for the other boreholes rely on discontinuous core samples, for which observations of all surfaces of each sample are combined into a single record with a modified assessment of relative frequency (present; few, 2 specimens; common, ≥3 specimens). Biofacies data for the Peterborough Member, collected at sites in eastern and central England (Duff 1974, 1975) and re-analysed as part of this work, are fully quantitative observations of aerially extensive bedding planes.

Statistical analysis of biofacies data uses a combination of Detrended Correspondence Analysis (DCA) and clustering (hierarchical clustering & Non-Euclidian Relational Clustering (NERC)) to explore: 1) the faunal composition of different samples; and 2) the grouping of samples into coherent biofacies. NERC clustering is typically more suited to analysis of palaeontological data which are incomplete (Vavrek 2016). However, because our data are from borehole core, with an implied age/depth relationship between consecutive samples, we combine both hierarchical and NERC clustering techniques in our results.

Primary data were conditioned by: removal of rare/ambiguous components that might otherwise distort the analysis; merging records of related components (e.g. species within a genus); coding sample composition, sample size and biozonal assignment, and standardising scale of relative frequency (see *Supplementary Data* for detailed procedure). All statistical analyses were performed in the open source environment R (R Core Team 2020) using the following packages: vegan (Oksanen et al. 2018) (DCA analysis based on upper quartile biofacies components); NbClust (Charrad et al. 2014) (optimum number of clusters for each borehole based on analysis of primary data); rioja (Juggins 2017) (hierarchical clustering); ecodist (Goslee and Urban 2007) (calculation of ecological distance matrix); fossil (Vavrek 2016) (NERC cluster analysis). An ecological distance matrix is required for NERC clustering, and for our semi-quantitative data we adopt the Sørenson dissimilarity index (or Dice index), one of the most commonly used and effective presence/absence dissimilarity measures (Southwood and Henderson 2000, Magurran 2004). Compilations of biofacies data for the analysed boreholes and details of their statistical analysis are provided as *Supplementary Data*.

The boreholes that are the source of our biofacies data are part of a larger suite of cored boreholes in the Peterborough Member across southern Britain, drilled in connection with BGS regional mapping programmes that date back to the late 1960s. Biostratigraphical interpretations of many of these successions, published in BGS memoirs and technical reports, were compiled for this study to provide precise stratigraphical understanding of geophysical log signatures, to allow accurate comparisons of biofacies data, and to provide additional insight into patterns of thickness variation.

Supplementary material: Geophysical log correlations, geochemical data and detailed biofacies data, methodology and results are available as *Supplementary Data*.

4. Results

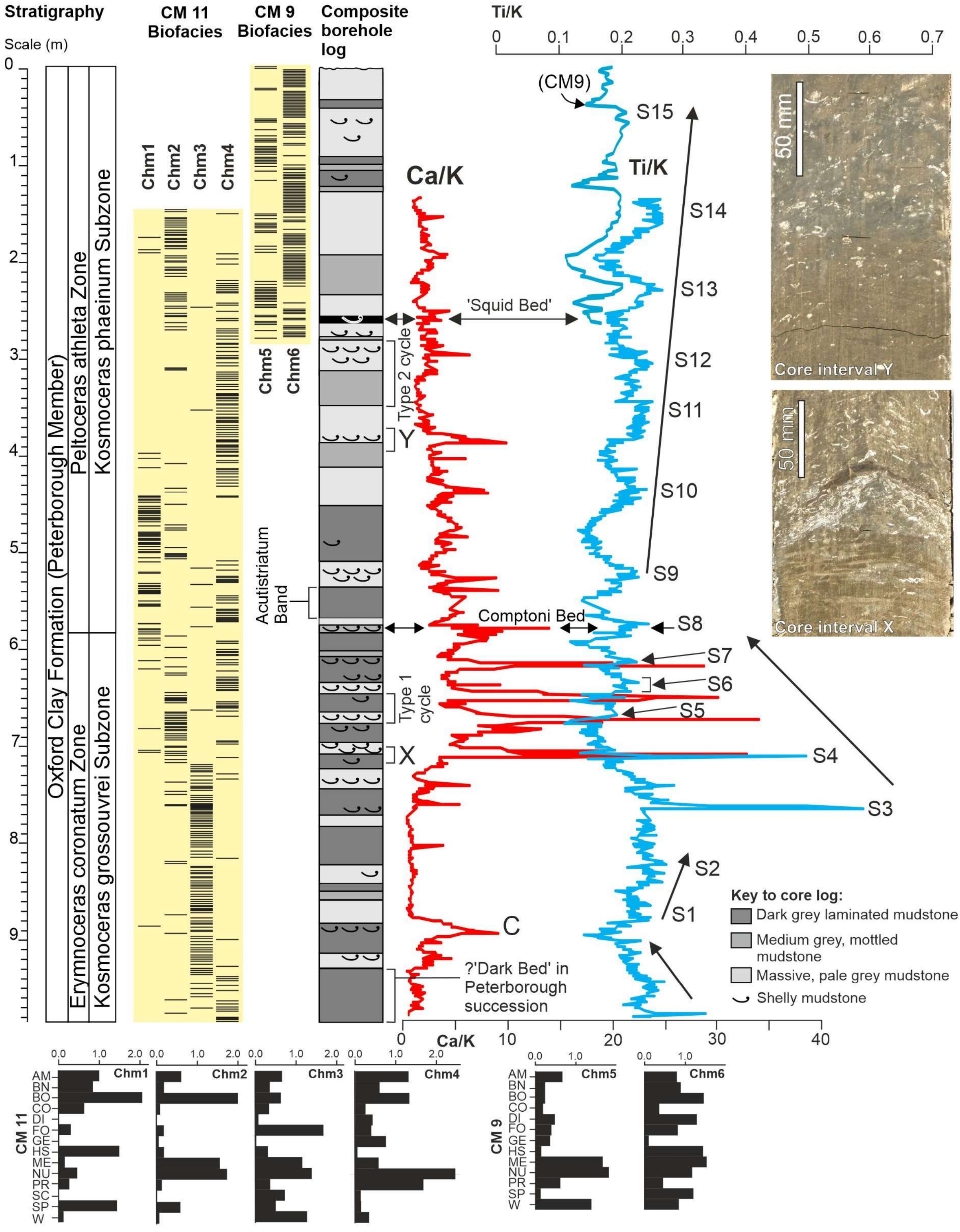
Geophysical log data provide a highly resolved picture of thickness variation for the Peterborough Member across Southern Britain, with correlation panels and biostratigraphical data compilation emphasising regions that were the long-term focus of sedimentation and others where deposition was persistently restricted (Figs 3, 4; 10). Cyclical trends in sedimentary geochemical data at Christian Malford (Fig. 5) show a strong relationship with patterns of sedimentation and biofacies in borehole core. Across the basin, biofacies data show significant lateral contrasts between sites (Fig. 6). The results for each category of data are discussed in turn below. Detailed compilations of our results are provided as *Supplementary Data*.

4.1 Geophysical log correlation and basin modelling

Along the northern margin of the Anglo-Brabant Massif (ABM), from the East Midlands Shelf in the NE, towards the Wessex Basin in the SW, there is a consistent regional trend of thickening, for both the Peterborough Member (<5 m to >55 m) and Oxford Clay Formation as a whole (<10 m to ca. 180 m) (Figs 3, 4). Significant thinning of the Peterborough Member (to ≤ 10 m) occurs on the flanks of the ABM, and likely also the whole of the Oxford Clay, although erosion of the succession prevents confirmation. The succession remains thin into the Weald Basin to the south, where the total Oxford Clay Formation is about 80 m thick in the Ashdown 2 Borehole, with ca. 15 m representing the Peterborough Member (Fig. 3). Offshore thickness trends are consistent with the onshore data, with extremely thin (possibly incomplete) Oxford Clay inferred to occur in the southern North Sea (where the formation is generally not separated from the parent Humber Group), and relatively thick Peterborough Member (ca. 42 m) forming part of an eroded Oxford Clay succession in the Channel Basin. As well as basin-scale features (e.g. ABM), there is an apparent association of local thickness patterns with 1:1500000 -scale structural lineament data (Fig. 3A), seen in parts of the Wessex Basin, for example local thickening near Shrewton, and thinning across the fault-bounded Norton Ferris High (Chadwick and Evans 2005, figs 86, 88).

4.2 Lithology

Borehole CM11 proved a strongly cyclical succession of lithofacies that can be matched with geochemical data (4.3 below; Fig. 5). Three broad lithofacies are recognised in borehole core: 1) pale grey silty mudstone with abundant shell remains, dominated by nuculacean bivalves, including specimens with articulated valves; 2) massive or very weakly fissile, medium – grey-brown silty mudstone with scattered or sparse shell remains, but including occasional bedding-plane plasters of the bivalves *Meleagrinella* and/or *Bositra* and, 3) dark grey-brown, organic-rich laminated mudstone with abundant plasters of *Bositra* and/or *Meleagrinella*. The bases of shell beds may be sharply defined or gradational, and cycles comprise either: 1) sharp-based shell bed with thin gradational intervals of weakly fissile mudstone into dark laminated mudstone (Type 1; Fig. 5), or 2) weakly fissile mudstone, with thicker gradational transition into a shell bed (Type 2; Fig. 5). Type 1 cycles are thin (ca. 30 cm) and occur in the middle part of the borehole succession, and Type 2 cycles are thicker (ca. 70 cm) and occur particularly in the higher parts of CM 11 (Fig. 5).


Stratigraphy
Scale (m)
CM 11 Biofacies
CM 9 Biofacies
Composite borehole log
Ti/K
Ca/K
Oxford Clay Formation (Peterborough Member)
Peltoceras athleta Zone
Kosmoceras phaeinum Subzone
Erymnoceras coronatum Zone
Kosmoceras grossouvrei Subzone
Chm1
Chm2
Chm3
Chm4
Chm5
Chm6
'Squid Bed'
Type 2 cycle
Y
Acutistriatum Band
Comptoni Bed
Type 1 cycle
X
C
?'Dark Bed' in Peterborough succession
(CM9)
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
S13
S14
S15
50 mm
Core interval Y
Core interval X
Key to core log:
Dark grey laminated mudstone
Medium grey, mottled mudstone
Massive, pale grey mudstone
Shelly mudstone
CM 11
CM 9
AM
BN
BO
CO
DI
FO
GE
HS
ME
NU
PR
SC
SP
W

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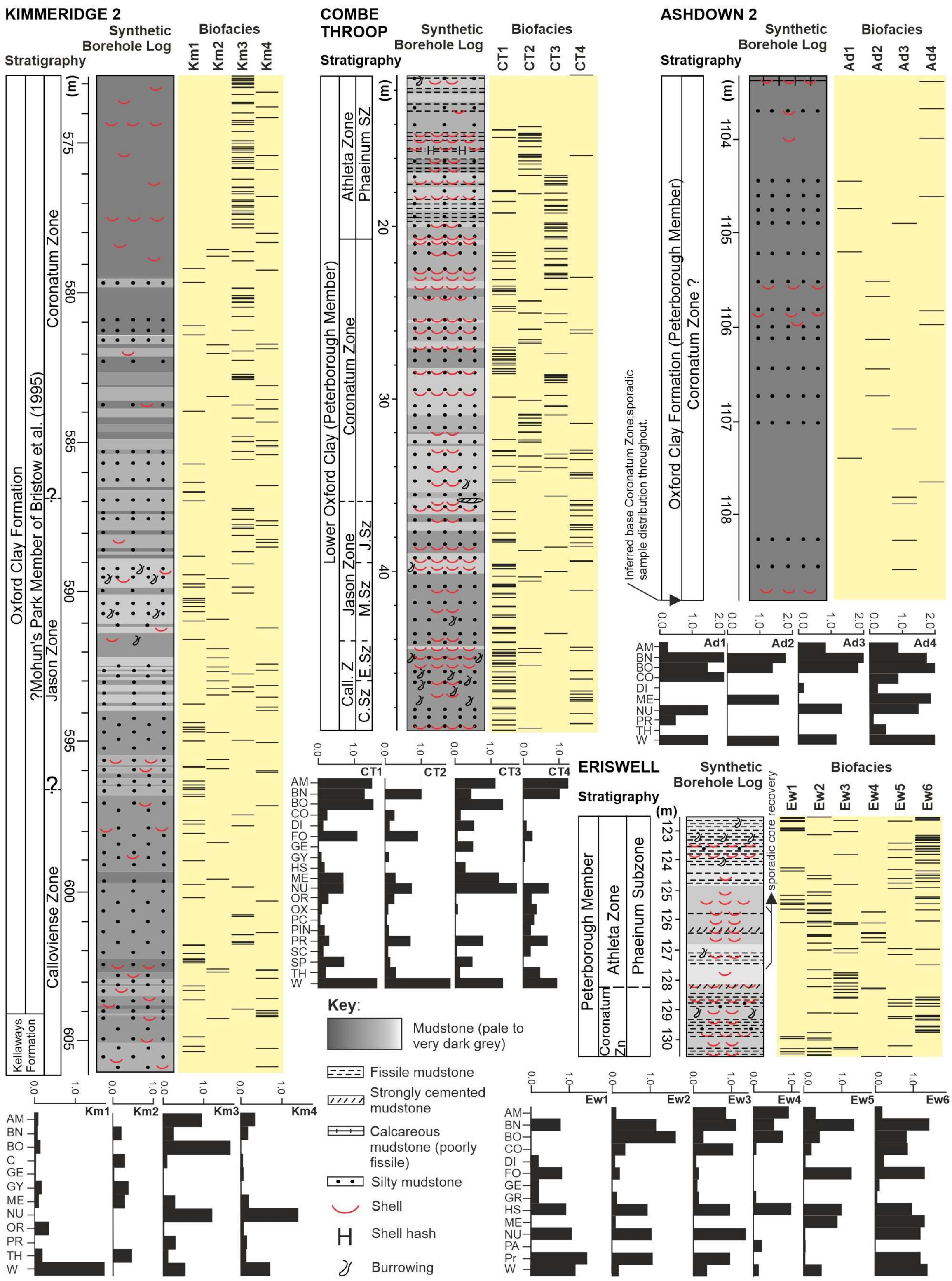
For sites across the rest of southern England, lithological data summarised on synthetic borehole logs (Fig. 6) show that in the Wessex Basin, conspicuously silty mudstone dominates in the lowest part of the Peterborough Member (Calloviense and Jason Zones) in the Kimmeridge 2 and Combe Throop boreholes. In the Kimmeridge Borehole this diminishes with the appearance of dark grey mudstone in the Coronatum Zone, but remains a persistent feature of the Combe Throop succession. Bioclastic mudstone is a feature of the Coronatum Zone in the CM 9 and CM11 boreholes, and extends north-eastwards, in both the Down Ampney 2 and Parson's Drove successions. In the Phaeinum Subzone, the rhythmic mudstone in CM9 and CM11 cannot be traced into the Down Ampney 2 succession. Here, this interval contains a sharp contrast between darker grey mudstone in the lower part of the subzone and much paler grey, biotubated mudstone in the upper part. This change occurs immediately above a ca. 2.5 m thick laminated interval in the lower part of the Phaeinum Subzone, that contains few fossils apart from wood, foraminifera and bone (Fig 6), and is unique to this borehole succession. A similar colour change occurs near the top of the Peterborough Member in the Parson Drove succession on the East Midlands Shelf, although here the lithology is laminated and silty, with greater development of dark mudstone in the underlying Phaeinum Subzone. On the flanks of the ABM, the Coronatum Zone and Phaeinum Subzone in the Eriswell Borehole comprises thin units of distinctively pale and medium grey, bioturbated mudstone with abundant finely comminuted shell. The correlative interval thickens at the edge of the Weald Basin in the Warlingham Borehole, where the lithology is rather uniformly bioclastic mudstone with occasional laminated intervals, becoming distinctly silty in the upper part. The sparse data for the central Weald Basin, from the Ashdown 2 Borehole, suggest a very different pattern of sedimentation, with samples from the ?Coronatum Subzone represented by very dark brownish-grey, hard, silty, pyritic calcareous mudstone.

4.3 Geochemistry

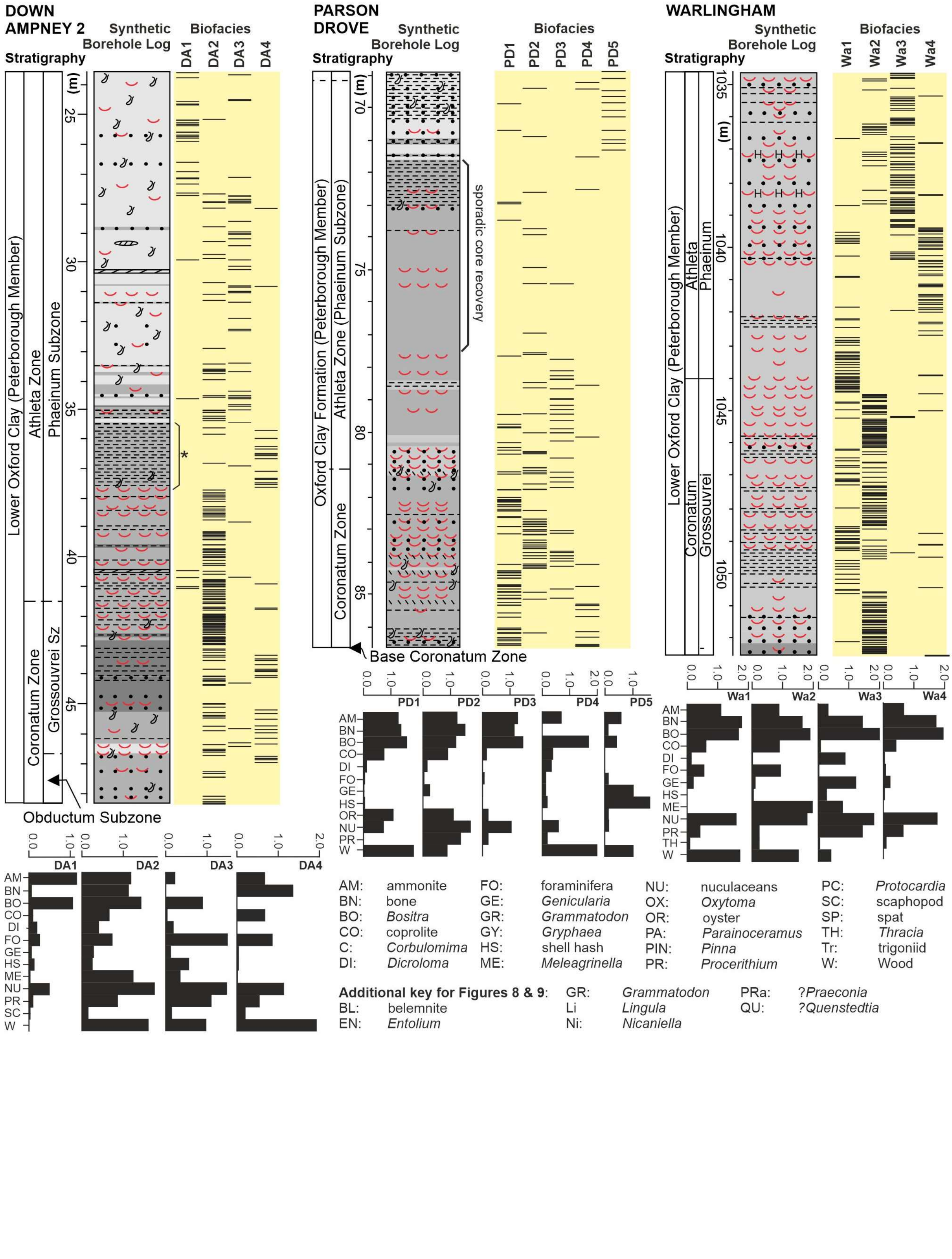
Titanium in the Peterborough Member shows a strong correlation with silica (Norry et al. 1994), and functions as a proxy for variability in the flux of hydrodynamically heavy detrital components to the depositional basin and/or winnowing. Figure 5 plots the variability of Ti normalised to K (the optimal proxy for understanding detrital fluxes in the absence of XRF values for Si, Zr and Al) through the CM11 and CM9 successions. The plot shows a strongly cyclic pattern, with an overall shift from relatively high values in the lower 2.5 m of the succession (Coronatum Zone), to relatively lower values in the middle part (interval above S4 and below S10 of Fig. 5), spanning the latest Coronatum and earliest Athleta zones. Shell concentrations are picked out by the Ca/K plot, with those characterising the Type 1 cycles in the CM11 succession forming four strong, closely spaced peaks (S4 – S7; Fig. 5). An inflection in the trend of Ti/K data, from sharply falling to gradually increasing, is coincident with the interval between two regionally extensive marker-beds in the Oxford Clay, the Comptoni Bed and the overlying Acutistriatum Band (Hudson and Martill 1994; Fig. 5). Above these, peaks S9 – S15 define a stacked succession of Type 2 cycles, with progressively increasing detrital content and shell beds coincident with sharp peaks in the Ca/K curve.

4.4 Biofacies

Litho- and biofacies variation occurs on a very fine (lamina) scale in the Oxford Clay (Macquaker and Howell 1999). Our biofacies data resolves this fine-scale variation into decimetre-scale trends, represented by the stratigraphical distribution of biofacies clusters (Figs 5 – 9), with the composition of each cluster summarised as relative proportions in bar charts below each borehole log. The number and composition of clusters is distinct for each site and determined by the data available for



325 **FIGURE 6**



326 **FIGURE 6 (continued)**

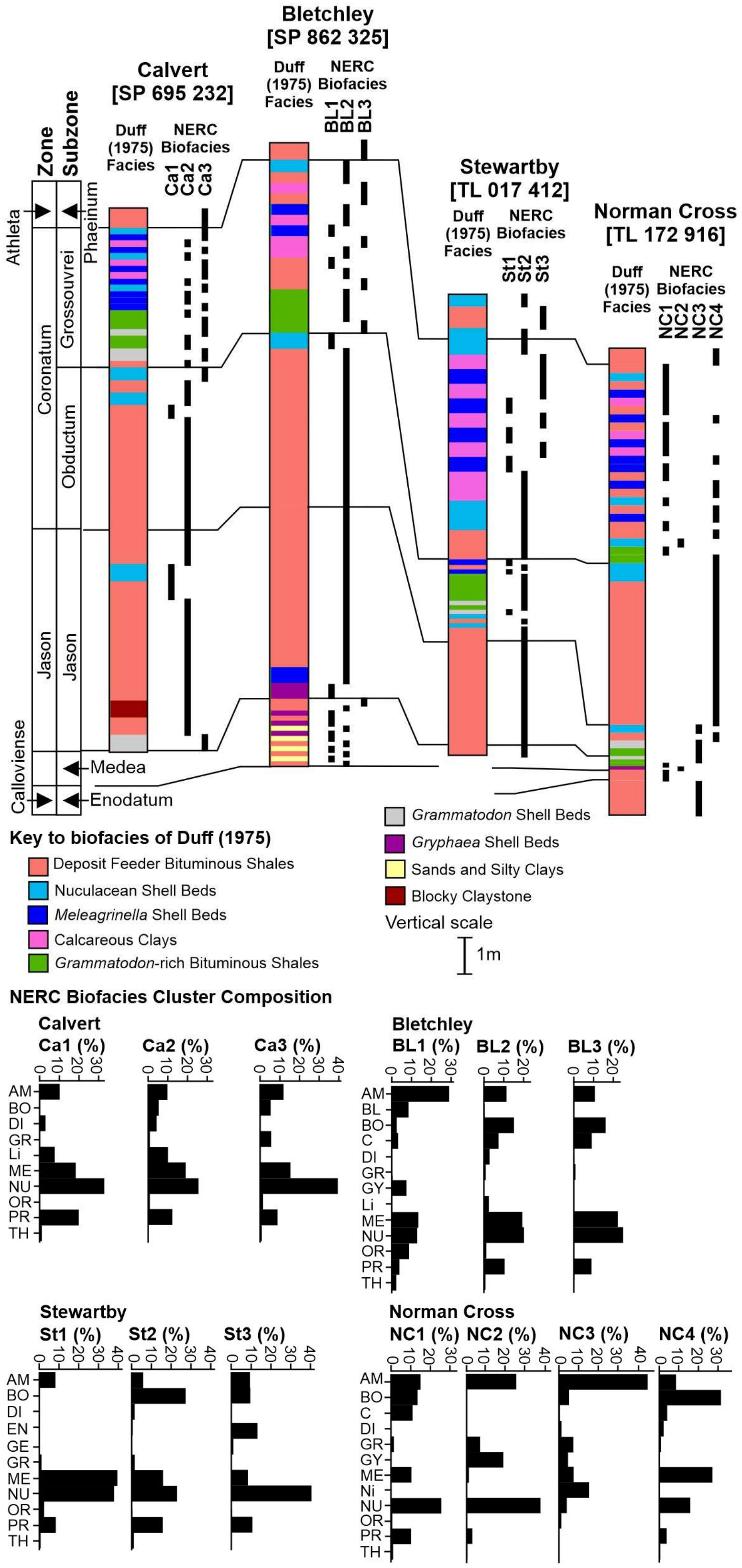
each site. Attempts to develop a unified biofacies classification across all sites forced removal of components that were defining and common at individual sites, suggesting a significant degree of site-specific biofacies character. Consequently, stratigraphical analysis of our biofacies data focuses on identifying major contrasts in the arrangement and composition of biofacies within borehole successions, and examining the extent to which these correspond with analogous or strongly contrasting biofacies in correlative successions at other sites across the basin.

DCA plots of samples and taxa provide insight into which taxa are important for characterising samples. DCA analysis for CM11 (Fig. 8A) is consistent with observations made during borehole logging, and indicate two strongly contrasting end-members: 1) dark, organic-rich, fissile mudstone dominated by remains of the thin-shelled bivalve *Bositra* (with or without *Meleagrinella*); 2) Shell beds associated with pale grey mudstone with abundant thick-shelled nuculacean bivalves, often associated with the gastropod *Procerithium* and sometimes also the serpulid *Genicularia*. Most biofacies clusters comprise mixtures of these end member components, and are therefore environmental composites that reflect the extent to which particular environmental settings are more or less dominant at the scale of individual laminations.

Differences between biofacies cluster composition for a given borehole can be subtle or very significant. Both the Warlingham and Parson Drove boreholes show a strong pattern of stratigraphical specificity in the distribution of biofacies clusters, but several of the cluster compositions are very similar, suggesting either a limited range of environmental change at these sites, or smearing of the ecological signal by external factors. It is notable that the extremely shell-rich Warlingham succession is characterised by an incongruent mixture of biofacies components (e.g. *Bositra*, *Meleagrinella*, nuculacean bivalves, *Genicularia*; Fig. 6) that characterise discrete intervals elsewhere.

The successions in the Kimmeridge 2 and Combe Throop boreholes show a regular repetition of biofacies clusters, with a tendency for particular biofacies to be slightly more dominant at some levels (Fig. 6). Kimmeridge 2 also shows a pronounced stratigraphical and compositional shift in biofacies at the top of the core log. In the Down Ampney 2 succession there is more marked domination of particular intervals by particular biofacies clusters (Fig. 6), and these are also more compositionally distinct, a pattern that is even more pronounced in the CM11 succession. The largest number of biofacies clusters are associated with the highly condensed Peterborough Member section at Eriswell (Fig. 6). Despite this, there is a strong unifying compositional feature (a high proportion of shell hash and relative paucity of ammonites) that is unique to this site. Data for Ashdown 2 are limited, but are notable for the extremely high proportions of bone and the bivalve *Bositra* in all biofacies clusters.

To explore the fidelity of our biofacies methodology and provide additional palaeoenvironmental data, we have used the raw quantitative data collected by Duff (1975) as part of his biofacies interpretation of the Peterborough Member (at Norman Cross near Peterborough, Stewartby, Bletchley and Calvert) to generate biofacies classifications based on NERC clustering. Figure 7 shows the correlation of the sections and compares the biofacies assignments of Duff (1975) with those assigned using NERC. Both facies classifications show striking similarity in the broad pattern of biofacies subdivisions for different biozonal intervals. The youngest and oldest parts of successions show significant facies variability in both interpretations, with less variation in the intervening part (Jason & Obductum subzones). In some cases there is direct correspondence of biofacies recognised by Duff (1975) with biofacies clusters defined by NERC, and in other cases the NERC analysis appears to be detecting contrasts identified by Duff (1975) although the boundaries of these units are not necessarily coincident. These patterns, and the similarity in the taxa that define distinct nodes in the DCA sample distribution (e.g. *Bositra*, *Meleagrinella*, nuculaceans, oysters; Fig.


Bletchley [SP 862 325]
Calvert [SP 695 232]
Stewartby [TL 017 412]
Norman Cross [TL 172 916]
Duff (1975) Facies
NERC Biofacies
Zone
Subzone
Athleta
Phaeinum
Grossouvrei
Coronatum
Obductum
Jason
Calloviense
Medea
Enodatum
Key to biofacies of Duff (1975)
Deposit Feeder Bituminous Shales
Nuculacean Shell Beds
Meleagrinella Shell Beds
Calcareous Clays
Grammatodon-rich Bituminous Shales
Grammatodon Shell Beds
Gryphaea Shell Beds
Sands and Silty Clays
Blocky Claystone
Vertical scale
1m
NERC Biofacies Cluster Composition

375 **FIGURE 7**

9) to other localities examined as part of this study (Fig. 8), suggests our combined NERC – DCA methodology is robust in identifying meaningful environmental gradients.

NERC biofacies data for the localities described by Duff (1975) show that, generally, the oldest parts of the succession (Enodatum/Medea subzones) seen at Norman Cross and Bletchley are relatively rich in ammonites and oysters, but including at Norman Cross thin intervals with sharply contrasting facies, where these faunal elements are sparse and *Bositra* more dominant. Higher in the succession (Jason/Obductum subzones), facies at most localities are dominated by a mixture of *Bositra*, *Meleagrinella* and nuculacean bivalves, with the Obductum Subzone at Norman Cross and Stewartby having a relatively higher proportion of *Bositra* compared to the corresponding interval at Calvert. The distinctly more cyclic facies of the Grossouvrei Subzone contains frequent shell beds in the Duff (1975) facies classification, corresponding with NERC facies clusters in which *Meleagrinella* and/or nuculacean bivalves tend to be more dominant compared to *Bositra*. The appearance of more shell-dominated facies appears somewhat delayed at Stewartby, occurring some distance above the base of the Grossouvrei Subzone. Scattered through the succession are relatively thin (ca. 1 m or less) organic-rich mudstone units identified by Duff (1975) as *Grammatodon*-rich Bituminous Shale, with apparently no consistent relationship to NERC biofacies clusters, and containing relatively low proportions of *Bositra* and *Meleagrinella* and high concentrations of deposit-feeding and infaunal suspension-feeding bivalves (particularly *Grammatodon*, nuculacean bivalves and the gastropod *Procerithium*). Apart from these horizons, *Grammatodon* is absent from most of the Peterborough Member.

Overall, the results suggest that there are strong site-specific factors influencing the composition and successions of biofacies, with stratigraphical persistence of the distinct character of sites suggesting that this pattern is not a consequence of chance variation in palaeoecological conditions. Detailed results of biofacies analysis for individual boreholes are discussed below in the context of environmental interpretations.

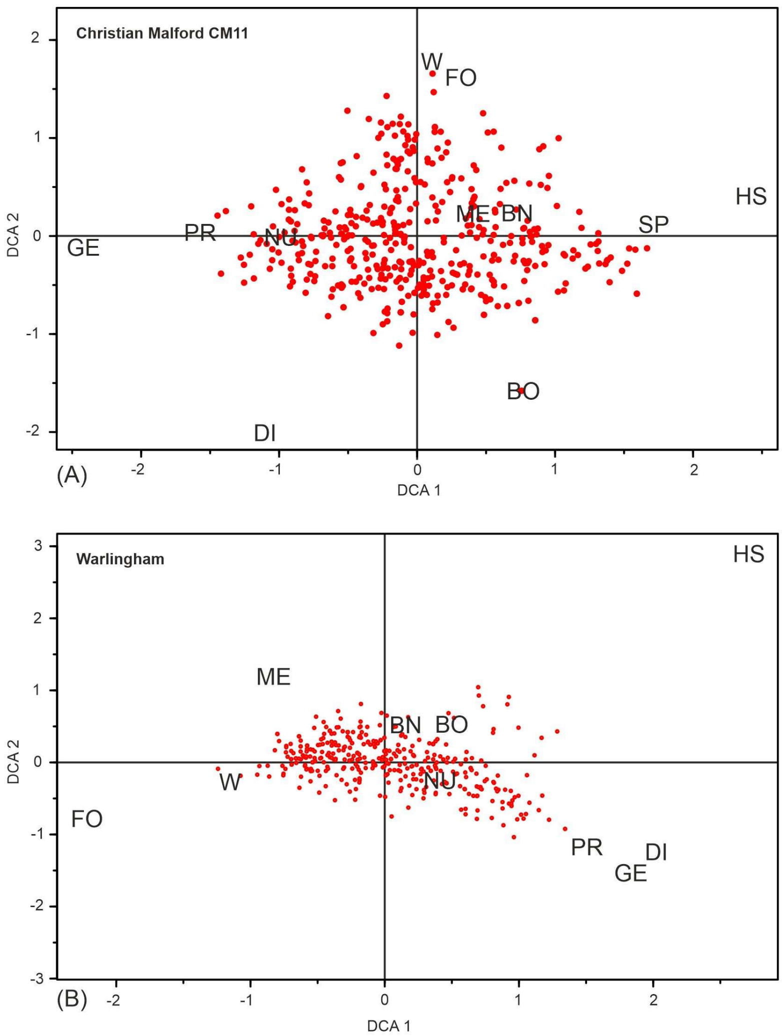
4.5 Biozonal data

Compilation of biozonal data for the Peterborough Member (Fig. 10) in boreholes extending along the same NE – SW alignment as our model thickness data reveals: 1) SW thickening is largely driven by expansion of biozones in the lower part of the Peterborough Member; 2) the Eriswell Borehole, located close to the ABM, shows maximum thinning of biozones, but expansion north-eastwards away from this structural feature and towards the East Midlands Shelf and Southern North Sea is muted, with the thickness of the Coronatum Zone in the Tydd St Mary and Parson Drove boreholes similar to Eriswell.

5 Discussion

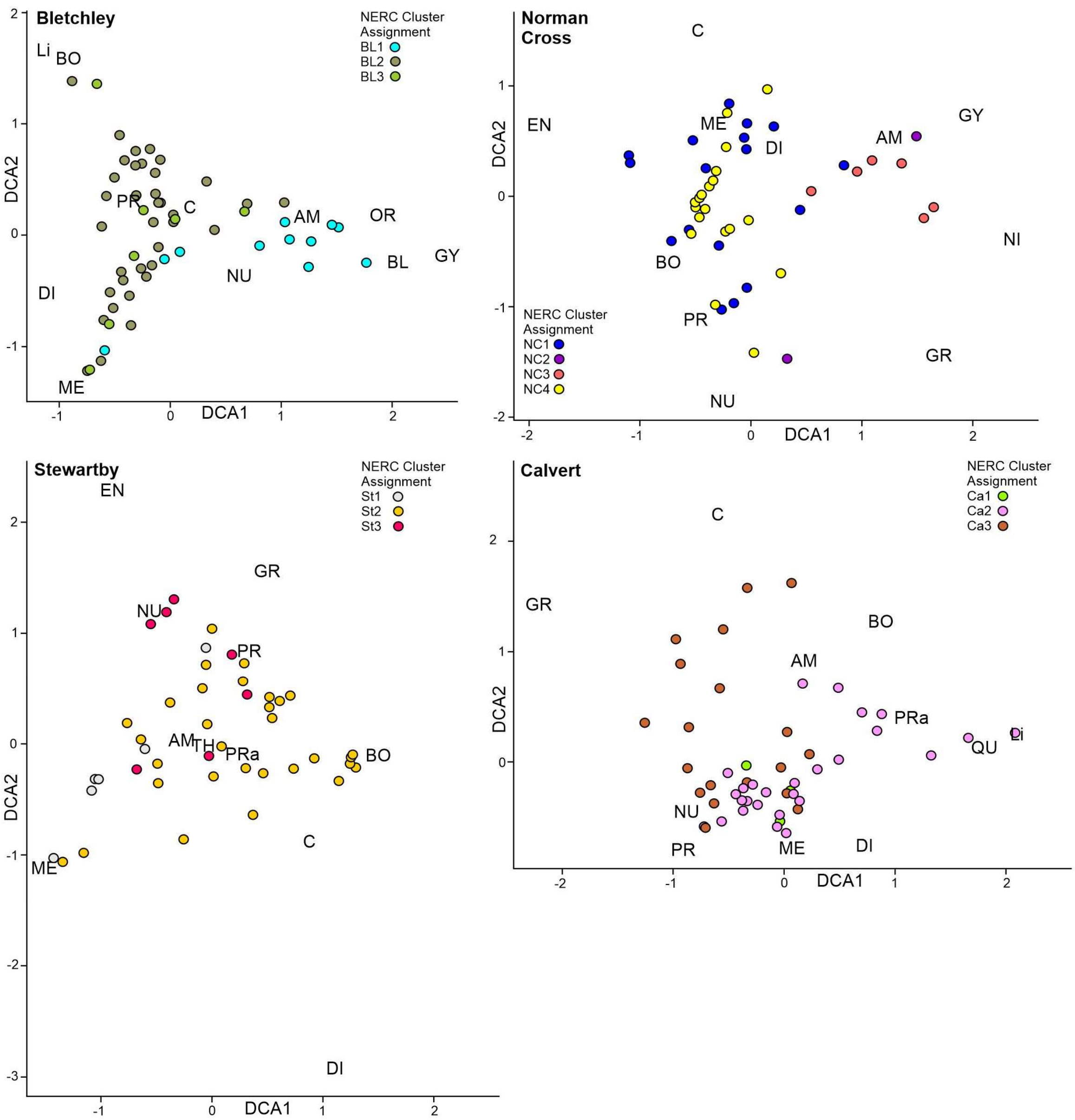
To understand the degree and likely causes of facies heterogeneity in the Peterborough Member we: 1) use our modelled thickness data to resolve depositional geometry in the context of basin structure and palaeogeography; 2) review existing sequence stratigraphy understanding for the Peterborough Member in light of our new geochemical and regional biostratigraphical data to establish a framework for understanding sea level variability, and 3) combine knowledge of (1) and (2) to develop a conceptual basin model that explains contrasts and similarities in biofacies patterns, and the extent to which they reflect basin-scale trends in mudstone variability. Finally, we make comparisons with other well-known organic-rich Jurassic mudstone successions.

The constituent taxa of our biofacies have been the subject of previous work to understand patterns of ecological change in the Peterborough Member, which are primarily controlled by seabed oxygenation and/or substrate consistency (Duff 1975, Martill et al. 1994, Kenig et al. 2004).



Christian Malford CM11
W
FO
HS
ME
BN
SP
PR
GE
NU
BO
DI
DCA 2
DCA 1
(A)
Warlingham
HS
ME
BN
BO
W
NU
FO
PR
DI
GE
DCA 2
DCA 1
(B)

422 **FIGURE 8**



Bletchley
NERC Cluster Assignment
BL1
BL2
BL3
Li
BO
PR
C
AM
OR
GY
BL
NU
DI
ME
DCA1
DCA2
Norman Cross
C
EN
ME
DI
AM
GY
BO
NI
PR
GR
NU
NERC Cluster Assignment
NC1
NC2
NC3
NC4
DCA1
DCA2
Stewartby
EN
NERC Cluster Assignment
St1
St2
St3
GR
NU
PR
AM
TH
PRa
BO
C
ME
DI
DCA1
DCA2
Calvert
NERC Cluster Assignment
Ca1
Ca2
Ca3
C
GR
BO
AM
PRa
QU
Li
NU
PR
ME
DI
DCA1
DCA2

FIGURE 9

Since our biofacies carry an ‘averaged’ environmental signal, our ecological conceptualisation of them (below) is necessarily simplified, effectively dampening short-term environmental “noise”. Here, we follow previous authors (Kauffman 1981, Etter 1996; Caswell et al. 2009; Danise et al. 2015) in regarding *Bositra* and *Meleagrinella* as opportunist suspension feeding taxa, tolerant of low oxygenation. In the context of previous work by Kenig et al. (2004) using geochemical data to understand environmental signals in the biofacies of the Peterborough Member, and the relationship of biofacies to Ti/K data in the CM11 succession, end-members (4.4 above) represented by (1) *Bositra* -rich organic mudstone and (2) nuculacean shell beds (+/- *Procerithium*, *Genicularia*) are interpreted to correspond with low oxygen (anoxic or dysoxic) and more oxygenated (oxic) settings, respectively. *Meleagrinella*-dominated successions appear to occupy a position between these two end members.

5.1 Basin geometry and palaeogeography

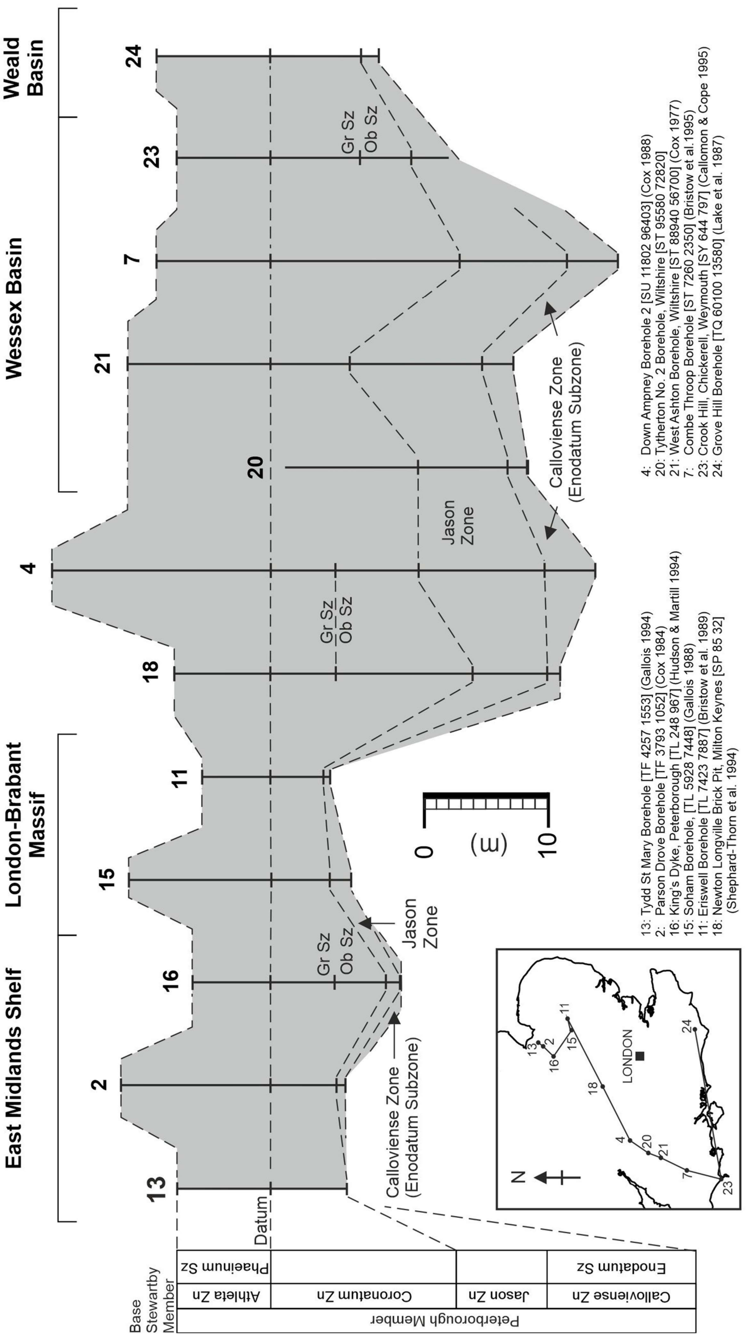
Modelled thicknesses reveal clear trends in the depositional pattern of the Peterborough Member, with distinctly wedge-shaped regional thickness geometries characterising the unit and wider Oxford Clay along the northern edge of the ABM, from the Southern North Sea into the Wessex Basin (Fig. 3), as well as from the eastern Weald westwards (Fig. 4). However, the palaeogeographical settings of these two regions are strongly contrasting in terms of likely sediment accommodation space (Fig. 1), suggesting that the similar geometries are a product of different processes. Along the northern margin of the ABM, north-eastward thinning closely corresponds with flanks of the Mid North Sea High, and the modelled thickness variation (Fig. 3A) seems consistent with a palaeobathymetric gradient from relatively shallow water conditions around this semi-emergent feature to deeper water conditions in the Wessex Basin. Certainly, there is evidence in the younger Corallian Group for the margins of the Mid North Sea High being associated with the development of shallow-water facies (Cameron et al. 1992), and it seems probable that prior to this the broad area of crust affected by North Sea doming (>1250 km diameter; Underhill and Partington 1993) extended to the East Midlands Shelf during deposition of the Peterborough Member.

Modelled thinning of the Peterborough Member and total Oxford Clay Formation across much of the Weald Basin is striking and consistent with biozonal data from cored boreholes (Fig. 10), including the Grove Hill [TQ 6008 1359] and Brightling No. 1 [TQ 6725 2182] boreholes in Sussex (Lake et al. 1987). This sharply contrasts with the significant thickening seen in this area during deposition of the prior Inferior and Great Oolite groups and subsequent Late Jurassic succession (Whittaker 1985). The conclusion from our modelling is that this area is likely to have been relatively sediment starved.

From the thick successions of Peterborough Member in the Wessex Basin there is evidence of a slight thinning trend into the Channel Basin, particularly seen in the pattern of biozonal data for Dorset (Fig. 10). This may reflect greater ability of the Wessex Basin to create additional accommodation space through sediment loading, with some differential compaction across fault lineaments potentially suggested by thickness data in the vicinity of the Shrewton Borehole (Fig. 3C).

5.2 Cyclicity and Sequence Stratigraphy

New geochemical data for Christian Malford, and its relationship to lithological features in borehole core (Fig. 5), allows interpretation of likely patterns of relative sea level change during this time. Combined with our basin-wide synthesis of biostratigraphical data (Fig. 10), and previously reported observations of Mid/Late Callovian successions in the wider UK region (including data for the Moray Basin), we outline a sequence stratigraphy framework for the Peterborough Member that can be used to understand controls on the pattern of deposition and potentially also decimetre-scale trends in biofacies data. Whilst often considered as a separate depositional entity, the succession



East Midlands Shelf
London-Brabant Massif
Wessex Basin
Weald Basin
13
2
16
15
11
18
4
20
21
7
23
24
Datum
Gr Sz
Ob Sz
Jason Zone
Calloviense Zone (Enodatum Subzone)
0
(m)
10
Base Stewartby Member
Peterborough Member
Athleta Zn
Phaeinum Sz
Coronatum Zn
Jason Zn
Calloviense Zn
Enodatum Sz
N
LONDON
13: Tydd St Mary Borehole [TF 4257 1553] (Gallois 1994)
2: Parson Drove Borehole [TF 3793 1052] (Cox 1984)
16: King's Dyke, Peterborough [TL 248 967] (Hudson & Martill 1994)
15: Soham Borehole, [TL 5928 7448] (Gallois 1988)
11: Eriswell Borehole [TL 7423 7887] (Bristow et al. 1989)
18: Newton Longville Brick Pit, Milton Keynes [SP 85 32] (Shephard-Thorn et al. 1994)
4: Down Ampney Borehole 2 [SU 11802 96403] (Cox 1988)
20: Tytherton No. 2 Borehole, Wiltshire [ST 95580 72820]
21: West Ashton Borehole, Wiltshire [ST 88940 56700] (Cox 1977)
7: Combe Throop Borehole [ST 7260 2350] (Bristow et al. 1995)
23: Crook Hill, Chickerell, Weymouth [SY 644 797] (Callomon & Cope 1995)
24: Grove Hill Borehole [TQ 60100 13580] (Lake et al. 1987)

FIGURE 10

developed on the margin of the Moray Basin (at Brora) shows noted similarity with that of eastern England (Page 2002); there is broad coincidence in the stratigraphical horizon of intervals showing particular sequence stratigraphical responses (e.g. progradation, maximum flooding), and palaeogeographical evidence supports probable wider marine connectivity with the Oxford Clay depositional system (Davies et al. 1996).

5.2.1 Current knowledge framework

The oldest part of the Peterborough Member, and coeval parts of the Heather and Brora Argillaceous formations in the Moray Basin (Fig. 2), relate to marine flooding at the base of the Enodatum Subzone and regression in the overlying Jason Zone (Davies et al. 1996, Nagy et al. 2001, Hesselbo 2008). At the type Peterborough section, initial flooding and later sea level fall corresponds with the 'Gryphaea and Reptile Beds', comprising a thin (1.2 m) unit of fissile pyritic mudstone rich in the oyster *Gryphaea*, consistent with shallow water oxic conditions (Duff 1975, Hudson and Martill 1994, Kenig et al. 2004). Maximum Flooding surfaces are usually associated with thickening of the associated stratigraphical intervals towards the basin margins where sediment becomes ponded on newly created shelf areas (Catuneanu et al. 2011). The thin Enodatum Subzone at Peterborough (compared to more basinal setting; Fig 10) suggests either a *very* proximal setting at the maximum extent of flooding, and/or significant erosion associated with later sea level fall.

Thickening of the Jason Zone into the Wessex Basin (Fig. 10) is consistent with relative sea level fall focussing sedimentation towards available accommodation space in more distal areas. In this context, organic-rich facies in the higher part of the Jason Zone at Peterborough (Bed 10 of Hudson and Martill 1994), sandwiched between *Gryphaea*-rich intervals, probably reflects the development of anoxia in a relatively shallow water setting, possibly in response to restricted local circulation (ponding, boosting organic matter preservation) associated with sea level fall. Sandstone in the likely Jason Zone at Stewartby (Bedfordshire), ca. 60 km to the south-west, is interpreted to reflect winnowing or bypass of fine -grained sediment in a more proximal setting (Macquaker 1994), providing further evidence of limited local sediment accommodation space close to the basin margin at this time.

Relative sea level fall is inferred to have continued into the early Coronatum Zone before rising in the later part of the Zone (Hesselbo 2008). In the Moray Basin this phase is represented by a wedge of coarse, glauconitic sandstone (Nagy et al. 2001), and by stacked parasequences in the Peterborough succession showing a trend of increasing up-section silt content (Macquaker and Howell 1999). These successions may be a response to lack of accommodation space caused by relative sea level fall, and/or reflect the rapid advance of sediment into limited areas of newly created accommodation space during early transgression.

5.2.2 Completing the knowledge framework

The remainder of the Peterborough Member reflects rising relative sea level, peaking in the lower part of the Phaeinum Subzone (Hesselbo 2008) and consistent with a widespread Maximum Flooding Surface recognised in the Moray Basin (Davies et al. 1996, Nagy et al. 2001). Trends in the Ti/K data from the Christian Malford Borehole CM 11 are a proxy for the delivery of coarse detrital components to the depositional site, and shed new light on the pattern of environmental change represented by the upper part of the Peterborough Member. We regard the regular cyclical pattern of Ti/K data in the Christian Malford succession (Fig. 5) as analogous to the systematic trends in the silt-content used by Mcquaker (1994) and Mcquaker and Howell (1999) to understand fluctuations in the length of sediment transport pathways between source and sink caused by relative sea level change. Individual cycles fine-up (Type 1 cycle) or coarsen-up (Type 2 cycle) and can be grouped into broader associations showing overall reductions in Ti/K or overall increases in Ti/K. These broader cycle trends, and the inflection points between these trends are used to infer likely changes in sediment accommodation space and to make interpretations of sequence stratigraphy.

The decline in the Ti/K ratio in the lowest ca. 1 m of the CM11 succession (Grossouvrei Subzone; Fig. 5), terminating abruptly at a peak in the Ca/K ratio ('C' of Fig. 5) suggests that an increase in accommodation space acted to reduce the flux of detrital material to this site. The conspicuous ammonite/foraminifera concentration at 'C' likely represents a period of sharply reduced sedimentation rate in response to sea level rise. Three cycles in the Ti/K ratio (S1 – 3, Fig. 5) in the overlying ca. 1.5 m of mudstone correspond with alternating paler and darker grey mudstone units, and show an overall upward increase in Ti/K. This trend through cycles S1 – 3 suggests progressively enhanced delivery (progradation) of coarser-grade sediment to the depositional site associated with shortening of sediment pathways. These are analogous to the parasequences described in the lower part of the Peterborough succession by Macquaker and Howell (1999). The largest peak (S3, Fig. 5) in Ti/K marks the beginning of a sharp upward shift to significantly lower Ti/K values that persists through several metres of the overlying succession. This peak is interpreted to represent a major pulse of marine transgression associated with current winnowing on newly flooded areas and significant increase in available accommodation space.

The four closely spaced Type 1 cycles (see above) in CM11, corresponding with peaks S4 – S7 (Fig. 5), are interpreted to represent a series of transgressive pulses, initially marked by sediment winnowing events, separated by periods with less current scour. The overall reduction in the Ti/K ratio through this interval is consistent with an increase in accommodation space and lengthening of sediment pathways. The major Ti/K peak (S4) associated with the lowest shell bed suggests that this was a particularly strong/prolonged pulse of transgression. It coincides with a major shift in biofacies, a sharp upward decline in the abundance of wood potentially reflecting increased distance from shorelines, and a decline in foraminifera that is a possible response to increased current scour (Fig. 5). Sharp/erosive ('X' Fig. 5) bases to the shell beds are consistent with significant current scour which was probably important for oxygenation and colonisation of seabed sediment by the infaunal bivalves that dominate these units. Minor Ti/K peaks (S5 – 7; Fig. 5) that cap subsequent shell beds suggest a phase of enhanced off-shelf movement of mobile sediment from newly flooded areas by wave scour following each transgressive pulse (including material swept across the site into more distal settings). The alternation of shell-rich units and intervening mudstone is matched by a pronounced oscillation in biofacies (Fig. 5). The less diverse fauna, dominated by foraminifera and the bivalves *Bositra* and *Meleagrinella*, in the dark, fissile units that cap the cycles, suggests quieter depositional conditions with less consistent sea bed oxygenation. The Comptoni Bed (peak S8), widely associated with a rolled and winnowed fauna (Hudson and Martill 1994), is inferred to mark the maximum extent of transgression, and therefore the Maximum Flooding Surface.

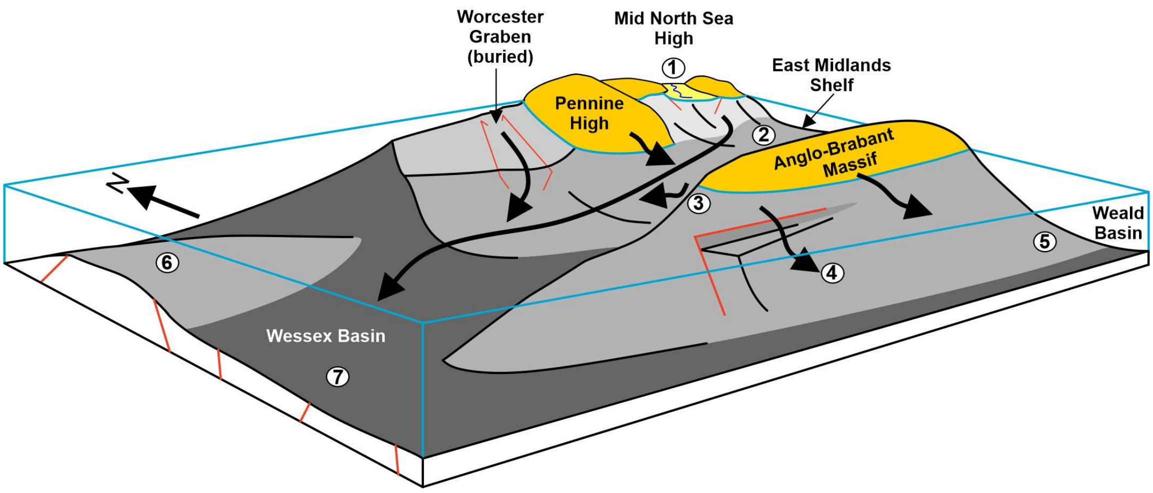
Above the Acutistriatum Band in CM11, the progressive cyclical build-up in Ti/K (Fig. 5, S9 – S14), indicates a major shift in basin evolution. Biofacies at and just above the Acutistriatum Band (and particularly between peaks S9 & S10) are indicative of dysoxic conditions (enrichment in *Bositra*, coprolite) and are consistent with low sedimentation rates (enrichment in bone), and the Acutistriatum Band is interpreted as a Condensed Section at the base of a Highstand Systems Tract (cf. Catuneanu et al. 2009). The stacked succession of Type 2 cycles (see above) with progressively increasing detrital content that form the remainder of the succession in CM11 and overlapping parts of CM9 are interpreted to form part of a 'normal regression' (Catuneanu et al. 2011) during sea level Highstand. Peaks S11 – 15 (Fig. 5), and likely represent the winnowed tops of prograding parasequences, represented by paler and generally more shell-rich mudstone units in borehole core. Reducing amplitude of Ca/K peaks upwards through the interval is probably a response to increasing dilution of shell by sediment influx, whilst the gradational bases of shell beds ('Y' Fig. 5) might reflect the ability of infauna colonising parasequences to progressively improve the habitability of deeper sediment layers by improving oxic water circulation. Decimetre-thick intervals of dark, organic-rich, fissile mudstones, that are either sparsely shelly or dominated by *Bositra* and ammonites, represent periods of deposition when creation of new accommodation space (e.g. from minor sea level fluctuation or basin subsidence) outstripped sediment flux, and current circulation was less effective at maintaining seabed oxygenation. Initially, the Type 2 cycles are poorly defined by biofacies data, but around the 'Squid Bed' (Fig. 5) and coincident with the horizon of the Christian Malford *Lagerstätte* (Wilby et al. 2008), the distinction of *Bositra*-rich intervals suggests an increasing trend towards anoxia/dysoxia. Plateauing of Ti/K values above S14 potentially reflects over-extension of sediment pathways, and diversion of material to adjacent regions with steeper shelf to basin gradients.

5.3 Conceptual basin model and mudstone heterogeneity

Modelled thickness data for the Peterborough Member, combined with knowledge of the palaeogeographical framework for the Mid Callovian (Figs. 1, 3), suggest that a depth gradient from the Mid North Sea High, and laterally contiguous areas, was likely significant in focusing sediment south-westwards towards the Wessex Basin, potentially augmented by sediment flows via the Worcester Graben. Palaeocurrent data for the Oxford Clay are sparse, but Hudson and Martill (1991) speculated that a large assemblage of belemnites seen at Peterborough (>300 specimens; Martill, 1985) with a N – S alignment might reflect the action of currents responsible for removing sediment from the East Midlands Shelf succession and depositing it in deeper parts of the basin. In the Mid Callovian, the Mid North Sea High formed an extensive semi-emergent area arcing around the southern North Sea Basin, with a coal-forming deltaic system in the Central North Sea (Møller and Rasmussen 2003), both providing significant potential for delivery of fine-grained sediment to offshore regions (Fig. 11). Thin and significantly condensed sedimentation on the flanks of the ABM (Figs. 3, 10) suggests that even if not fully emergent, it likely formed a significant structural feature. However, similarly thin Peterborough Member successions in the Weald Basin, where sediment accommodation space is unlikely to have been limited, suggest sediment starvation, with limited supply of sediment from the ABM itself and likely shielding by the ABM from sediment sources further north.

In the Wessex Basin, the thick Peterborough Member potentially includes material fed via the Worcester Graben (Fig. 11), which structural and regional gravity data (Chadwick and Evans, 2005; Fig. 12) suggest was a long-lived conduit for Mesozoic sediments. Published data for the source of Oxford Clay sediments are lacking, but it is noticeable that thickening of the Peterborough Member occurs in geophysical log transects across the buried mouth of this structure, located north of the current outcrop margin (Fig. 12). Maintenance of accommodation space in the Wessex Basin was probably a response of the highly fractured basement to the extensional stresses responsible for North Sea rifting, coupled with greater potential for compactional subsidence of the thick underlying Triassic and Early Jurassic succession, in contrast to the shallow-buried Variscan basement on the East Midlands Shelf (Whittaker 1985, Map 3).

The inferred patterns of sea level change are reflected by variable litho- and bio-facies across the basin, that appears largely a response to local basin setting. Thus, sea level fall in the Jason Zone is associated with the development of organic-rich mudstone in probable shallow water settings on the East Midlands Shelf, whereas coeval strata at Combe Throop and Kimmeridge 2, in the Wessex Basin, contain relatively low proportions of *Bositra*, and high proportions of oysters, nuculacean bivalves and the deep burrowing bivalve *Thracia* (Fig. 6), indicative of broadly oxic conditions. Higher in the succession, sea level rise across the Coronatum/Athleta Zone boundary is reflected by a shift to more organic-rich facies at Christian Malford. Further south-west in the Wessex Basin, correlative strata at Combe Throop comprise silty laminated sediments characterised



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by high proportions of both *Bositra* and nuculacean bivalves (Fig. 6), suggesting more rapidly fluctuating oxic/suboxic/anoxic environments. This plausibly reflects the position of the borehole on the Hampshire – Dieppe High, and perhaps also contrasting conditions affecting the fault-bounded Mere Basin opening immediately to the north (Chadwick and Evans 2005, fig. 85).

In the Down Ampney 2 Borehole, 30 km NE of CM11, laminated mudstone facies in the lower part of the Phaeinum Subzone (Fig. 6) contains common wood, bone and foraminifera, but few other fossil remains. The abundance of wood and bone in laminated mudstone facies suggests low rates of sedimentation in a low energy, near-shore setting. The general absence of biota might indicate significant localised freshwater run-off affecting both salinity and potentially also oxygenation. This unusual and unique unit suggests significant influence of local basin/environmental factors. It occurs between two contrasting successions: dark grey laminated bioclastic mudstone in the early Phaeinum Subzone (with biofacies dominated by *Bositra*, *Meleagrinella* & nuculacean bivalves) suggesting an intermittently dysoxic marine setting, and pale grey, poorly laminated and conspicuously bioturbated silty and shelly mudstone above (with biofacies dominated by nuculaceans, *Procerithium*, foraminifera and subsidiary *Bositra*), suggesting more, oxic, open marine circulation.

In the Parson Drove Borehole on the East Midlands Shelf, biofacies clusters with high proportions of *Bositra* dominate much of the succession, suggesting a persistent pattern of low oxygenation (Fig. 6). Pale grey, silty mudstone facies that dominate most of the Phaeinum Subzone in the Down Ampney succession, only occur near the top of the Phaeinum Subzone in the Parson Drove succession. This interpretation is supported by the sparse record of *Genicularia* in much of the Pason Drove succession, seen also in the voluminous quantitative data of Duff (1974, 1975) collected from the East Midlands Shelf. *Genicularia* is an epifaunal suspension feeding serpulid (Duff, 1975) that our biofacies data show is predominantly associated with strongly developed nuculacean shell beds. On DCA data plots (Fig. 8) *Genicularia* is consistently distant from poles defined by fauna linked to dysoxic environments (e.g. *Bositra*, *Meleagrinella*), and Duff (1975) recorded it as a dominant component in his calcareous clay facies, characterised by a diverse fauna including nuculaceans and oysters and low Total Organic Carbon (TOC). With these characteristics, we regard *Genicularia* in our biofacies data as an indicator of some of the least dysoxic conditions in the Peterborough Member. In the Parson Drove Borehole, *Genicularia* is present towards the top of the succession, coincident with a shift to much paler grey, silty mudstone (Fig. 6), potentially presaging wider regional environmental change in the later part of the Athleta Zone.

The sporadic distribution of the *Grammatodon*-rich Bituminous Facies of Duff (1975), and its unusual fauna dominated by elements more typical of oxic conditions is enigmatic. Duff (1974) suggested that this facies was likely associated with a slight increase in current activity, and many modern arcid bivalves (like *Grammatodon*) are adapted to life in unstable environments from which they might be dislodged by currents (Thomas 1978). Such an environment seems unfavourable for the build-up of significant organic enrichment (up to 6.1% TOC; Duff, 1974), unless this was prolific and occurred in periods of relatively short duration (e.g. linked to disturbance of redox boundaries across the East Midlands Shelf by enhanced storm activity).

Significant contrasts with the East Midlands Shelf and Wessex Basin occur in the facies at the margin of the ABM at Eriswell, and at Warlingham on the edge of the Weald Basin. At Eriswell, biofacies are consistently rich in broken-up shell material and generally poor in ammonites, where current winnowing in a relatively shallow water setting likely shaped deposition of the thin and condensed succession. The large number of faunal clusters might reflect the development of cryptic omission surfaces separating units with subtly varying faunal composition. Here, the relative rarity of *Genicularia* is unexpected in a setting that evidence suggests was likely well oxygenated, and may be a response to the high energy marine setting. The main facies response to rising sea level at the base of the Athleta Zone in the Eriswell succession is a slight increase in the frequency of ammonites as marine deepening likely strengthened connectivity with open marine settings. In contrast, *Genicularia* is unusually abundant in the Athleta Zone in the Warlingham succession (CL3, Fig. 6), where the DCA plot and the composition of biofacies clusters (Fig. 6, 9B) show that *Bositra* and nuculacean bivalves are closely associated and present in high proportions throughout the succession. Here, inferred sea level rise across the Coronatum/Athleta Zone boundary is marked by a subtle change in biofacies composition, largely related to the disappearance of the bivalve *Meleagrinella* in the lower part of the *Athleta* Zone. A similar gap in the record of this bivalve is noticeable at other sites (e.g. Eriswell, CM11, Combe Throop), and is likely driven by factors that are not site specific. Thus, at Warlingham, the significance of this bivalve for defining a change in biofacies at the Coronatum/Athleta Zone boundary is largely an indication of the unusual compositional stability of other biofacies components through much of the succession. High concentrations of bone suggest low sedimentation rates and/or in situ sediment winnowing (Boessenecker et al. 2014) causing mixing of faunal components. This process may have been helped by export of winnowed sediment from the adjacent ABM, potentially aided by Callovian syn-depositional normal faulting at the margin of the Weald Basin (Holloway 1985), creating a steep sediment pathway. Further out into the Weald Basin the conditions influencing deposition are unclear. The thin succession and evidence of pyritic and organic-rich lithologies rich in *Bositra* and bone seen in Ashdown 2 Borehole, suggest a poorly oxygenated, sediment starved setting.

6. The Peterborough Member in context

Facies patterns in the Peterborough Member appear more laterally variable than other organic-rich Jurassic mudstone units in SE Britain, like the underlying Lias Group and overlying Kimmeridge Clay Formation (Wignall 1991, Taylor et al. 2001), in which depositional patterns are predominantly modulated by Milankovitch climate cycles (Weedon et al., 2004, Pearce et al. 2010, Xu et al. 2017) or major oceanographic change (Toarcian Oceanic Anoxic Event (OAE); McArthur et al. 2008). The evidence from this work is that basin palaeogeography produced a more laterally variable response of facies in relation to relative sea level change in the Peterborough Member. This facies variability may, at least in part, reflect the timing of deposition of the Peterborough Member, which occurred at a relatively early stage in a cycle of broader sea level rise following rifting, potentially providing a more dynamic and accentuated basin environment for its deposition compared to other Jurassic mudstones. The contrasting development of organic-rich mudstones in the lower Phaeinum Subzone at Christian Malford, compared to some more distal parts of the Wessex Basin, might not only reflect the influence of complex structure transecting the basin; it might also indicate that shallower regions of the basin margin more easily became thermally stratified and anoxic. This is somewhat analogous to transgressive nearshore black shales described by Wignall and Newton (2001) in the Kimmeridgian, and by Leonowicz (2016) in the Middle Jurassic of Poland, although the Christian Malford organic mudstone succession appears to represent deposition during early Highstand and also in a more distal, though not basinal, setting.

Although some previous workers have characterised the Callovian as an OAE (Hautevelle et al. 2006, Soua 2014), widespread deposition of organic-rich facies (Dromart et al. 2003, Martinez and Dera 2015) appears more strongly related to continental rifting (Robertson and Ogg 1986) and the creation of intra-shelf basins (Carrigan et al. 1995). These widely distributed but more localised tectonic settings, coupled with marine transgression and a nutrient supply fed by humid climate weathering, seem likely to have been controlling influences in both organic matter accumulation in the Callovian, and the demise of contemporary shallow-water carbonate platforms (Hautevelle et al. 2006, Andrieu et al. 2016).

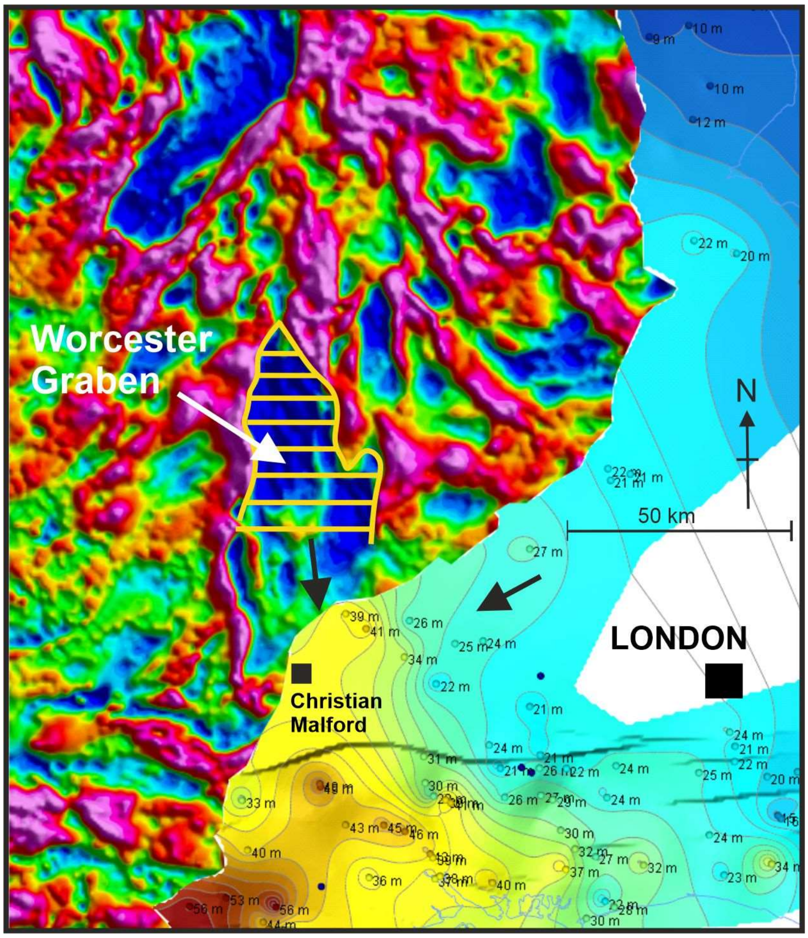

FIGURE 12

Termination of Callovian organic matter sequestration that defines the Peterborough Member coincides with evidence of southward migration of polar and sub-polar waters across the Eur-Russian area and a major shift in the Late Jurassic climate system (Dromart et al. 2003, Dera et al. 2015). This may have been a consequence of carbon-burial and CO_2 draw-down (Dromart et al. 2003), or potentially in response to the impact of rifting on patterns of marine circulation.

7. Conclusions

Deposition of the Peterborough Member was likely strongly influenced by highly variable basin architecture, with a depositional gradient from the Mid North Sea High channelling sediment towards the Wessex Basin, and the Anglo-Brabant Massif acting to shield the Weald Basin from this sediment source. Deposition on the flanks of the ABM is thin and condensed, and limited in the Weald Basin, suggesting sediment starvation, despite the likely presence of significant sediment accommodation space.

The facies at given points in the basin reflect the impact of local basin architecture and its interplay with variable sea level. Spatial contrasts in facies across the basin provide evidence of environmental gradients that can be used to inform how these facies are likely to be distributed and transition across the basin. For example, organic-rich mudstones on the East Midlands Shelf in the Jason Zone, coincident with low relative sea level, correspond with biofacies in the Wessex Basin indicative of relatively greater oxygenation, with significant silt content, and containing limited lithological evidence for poor circulation. The facies response of the Peterborough Member to relative sea level rise at the base of the Athleta Zone is markedly variable. At the edge of the Wessex Basin there is a sharp transition into organic-rich mudstone with a sparse fauna of infaunal bivalves; further into the Wessex Basin the signal is much less stark, with no sustained facies shift, but instead evidence of rapid oscillation between more and less oxic facies; and at the margin of the Weald Basin the event occurs within a shell-rich interval, with components indicative of a range of environments, that may reflect the impact of steep (?fault-controlled) depositional gradients.

Compared to other organic-rich mudstones, like the Kimmeridge Clay Formation, the Peterborough Member seems to be a product of a much more heterogeneous depositional environment. This may reflect deposition at an early stage in the cycle of regional sea level rise combined with the continued impact of earlier regional uplift, both potentially acting to restrict accommodation space (Macquaker, 1994) and accentuate the impact of basin irregularity on facies patterns. Given the broad and varied character of the successions investigated for this work, the location of the stratotype Peterborough Member appears unrepresentative of conditions across the wider depositional basin. It cautions against developing basin-scale models from a few well exposed and heavily researched outcrop successions, and emphasises the value of multidisciplinary studies for revealing the underlying depositional controls that shape the geometry and complexity of mudstone heterogeneity.

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References

Andrieu, S., Brigaud, B., Barbarand, J., Lasseur, E., & Saucède, T. (2016). Disentangling the control of tectonics, eustasy, trophic conditions and climate on shallow-marine carbonate production during the Aalenian – Oxfordian interval: From the western France platform to the western Tethyan domain. *Sedimentary Geology, 345*, 54 – 84.

Birgenheier, L. P., Horton, B., McCauley, A. D., Johnson, C. L., & Kennedy, A. (2017). A depositional model for offshore deposits of the lower Blue Gate Member, Mancos Shale, Uinta Basin, Utah, USA. *Sedimentology, 64*, 1402 – 1438.

Boessenecker, R. W., Perry, F., & Schmitt, J. G. (2014). Comparative Taphonomy, Taphofacies, and Bonebeds of the Mio-Pliocene Purisima Formation, Central California: Strong Physical Control on Marine Vertebrate Preservation in Shallow Marine Settings. *PLOSONE* https://doi.org/10.1371/journal.pone.0091419.

Bradshaw, M. J., Cope, J. C. W., Cripps, D. W., Donovan, D. T., Howarth, M. K., Rawson, P. F., West, I. M., & Wimbledon, W. A. (1992). Jurassic. In Cope, J. C. W., Ingham, J. K. & Rawson, P. F. (Eds.), *Atlas of Palaeogeography and Lithofacies, Geological Society Memoir, 13*, 107 – 129.

Bristow, C. R., Barton, C. M., Freshney, E. C., Wood, C. J., Evans, D. J., Cox, B. M., Ivimey-Cook, H. C., & Taylor, R. T. (1995). Geology of the country around Shaftesbury. *Memoir of the British Geological Survey, 1:50 000 geological sheet 313* (England & Wales).

Bristow, C. R., Cox, B. M., Ivimey-Cook, H. C., & Morter, A. A. (1989). The stratigraphy of the Eriswell Borehole, Suffolk. *British Geological Survey Research Report, SH/89/2*.

Buckley, D. K., Cripps, A. C., Barron, A. J. M., & Evans, A. D. (1991). Geophysical logging of several boreholes in Marston Vale, Bedfordshire. *British Geological Survey Technical Report, WN/91/23*.

Butler, D. (2010). France digs deep for nuclear waste. *Nature, 466*, 804 – 805.

Callomon, J. H. (1968). The Kellaways Beds and the Oxford Clay. In Sylvester-Bradley, P. C., & Ford T. D. (Eds.), *The Geology of the East Midlands* (pp. 264 – 290). Leicester: University Press.

Callomon, J. H., & Cope, J. C. W. (1995). The Jurassic Geology of Dorset. In Taylor, P. D. (Ed.), *Field Geology of the British Jurassic* (pp. 51 – 103). London: The Geological Society.

Callomon, J. H., & Cope, J. C. W. (1971). II. – The stratigraphy and ammonite succession of the Oxford and Kimmeridge Clays in the Warlingham Borehole. *Bulletin of the Geological Survey of Great Britain, 36*, 147 – 168.

Carrigan, W. J., Cole, C. A., Colling, E. I., & Jones, P. J. (1995). Geochemistry of the Upper Jurassic Tuwaiq Mountain and Hanifa Formation Petroleum Source Rocks of Eastern Saudi Arabia. In Katz, B. J. (Ed.), *Petroleum Source Rocks* (pp. 67 – 87). Berlin, Heidelberg: Springer.

Caswell, B. A., Coe, A. L., & Cohen, A. S. (2009). New range data for marine invertebrate species across the early Toarcian (Early Jurassic) mass extinction. *Journal of the Geological Society, London, 166*, 859 – 872.

Catuneanu, O., Galloway, W. E., Kendall, C. G. St. C., Miall, A. D., Posamentier, H. W., Strasser, A., & Tucker, M. E. (2011). Sequence Stratigraphy: Methodology and Nomenclature. *Newsletters on Stratigraphy, 44*, 173 – 245.

Catuneanu, C., Abreu, V., Bhattacharya, J. P., Blum, M. D., Dalrymple, R. W., Eriksson, P. G., Fielding, C. R., Fischer, W. L., Galloway, W. E, Gibling, M. R., Giles, K. A., Holbrook, J. M., Jordan, R., Kendall, C. G. St. C., Macurda, B., Martinsen, O. J., Miall, A. D., Neal, J. E., Nummedal, D., Pomar, L., Posamentier, H. W., Pratt, B. R., Sarg, J. F., Shanley, K. W., Steel, R. J., Strasser, A., Tucker, M. E., & Winker, C. (2009). Towards the standardization of sequence stratigraphy. *Earth Science Reviews, 92*, 1 – 33.

Chadwick, R. A., & Evans, D. J. (2005). *A seismic atlas of Southern Britain*. Keyworth: The British Geological Survey.

Charrad, M., Ghazzali, N., Boiteau, V., & Niknafs, A. (2014). NbClust: An R Package for Determining the Relevant Number of Clusters in a Data Set. *Journal of Statistical Software, 61(6)*, 1 – 36.

Cope, J. C. W. (2006). 14 Jurassic: the returning seas. In Brenchley, P. J., & Rawson, P. F. (Eds.), *The Geology of England and Wales* (pp. 325 – 363). London: The Geological Society.

Cox, B. M. (1991). Combe Throop Borehole, Combe Throop, Somerset, Oxford Clay. *British Geological Survey Technical Report, WH/91/310R*.

Cox, B. M. (1990). A review of Jurassic Chronostratigraphy and age indicators for the UK. In Hardman, R. F. P. & Brooks, J. (eds), Tectonic Events Responsible for Britain's Oil and Gas Reserves, *Geological Society Special Publication, 55*, 169-190

Cox, B. M. (1988). Fluid Processes Research Group: Down Ampney Fault Study. Stratigraphic classification of boreholes. *British Geological Survey Technical Report, WH/88/182R*.

Cox, B. M. (1984). Parson Drove (West's Bridge Borehole), Cambs. *British Geological Survey Technical Report, PDL/84/70*.

Cox, B. M. (1977). Ashton 1 Borehole. *British Geological Survey Technical Report, PD/77/22*.

Cox, B. M., Hudson, J. D., & Martill, D. M. (1992). Lithostratigraphic nomenclature of the Oxford Clay (Jurassic). *Proceedings of the Geologists' Association, 103*, 343 – 345.

Danise, S., Twitchett, R. J., & Little, C. T. S. (2015). Environmental controls on Jurassic marine ecosystems during global warming. *Geology, 43*, 263 – 266.

Davies, R. J., Stephen, K. J., & Underhill, J. R. (1996). A re-evaluation of Middle and Upper Jurassic stratigraphy and the flooding history of the Moray Firth Rift System, North Sea. In Hurst, A. (Ed.), Geology of the Humber Group: Central Graben and Moray Firth, UKCS. *Geological Society Special Publication*, 114, 81 – 108.

Delay, J., Rebours, H., Vinsot, A., & Pierre, R. (2007). Scientific investigation in deep wells for nuclear waste disposal studies at the Meuse/Haute Marne underground research laboratory, northeastern France. *Physics and Chemistry of the Earth, 32*, 42 – 57.

Dera, G., Prunier, J., Smith, P. L., Haggart, J. W., Popov, E., Guzhov, A., Rogov, M., Delsate, D., Thies, D., Cuny, G., Pucéat, E., Charbonnier, G., & Bayon, G. (2015). Nd isotope constraints on ocean circulation, paleoclimate, and continental drainage during Jurassic breakup of Pangea. *Gondwana Research, 27*, 1599 – 1615.

Dromart, G., Garcia, J.-P., Picard, S., Atrops, F., Lécuyer, C., & Sheppard, S. M. F. (2003). Ice age at the Middle – Late Jurassic transition? *Earth and Planetary Science Letters, 213*, 205 – 220.

Duff, K. L. (1975). Palaeoecology of a bituminous shale – the Lower Oxford Clay of central England. *Palaeontology, 18*, 443 – 482.

Duff, K. L. (1974). *Studies of the Palaeontology of the Lower Oxford Clay of Southern England*. PhD Thesis, University of Leicester.

Etter, W. (1996). Pseudoplanktonic and benthic invertebrates in the Middle Jurassic Oplalinum Clay, northern Switzerland. Palaeogeography, Palaeoclimatology, Palaeoecology, 129, 325 – 341.

Gallois, R. W. (1994). Geology of the country around King's Lynn and The Wash. *Memoir of the British Geological Survey*, 1:50 000 Sheet 145 and part of Sheet 129 (England & Wales).

Gallois, R. W. (1988). Geology of the country around Ely. *Memoir of the British Geological Survey*, 1:50 000 Sheet 173 (England & Wales).

Gallois, R. W. (1979). Geological investigations for The Wash Water Storage Scheme. *Report of the Institute of Geological Sciences, 78/19*.

Gallois, R. W., & Worssam, B. C. (1983). Stratigraphy of the Harwell Boreholes. *Institute of Geological Sciences, Technical Report FLPU 83-14*.

Goslee, S. C., & Urban, D. L. (2007). The ecodist package for dissimilarity-based analysis of ecological data. *Journal of Statistical Software 22(7)*, 1 – 19.

Hart, M. B., Page, K. N., Price, G. D., & Smart, C. W. (2019). Reconstructing the Christian Malford ecosystem in the Oxford Clay Formation (Callovian, Jurassic) of Wiltshire: exceptional preservation, taphonomy, burial and compaction. *Journal of Micropalaeontology, 38*, 133 – 142.

Hart, M. B., De Jonghe, A., Page, K. N., Price, G. D., & Smart, C. W. (2016). Exceptional accumulations of statoliths in association with the Christian Malford Lagerstätte (Callovian, Jurassic) in Wiltshire, United Kingdom. *Palaios, 31*, 203 – 220.

Hautevelle, Y., Michels, R., Malartre, F., & Trouiller, A. (2006). The initiation and end of a Mesozoic crisis of carbonate productivity as recorded by organic geochemical proxies. Relations with oceanic anoxic events and paleoclimate changes. *Geophysical Research Abstracts, 8*, 08639.

Hesselbo, S. P. (2008). Sequence stratigraphy and inferred relative sea-level change from the onshore British Jurassic. *Proceedings of the Geologists' Association, 119*, 19 – 34.

Holloway, S. (1985). Upper Jurassic: early Callovian to Middle Oxfordian. In Whittaker, A. (Ed.), *Atlas of Onshore Sedimentary Basins in England and Wales: Post-Carboniferous Tectonics and Stratigraphy*. Glasgow: Blackie, 47 – 48.

Hudson, J. D., & Martill, D. M. (1994). The Peterborough Member (Callovian, Middle Jurassic) of the Oxford Clay Formation at Peterborough, UK. *Journal of the Geological Society, London, 151*, 113 – 124.

Hudson, J. D., & Martill, D. M. (1991). The Lower Oxford Clay: production and preservation of organic matter in the Callovian (Jurassic) of central England. In Tyson, R. V. & Pearson, T. H. (Eds.), Modern and Ancient Continental Shelf Anoxia. *Special Publication of the Geological Society, London, 58*, 363 – 379.

Juggins, S. (2017). *rioja: Analysis of Quaternary Science Data, R package version (0.9-15.1)*. http://cran.r-project.org/package=rioja.

Kauffman, E. G. (1981). Ecological reappraisal of the German Posidonienschiefer (Toarcian) and the stagnant basin model. In Gray, J., Boucot, A. J. & Berry, W. B. N. (Eds) Communities of the Past. Stroudsberg, Pennsylvania: Hutchinson Ross, 311 – 381.

Kenig, F., Hudson, J. D., Damsté, J. S. S., Popp, B. N. (2004). Intermittent euxinia: Reconcilliation of a Jurassic black shale with its biofacies. Geology, 32, 421 – 424.

Kenig, F., Hayes, J. M., Popp, B. N., & Summons, R. E. (1994). Isotopic biogeochemistry of the Oxford Clay Formation (Jurassic), UK. *Journal of the Geological Society, London, 151*, 139 – 152.

Lake, R. D., Young, B., Wood, C. J., & Mortimore, R. N. (1987). Geology of the country around Lewes. *Memoir of the British Geological Survey*, 1:50 000 Sheet 319 (England & Wales).

Leonowicz, P. (2016). Nearshore transgressive black shale from the Middle Jurassic shallow-marine succession from southern Poland. *Facies, 62*, 16.

Lott, G. K., & Knox, R. W. O'B. (1994). 7. Post-Triassic of the Southern North Sea. In Knox, R. W. O'B., Cordey, W. G. (Eds.), *Lithostratigraphic nomenclature of the UK North Sea*. Keyworth, Nottingham, UK: British Geological Survey on behalf of the UK Offshore Operators Association.

Macquaker, J. H. S. (1994). A lithofacies study of the Peterborough Member, Oxford Clay Formation (Jurassic), UK: an example of sediment bypass in a mudstone succession. *Journal of the Geological Society, London, 151*, 161 – 172.

Macquaker, J. H. S., & Bohacs, K. M. (2007). On the accumulation of mud. *Science, 318*, 1734 – 1735.

Macquaker, J. H. S., & Howell, J. K. (1999). Small-scale (<5.0 m) vertical heterogeneity in mudstones: implications for high-resolution stratigraphy in siliciclastic mudstone successions. *Journal of the Geological Society, London, 156*, 105 – 112.

Magurran, A. E. (2004). *Measuring Biological Diversity*. Oxford, UK: Blackwell Publishing.

Mallet, J. L., (1989). Discrete Smooth Interpolation. *ACM Transactions on Graphics, 8*, 121 – 144. http://dx.doi.org/10.1145/62054.62057

Martill, D. M. (1985). Studies of the vertebrate palaeontology of the Oxford Clay (Jurassic) of England. Unpublished PhD thesis, University of Leicester.

Martill, D. M., Taylor, M. A., Duff, K. L., Riding, J. B., & Bown, P. R. (1994). The trophic structure of the biota of the Peterborough Member, Oxford Clay Formation (Jurassic), UK. *Journal of the Geological Society, London, 151*, 173 – 194.

Martinez, M., & Dera, G. (2015). Orbital pacing of carbon fluxes by a ~9-My eccentricity cycle during the Mesozoic. *PNAS, 112*, 12604 – 12609.

McArthur, J. M., Alegro, T. J., Schootbrugge, B. van de, Li, Q., & Howarth, R. J., (2008). Basinal restriction, black shales, Re-Os dating, and the Early Toarcian (Jurassic) oceanic anoxic event. *Paleoceanography, 23*, PA4217.

Møller, J. J., & Rasmussen, E. S. (2003). Middle Jurassic – Early Cretaceous rifting of the Danish Central Graben. *Geological Survey of Denmark and Greenland Bulletin*, *1*, 247 – 264.

Nagy et al., Finstad, E. K., Dypvik, H., & Bremer, G. A. (2001). Response of foraminiferal facies to transgressive-regressive cycles in the Callovian of northeast Scotland. Journal of foraminiferal Research, 31, 324 – 349.

National Infrastructure Commission (2018). *Cambridge, Milton Keynes and Oxford Future Planning Options Project: Final Report (Revision A)* (https://www.nic.org.uk/wp-content/uploads/NIC-FinalReport-February-2018-Rev-A-optimised.pdf).

Norris, S. (2017). Radioactive waste confinement: clays in natural and engineered barriers – introduction. In Norris, S., Bruno, J., Van Geet, M., & Verhoef, E. (eds), Radioactive Waste Confinement: Clays in Natural and Engineered Barriers. *Geological Society, London, Special Publications, 443*, 1– 8.

Norris, M. A., & Hallam, A. (1995). Facies variations across the Middle – Upper Jurassic boundary in Western Europe and relationship to sea level change. *Palaeogeography, Palaeoclimatology, Palaeoecology, 116*, 189 – 245.

Norry, M. J., Dunham, A. C., & Hudson, J. D. (1994). Mineralogy and geochemistry of the Peterborough Member, Oxford Clay Formation, Jurassic, UK: elemental fractionation during mudrock sedimentation. *Journal of the Geological Society, London, 151*, 195 – 207.

Oksanen, J., Guillaume Blanchet, F., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G. L., Solymos, P., Stevens, M. H. H., Szoecs, E., & Wagner, H. (2018). vegan: Community Ecology Package. R package version 2.5-2. https://CRAN.R-project.org/package=vegan.

Page, K. N., (2002). Brora (Callovian), Sutherland. In Cox, B. M., & Sumbler, M. G. (2002). *British Middle Jurassic Stratigraphy. Geological Conservation Review Series No. 26, Joint Nature Conservation Committee, Peterborough*, 372 – 376.

Page, K. N., Melendez, G., Hart, M. B., Price, G. D., Wright, J K., Bown, P., & Bello, J. (2009). Integrated stratigraphical study of the candidate Oxfordian Global Stratotype Section and Point (GSSP) at Redcliff Point, Weymouth, Dorset, UK. *Volumina Jurassica*, *7*, 101 – 111.

Partington, M. A., Copestake, P., Mitchener, B. C., & Underhill, J. R. (1993). Biostratigraphic calibration of genetic stratigraphic sequences in the Jurassic – lowermost Cretaceous Hettangian to Ryazanian of the North Sea and adjacent areas. In Parker J. R. (Ed.), *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference, Geological Society, London* (pp. 371 – 386).

Pearce, C. R., Coe, A. L. & Cohen, A. S. (2010). Seawater redox variations during the deposition of the Kimmeridge Clay Formation, United Kingdom (Upper Jurassic): Evidence from molybdenum isotopes and trace metal ratios. *Paleoceanography, 25*, PA4213.

Penn, I. E., Cox, B. M. & Gallois, R. W. (1986). Towards precision in stratigraphy: geophysical log correlation of Upper Jurassic (including Callovian) strata of the Eastern England Shelf. *Journal of the Geological Society, London, 143*, 381 – 410.

Pharaoh, T. C., Morris, J. H., Long, C. B., & Ryan, P. D. (1996). *Tectonic Map of Britain, Ireland and adjacent areas, Sheet 1, 1:1 500 000*. Keyworth, Nottingham: British Geological Survey.

Powell, J. H., Rawson, P. F., Riding, J. B., & Ford, J. R. (2018). Sedimentology and stratigraphy of the Kellaways Sand Member (Lower Callovian), Burythorpe, North Yorkshire, UK. *Proceedings of the Yorkshire Geological Society, 62*, 36 – 49.

R Core Team (2020). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Rhys, G. H., Lott, G. K., Calver, M. A. (1981). The Winterborne Kingston borehole, Dorset, England. *Report of the Institute of Geological Sciences, 81/03*.

Robertson, A. H. F., & Ogg, J. G. (1986). Palaeoceanographic setting of the Callovian North Atlantic. In Summerhayes, C. P., & Shackleton, N. J. (Eds.), North Atlantic Palaeoceanography. *Special Publication of the Geological Society, London, 21*, 283 – 298.

Scheiber, J., Southard, J., & Thaisen, K. (2007). Accretion of Mudstone Beds from Migrating Floccule Ripples. *Science*, *318*, 1760 – 1763.

Shephard-Thorn, E. R., Moorlock, B. S. P., Cox, B. M., Allsop, J. M., & Wood, C. J. (1994). Geology of the country around Leighton Buzzard. *Memoir of the British Geological Survey, Sheet 220* (England & Wales).

Smith, I F., & Edwards, J. W. F. (compilers). (1997). *Colour Shaded Relief Gravity Anomaly Map of Britain, Ireland and adjacent areas, 1:1500 0000 scale*. Keyworth, Nottingham, UK: British Geological Survey.

Soua, M. (2014). A Review of Jurassic Oceanic Anoxic Events as Recorded in the Northern Margin of Africa, Tunisia. *Journal of Geosciences and Geomatics, 2*, 94 – 106.

Southwood, T. R. E., & Henderson, P. A. (2000). *Ecological Methods*. Blackwell Science.

Taylor, S. P., Sellwood, B. W., Gallois, R. W., & Chambers, M. H. (2001). A sequence stratigraphy of the Kimmeridgian and Bolonian stages (late Jurassic): Wessex – Weald Basin, southern England. *Journal of the Geological Society, London, 158*, 179 – 192.

Thomas, R. D. K. (1978). Shell form and ecological range of living and extinct Arcoida. *Paleobiology*, 4, 181 – 194.

Underhill, J. R. (1998). Chapter 8: Jurassic. In Glennie, K. W. (Ed.), *Petroleum Geology of the North Sea – Basic concepts and recent advances* (4th Edition). Blackwell Science.

Underhill, J. R., & Partington, M. A. (1993). Jurassic thermal doming and deflation in the North Sea: implications of the sequence stratigraphy evidence. *Geological Society, London, Petroleum Geology Conference Series 4*, 337 – 345.

Vavrek, M. J. (2016). A comparison of clustering methods for biogeography with fossil datasets. *PeerJ, 4*, e1720.

Weedon, G. P., Coe, A. L., & Gallois, R. (2004). Cyclostratigraphy, orbital tuning and inferred productivity for the type Kimmeridge Clay (Late Jurassic), Southern England. *Journal of the Geological Society, London, 161*, 655 – 666.

Whittaker, A., (Ed.). (1985). *Atlas of Onshore Sedimentary Basins in England and Wales: Post-Carboniferous Tectonics and Stratigraphy*. Glasgow: Blackie.

Whittaker, A., Holliday, D. W., & Penn, I. E. (1985). Geophysical logs in British Stratigraphy. *Geological Society Special Report, 18*, 74 pp.

Wignall, P. B. (1991). Test of the concepts of sequence stratigraphy in the Kimmeridgian (Late Jurassic) of England and northern France. *Marine and Petroleum Geology, 8*, 430 – 441.

Wignall, P. B. (1989). Sedimentary dynamics of the Kimmeridge Clay: tempests and earthquakes. Journal of the Geological Society, London, 146, 273 – 284.

Wignall, P. B., & Newton, R. (2001). Black shales on the basin margin: a model based on examples from the Upper Jurassic of the Boulonnais, northern France. Sedimentary Geology, 114, 335 – 356.

Wilby, P. R., Duff, K., Page, K. & Martin, S. (2008). Preserving the unpreservable: a lost world rediscovered at Christian Malford, UK. Geology Today, 24, 95 – 98.

Wilhelm, C. (2014). Notes on Maps of the Callovian and Tithonian Palaeogeography of the Caribbean Atlantic, and Tethyan Realms: Facies and Environments. *Geological Society of America Digital Map and Chart Series, 17*, 1 – 9.

Xu, W., Ruhl, M., Hesselbo, S. P., Riding, J. B., & Jenkyns, H. C. (2017). Orbital pacing of the Early Jurassic carbon cycle, black shale formation and seabed methane seepage. *Sedimentology, 64*, 127 – 149.

FIGURE CAPTIONS:

Fig. 1. UK (Mid Callovian, E. coronatum Zone) palaeogeography for the Oxford Clay Formation, and location of key outcrop and borehole data referred to in this study. Palaeogeography based on Bradshaw et al. (1992, Map J8). Lines 1 & 2 are borehole correlation lines shown in Fig. 3. Map references for localities are given in text and/or *Supplementary Data*.

Fig. 2. The stratigraphy of the Oxford Clay Formation and coeval geological units in the Southern North Sea and Moray basins. Grey highlight indicates stratigraphy that is the focus of this study. Boreholes are continuously cored successions drilled for BGS, or partially cored successions drilled by others for hydrocarbons exploration (Ashdown 2, Kimmeridge 2) and held in the BGS national borehole archive at Keyworth, Nottingham. Biozonal nomenclature used in the text follows the conventions discussed by Cox (1990), in regarding Jurassic ammonite zones as chronostratigraphical units, referred to by species name with an initial capital letter written in non-italicized text. For clarity, we include the genus name on Figure 2, abbreviated by an initial letter for Subzones where this is the same as the genus used for the corresponding zone.

Fig. 3. Modelled thickness and correlation of the Peterborough Member. (A) Gamma ray log correlation: Southern North Sea - East Midlands Shelf - Wessex Basin - Channel Basin (Line 1 of Fig. 1). (B) Gamma ray log correlation: East Midlands Shelf - Anglo-Brabant Massif - Weald Basin (Line 2 of Fig. 1). (C) Interpolated thickness map showing faults (from Pharaoh et al. 1996) and borehole locations. Borehole numbering follows that used on Fig. 1. WWB (West Walton Beds); MD (measured depth, metres); TVD (true vertical depth, metres); gAPI (gamma ray American Petroleum Institute units). Cored boreholes (annotated) provide stratigraphical control for interpretations.

Fig. 4. Gamma log correlation of the Oxford Clay Formation and Peterborough Member in the Weald and Wessex basins. Log interpretations are guided by the records from cored and geophysically logged boreholes, published log interpretations (e.g. Winterborne Kingston; Rhys et al., 1981), and related borehole data held in BGS data archives.

Fig. 5. Stratigraphy, geochemistry and biofacies of the CM9 and CM11 boreholes. Geochemical data show patterns of enrichment in shell (red curve) and detrital material (blue curve). The stratigraphical distribution of samples and their biofacies assignment is represented by the pattern of short horizontal lines plotted for each defined biofacies cluster (Chm 1, 2 etc). The composition of biofacies clusters is given in bar charts showing relative proportions of the key components, calculated by dividing the total number of records for each component by the total number of samples. See Supplementary Data for full details. Contrasting detail of shell beds at different levels in

the succession are shown as core images for interval 'X' (sharp-based shell bed) and for interval 'Y' (shell bed with gradational base). ‘C’ and S1 – S15 are geochemical peaks discussed in the text.

Fig. 6. Lithology and biofacies of cored borehole successions in the Peterborough Member. Biofacies clusters are unique to each site and based on NERC clustering. See caption to Fig. 5 for explanation. NB: for clarity of other detail, shell hash not annotated on Eriswell log, but it is common throughout. * denotes lithologically and faunally distinct interval in Down Ampney 2 Borehole characterised by concentration of wood, foraminifera and bone.

Fig. 7. Correlation and biofacies classification of Peterborough Member successions according to Duff (1974, 1975) compared with biofacies classifications assigned using DCA and NERC clustering. The comparison shows broad similarity in the pattern of classification deduced by the contrasting methodologies. The stratigraphical ranges of NERC biofacies clusters (Ca1, BL1, St1, NC1, etc.) corresponds with quantitative data for individual beds within each succession. The composition of biofacies clusters is given in bar charts showing percentages of key components in each NERC cluster.

Fig. 8. Detrended Correspondence Analysis (DCA) of fossil assemblages in the Christian Malford CM 11 (A) and Warlingham (B) boreholes, showing positions of samples and upper quartile taxa. The highly contrasting geometry of sample points with respect to key taxa at Warlingham compared to Christian Malford suggests a significantly contrasting relationship in the association of different taxa that characterise biofacies at the two sites. The distributions at Warlingham are inferred to be a mixing signal rather than an indication of altered palaeoecological relationships between taxa (see text for details). The proximity of Bositra and nuculacean bivalves on the DCA plot for Warlingham is reflected in their unusually close association in biofacies clusters throughout this succession (Fig. 7). See Fig. 7 for key to biofacies components. DCA plots for all cored boreholes forming part of this study are given in Supplementary Data.

Fig. 9. Detrended Correspondence Analysis (DCA) for localities described by Duff (1974, 1975) showing positions of samples and upper quartile taxa, with samples classified according to NERC cluster assignment. See Fig. 7 for key to taxa. DCA plots for all cored boreholes forming part of this study are given in Supplementary Data.

Fig. 10. Biozonal correlation of cored boreholes and key outcrops in the Peterborough Member. Borehole numbering follows that used on Fig. 1. Zn (Zone), Sz (Subzone), Gr (Grossouvrei), Ob (Obductum).

Fig. 11. Conceptual basin model for deposition of the Peterborough Member, showing key palaeogeographical and structural elements. 1: deltaic deposition in collapsed graben along crest of Mid-North Sea High; 2: thin successions with organic-rich mudstone on East Midlands Shelf; 3: highly condensed deposition with abundant shell hash on flanks of Anglo-Brabant Massif; 4: shell-rich mudstone at faulted margin of Weald Basin, fed by sediment from higher on flank of Anglo-Brabant Massif; 5: sediment-starved basin with thin, organic-rich and pyritic mudstone and limestone; 6: intra-basinal high with silty and sand-rich mudstone; 7: main depocentre underlain by extensive network of east-west faults, fed by sediment from flanks of Mid-North Sea High, East Midlands Shelf and pathways associated with the buried Worcester Graben. Note: vertical scale exaggerated.

Fig. 12. The Worcester Graben defined by regional gravity data, with significant thickening of Peterborough Member occurring to the south and south-west, in line with the mouth of this

structure. Black arrows denote likely sediment pathways. Gravity data from Smith and Edwards (1997), https://www.bgs.ac.uk/datasets/gb-land-gravity-survey/.

Appendix 1 – Biofacies components and their abbreviation used in statistical analysis. Data list has been conditioned to remove species-level data (mainly applicable to data originally collected by Duff (1974, 1975)

ammonite	(AM)
ammonite spat	(AmS)
Anisocardia	(Aic)
aptychus	(AP)
arcid	(AR)
Bathrotomaria	(BA)
belemnite	(BL)
Belemnotheutis	(BT)
bone	(BN)
Bositra	(BO)
bryozoan	(BR)
burrowing	(BU)
Camptonectes	(Ca)
Chlamys	(CH)
cirripede	(CI)
coprolite	(CO)
Corbicella	(CL)
Corbulomima	(C)
crinoid ossicle	(Cr)
Dicroloma	(DI)
Discomiltha	(Dm)
Echinoid spine	(Es)
Entolium	(EN)
foraminifera	(FO)
gastropod (juvenile)	(GJ)

1204	*Genicularia*	(GE)
1205	*Grammatodon*	(GR)
1206	*Gryphaea*	(GY)
1207	Shell hash	(HS)
1208	Hooks (belemnoid)	(HO)
1209	*Isocyprina*	(IS)
1210	*Isognomon*	(IG)
1211	*Lingula*	(Li)
1212	*Mastigophora*	(MA)
1213	*Mecochirus*	(MS)
1214	*Meleagrinella*	(ME)
1215	*Mesosacella*	(MC)
1216	*Modiolus*	(MO)
1217	*Myophorella*	(MP)
1218	*Nanogyra*	(NG)
1219	*Neocrassina*	(NE)
1220	*Nicaniella*	(NI)
1221	nuculaceans	(NU)
1222	*Ooliticia*	(OO)
1223	Ophiuroid	(OP)
1224	*Orbiculoidea*	(Orb)
1225	ostracod	(OS)
1226	otolith	(OT)
1227	*Oxytoma*	(OX)
1228	oyster	(OR)
1229	*Parainoceramus*	(PA)
1230	*Pecten*	(PN)
1231	*Pholadomya*	(PM)
1232	*Pinna*	(PIN)
1233	*Plagiostoma*	(PG)
1234	*Pleuromya*	(PL)

?*Praecoria*	(PRa)
Procerithium	(PR)
Protocardia	(PC)
Pteroperna	(PT)
Quenstedtia	(QU)
rhynchonellid	(Rh)
Rollierella	(Ro)
scaphopod	(SC)
serpulid	(SE)
shell hash	(HS)
Solemya	(SO)
solitary coral	(Sco)
spat	(SP)
sponges	(Spo)
terebratulid	(TE)
Thracia	(TH)
trigoniid	(Tr)
wood	(W)

Appendix 2 – Other abbreviations used in statistical outputs

Athleta Zone	(Az)
Calloviense Subzone	(Csz)
Calloviense Zone	(Caz)
Combined Coronatum, Jason, Calloviense Zones	(CJC)
Coronatum Zone	(Cz)
Enodatum Subzone	(Esz)
Grossouvrei Subzone	(Gsz)
Jason Subzone	(Jsz)
Jason Zone	(Jz)

Medea Subzone	(Msz)
Phaeinum Subzone	(Psz)
Sample Size	(Sz)