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UK Stratigraphical Framework Series: Oxford Clay Formation

National Geoscience Programme

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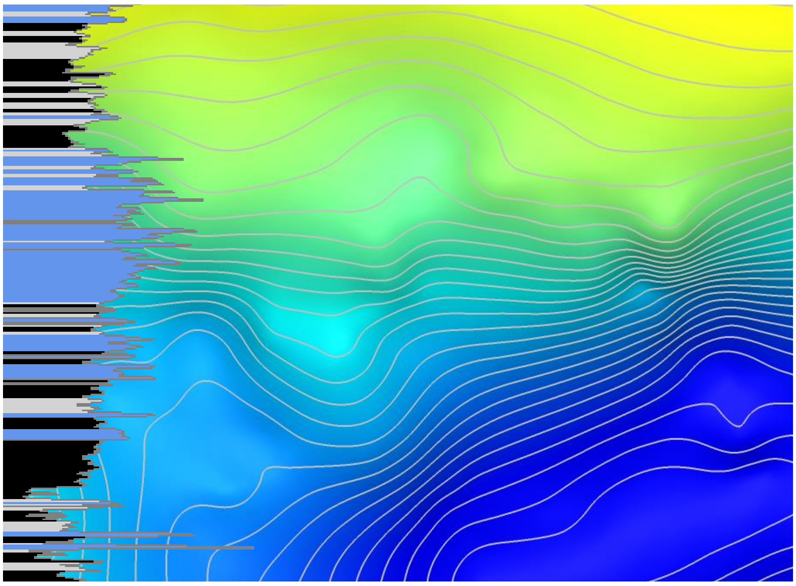

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Foreword

This report provides a high-level overview of the stratigraphy of the Oxford Clay based on recent work by the BGS, and is intended to provide a broad geological context for any future investigations of this interval.

Acknowledgements

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Contents

TABLES

FIGURES

Summary

This report forms part of the UK Stratigraphical Framework Series (UKSFS) and provides an overview of the stratigraphy of the Oxford Clay of southern and eastern England. The work covers both outcrop and subcrop areas and is primarily based on new interpretations of borehole geophysical log and core sample data with reference to published materials and outcrop sections as required. The emphasis of the report is on regional structure, thickness and facies trends in the Oxford Clay Formation. It should provide a framework for site-specific geological investigations that require understanding of the Oxford Clay Formation.

1 Introduction

1.1 BACKGROUND TO REPORT SERIES

This report on the Oxford Clay Formation forms part of the UK Stratigraphical Framework Series (UKSFS) which aims to generate new information on the structure, stratigraphy and facies (lithology) trends within UK bedrock geology units (formations or groups) of sedimentary origin. The emphasis of the report series is primarily (but not exclusively) on onshore UK geology and on stratigraphical trends across the entire areal distribution of the rock unit, at both outcrop and in the subsurface. The reports thus make extensive use of borehole data where these are available, for example, in the post-Devonian sedimentary basins of the UK where there has been a long history of exploration for groundwater, hydrocarbons, coal and other mineral resources.

The over-arching aim of the UKSFS is to create concise stratigraphical frameworks that can provide regional understanding of key UK stratigraphical units and can form the context and basis for further site-specific work where and when this is required. An emphasis on surface to subsurface correlations should make the reports and associated datasets applicable to many sectors where the subsurface understanding is important (e.g. hydrogeology, deep geothermal energy, geological containment of hydrogen, carbon dioxide and radioactive waste).

Where input datasets allow, the specific technical aims of the report series are to:

- Interpret borehole data and produce a robust set of stratigraphical markers using all available evidence (e.g. core, cuttings, biostratigraphy, chemostratigraphy and geophysical logs).
- Create structure maps of the stratigraphical unit fitted to verified borehole markers and other data (e.g. available depth-converted seismic picks and outcrop lines) where available.
- Create thickness maps of stratigraphical units and any key internal subdivisions using verified borehole markers and correcting for borehole inclination and structural dips where required. Attempt to understand trends within the thickness maps and the role of basin structure in controlling depositional trends.
- Classify boreholes for lithology (facies) using combinations of core, cuttings and geophysical logs and use this information to provide greater insight into patterns, trends and subsurface heterogeneity of the rock unit.

The emphasis of the report series is on the concise delivery of new stratigraphical data and associated datasets at the UK scale. The reports do not aim to summarise all published information on a particular rock unit or specifically address issues around stratigraphical nomenclature which are covered in BGS stratigraphical formational reports (e.g. Barron et al. 2012), BGS Memoirs and in the BGS Lexicon of named rock units (www.bgs.ac.uk).

1.2 REPORT STRUCTURE AND ASSOCIATED DATASETS

The report is structured with text and tables at the front of the documents and (for reasons of practicality) 20 full-page figures at the rear with detailed captions. The text includes an overview of methods, background information on the Oxford Clay Formation and a discussion of structure, thickness and facies trends shown by each map and section. Most of the raw data (where publicly released) and information shown in the figures are available as spatial data files (Table 1).

File	Description	Projection
BoreholeLocations.txt	Point file showing boreholes used in the Oxford Clay study	OSGB 1936/BNG
WellMarkers.txt	List of Oxford Clay well markers and measured depths	
BaseOxfordClayFmStructureMap.asc	Downsampled 5 km ASCII grid	OSGB 1936/BNG
OxfordClayThicknessMap.asc	Downsampled 5 km ASCII grid	OSGB 1936/BNG
PeterboroughMemberThicknessMap.asc	Downsampled 5 km ASCII grid	OSGB 1936/BNG
StewartbyMemberThicknessMap.asc	Downsampled 5 km ASCII grid	OSGB 1936/BNG
WeymouthMemberThicknessMap.asc	Downsampled 5 km ASCII grid	OSGB 1936/BNG
OxfordClayFaciesLogs.txt	Computed (see text for details) facies logs	

Table 1 List of data files associated with this report

1.3 METHODS

The Oxford Clay Formation occurs in the south eastern part of the UK in an area with a high density of released deep borehole data and this information was central to this stratigraphical project (Figure 1). The series of stages by which the boreholes were processed to generate structure and thickness maps is described below:

1. Borehole locations were plotted in 2D GIS (ArcGIS 10.3) and 3D Geological modelling software (Emerson SKUA-GOCAD 2019) using OSGB/British National Grid projection. Elevations were set at geophysical log datum (KB) where applicable or ground level. A number of borehole identifiers were used including borehole name, BGS SOBI identifier and BGS ID number. BGS SOBI and ID numbers can both act as unique well identifiers.
2. Borehole paths were created, either as vertical or deviated as required. Well deviation files were primarily sourced from UK Onshore Geophysical Library.
3. Geophysical logs (mostly gamma-ray and sonic) were extracted from BGS archives, cleaned, resampled at 0.15 m and loaded onto well paths.
   Existing stratigraphical borehole markers from the BGS UK Stratigraphical Surfaces Database (SSD) were loaded onto the well paths and served as a starting point for verification and editing into a new project set. Stratigraphical markers were created using BGS Lexicon codes with the format [unit below]_[unit above]_[type of contact]. The type of contact included normal (conformable) stratigraphical (N), unconformity (U) and faulted (F). A key to the stratigraphical markers created during the work is shown in Table 2.

Marker Code	Unit Below	Unit Above	Contact	Number
KLB_OXC_N	Kellaways Formation	Oxford Clay Formation	Normal	143
OSBY_OXC_N	Osgodby Formation	Oxford Clay Formation	Normal	12
PET_SBY_N	Peterborough Member	Stewartby Member	Normal	125
SBY_WEY_N	Stewartby Member	Weymouth Member	Normal	77
OXC_CR_N	Oxford Clay Formation	Corallian Group	Normal	102
OXC_WWAC_U	Oxford Clay Formation	West Walton Formation and Ampthill Clay Formation (Undifferentiated)	Unconformity	25

OXC_GLT_U	Oxford Clay Formation	Gault Formation	Unconformity	3
OXC_UGS_U	Oxford Clay Formation	Upper Greensand Formation	Unconformity	1
OXC_KC_F	Oxford Clay Formation	Kimmeridge Clay Formation	Faulted	1

Table 2 List of stratigraphical markers created for the Oxford Clay UKSFS report

4. Borehole correlation was undertaken as a team exercise within the BGS 3D Visualisation Suite. Where possible the placement of markers was constrained and conditioned by control wells where geophysical logs occur in association with core and biostratigraphical control (see Table 4).
5. Outcrop linework for the Oxford Clay Formation and associated units was extracted from BGS 1:50000 scale geological maps (DigMapGB50) and converted into polygons showing erosion limits at surface. OS Terrain 50 was used as the digital terrain model.
6. Structure maps on base and top Oxford Clay Formation were created using implicit geological modelling methods (Newell, 2020) using erosion limits, well markers and UK3D cross-section polylines as constraints (Table 3) . Gridded surfaces were fitted to well markers ensuring zero error. For the purposes of this study, the surfaces were modelled as unfaulted. The position of faults was simply shown using data from BGS Tectonic Map. One of the reasons for omitting faults was that in many areas much of the normal displacement has subsequently been removed by reverse movement during Cenozoic basin inversion.

Data	Data source	Projection
OS Terrain 50	Ordnance Survey 50 m digital terrain model	OSGB 1936/BNG
KLOX-MDSS.pl	GB3D	OSGB 1936/BNG
Well markers	This project	OSGB 1936/BNG
Outcrop erosion outlines	BGS DigMapGB-50	OSGB 1936/BNG
Jurassic faults	BGS Tectonic Map UKCS	OSGB 1936/BNG

Table 3 Input data for structural grids

7. Thickness maps were constructed by interpolating thickness data from borehole stratigraphical markers. Marker thickness values were corrected for borehole inclination where required (True Vertical Thicknesses) but not structural dip which was sufficiently low in all borehole locations to be a minor component of the total variation. Thickness values were interpolated using the Inverse Distance method where the weighting of each data point is inversely proportional to the distance or some exponential function of the distance between the data point and the interpretation point. The further away the data point is, the less influence it has on the estimation. For all maps an inverse distance exponent of 2 was used to provide a balance between sufficient granularity and smoothing of thickness variation. No fault barriers were used during the interpolation. The visualisation of regional trends was further enhanced by using a colour ramp where values were binned at 5 metre intervals.
8. A simple facies analysis on the Oxford Clay was undertaken using median (P50) cut off values on gamma-ray and sonic curves and is described in more detail later.

The borehole data was not interpreted in isolation but were considered against a wide range of new unpublished and published stratigraphical information and datasets using the workflow shown in Figure 2.

2 Oxford Clay Formation: Geological Background

2.1 DEPOSITIONAL SETTING

The Oxford Clay Formation (or ‘Oxford Clay’ for brevity) is a marine mudstone-dominated succession spanning the boundary of the Middle and Upper Jurassic (Callovian/Oxfordian). It marks the beginning of a phase of relative sea level rise and moderately deeper water deposition following the generally shallower water conditions that characterise much of the Middle Jurassic (Hallam, 2001).

Deposition occurred around a collection of island land areas variably covering parts of South-East England, South-West England, Wales, parts of Northern England, Scotland and the North Sea (Figure 3). The main areas of Oxford Clay deposition are the intra-shelf basins and marine corridors that fringe the land areas, particularly the onshore Weald-Wessex Basin and laterally contiguous Channel Basin in southern England, the East Midlands Shelf in eastern England, and the Cleveland Basin spanning parts of Yorkshire and the adjacent North Sea region (Figure 3). Three of these depo-centres (Wessex Basin, Weald Basin, Cleveland Basin) are dominated by E-W fault lineaments, and coincide with regions with a prolonged history of accumulation of low density sediments (signalled by blue colours on regional gravity data; Figure 4). A corridor bounded by N – S faults extends north of the outcrop of the Oxford Clay in the vicinity of Swindon (Fig. 3). These faults define the Worcester Graben (Chadwick and Evans, 2005), and the continuity of the low regional gravity anomaly data into this structure from the wider Wessex-Weald Basin (Figure 4) suggests that it may have been an important conduit for Mesozoic source-rock sediments, including the Oxford Clay.

Deposition of the Oxford Clay is generally understood to have coincided with a period dominated by gentle regional subsidence with limited tectonic activity (Holloway, 1985; Norris and Hallam, 1995), and sea level is thought to have progressively (though intermittently) risen during deposition of the formation (Hesselbo, 2008), with increased flooding of marginal land areas.

Traditionally the Oxford Clay has been regarded as rather uniform (Hallam and Norris; Holloway; Hesselbo, 2000), with generally more organic-rich laminated mudstones in the lower part, and more silty and calcareous mudstones in the middle and upper parts. However, there is evidence that the complex arrangement of basins and land areas has influenced the character of local successions (e.g. the notably thin successions on the flanks of the Anglo-Brabant Massif reported by Bristow et al., 1989), and it is possible that variation within this unit between different regions is greater than has generally previously been appreciated (Macquaker, 1994; Macquaker & Howell, 1999; Woods et al., in review).

2.2 KEY OUTCROP REFERENCE SECTIONS AND BOREHOLES

Across England, the outcrop of the Oxford Clay extends from the Scarborough area on the Yorkshire coast in the NE, to Dorset in the SW (Figure 1). There are relatively few good exposures of Oxford Clay, apart from in the vicinity of the type areas from which the component members take their names (Peterborough, Cambridgeshire; Stewartby, near Milton Keynes, Bedfordshire; Weymouth, Dorset; Figure 1). However, these can be supplemented by a much larger number of borehole records with core and/or geophysical logs, including from parts of the southern North Sea and Channel Basin (Figure 1). Most of the cored boreholes have been the subject of previous study and analysis by the BGS, particularly for biostratigraphy, and provide a means of calibrating geophysical log inflections to lithostratigraphy. The key reference sections and boreholes are listed in Table 4, and many are represented by extensive collections of sample material in BGS archives.

Locality	Key Oxford Clay Stratigraphy	Information Source(s)
King's Dyke Pit, Peterborough, Cambridgeshire [NGR TL2397]	Peterborough Member (type section)	Hudson and Martill (1994) Page (2002a)
Stewartby brick pits, Bedfordshire [NGR TL 0242]	Peterborough Member, Stewartby Member	Callomon (1968); Shephard-Thorn et al. (1995)
Crookhill Brickpit, Weymouth, Dorset [NGR SY6479]	Peterborough Member, ?Stewartby Member	Arkell (1947), Page (2002b)
Furzy (or Jordan) Cliff and Ham Cliff, Weymouth, Dorset [NGR SY 7081] (Furzy Cliff) [NGR SY 7181] (Ham Cliff)	Weymouth Member (type sections)	Arkell (1947), Wright (1986), Callomon and Cope (1995)
Newton Longville Brickpit, Bedfordshire [NGR SP 8532]	Peterborough Member, Stewartby Member (pars)	Shephard-Thorn et al. (1995)
BGS Ampthill Borehole, Bedfordshire [NGR TL 0238]	Weymouth Member	Shephard-Thorn et al. (1995)
Nettleton Bottom Borehole, Lincolnshire [NGR TF 1298]	Peterborough, Stewartby, Weymouth members	Penn et al. (1986)
Parson Drove Borehole, Cambridgeshire [NGR TF 3710]	Peterborough, Stewartby, Weymouth members	Penn et al. (1986); Cox (1984)
Eriswell Borehole, Suffolk [NGR TL 7478]	Peterborough Member, Stewartby Member	Bristow et al. (1989)
Down Ampney 2 Borehole, Gloucestershire [NGR SU 1196]	Peterborough Member, Stewartby Member	Cox (1988)
Combe Throop Borehole, Dorset [NGR ST 7223]	Peterborough Member, Stewartby Member	Bristow et al. (1995)
Warlingham Borehole, Surrey [NGR TQ 3457]	Peterborough Member, Stewartby Member, Weymouth Member	Callomon and Cope (1971)

Table 4 Key outcrop localities and cored boreholes for the Oxford Clay Formation lithostratigraphy

The Oxford Clay was traditionally subdivided into 3 lithostratigraphical units, Lower, Middle and Upper Oxford Clay, coextensive with the Peterborough, Stewartby and Weymouth members respectively of the revised stratigraphy of Cox et al. (1994). The typical features of these units, and their component marker-beds, are summarised in Table 5. Marker-beds are units that are distinctive because of their lithological properties and/or fossil content, and are important for the correlation of successions.

Member	Typical features	Maximum Thickness	Key marker-beds	Marker-bed features
Weymouth Member	Mainly pale-grey, blocky, calcareous mudstone with thin carbonaceous mudstone units. Generally weakly silty but some thin calcareous siltstones present. Large oysters (*Gryphaea*). Horizons of concretionary limestone.	Up to ca. 70 m	**Pans Hill Siltstone** (locally in south Midlands; Horton et al., 1995)	Ca. 0.3 – 0.5 m thick brownish-grey calcareous siltstone (Mariae Zone, upper Scarburgense Subzone)
Stewartby Member	Pale – medium grey, typically smooth-textured, variably silty blocky calcareous mudstone. Generally silty and calcareous in upper part with limestone in some areas (Lamberti Limestone). Rather poorly fossiliferous. Horizons of concretionary limestone.	Up to ca. 50 m	**Lamberti Limestone** (present mainly in south Midlands; Cope, 2006) **Trochocyathus Band**	Pale grey or cream-coloured, soft, silty limestone or calcareous siltstone/mudstone with abundant fossils including the bivalve *Oxytoma*, belemnites, gastropods and the ammonite *Quenstedtoceras lamberti*. Typically about 0.3 m thick. Horizon with common remains of the solitary button-shaped coral *Trochocyathus magnevillianus*. Occurs close to the boundary of the Proniae and Spinosum subzones.
Peterborough Member (includes the Mohuns Park Member of Bristow et al., 1995)	Common laminated, organic-rich mudstone and subordinate beds of pale/medium-grey mudstone. Horizons of concretionary limestone. Very fossil-rich, especially with ammonites, bivalves and gastropods	Up to ca. 65	**Acutistriatum Band**	Hard calcareous mudstone that may contain concretionary limestone nodules. Rather sparsely shelly. Characterised by the ammonite *Kosmoceras acutistriatum*. About 0.3 m thick.
			Comptoni Bed	Coarse, gritty shelly pyritic mudstone that may contain concretionary limestone nodules. Characterised by the ammonite *Binatisphinctes comptoni*. Application of this term may be restricted to a thin pyritic shell bed, or include more than a metre of underlying shelly calcareous mudstone.

Table 5 Characteristic features of lithostratigraphical units in the Oxford Clay Formation

Note: In the Cleveland Basin, a shallow structural block (Market Weighton Axis; Figure 4) affected deposition of the Oxford Clay. Here, only the Weymouth Member is developed, with the Peterborough and Stewartby members replaced by sandstones of the Osgodby Formation (Cope 2006, Powell et al. 2018, fig. 13; Figure 5).

Offshore, strata equivalent to the Oxford Clay are sandy and silty in the Southern North Sea (Seeley Formation; Lott and Knox 1994; Fig. 3) and become deltaic and coal-bearing in the Central Graben (Møller and Rasmussen 2003).

2.3 BOUNDARIES OF STRATIGRAPHICAL UNITS

Features used to define the limits of the Oxford Clay and of its component members in southern England and on the East Midlands Shelf are as follows:

- Base Oxford Clay Formation/Peterborough Member: Appearance of dark, silty mudstone above sandstones of the underlying Kellaways Formation (Cox et al., 1994).
- Top Peterborough Member/base Stewartby Member: Highest unit of organic-rich mudstone, with up to 3 m thick transition into pale-grey calcareous mudstone of Stewartby Member (Cox et al., 1994).
- Top Stewartby Member/base Weymouth Member: Top of Lamberti Limestone (where developed) or equivalent shell bed/siltstone. Can also be recognised by changes in fossil content (particularly ammonites and the fossil oyster *Gryphaea*) (Cox et al., 1994).
- Top Oxford Clay/top Weymouth Member: Transition into more silty mudstone and siltstone of overlying West Walton Formation or sand-rich base of the correlative Corallian Group (Cox et al., 1994).

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. In the Cleveland Basin, thickness variations in the Weymouth Group have been related to erosion at a disconformable contact with the overlying Corallian Group (Coe, 1995; Brenchley and Rawson., 2006).

2.4 BIOSTRATIGRAPHY

The standard biostratigraphical classification is based on ammonites, the preserved remains of which are generally abundant, although other types of fossils (e.g. bivalves, marine serpulids) can also be useful for recognising discrete intervals of strata within the succession. The standard biozonation of the Oxford Clay is shown in Figure 5.

Compilations of biostratigraphical data from outcrops and cored boreholes (particularly data contained in BGS memoirs and technical reports) provide a detailed picture of the lateral variation in the age of sediment within member subdivisions. Figures 6-8 summarise these data for the Peterborough, Stewartby and Weymouth Members. For the Peterborough Member Figure 6 shows that patterns of sedimentation are relatively thin on the East Midlands Shelf, across the London-Brabant Massif and in the Weald Basin, with significant thickening of biozonal intervals into the Wessex Basin. For the Stewartby Member (Figure 7), the Anglo-Brabant Massif continues to be associated with thinning, with sharper differentiation from the East Midlands Shelf compared to the Peterborough Member. Thinning also persists into the Weald Basin. Whilst biozonal data suggest that the Wessex Basin remains the predominant focus of overall sedimentation for the Stewartby Member, data for Warlingham, at the edge of the Weald Basin, shows a very significant expansion of the lower (Athleta Zone) part of the Member. Biozonal data for the Weymouth Member (Figure 8) show a broad split between restricted sedimentation on the East Midlands Shelf and across the Anglo-Brabant Massif, and much more expanded sedimentation in the Wessex and Weald basins. As with the lower part of the Stewartby Member, the lower part of the Weymouth Member (Mariae Zone) in the Warlingham Borehole appears greatly expanded compared to the West Ashton Borehole on the northern edge of the Wessex Basin.

2.5 SEQUENCE STRATIGRAPHY AND GEOCHEMISTRY

Sequence stratigraphy attempts to divide rock successions into packages of sediment that represent particular responses to changes in relative sea level (Catuneanu et al., 2011). The technique has significant predictive capability about the likely geometry and nature of sediments in particular basin settings, and is also of value for correlation. Sequence stratigraphy works best where deposition occurred across strongly contrasting shelf and basin settings and where tectonic effects are limited. In these settings, changes in relative sea level produce strong lateral shifts in lithofacies and generates distinctive surfaces that can be used for long range correlation. The technique can be applied in a modified form to understand the geometry and facies of successions developed across intra-shelf basins, such as the Oxford Clay. Sequence stratigraphy data for part of the Oxford Clay has been published by Macquaker (1994), and patterns of relative sea level change are described by Hesselbo (2008). Significantly more information has been published about the sequence stratigraphy of strata that are coeval with the Oxford Clay in the offshore and contiguous onshore parts of the Moray Basin in the vicinity of Brora, Scotland (Davies et al., 1996; Nagy et al. 2001). Recent work by Woods et al. (in review) has shown that bulk geochemical data from borehole successions can be valuable for developing sequence stratigraphy models in the Oxford Clay (Figure 9).

2.6 GEOPHYSICAL LOG SIGNATURES

The responses of borehole geophysical logs in the Oxford Clay have been illustrated by Whittaker et al., (1985), Penn et al., (1986); Bristow et al. (1995) and Horton et al. (1995, appendix 5). These include cored boreholes with detailed stratigraphical and facies data, allowing calibration of lithostratigraphy against geophysical log signatures and facilitating subsurface correlation of the Oxford Clay across southern and eastern England. Figure 9 shows the typical response of gamma and sonic logs in the Oxford Clay, and Figure 10 (A – C) illustrates borehole geophysical log correlations in the formation along 3 sections across southern England. The log responses on Figure 9 illustrate the typically high gamma signal produced by the organic-rich mudstones that characterise the Peterborough Member, and the low gamma/fast sonic log response that is distinctive of the Lamberti Limestone at the top of the Stewartby Member.

3 Structural and thickness trends in the Oxford Clay

3.1 STRUCTURAL TRENDS

Figure 11 shows a structure map on the base of the Oxford Clay Formation. The base of the formation occurs across an elevation range of 275 mAOD to -1750 mBOD, with the deepest Oxford Clay located in a W-E trending elliptical zone centred on the Weald Basin beneath Haslemere in the North Surrey Hills. This deep part of the Weald Basin was both an area of rapid subsidence in the Jurassic and Early Cretaceous and an area of reduced basin inversion and uplift during the Late Cretaceous and Cenozoic. The net result of these opposing basin subsidence and inversion processes controls the present elevation of the Oxford Clay.

To the north of the Weald Basin, the elevation of the Oxford Clay decreases rapidly across the southern faulted margin of the Anglo-Brabant Massif. Across this broad and long-lived Palaeozoic basement high the Oxford Clay has low structural dips and mostly occurs at shallow elevations above -200 mBOD. North of The Wash, the Oxford Clay dips eastward into the Southern North Sea Basin. In the Cleveland Basin, the Oxford Clay reaches a maximum of -700 mBOD in a system of W-E trending faulted graben and half-graben.

To the west of the Weald Basin, the elevation of the Oxford progressively decreases toward the broadly N-S striking outcrop belt in Dorset and Somerset.

The Anglo-Brabant Massif, Market Weighton High and South Dorset High form notable localised areas of non-deposition and/or post-depositional erosion within the wider area where the Oxford Clay is presently preserved.

3.2 TOTAL OXFORD CLAY THICKNESS

Figure 12 shows a thickness map for the Oxford Clay Formation. This map covers the interval between the top of the Kellaways Formation (or Osgodby Formation) and the base of the Corallian Group where this is present. On the Anglo-Brabant Massif and East Midlands Shelf it covers the interval between the top of the Kellaways Formation and the West Walton Formation. Boreholes where the succession is faulted or eroded (by post-Jurassic) units are omitted. Thicknesses are true vertical thicknesses (TVT) corrected for borehole deviation where present. The mean thickness is 97 m with a maximum thickness in the boreholes examined of 214 m.

The thickest successions of Oxford Clay occur in the south western part of its distribution, in the basins to the south and north of the South Dorset High and further north in the Mere and Pewsey basins. Here the Oxford Clay typically exceeds 150 m thick.

From this thick zone in south Dorset the formation generally thins in a relatively progressive way across the Wessex and Weald basins and onto the Anglo-Brabant Massif in North Kent where the Oxford Clay is around 60 m thick.

It is notable that the thickest part of the Oxford Clay is offset from what is now the structurally deepest part of the formation in the Weald Basin (Figure 13) and occurs close to the present outcrop limits. The progressive thickening trend from north Kent into south Dorset is highlighted by the log correlation panel shown in Figure 14.

In southern parts of the Anglo-Brabant Massif, just to the north of the bounding faults of the Pewsey and Weald basins, the Oxford Clay is around 100 m thick. There is some evidence for westward thickening into the southern part of the Worcester Graben where the Oxford Clay reaches 135 m thick. In northern parts of the Anglo-Brabant Massif and onto East Midlands Shelf the Oxford Clay is relatively thin at around 30-60 m (Figure 15). In the Cleveland Basin, the Oxford Clay is also thin at around 60 m, but here also excludes older parts of the formation (Peterborough and Stewartby members).

The overall trend across the entire Oxford Clay distribution is thus a progressive thickening from NE to SW.

3.3 COMPONENT MEMBER THICKNESS VARIATION

Figure 16 compares the thickness of the three Oxford Clay members in the Wessex/Weald Basin and southern Anglo-Brabant Massif area where these are present. In general, the thicknesses of the Peterborough Member (Figure 16A) and Stewartby Member (Figure 16B) show a similar pattern to the total thickness map, but with relatively thin successions extending somewhat further eastwards, and a relatively sharp gradient into the thicker successions in the Wessex Basin, particularly towards the Dorset coast within a zone of closely spaced fault lineaments.

Thickness data for the Weymouth Member (Figure 16C) appear to show a marked difference with a less pronounced NE-SW gradient into the thickest successions on the south Dorset coast. There is also some apparent thickening in the Weald Basin which formerly was an area of relatively thin Oxford Clay. It is known that immediately overlying Upper Jurassic units (Corallian Group and Kimmeridge Clay Formation) thicken markedly in this fault-bounded basin so the change in thickness pattern seen in the Weymouth Member may mark the inception of this area as a major depocentre.

4 Facies Variation in the Oxford Clay

4.1 DOCUMENTED RANGE OF LITHOFACIES IN THE OXFORD CLAY

Dark grey mudstones are the signature lithology of the Oxford Clay, but it also includes a variety of other rock types. These are summarised in Table 6 which is based on published descriptions of outcrops and boreholes.

Principal Facies	**Facies sub-types**	**Stratigraphical Distribution** (Pet=Peterborough Member; Stew = Stewartby Member; Wey = Weymouth Member	**Likely response on borehole geophysical logs**	**Principal Information Sources**
Mudstone (may be variably pyritic)	Laminated mudstone	Pet (predominantly) Wey (locally)	High gamma, low sonic	Barron et al. (2011) Bristow et al. (1995) Callomon and Cope (1995) Cox and Sumbler (2002) Cox et al., (1992) Duff (1975) Hollingworth and Wignall (1992); Horton et al. (1995) Hudson and Martill (1994) Macquaker (1994) Norris and Hallam (1995) Shephard-Thorn et al. (1994); Wright and Cox (2001)
	Laminated organic-rich mudstone	Pet (predominantly)	Very high gamma, low sonic	
	Blocky calcareous mudstone	All members	Moderate gamma, low sonic	
	Blocky carbonaceous mudstone	Wey	Very high gamma, low sonic	
	Silty mudstone	All members (particularly lower part of Pet in SW England)	Moderate gamma, moderate sonic	
	Sandy mudstone	Pet (locally in basal part) Wey (especially Yorkshire)	Moderate gamma, moderate sonic	
	Ooidal mudstone	Wey (Yorkshire)	Moderate gamma, moderate sonic	
Siltstone	Calcareous siltstone	All members	Moderate gamma, moderate sonic	
Sandstone	Muddy sandstone	Pet (at/near base and locally higher)	Moderate to Low gamma, moderate sonic	
Shell beds		All members (but dominant at certain levels and in particular regions)	Low gamma, moderate sonic	
Limestones	Silty limestone (including firmgrounds)	Stew (upper part)	High gamma, mod-high sonic	
	Muddy limestones (predominantly as rounded or lenticular masses). Predominantly concretionary and locally sideritic	All members	Low – high gamma (depending on pyrite content), high sonic	

Table 6 Principal litho-facies types in the Oxford Clay and their stratigraphical distribution.

4.2 KNOWN STRATIGRAPHIC AND SPATIAL TRENDS

Known stratigraphical and regional trends in the facies composition of the Oxford Clay are as follows:

1. Organic-rich laminated mudstones are mainly confined to the Peterborough Member.
2. Increased silt content in the lower part of the Peterborough Member in SW England. Bristow et al. (1995) identified silty mudstone equivalent to the lower part of the Peterborough Member as the Mohuns Park Member.
3. Increased silt content in the Weymouth Member of the Cleveland Basin.
4. Increased limestone in the top of the Stewartby Member in the South Midlands (Norris and Hallam, 1995).
5. Greater tendency for organic-rich laminated beds to occur in the Peterborough Member on the East Midlands Shelf compared to SW England (Woods et al., in review).
6. Tendency for pale, calcareous mudstone to be more prevalent in the Peterborough Member across the Anglo-Brabant Massif (Woods et al., in review).
7. Tendency for shell-rich mudstone to occur in the Peterborough Member at the edge of the Weald Basin (Woods et al., in review).

4.3 FACIES DISCRIMINATION USING GEOPHYSICAL LOGS

Borehole geophysical logs provide continuous downhole records of rock physical properties (and any contained pore fluids) such as natural radioactivity, electrical resistance and sonic velocity and they can act as powerful discriminators of different rock types (facies), providing valuable information where this is often absent such as in uncored boreholes (Newell et al., 2020).

Cross-plots of different geophysical log types (on two or more axes) can sometimes be used to isolate discrete (but generally overlapping) clusters that are representative of different rock types (Newell et al., 2020). This approach was attempted for the Oxford Clay using gamma-ray and sonic travel time logs but all of the cross-plots produced relatively amorphous point clouds with no clear discrimination of clusters that could be directly mapped to the typical Oxford Clay facies types shown in Table 6. Further work with additional log types and other methods (see Newell et al., 2020) may produce improved cluster discrimination but, for the present work, the cross-plots were simply segregated into quadrants using the median (P50) value of each gamma-ray and sonic transit time distribution within the Oxford Clay log interval (Figure 17A). This effectively created four 'electrofacies' which can be broadly mapped to lithofacies. For example, limestones will fall within low gamma ray/low sonic transit time (fast) sector while mudstones (and particularly organic rich mudstones) will have high gamma-ray and high sonic transit times (Figure 17A). The relationship of the electrofacies classification to actual lithology or lithofacies can be checked by creating a facies stratigraphy using the P50 cut-off values and comparing against known rock properties from core and cuttings (Figure 17B). A histogram showing the relative proportion of each electrofacies is shown in Figure 18A.

The results of the geophysical log electrofacies classification confirm many of the known facies trends in the Oxford Clay. In boreholes such as Winterborne Kingston each member broadly represents an upward transition from mudstone to more carbonate-rich facies (Figure 17B). Taking the dataset as a whole, two mudstone>carbonate cycles are particularly clear (Figure 18B). The main carbonates occur at the top of the Stewartby and Weymouth Members.

The development of carbonate shows strong regional variation. In areas of thinner Oxford Clay on the Anglo-Brabant Massif the carbonate is strongly condensed into a single unit at the top of the Stewartby Member: the Lamberti Limestone (Figure 19). Correlation panels show that this limestone becomes more diffuse as the Oxford Clay thickens into basinal areas in south Dorset (Figure 19). A similar pattern is observed in correlation panels which pass from the thin Oxford Clay successions of the Weald Basin into the south Dorset area (Figure 20). Facies proportion maps broadly confirm this trend (Figure 18C).

In the thick Oxford Clay successions of south Dorset, the basal part of the Peterborough Member is characterised by a wedge of lithofacies with characteristic high gamma-ray response and low sonic travel times (Figure 19 and Figure 20). Comparison to cutting suggests these are well-cemented siltstones, possibly analogous to the Mohuns Park Member. Their basinal location suggests they represent a low-stand wedge of relatively coarse-grained sediment that accumulated prior to significant Oxford Clay sea-level rise.

4.4 BIOFACIES

Historical work on the Peterborough Member (Duff, 1974, 1975) revealed the potential for using particular associations of fossils (biofacies) in intervals of sediment to infer aspects of the depositional environment and explain features of the associated lithofacies. Across multiple sites, stratigraphical changes in biofacies patterns can be used to understand the evolution of depositional environments and the contemporaneous gradients that existed between them. This technique has been further developed by Woods et al. (in review), using detrended correspondence analysis and clustering to explore the extent and nature of environmental heterogeneity in the Peterborough Member, and how this is manifest in the sediment record. Figure 14 shows the pattern of biofacies determined using this approach for borehole successions at the northern margin of the Wessex Basin.

5 Conclusions

- The Oxford Clay thickens from NE to SW across its outcrop/subcrop distribution.
- The structurally deepest part of the Oxford Clay does not correspond to the thickest Oxford Clay: the Weald Basin having been an area of low subsidence/low deposition rate during the Oxford Clay.
- The Weymouth Member at the top of the Oxford Clay provides some evidence for the activation of the Weald Basin as a depocentre.
- There are strong shelf to basin trends in lithofacies distribution.

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British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://of-ukrinerc.olib.oclc.org/folio/.

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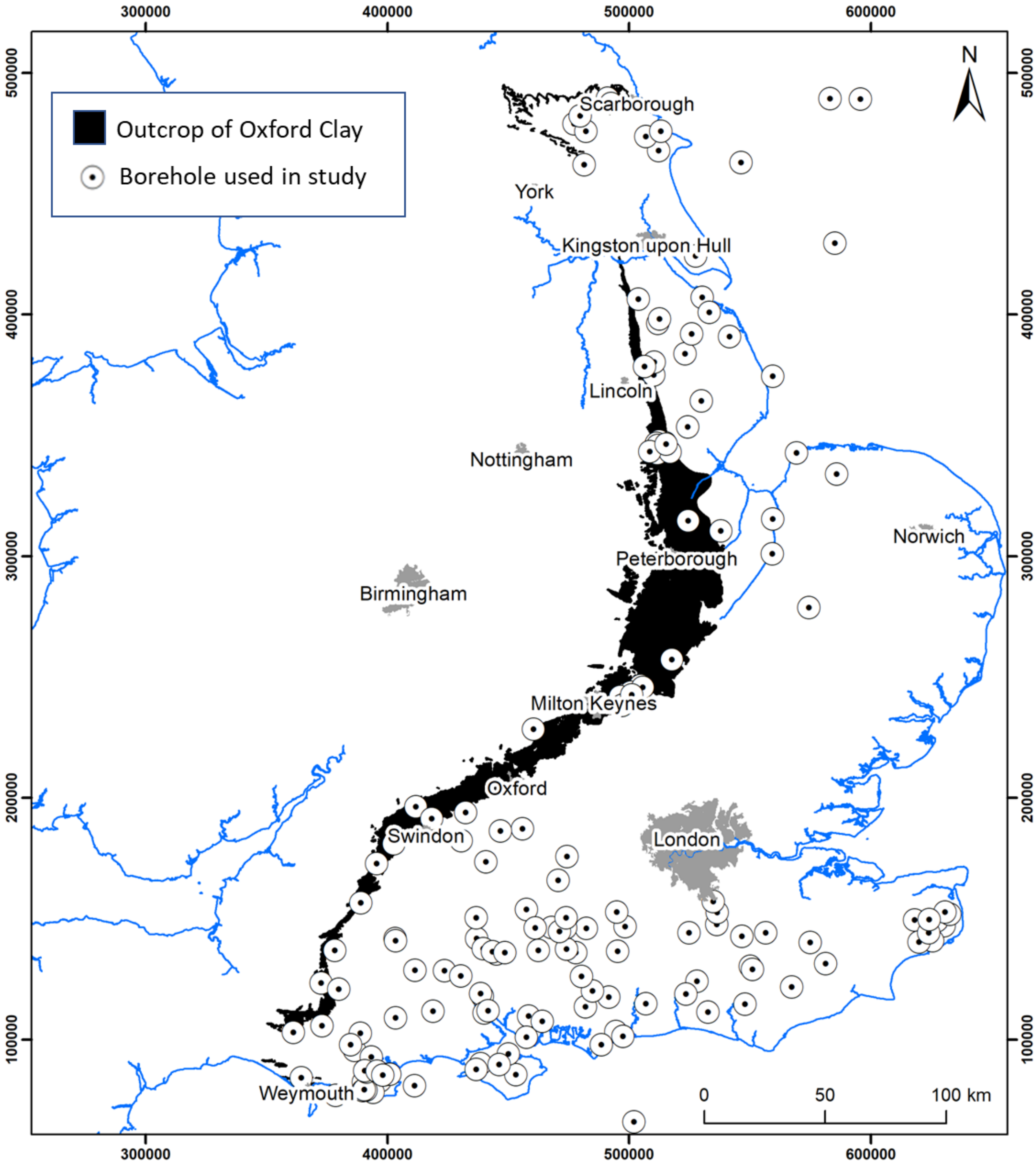

Figure 1 Location map showing outcrop of Oxford Clay Formation and boreholes used in the study which broadly define the subcrop extent of the formation. Contains Ordnance Survey data © Crown copyright and database rights 2021.

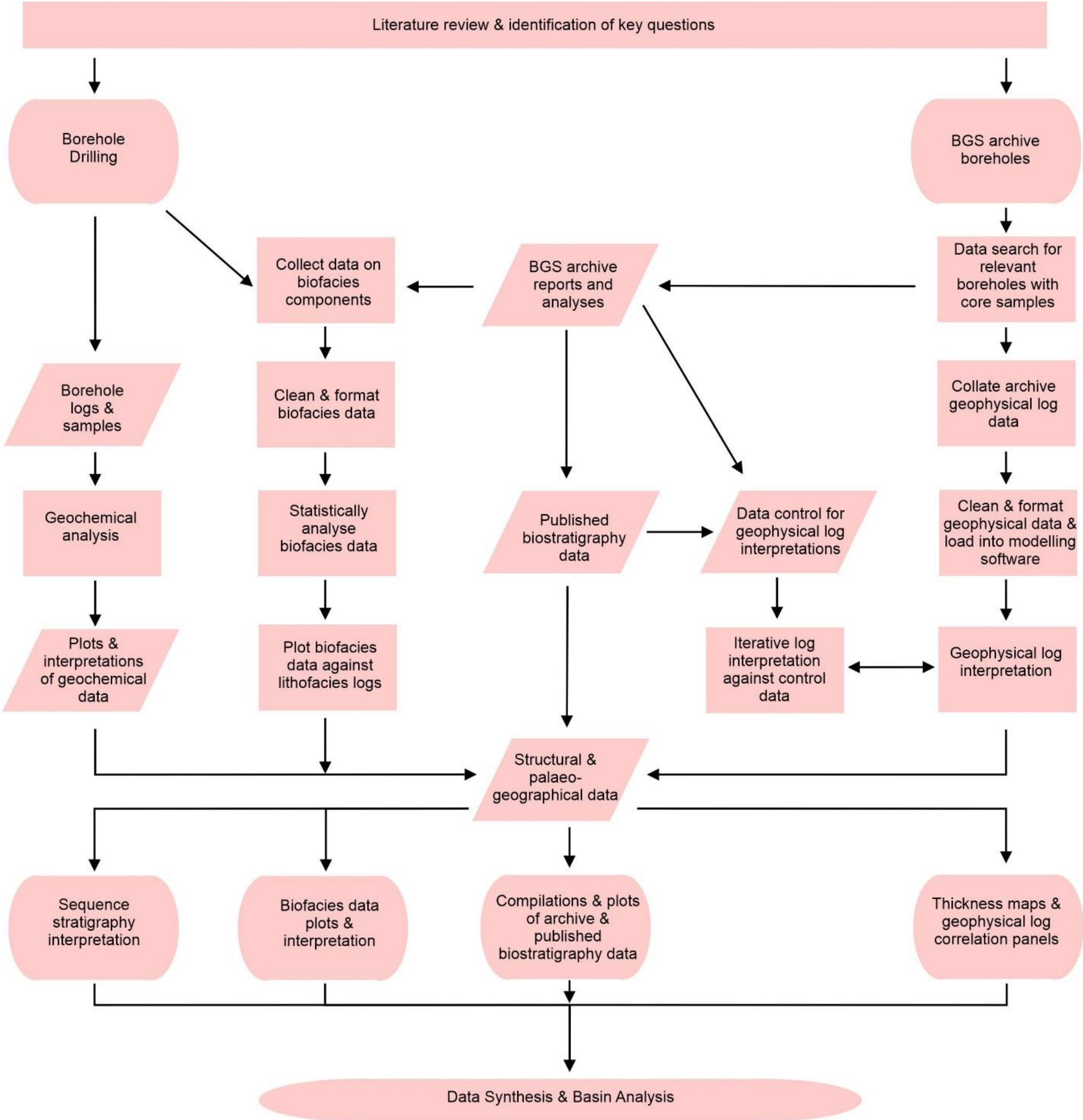

Figure 2 Project workflow showing key information sources and stages of data acquisition, formatting and analysis needed to derive key interpretational outputs.

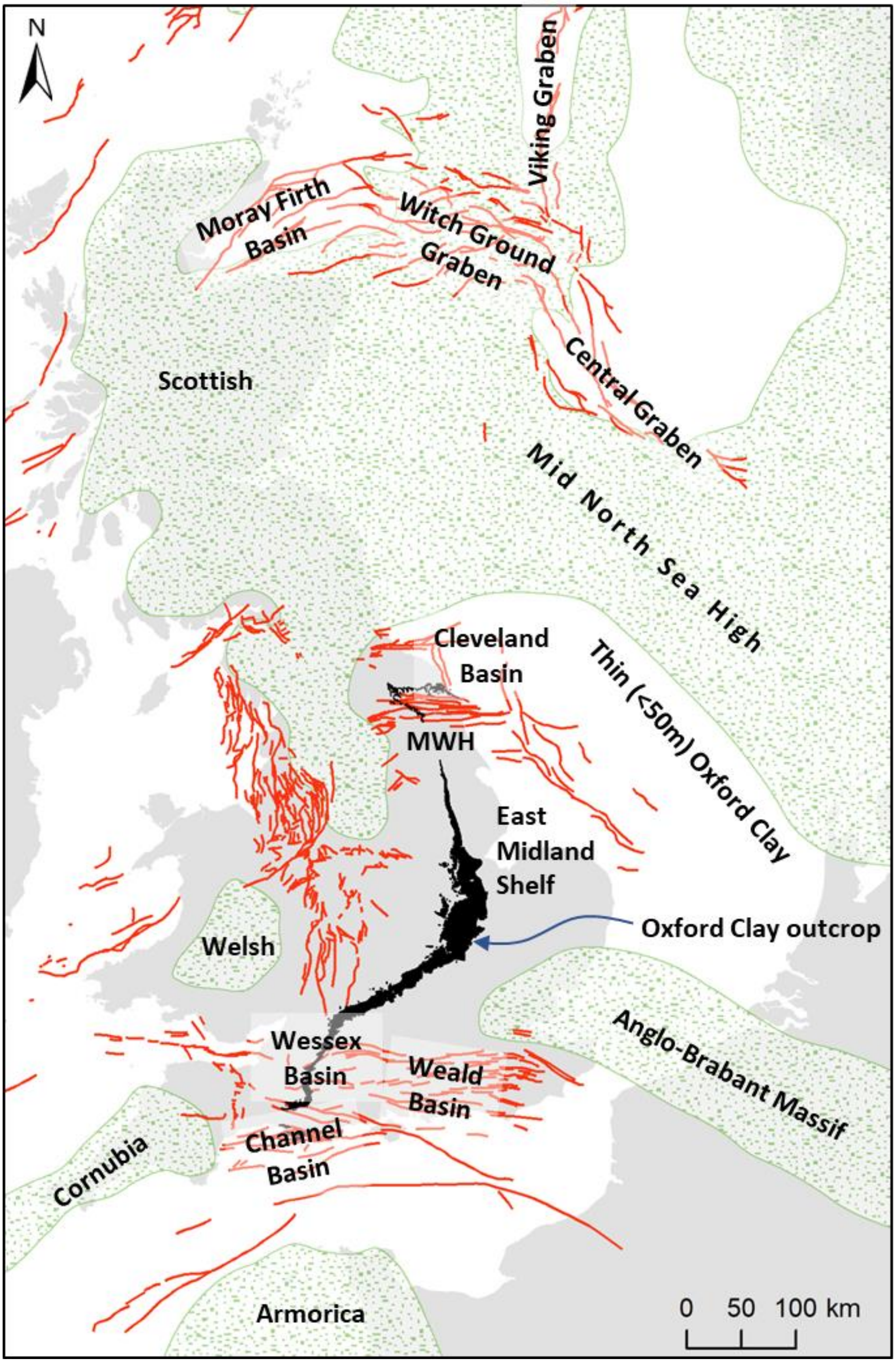

Figure 3 Relationship of current outcrop of the Oxford Clay to Early Callovian palaeogeography and depositional basins. Probable land areas are shown in green stipple but, in most cases, the evidence that these formed areas of non-deposition or erosion is uncertain due to large-scale Cenozoic uplift and erosion. Contains Ordnance Survey data © Crown copyright and database rights 2021.

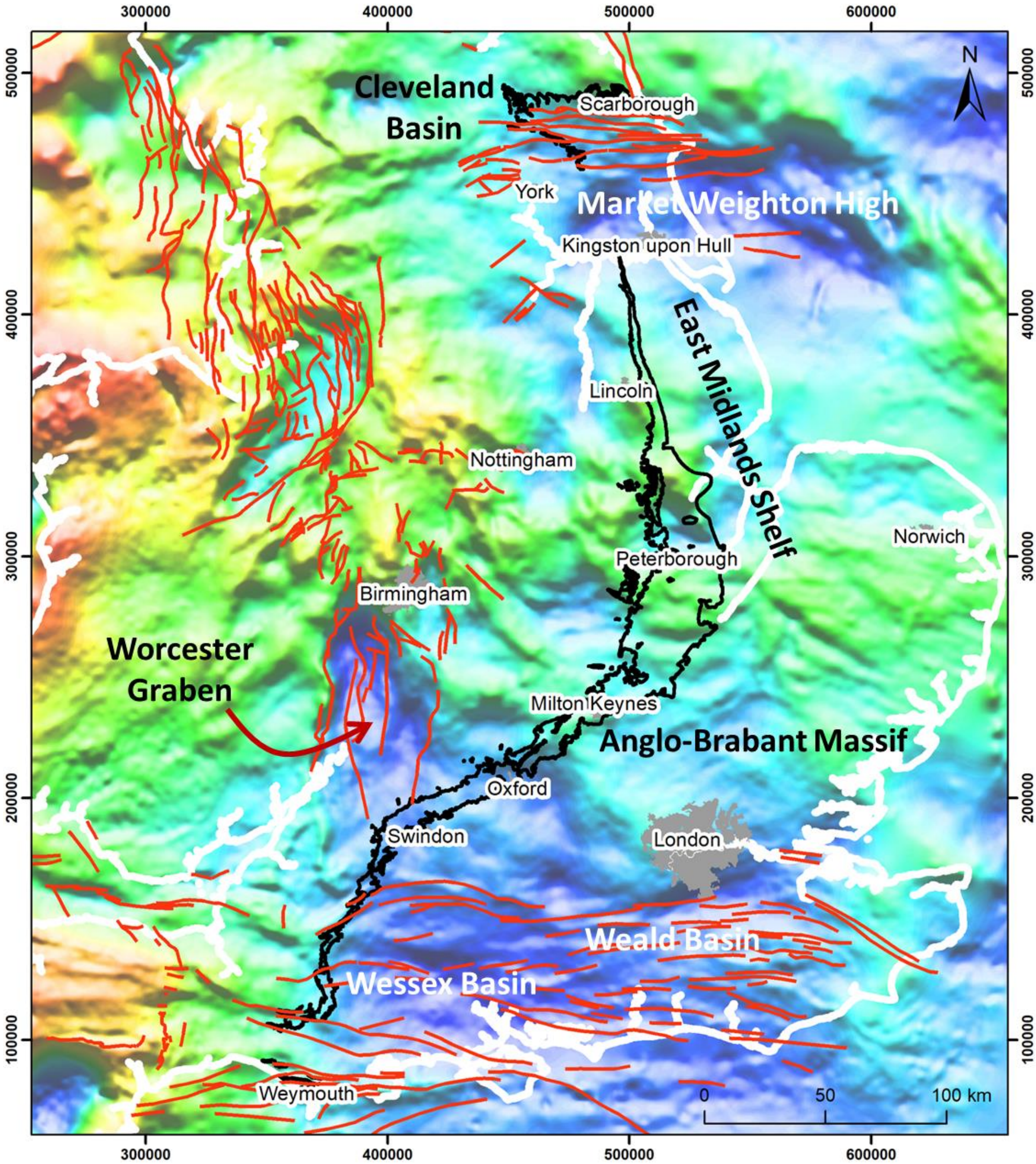

Figure 4 The outcrop of the Oxford Clay (black outline) in the structural framework of southern Britain shown by major Jurassic faults (red lines) from BGS Tectonic map of Britain, Ireland and adjacent areas and BGS regional gravity anomaly map. In broad terms the blues are attributable to large volumes of low density rocks, the reds to high density rocks. Significant lows occur, for instance, over areas of thick, low density sedimentary rocks (e.g. Worcester Graben, Wessex Basin), or large granites (e.g. Market-Weighton High). Contains Ordnance Survey data © Crown copyright and database rights 2021.

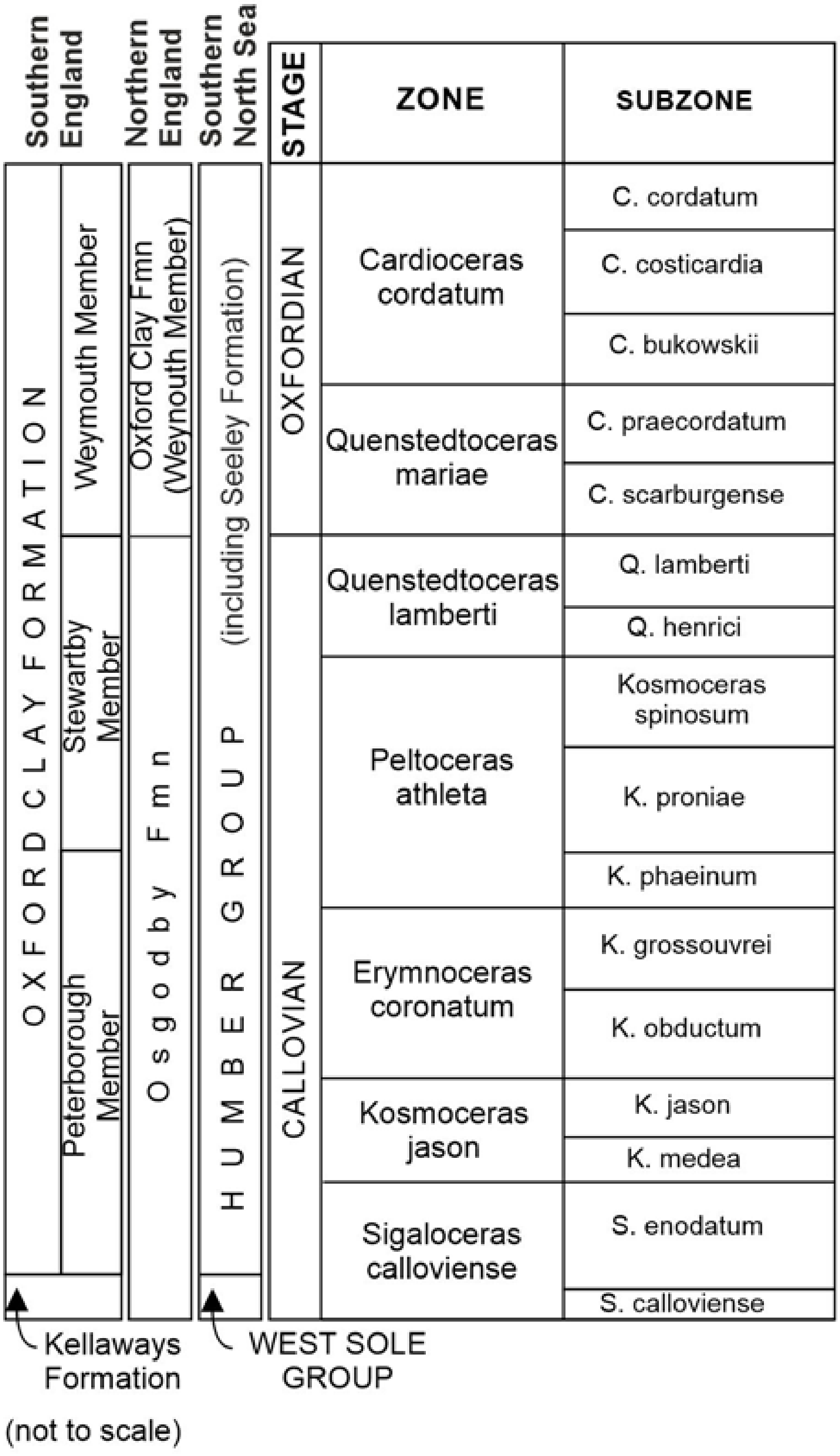

Figure 5 Ammonite biozonation of the Oxford Clay and coeval subdivisions in northern England and the southern North Sea.

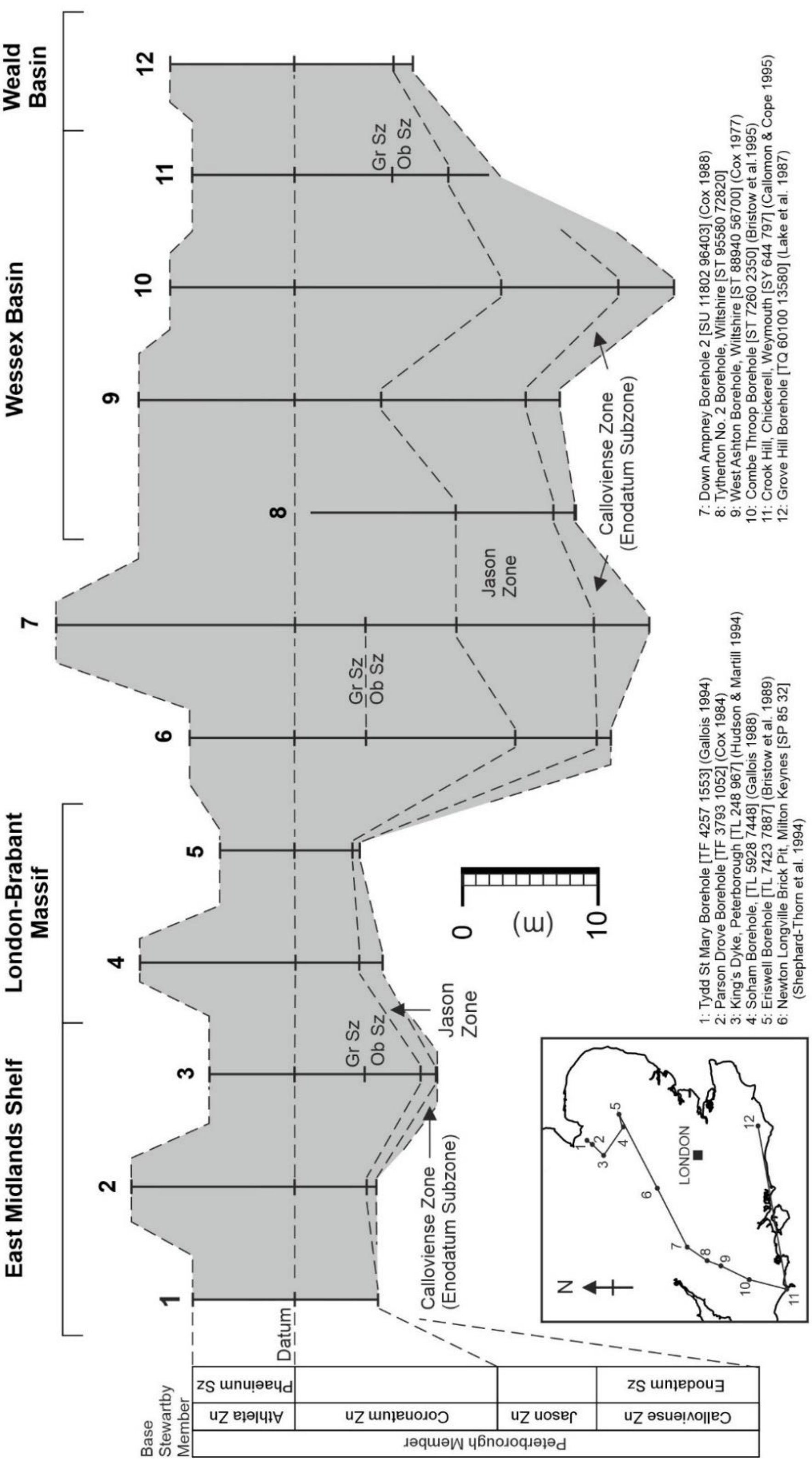

Figure 6 Biostratigraphical correlation of key outcrops and boreholes in the Peterborough Member of the Oxford Clay Formation. Biozones are generally thin across the East Midlands Shelf and Anglo-Brabant Massif, but significantly thicken into the Wessex Basin, before thinning into the Weald Basin.

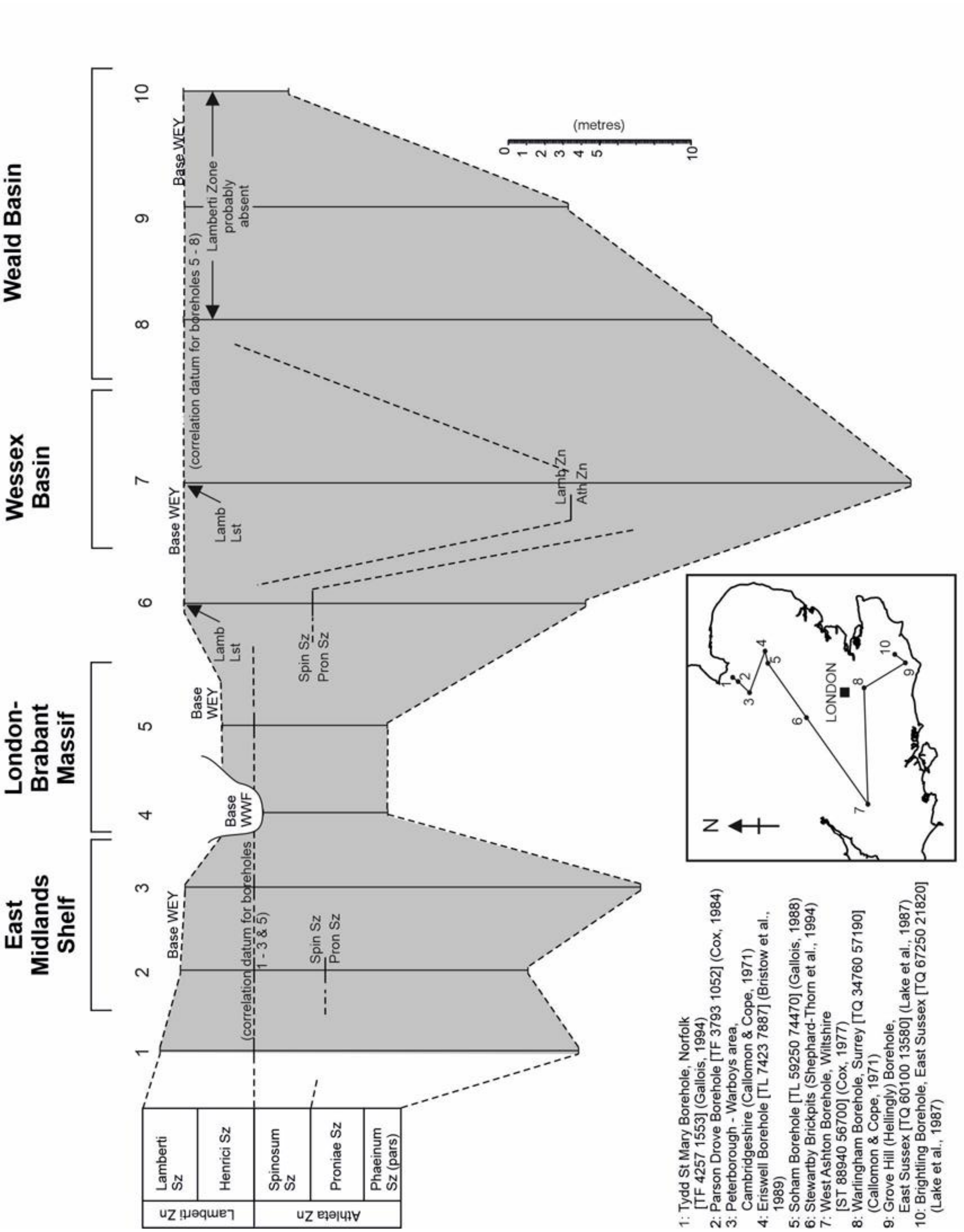

Figure 7 Biostratigraphical correlation of key outcrops and boreholes in the Stewartby Member of the Oxford Clay Formation. Significant thinning and erosion of the Stewartby Member occurs across the London-Brabant Massif, with moderate thicknesses on the East Midlands Shelf and substantial thickening into the Wessex Basin. A thinning trend occurs into the Weald Basin

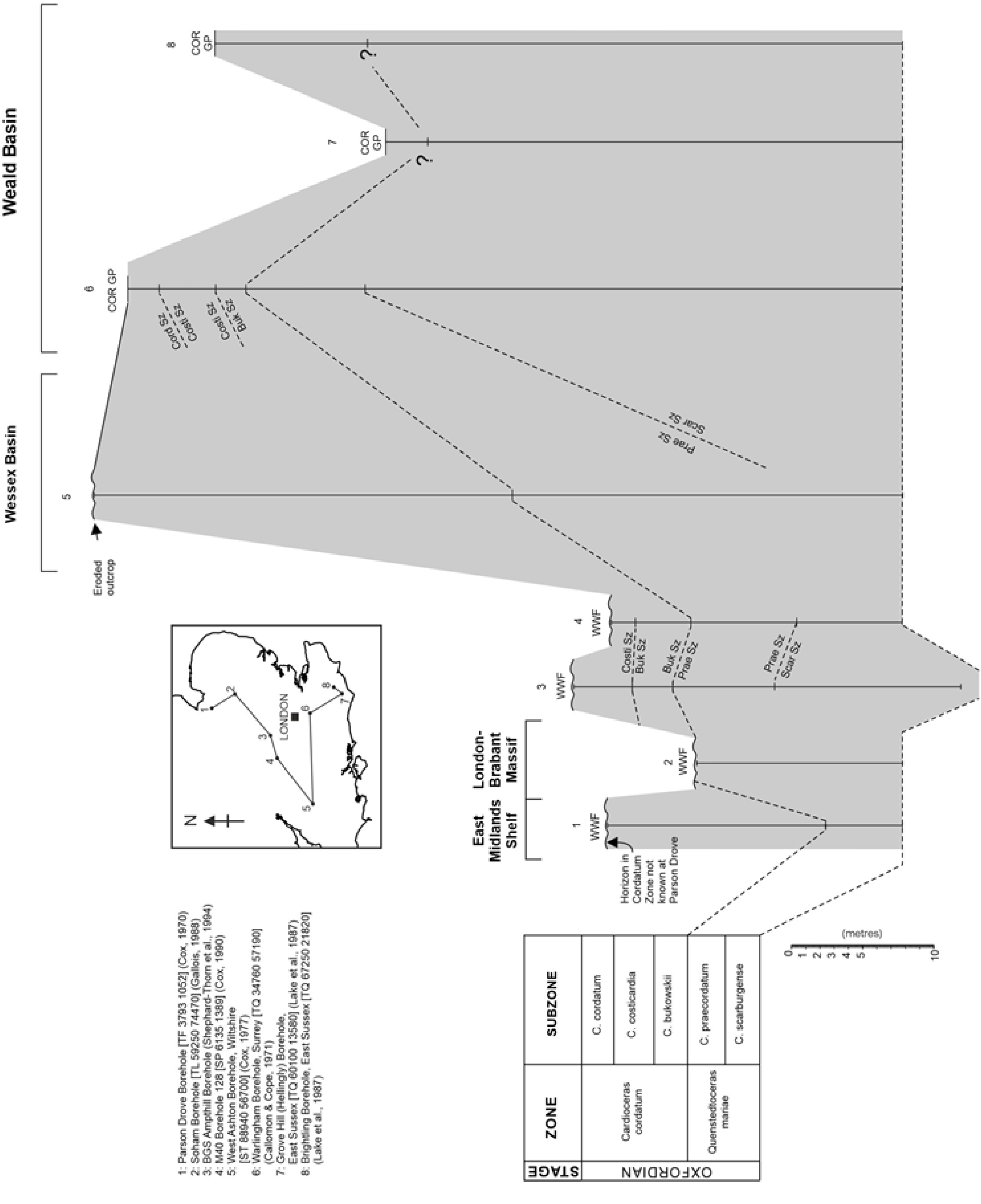

Figure 8 Biostratigraphical correlation of key boreholes in the Weymouth Member of the Oxford Clay Formation.Thin successions in the Weymouth Member on the East Midlands Shelf and across the Anglo-Brabant Massif contrast with much thicker successions in the Wessex and Weald basins. In the Weald Basin, the lower part of the Weymouth Member (Mariae Zone) is very significantly thickened compared to the Wessex Basin.

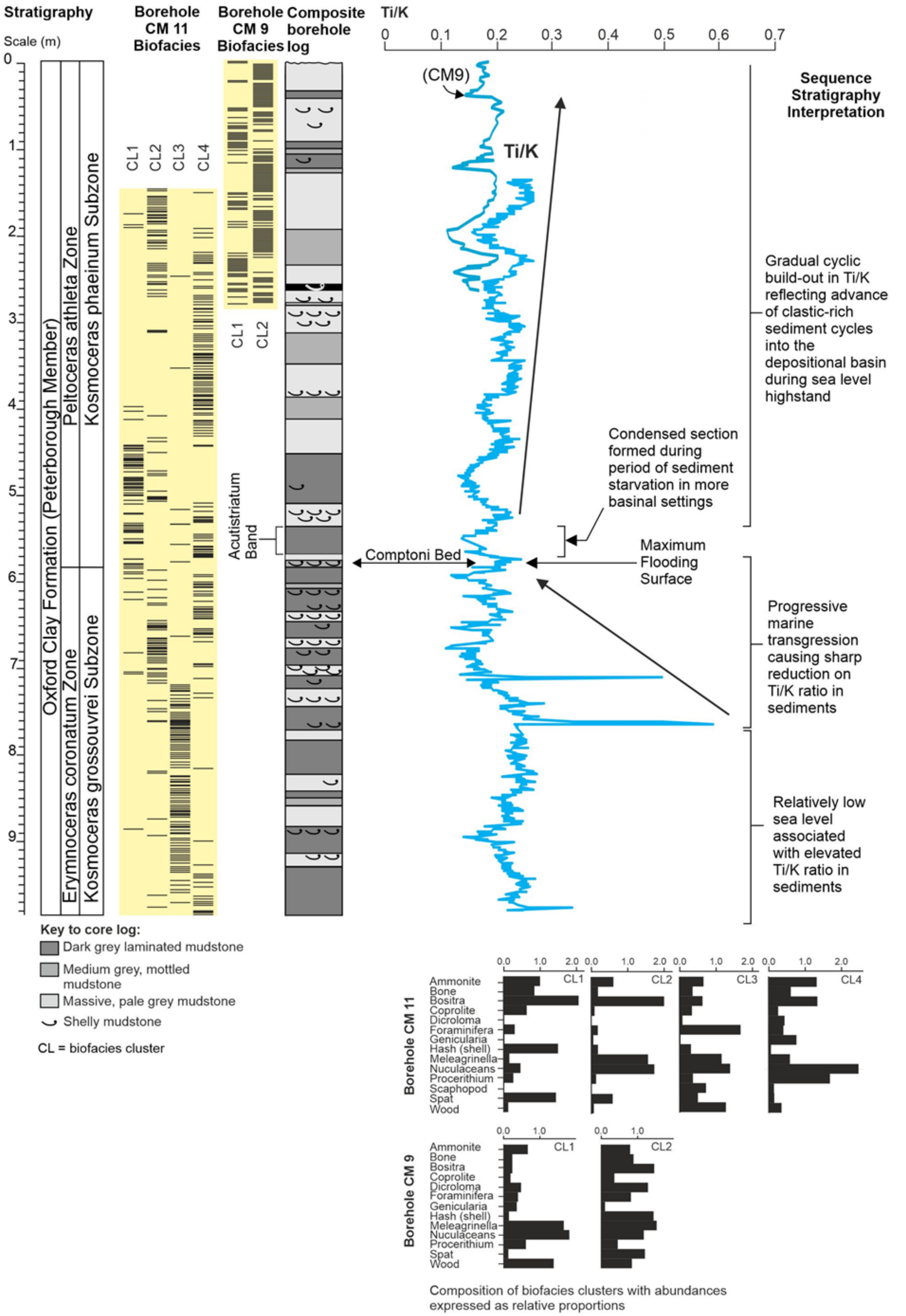

Figure 9 Biofacies, geochemistry and sequence stratigraphy for cored boreholes on the northern margin of the Wessex Basin. Biofacies data show that particular associations of fossils are dominant over parts of the borehole succession. The ecological factors that are inferred to

influence the component taxa of biofacies can be used to understand patterns of environmental change through the sedimentary succession, and related to lithological and geochemical data to infer sequence stratigraphy. The ratio of Ti/K is a proxy for varying detrital content, and the cyclic changes in this ratio can be used to infer the changing length of sediment pathways caused by relative sea level change.

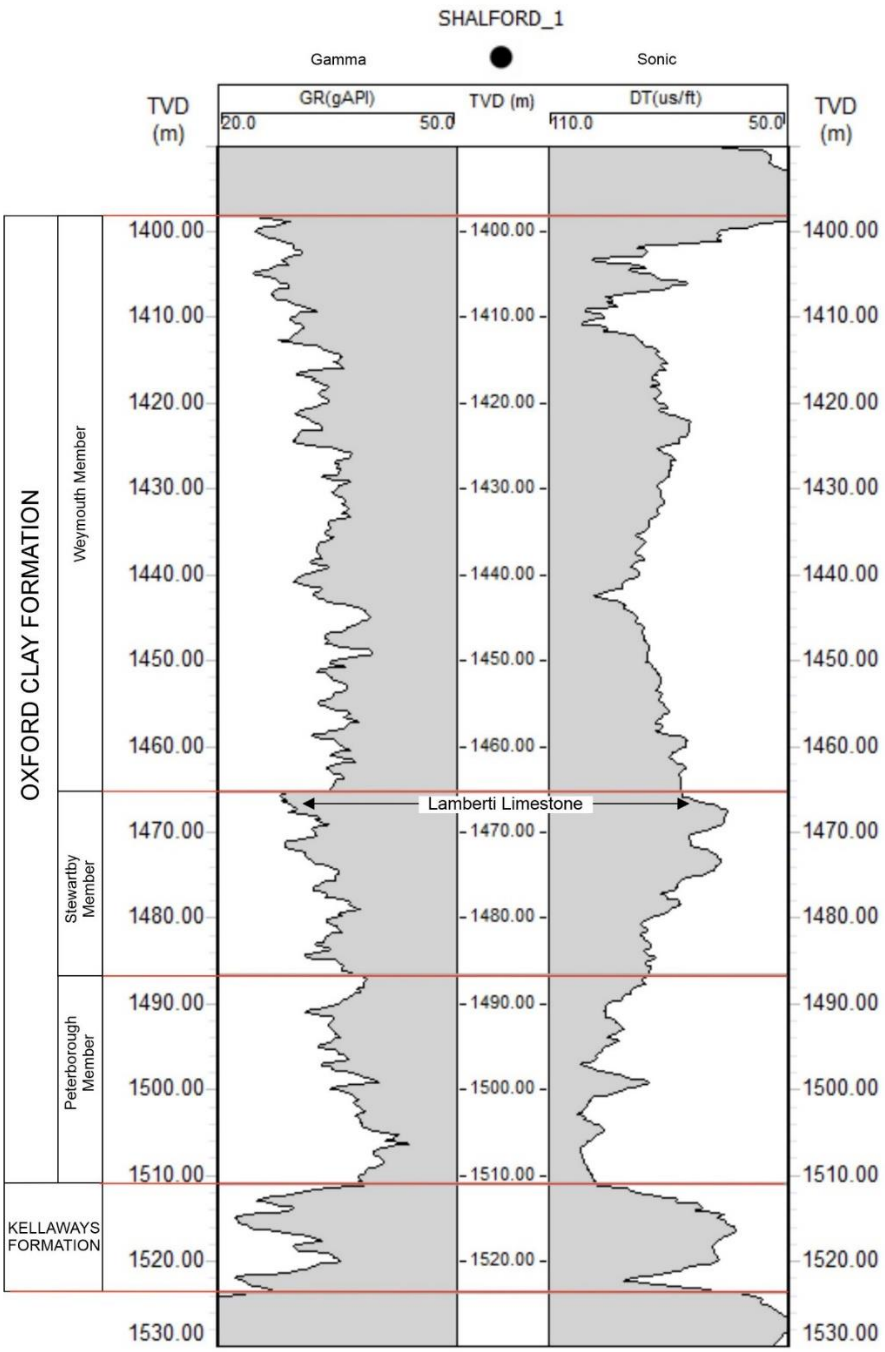

Figure 10 Typical Gamma-ray and sonic log responses in the Oxford Clay Formation. Organic-rich mudstones are typified by high gamma log values and low sonic velocities, whereas limestones (e.g. Lamberti Limestone) are associated with lower gamma log values and higher sonic velocity.

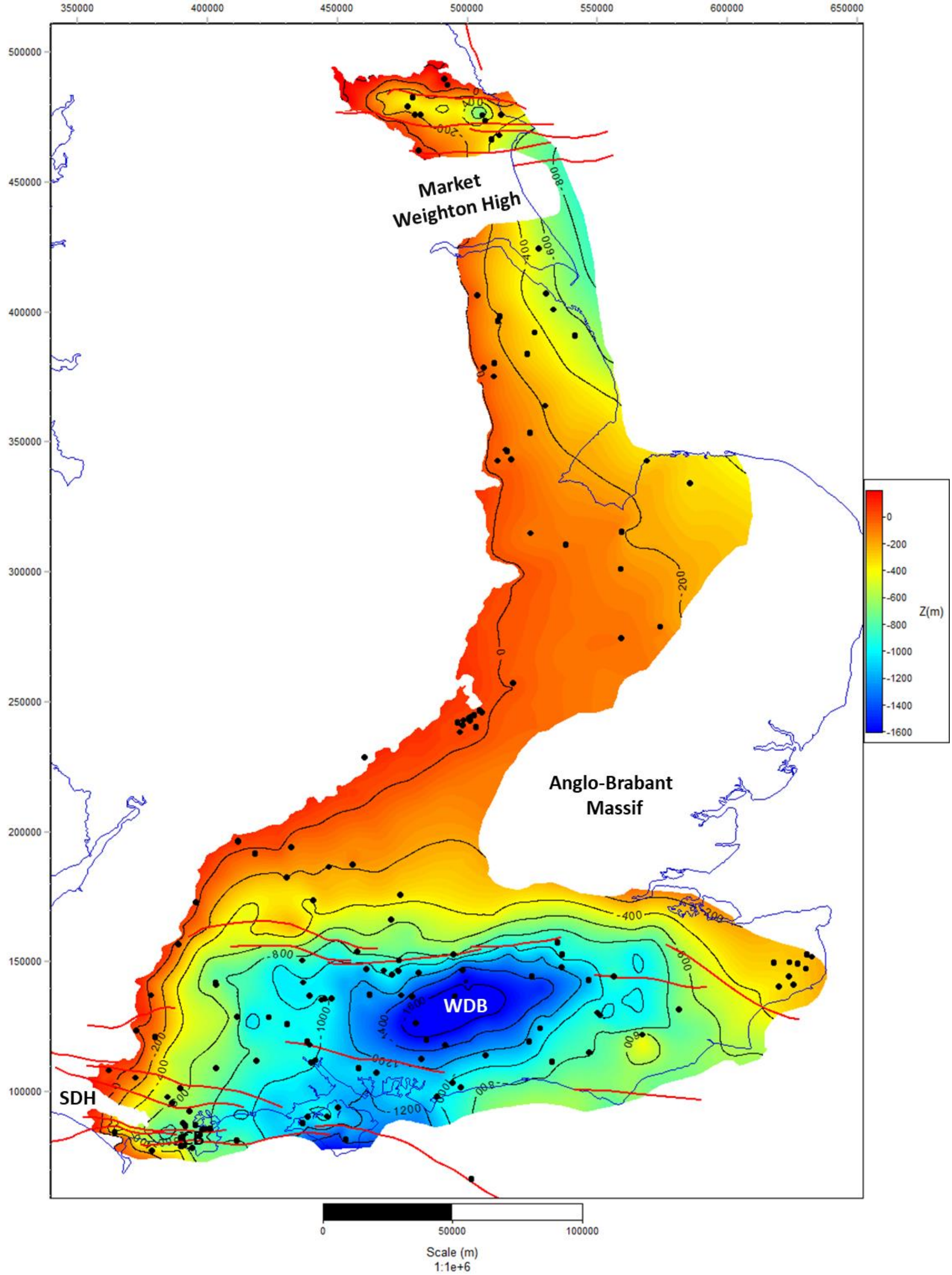

Figure 11 Elevation of the base Oxford Clay Formation (WDB=Weald Basin, SDH=South Dorset High). Contains Ordnance Survey data © Crown copyright and database rights 2021.

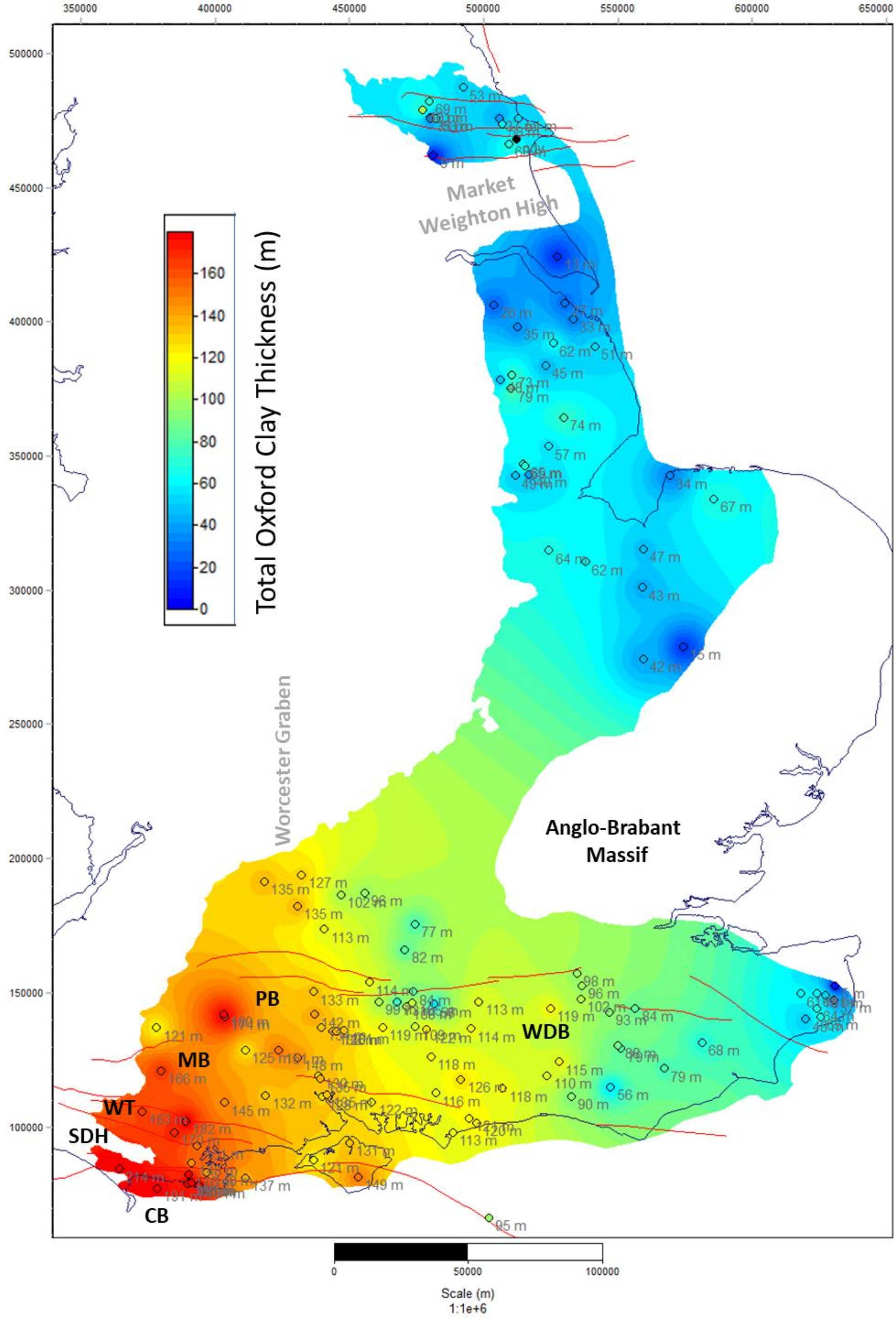

Figure 12 Total thickness map of the Oxford Clay Formation (CB=Channel Basin, SDH=South Dorset High, WT=Winterborne Trough, MB=Mere Basin, PB=Pewsey Basin, WDB=Weald Basin). Contains Ordnance Survey data © Crown copyright and database rights 2021.

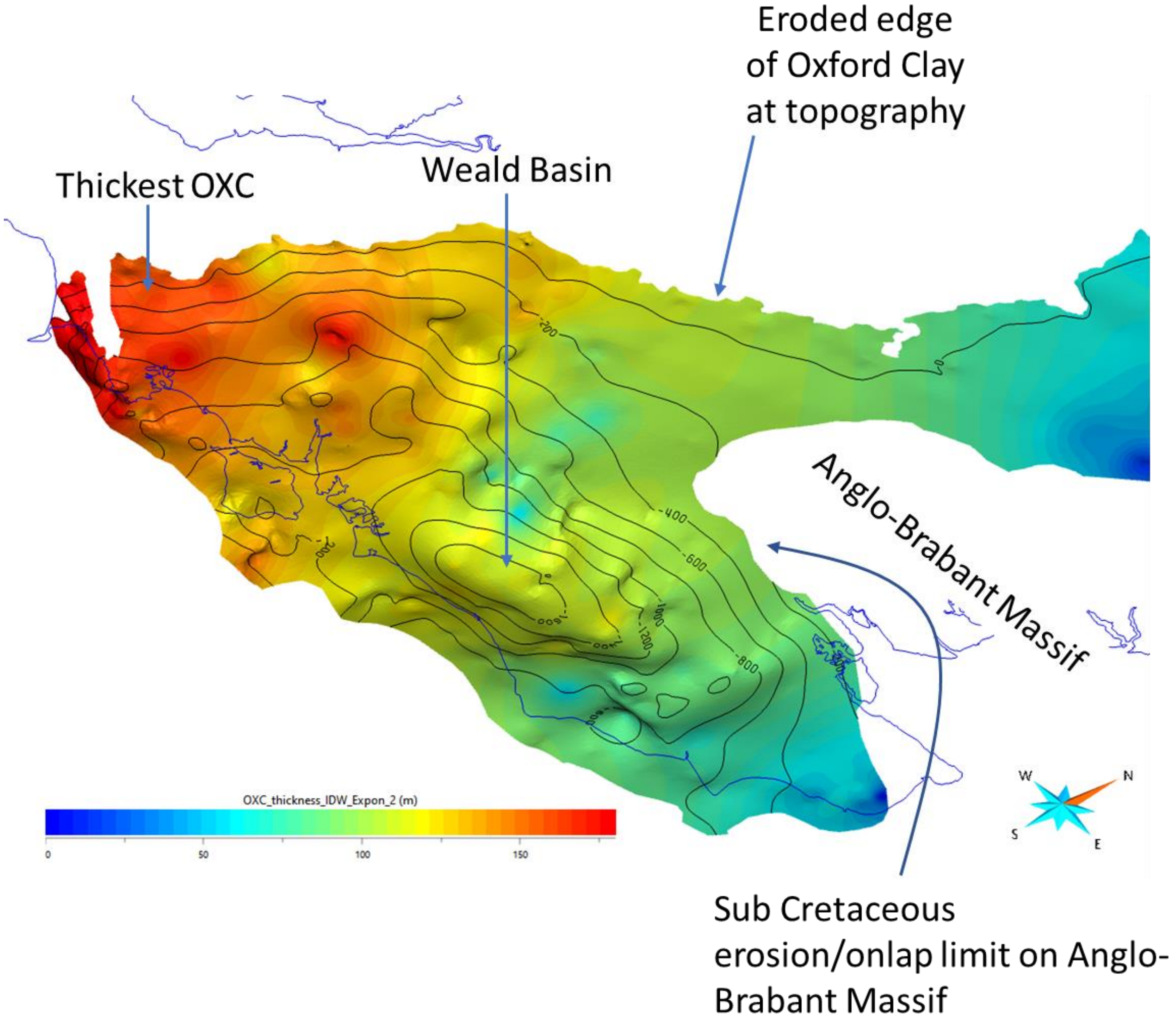

Figure 13 Perspective view showing the offset between the structurally deepest part of the Oxford Clay Formation and the thickest part of the Oxford Clay in south Dorset close to the eroded outcrop margin. Contains Ordnance Survey data © Crown copyright and database rights 2021.

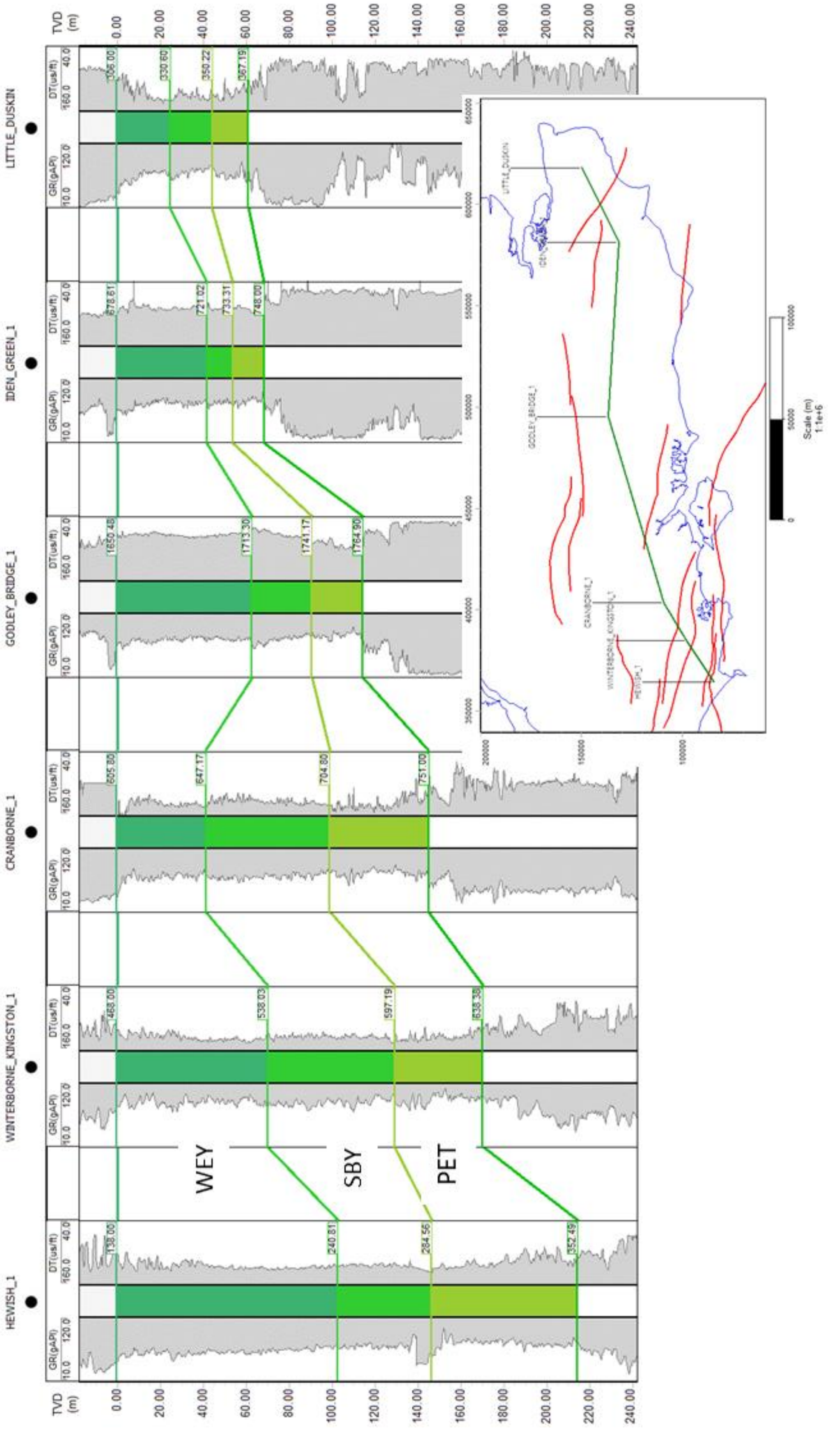

Figure 14 Correlation of borehole geophysical (gamma) logs in the Oxford Clay of southern England showing pattern of eastward thinning into the Weald basin, and westward thickening into the Wessex Basin. Contains Ordnance Survey data © Crown copyright and database rights 2021.

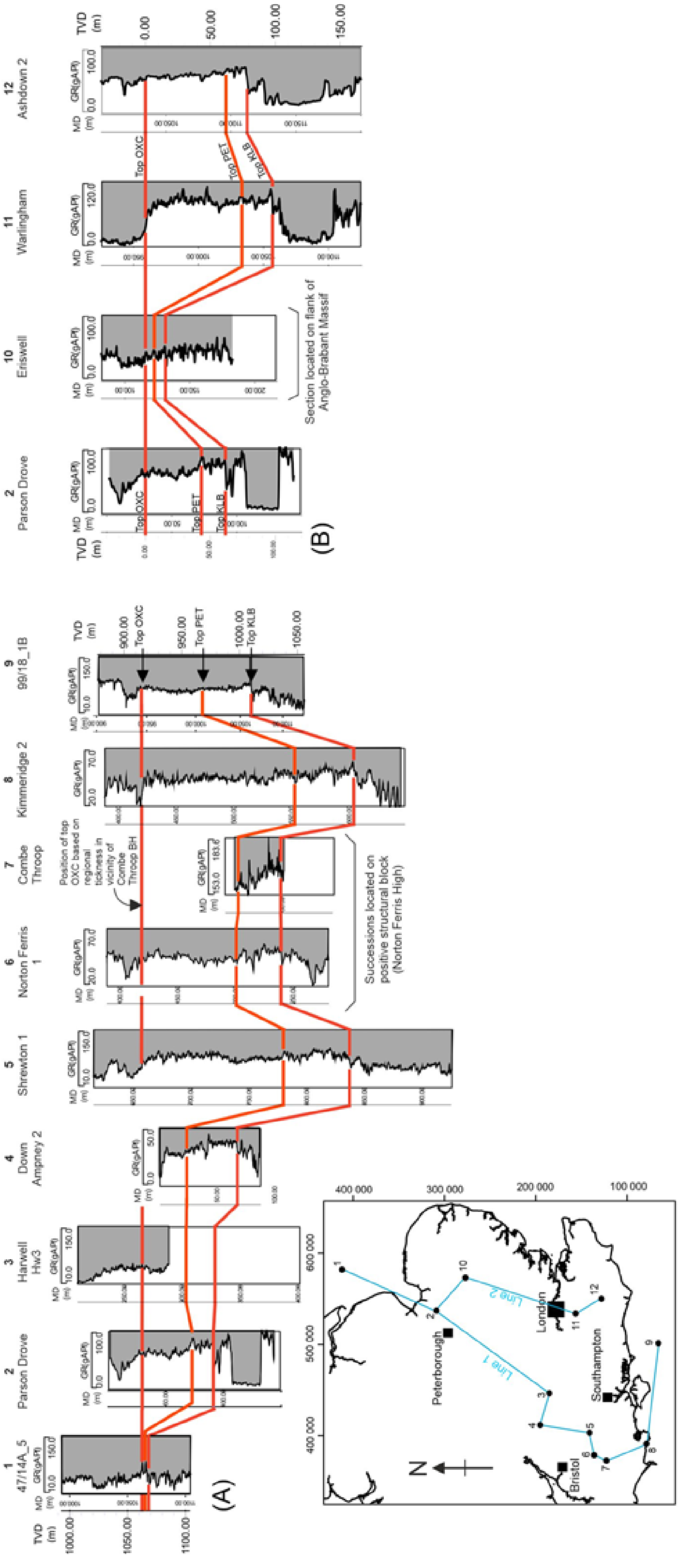

Figure 15 Log correlations across the Anglo-Brabant Massif into the Wessex-Weald basins. The Oxford Clay is very thin in the southern North Sea, thickening somewhat onto the East Midlands Shelf and then thickening significantly into the Wessex Basin. Parts of the Wessex Basin contain fault bounded massifs, and thinning in the Norton Ferris and Combe Throop boreholes probably reflects the influence of the Norton Ferris High. Correlation between the East Midlands Shelf and Wessex Basin shows the extreme thinning associated with the intervening Anglo-Brabant Massif.

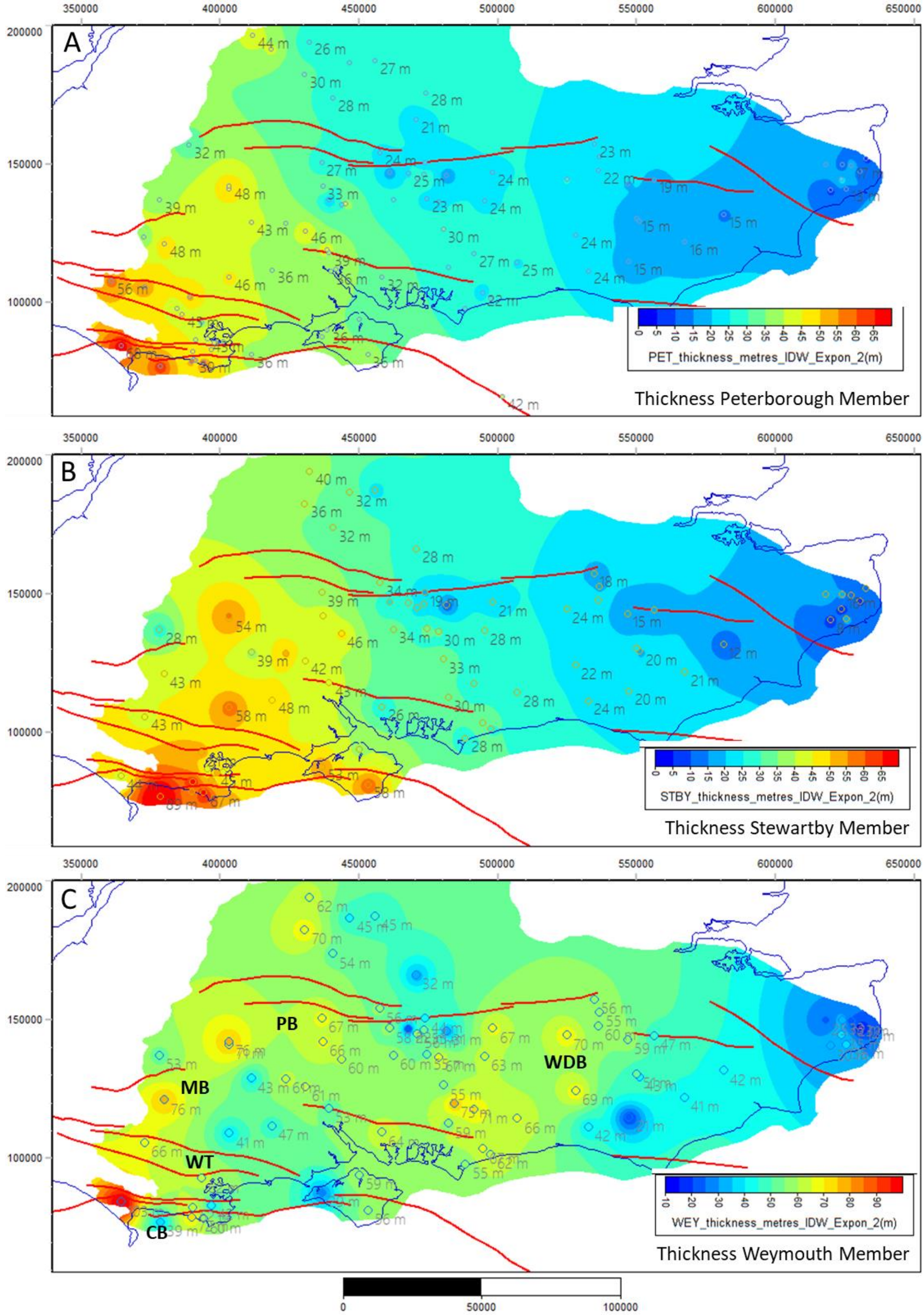

Figure 16 Thickness map of the (A) Peterborough Member, (B) Stewartby Member (C) and Weymouth Member in the Wessex-Weald basins. (CB=Channel Basin, SDH=South Dorset High, WT=Winterborne Trough, MB=Mere Basin, PB=Pewsey Basin, WDB=Weald Basin). The Peterborough and Stewartby members are characterised by similar thickness patterns, with significantly thin successions in the eastern Weald, and a sharp gradient of thickening into the Wessex Basin. The thickest parts of these successions occur close to the Dorset coast, associated with a narrow corridor of faulting. In contrast, westward thickening of the Weymouth Member occurs across a broader geographical range, with evidence that the western part of the Weald Basin is beginning to function as a depo-centre. Contains Ordnance Survey data © Crown copyright and database rights 2021.

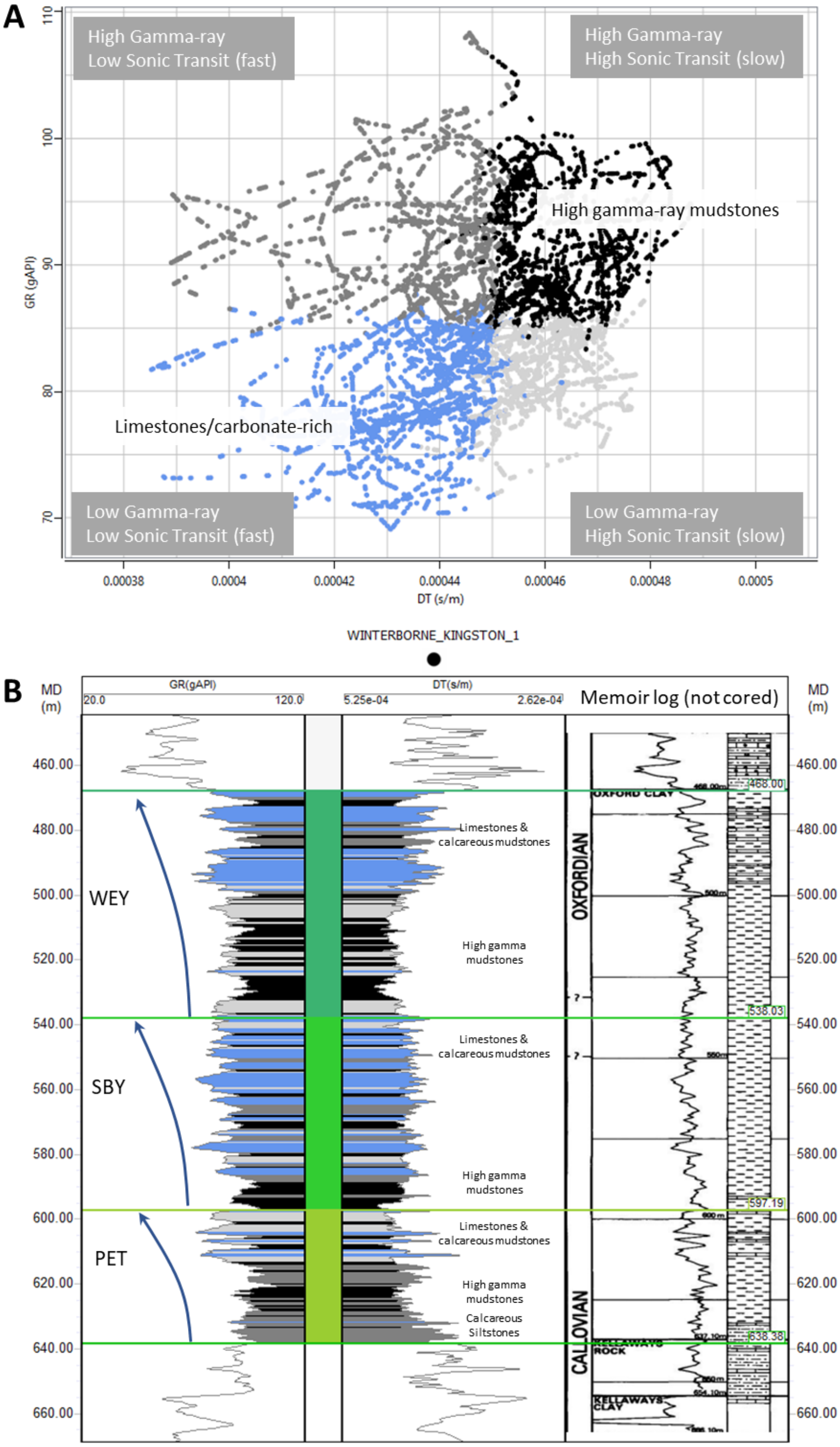

Figure 17 (A) Cross-plot of gamma-ray and sonic transit time for the Oxford Clay Formation in the Winterborne Kingston borehole. The cross-plot does not reveal clear clusters but can be simply segregated into quadrants using the median value (P50) of each distribution. The low gamma/low sonic transit sector is likely to map to limestones while high gamma/high sonic transit times sector will map to mudstones. In the lower image (B) the classification shown in the cross-plot is mapped to the geophysical logs to reveal the stratigraphical patterns. Composite log is shown for comparison. The Oxford Clay interval was not cored and the precise basis for the generalised lithological classification is unknown but probably geophysical logs and cuttings.

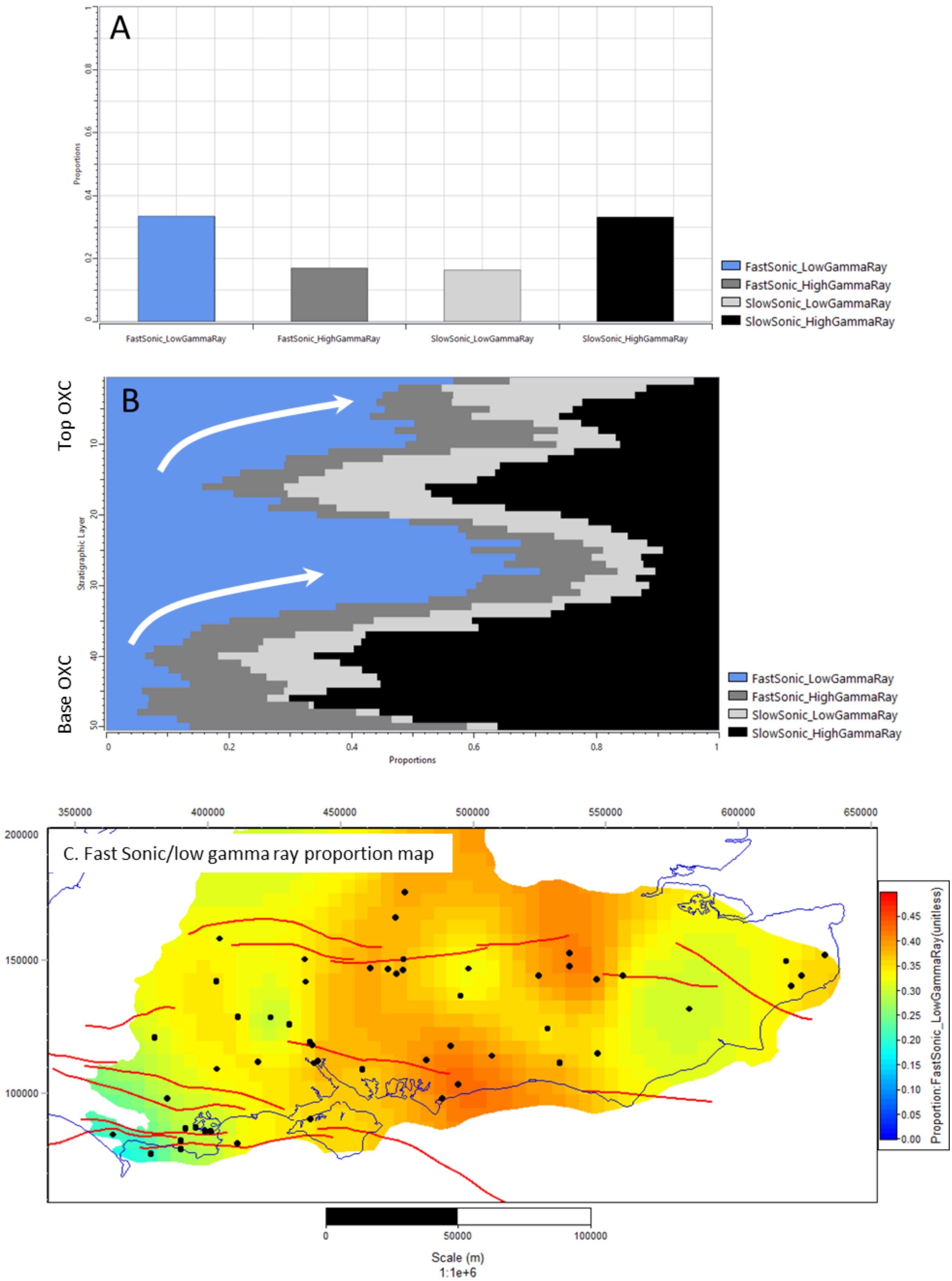

Figure 18 (A) Relative proportion of the different electrofacies within the borehole set (B) Vertical trends in the proportion of different facies, (C) Map showing the proportion of fast sonic/low gamma ray electrofacies (approx. limestones) with decrease into deeper basinal areas in south Dorset. Contains Ordnance Survey data © Crown copyright and database rights 2021.

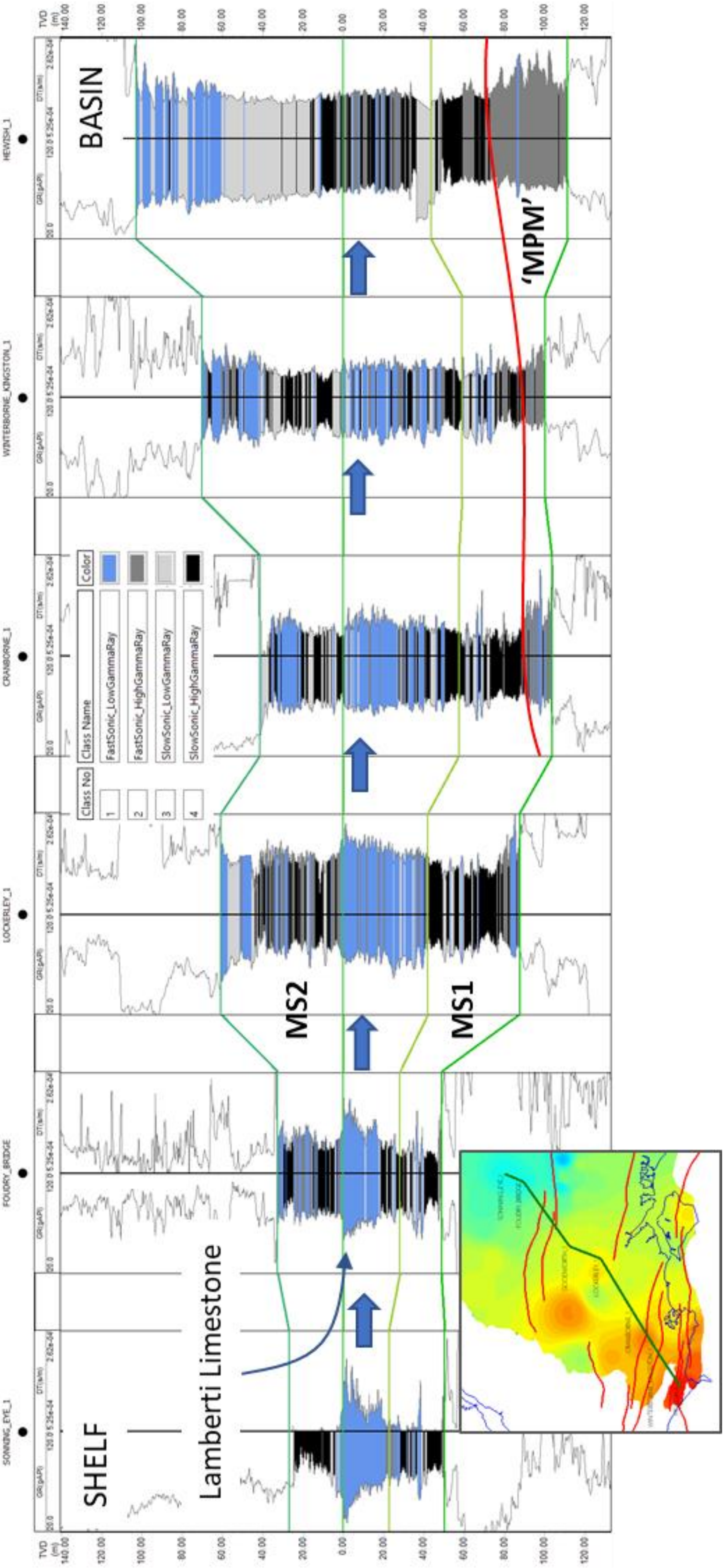

Figure 19 Shelf to basin trends revealed by classifying gamma ray and sonic travel time logs into four classes ('electrofacies') based on median values for each curve. In shelf areas the Lamberti Limestone forms a single well-developed unit in thin Oxford Clay successions with high gamma/slow sonic mudstones (black) above and below. In basinal successions, blue low gamma/fast sonic (limestones and carbonate rich 'muds') become more diffuse. Contains Ordnance Survey data © Crown copyright and database rights 2021.

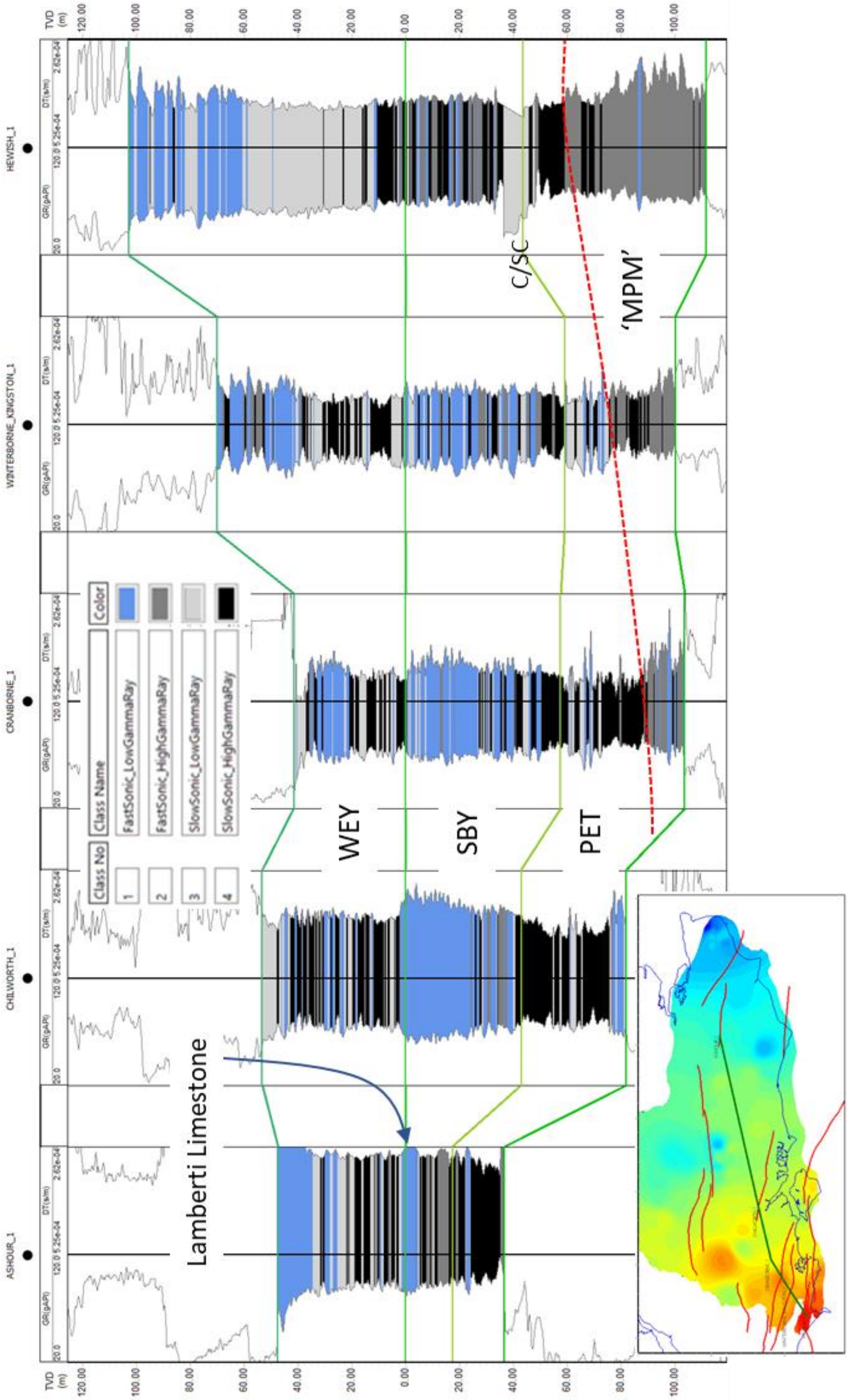

Figure 20 Section across the Weald and Wessex basins showing similar discrete condensation of carbonate units at the top of the Stewartby Member. Contains Ordnance Survey data © Crown copyright and database rights 2021.