UK Stratigraphical Framework Series: Lower Cretaceous (Aptian-Albian) of Southern and Eastern England, and the Southern North Sea

National Geoscience Programme

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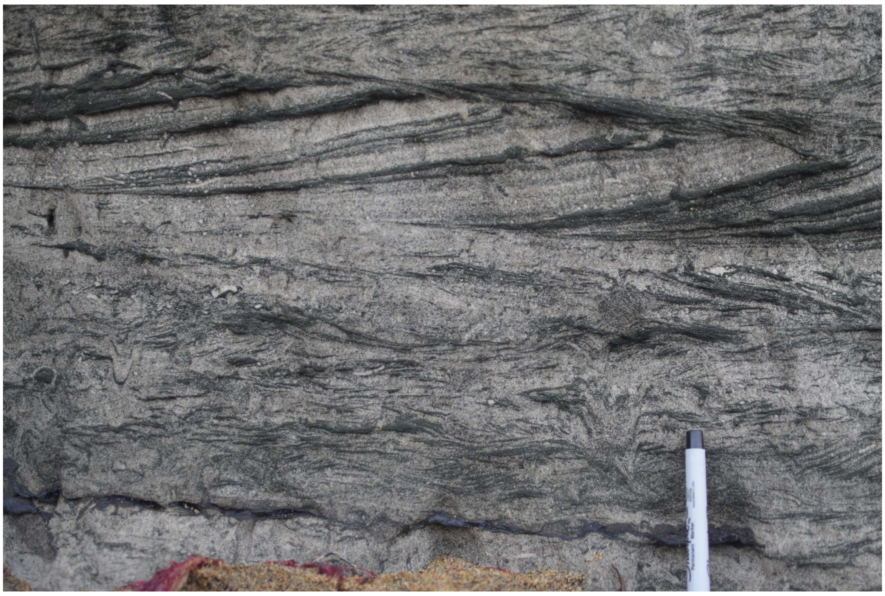

BRITISH GEOLOGICAL SURVEY

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Tidally influenced sedimentary structures in the Sandrock Formation of the Isle of Wight

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UK Stratigraphical Framework Series: Lower Cretaceous (Aptian-Albian) of Southern and Eastern England, and the Southern North Sea

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Foreword

This report provides a high-level overview of lithofacies and thickness trends within the Lower Cretaceous (Aptian-Albian) of southern and eastern England, and the southern North Sea. The report provides new information on the Lower Greensand Group and the Selborne Group based primarily on recent borehole geophysical log interpretation by the BGS. The report is designed to provide a broad national scale geological context for any future investigations of this interval.

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Summary

This report forms part of the UK Stratigraphical Framework Series (UKSFS) and provides an overview of the stratigraphy of the Aptian-Albian (Lower Cretaceous) of southern and eastern England (and adjacent offshore areas). This interval includes the Lower Greensand and the Selborne Groups, the latter comprising the Gault and Upper Greensand Formations and coeval strata of the East Midlands Shelf. This interval forms a coherent body of transgressive marine siliciclastic deposits between the terrestrial to marginal-marine Wealden Group and the carbonates of the Chalk Group.

The study adopted a surface to subsurface approach and makes extensive use of borehole geophysical log data. Stratigraphical picks based on geophysical log correlations were used to construct thickness maps. These maps were used in conjunction with borehole correlation panels to understand regional trends in thickness and lithology and how these evolved during Aptian-Albian marine transgression.

1 Introduction

1.1 BACKGROUND TO REPORT SERIES

This report on the Lower Cretaceous (Aptian-Albian) of southern and eastern England forms part of the UK Stratigraphical Framework Series (UKSFS) which aims to generate new information on structure, stratigraphy and facies (lithology) trends within UK bedrock geology units (formations or groups) of sedimentary origin. The report covers the Lower Greensand and Selborne Groups (and related offshore Aptian-Albian strata) which together form a coherent, marine transgressive siliciclastic package between the Wealden Group and the Chalk Group (Figure 1).

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. Report areas extend offshore into correlative stratigraphy where this helps with greater understanding of both onshore and offshore successions. The report thus makes 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 basis for 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 storage 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 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 literature and other geological data sources, geophysical logs and use this information to provide greater insight into patterns, trends and subsurface heterogeneity of the rock unit.

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. Hopson et al. 2008), 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) 19 full-page figures at the rear with detailed captions. The text includes an overview of data sources, methods, background information on the Aptian-Albian succession and new information on thickness and lithology trends (presented as maps and borehole correlation panels).

1.3 METHODS

1.3.1 Data sources

The report combines information from the outcrop of Aptian-Albian strata and approx. 60 boreholes which prove this interval in the subsurface (Figure 2).

Outcrop information was sourced primarily from BGS memoirs, maps and reports and the wider published literature (see references and Appendix 1). In addition, field visits were undertaken to key Aptian – Albian outcrops in Bedfordshire, the Weald and the Isle of Wight.

Most of the boreholes used in the study were drilled for the purpose of hydrocarbon exploration and occur within the deep sedimentary basins in the southern England and across the East Midlands Shelf. These provide a wide coverage, albeit with a bias toward structural highs. The UK Onshore Geophysical Library (https://ukogl.org.uk/) is the primary source for this information.

Away from prospective basins (for example, on the London-Brabant Massif) water boreholes and those drilled for stratigraphical research (primarily by BGS mapping programs) are important sources of information (see Appendix 1). Many of these can be found in the BGS borehole archives (https://www.bgs.ac.uk/information-hub/borehole-records).

Boreholes were selected on the availability of geophysical logs, which provide a powerful means of stratigraphical interpretation (Whittaker et al., 1985). Like borehole log data, geophysical logs vary widely in age, quality, and the suite of available log types.

1.3.2 Geophysical log interpretation

Natural gamma-ray and sonic logs are the predominant log types used in the downhole stratigraphical interpretation. These logs are commonly available in wireline datasets of all vintages and generally give reliable proxy information for the target siliciclastic sedimentary strata (Whittaker et al, 1985). Sonic logs were often not available where Aptian-Albian rocks were close to surface and the borehole was cased.

Gamma-ray instruments are sensitive to changes in the natural background gamma-ray radiation and discriminate rock types with naturally high radioactivity (clay-rich mudstones) and those with naturally low radioactivity (quartz-rich sandstones). Sandstones with phosphate and glauconite are common in the Aptian-Albian, and these can give high background radiation values which mimic mud-rich lithologies. Log interpretations were thus checked against core and cuttings return descriptions where these were available. Cuttings descriptions are often shown on borehole composite logs, together with stratigraphical interpretations made when the borehole was drilled.

Sonic instruments record changes in the transit time of sonic waves through the strata, and as such serve as a proxy method for changes in porosity (compaction and cementation) of rock material.

The caliper log provides an important control on borehole quality and identifying intervals where anomalous log responses are related to wall caving and intervals of casing.

BGS stratigraphical research boreholes are particularly important because these often combine geophysical logs with core descriptions and biostratigraphy (Appendix 1). The general workflow for geophysical log correlation involved establishing the relationship between log response and stratigraphical boundaries and biozones in these control boreholes before extending correlations into uncored boreholes.

1.3.3 Stratigraphical marker picking

Borehole geophysical log interpretation was undertaken using SKUA-GOCAD 22 software which allows the creation of multi-borehole correlation panels and the interactive picking and depth adjustment of stratigraphical markers. Multiple intersecting correlation lines were used to cross-check interpretations in an iterative process of position adjustment. Flattening borehole correlations on stratigraphical horizons was used to remove the effects of post-depositional structure and ease comparison and correlation of specific units. For these reasons, all borehole correlation panels illustrated in this report are flattened on selected stratigraphical horizons rather than plotting to Ordnance Datum.

To aid consistency of interpretation and mitigate individual bias, borehole correlation and marker picking was mostly undertaken as a collective (team) exercise on a large display screen in the BGS 3D Visualisation Suite (https://www.bgs.ac.uk/geology-projects/3d-visualisation-systems).

1.3.4 Stratigraphical marker naming convention

Markers were named using the convention:

(Stratigraphic unit below)_(Stratigraphic unit above)_(Type of contact)

Stratigraphical units are referenced using the BGS Lexicon code (https://www.bgs.ac.uk/technologies/the-bgs-lexicon-of-named-rock-units). Contacts were denoted N (Normal, conformable), U (Unconformable), F (Faulted). Table 1 provides the full list of markers picked during the study.

Table 1 List of markers picked as part of this study

Marker code	Unit Below (LEX code)	Unit Above (LEX code)	Type	Unit below (Full name)	Unit above (Full name)
CRRC_HUCK_N	CRRC	HUCK	N	Carrack Formation	Hunstanton Formation
CA_HUCK_N	CA	HUCK	N	Carstone Formation	Hunstanton Formation
CA_GLT_N	CA	GLT	N	Carstone Formation	Gault Formation
CI_TBF_N	CI	TBF	N	Claxby Ironstone Formation	Tealby Formation
CR_WBS_U	CR	WBS	U	Corallian Group	Woburn Sands Formation
GLT_LCK_N	GLT	LCK	N	Gault Formation	Lower Chalk Formation [Remains Informal Use But Generally Regarded As Obsolete Onshore]
GLT_UGS_N	GLT	UGS	N	Gault Formation	Upper Greensand Formation
HUCK_FYCK_N	HUCK	FYCK	N	Hunstanton Formation	Ferriby Chalk Formation
HUCK_CK_N	HUCK	CK	N	Hunstanton Formation	Chalk Group
KC_VALH_U	KC	VALH	U	Kimmeridge Clay Formation	Valhall Formation
KC_HUCK_U	KC	HUCK	U	Kimmeridge Clay Formation	Hunstanton Formation
KC_SYS_U	KC	SYS	U	Kimmeridge Clay Formation	Spilsby Sandstone Formation
KC_ROA_U	KC	ROA	U	Kimmeridge Clay Formation	Roach Formation
KC_SAS_U	KC	SAS	U	Kimmeridge Clay Formation	Sandringham Sand Formation
KC_CA_U	KC	CA	U	Kimmeridge Clay Formation	Carstone Formation
LI_HUCK_U	LI	HUCK	U	Lias Group	Hunstanton Formation
JURM_HUCK_U	JURM	HUCK	U	Middle Jurassic Rocks (Undifferentiated)	Hunstanton Formation
JURM_CA_U	JURM	CA	U	Middle Jurassic Rocks (Undifferentiated)	Carstone Formation
ROA_SKEG_N	ROA	SKEG	N	Roach Formation	Skegness Clay Formation
SAS_SNC_N	SAS	SNC	N	Sandringham Sand Formation	Snettisham Clay Member
SAS_DEB_N	SAS	DEB	N	Sandringham Sand Formation	Dersingham Formation
SAS_CA_N	SAS	CA	N	Sandringham Sand Formation	Carstone Formation
SILU_GLT_U	SILU	GLT	U	Silurian Rocks (Undifferentiated)	Gault Formation
SNC_CA_N	SNC	CA	N	Snettisham Clay Member	Carstone Formation
SYS_VALH_N	SYS	VALH	N	Spilsby Sandstone Formation	Valhall Formation
SYS_LOCR_N	SYS	LOCR	N	Spilsby Sandstone Formation	Lower Cretaceous Rocks (Undifferentiated)
SYS_CI_N	SYS	CI	N	Spilsby Sandstone Formation	Claxby Ironstone Formation
SBM_CA_N	SBM	CA	N	Sutterby Marl Formation	Carstone Formation
TBF_ROA_N	TBF	ROA	N	Tealby Formation	Roach Formation
VALH_CRRC_N	VALH	CRRC	N	Valhall Formation	Carrack Formation

VALH_HUCK_N	VALH	HUCK	N	Valhall Formation	Hunstanton Formation
WBS_GLT_N	WBS	GLT	N	Woburn Sands Formation	Gault Formation

1.3.5 Surface and thickness map generation

The interpreted set of borehole stratigraphical markers were used to produce structural models and thickness maps using SKUA-GOCAD 22.

Structural models were created using the implicit modelling engine in SKUA-GOCAD 22. In addition to the stratigraphic markers obtained from geophysical log correlations, a variety of other data sources were used in this study (Table 2).

Table 2 Datasets used in this study.

Dataset	Description
Well markers	Borehole stratigraphical interpretation produced as part of this study
Shapefile of outcrop extent of onshore Aptian-Albian strata	BGS Geology 50K https://www.bgs.ac.uk/datasets/bgs-geology-50k-digmapgb/
UK3D v2015	National scale fence diagram https://www.bgs.ac.uk/datasets/uk3d/
LGS1 and LGS2	Regional scale models commissioned by the Environment Agency in the Bedfordshire district; base of the Lower Greensand Group used.
Shapefile of post-Jurassic tectonic faults	From BGS Tectonic map of Great Britain and Northern Ireland. Used to illustrate and understand the distribution of major structures https://webapps.bgs.ac.uk/data/maps/maps.cfc?method=viewRecord&mapId=12084
Digital terrain model	OS Terrain 50 https://www.ordnancesurvey.co.uk/products/os-terrain-50

Maps showing the thickness distribution of selected Aptian-Albian stratigraphical units were produced from well markers. Thickness values were corrected for well path deviation (where present) but not stratal dip, which was mostly low.

Borehole thickness values were interpolated across a 2D grid (500 m cell size) using Inverse Distance Weighted (IDW) interpolation. The power function was set at 3 to achieve a balance between sufficient granularity and the recognition of regional trends. Colour ramps used binned thickness values to further improve the visualisation of regional trends. No interpolation barriers (faults) were applied during map production.

Borehole thickness values were supplemented with thicknesses derived from key measured sections at outcrop where these improved the maps or infilled gaps in borehole coverage.

Thickness maps were painted onto the structural models to allow the relationships between structure and stratigraphy to be explored.

2 Geological Background

2.1 OUTCROP DISTRIBUTION

In England, Aptian-Albian deposits form a near-continuous, sinuous arc stretching from Devon to Yorkshire (Figure 2). Extensive outcrops also occur in the southern half of the Isle of Wight and as a curved belt around the Weald Anticline, truncated at the coast near Folkestone and Hastings.

As detailed in following sections, the various components of the Aptian-Albian succession (Lower Greensand Group, Selborne Group) are highly variable in both distribution pattern and thickness, reflecting the evolution of marine depositional environments under long-term transgression; and the complex tectonic topography inherited from Late Jurassic-Early Cretaceous extensional tectonics; and the presence of long-lived structural highs such as the London-Brabant Massif (Figure 3 and Figure 4).

2.2 BIOSTRATIGRAPHY

The ammonite sequence is known in detail (Casey, 1964; Rawson, 2006) and provides the basis for the division of the Aptian and Albian into 14 standard ammonite zones (Figure 1). Ammonites are reasonably common in most units except for the shallow sub-tidal sandstones of the Late Aptian-Early Albian Woburn Sands-Folkestone Sands-Sandrock interval.

2.3 SUBCROP DISTRIBUTION AND STRUCTURE

Apart from the central Weald, Aptian-Albian deposits subcrop across much of south-eastern England, underlying some of the most densely populated areas in the UK (including the megacity of London), and some units are designated principal aquifer status by the Environment Agency. As at outcrop, the subsurface stratigraphy proved by boreholes is highly variable in different locations.

The present structural disposition of Aptian-Albian deposits (Figure 4) is dominated by the effects of Cenozoic compression and basin inversion related to Alpine-Pyrenean Mountain building (Chadwick, 1986).

Former deep sedimentary basins (Portland-Wight Basin, Weald Basin, Sole Pit Trough and Cleveland Basin) have been uplifted and eroded, often resulting in the total removal of deposits that are Cretaceous or younger in age. During the Early Cretaceous, these were areas that probably accumulated the thickest sequences, but evidence for the character of these basinal successions has been widely obliterated.

Conversely, Aptian-Albian deposits that were deposited across former Early Cretaceous structural highs are now preserved within deep synclinal basins, often to the north of major reverse reactivated basin-bounding normal faults. These include the present Hampshire and Farnborough-London 'basins', and an analogous synclinal structure to the west of the Sole Pit Basin.

2.4 TOTAL APTIAN-ALBIAN THICKNESS TRENDS

Figure 5 shows a map of total Aptian-Albian thickness. In 'complete' basinal successions this includes all strata from the base of the Atherfield Clay Formation to the base of the Chalk Group, an interval that ranges up to approximately 280m thick. Outside the major basins, the lower (Early-Late Aptian) part of the succession is often missing (Figure 1). On parts of the London-Brabant Massif, the Gault Formation is often the sole representative of the Aptian-Albian interval.

Thick Aptian-Albian deposits (ca. 200m) occur in Surrey and West Sussex around the west-plunging nose of the Weald Anticline (Figure 6). From here, in the preserved parts of the former Weald Basin, they thin progressively westwards into the adjoining Pewsey Basin.

To the north of the Weald Basin, Aptian-Albian deposits thin rapidly across the southern bounding faults of the London Platform. Comparable thinning is not seen across northern bounding faults of the Pewsey Basin, where the succession maintains a thickness of around 100-130m as far north as the Leighton-Buzzard Trough.

The thickest Aptian-Albian deposits (around 280m) occur on the Isle of Wight, which preserves remnants of the Cretaceous fill of the former Portland-Wight Basin to the south of the Purbeck-Wight-Bray Fault. North (and east) of this curving fault zone, Aptian-Albian deposits thin rapidly and they are typically 60m or less across the South Dorset High and the Hampshire-Dieppe High (Figure 5). In contrast to Jurassic sedimentation patterns, the map indicates that the Dorset Basin was not a significant localised depocentre during the Aptian and/or Albian.

Across Norfolk and the East Midlands Shelf, the Aptian-Albian rarely exceeds 20m, and thins dramatically to under a metre across the Market Weighton High. Thicker sequences (up to around 100m) are present in the Cleveland Basin and along the periphery of the Sole Pit Trough. The Cleveland Basin is essentially an onshore extension of the Sole Pit Trough.

Plotting the thickness map on structural models provides a graphic illustration that, in all areas, the thickest Aptian-Albian deposits now occur on structural highs (or on the preserved flanks of structural highs), while the thinnest successions are found in deep structural synclines (Figure 6). This somewhat counterintuitive configuration results from post-depositional Cenozoic basin inversion.

2.5 OVERVIEW OF STRATIGRAPHICAL EVOLUTION

Aptian and Albian deposits form a coherent body within the Mesozoic onshore sedimentary rock record of England; as a dominantly siliciclastic marine wedge between the terrestrial (or marginal marine) Wealden Group (and equivalents) and the marine carbonates of the Upper Cretaceous Chalk Group (Figure 1). They offer a snapshot into evolving Early Cretaceous environments under a regime of sea-level rise and a reduction in the magnitude of extensional fault-driven subsidence, which peaked during the latest Jurassic and earliest Cretaceous times in southern Britain (Chadwick, 1986).

The overall transgressive stratigraphy of the Aptian and Albian records a change from the relatively localised and basin-centred deposition of marine mudstones and bioturbated glauconitic sandstones in the Early-Late Aptian (Atherfield Clay-Hythe Formation-Ferruginous Sands Formation) toward Late Aptian and Albian marine deposits (e.g., Woburn Sands and correlatives) with a much wider distribution that onlapped former areas of deep terrestrial erosion.

With ongoing sea-level rise, changing basin geometries and greater oceanic connection amplified tidal activity in the Late Aptian-Early Albian (Wells et al., 2010). This is evidenced by the spectacular mud-draped foresets and tidal bundles of the Woburn Sands, Folkestone Sand and Sandrock formations. Figure 7 and Figure 8 are outcrop images that highlight the contrasting style of Early-Late Aptian and Late Aptian-Early Albian marine sandstone facies.

With further sea-level rise, high energy sands were replaced by marine muds of the Gault Formation, which covered many remaining highs, including the London-Brabant Massif. Closer to source, in southwest England, the Gault Formation passes laterally into shallow marine sandstones of the Upper Greensand Formation. Further from source, on the East Midlands Shelf, the Gault Formation passes laterally into muddy carbonates of the Hunstanton Formation.

The East Midlands Shelf remained a distinct depositional province throughout much of the Aptian and Albian, accumulating a much thinner succession of muds and carbonates on a shallow marine shelf which bordered the Cleveland Basin and the Sole Pit Trough. Even within these basins, Aptian-Albian deposits are thin and relatively shallow water marine mudstones.

Thus, for this work, Aptian-Albian deposits are discussed in terms of two distinct provinces: i) ‘Southern England’ Province, covering Aptian-Albian deposits of the Leighton Buzzard Trough and the Weald, Wessex and Vectian (Isle of Wight) basins; ii) East Midlands Shelf and adjacent North Sea Basin.

3 Aptian-Albian of the Leighton Buzzard-Weald-Wessex-Vectian (‘Southern England’) Province

3.1 LITHOLOGICAL CHARACTERISTICS OF MAIN STRATIGRAPHIC UNITS

In general, the Aptian-Albian stratigraphy of southern England records a broadly transgressive and upward-fining package dominated by shallow marine depositional environments. Table 3 provides a summary of the key lithological characteristics and depositional environments of the main lithostratigraphical units.

Table 3 List of major stratigraphical units in the southern province.

Unit	Lithologies	Depositional environment
Upper Greensand Formation [all areas]	Siltstones, fine to coarse grained calcareous sands and sandstones, often glauconitic, sometimes with subsidiary conglomerate and mudstone. Bivalves are the predominant macrofauna.	Shallow marine, most likely above storm wave base. Diachronous transition eastwards into the mudstones of the Gault Formation.
Gault Formation [all areas]	Pale to dark grey to blue-grey calcareous, fossiliferous clay or mudstone, containing bands of phosphatic nodules; it also contains some pyrite and calcareous nodules. Informal 'Upper Gault' (paler and more calcareous) and 'Lower Gault' (darker grey & more lithologically diverse) (Figure 9), marked by a hiatus in deposition. In places, shows numerous district cyclic fining upward cycles. Basal 1-2m of 'Junction Bed' facies, consisting of fossiliferous and phosphatic rich nodule horizon. Ammonites are the predominant macrofauna.	Transgressive, open marine, mid or outer shelf mud, with depths of 50-100m, below the storm wave base (Gallois, 2019). Marine floor swept by cold, nutrient dense waters that varied in strength. Shallow water depth where the Gault onlaps onto emergent highs such as the London-Brabant Landmass (Rawson, 2006).
Lower Greensand Group [undifferentiated]	Predominantly fine to coarse grained, glauconitic sands and sandstones, with subsidiary mudstones, siltstones and pebbly sandstones.	Estuarine to shallow marine, restricted embayment, to open shallow marine shelf.
Woburn Sands Formation [Leighton Buzzard Trough]	Cross-bedded, well sorted, fine to medium sands and sandstone. Trace lignite, nodular phosphorite and smectite-claystone.	Tidally influenced shallow estuarine to restricted shallow marine embayment, (Yoshida et al, 2004).
Folkestone Formation [Weald Basin]	Medium to coarse grained, well sorted, cross-bedded, glauconitic sands and sandstone, occasional pebbly and silty intervals, and trace amounts of clay.	Shallow marine; tidally influenced shelf sand waves (Wells et al, 2010).
Sandgate Formation [Weald Basin]	Predominately fine sands and sandstones, silts, and silty clays. Lenticular seams of local fuller's earth (calcium smectite) around northern part of Weald. Includes a basal nodule bed in the basin margins.	Transgressive, shallow marine; includes near-shore basin margin to basin centre open shallow marine, deepening basin (Ruffell et al, 1996).
Hythe Formation [Weald Basin]	In the eastern Weald Basin, 'rag and hassock' facies; alternating cycles of hard sandy limestone, which is the 'rag' and poorly cemented sandy mudstone and clayey sandstones known as 'hassock' and siltstone and trace smectite-claystone. Western Weald Basin, less calcareous, fine to medium grained sandstones with lenticular beds of chert and clay interbeds (Ruffell et al, 1996).	Shallow marine, shelf conditions; tidally influenced.
Atherfield Clay Formation [Weald and Portland-Wight Basins]	Silty clays and sandy clays, with widespread clay-ironstone concretions (Portland-Wight Basin) and localised seams of fuller's earth (calcium smectite) (Weald Basin).	Transgressive shallow marine, influenced by intermittent storms (Rawson, 2006).

3.2 GEOPHYSICAL LOG CHARACTERISTICS OF MAIN STRATIGRAPHIC UNITS

A key part of the study is the correlation of Aptian-Albian stratigraphical units using borehole geophysical logs – primarily using the widely-available gamma-ray log. Some of the diagnostic criteria for recognising stratigraphical contacts from geophysical logs are outlined below. Figure 9 provides a representative set of gamma-ray curves for different basinal settings within southern England.

3.2.1 Lower Greensand Group

3.2.1.1 Atherfield Clay Formation

Where present, Atherfield Clay Formation rests on Wealden Group with a disconformity and marine transgressive surface. This is developed on the Vectis Formation in the Isle of Wight and the Weald Clay Formation in the Weald Basin. Although sharp, because clays predominate above and below the contact it is difficult to determine using gamma-ray logs (e.g., East Worldham 1 in Figure 9). Other information such as cuttings descriptions (proving a colour change), core and biostratigraphy are usually required.

In the Weald Basin, the base of the sand-rich part of the Lower Greensand Group (LGS) succession overlying the Atherfield Clay Formation can be readily picked as a sharp decrease in gamma-ray value. Beyond these depocentres, where the LGS rests unconformably on Wealden Group, or older Jurassic strata, the contact is still a generally straightforward pick on gamma-ray logs and is marked by an abrupt decrease in response relative to underlying Jurassic mudstone facies. In the Portland-Wight Basin, the LGS shows an overall pronounced upward decrease in gamma-ray signature, with glauconite and mudstone creating relatively high values toward the base (e.g., borehole 99/16-1 in Figure 9).

3.2.1.2 Hythe Formation

The Hythe Formation can be recognised by the highly serrated sonic log and relatively low and uniform gamma-ray values (Figure 10). This is due to the development of 'rag and hassock' facies within the Hythe Formation, consisting of alternating beds of hard, sandy limestones (the Kentish rag) and soft, clayey, glauconitic sandstones (the hassock) (Figure 7).

3.2.1.3 Sandgate Formation

The Sandgate Formation, which is locally present in the Weald Basin, can be tentatively picked as an interval of higher and more variable gamma-ray response. This contrasts with the uniform low response of the overlying Folkestone Formation (Figure 10).

3.2.1.4 Folkestone Formation

The Folkestone Formation is equivalent to the Woburn Sands Formation of the Leighton Buzzard Trough where a similar low blocky gamma ray response is seen (Figure 9).

3.2.2 Gault Formation

There is a clear lithological contrast between the 'clean' sandstones of LGS strata (especially the Woburn Sand and the Folkestone Formations), and the sharply overlying clays of the Gault Formation. The Gault Formation generally produces an abrupt increase in gamma-ray response. In some areas, there is amplified by the presence of phosphatic nodules in the 'Junction Beds' at the base of the Gault Formation (Figure 9).

North of the Weald Basin (including areas over the London-Brabant Massif), the Gault Formation contains two distinct lithofacies which create two informal subdivisions; a darker grey, less calcareous mudstone ('Lower Gault'), overlain by a more silty and calcareous 'Upper' Gault' mudstone facies. This can be seen on some geophysical log signatures (Figure 9) as a marked decrease in gamma values which represents an intra-Gault unconformity (see Gallois et al, 2016). Ruffell (1991) recognised and correlated five distinct Gault lithofacies in geophysical log signatures across the Wessex Basin of England.

3.2.3 Upper Greensand Formation

The Gault to Upper Greensand formational boundary is transitional and is often difficult to pick with confidence on geophysical log signatures alone (Figure 9 and Figure 10). Oftentimes, a relatively arbitrary cut-off value must be selected in the progressively decreasing gamma-ray signature.

3.2.4 Upper Greensand Formation to Chalk Group

In general, the top of the Upper Greensand Formation is clearly marked by a strong gamma spike created by the Glauconitic Marl Member at the base of the overlying Chalk Group. Where the spike is not present (or recorded) the boundary is defined by a change in log trend to upwardly decreasing gamma log values within the lower part of the Chalk Group.

3.3 THICKNESS AND FACIES TRENDS IN THE LOWER GREENSAND GROUP

Figure 11 shows a thickness map for the Lower Greensand Group (LGS). The most striking feature of the map is the highly localised area of thickening at the western end of the Weald Anticline in Surrey and West Sussex. A second area of thick LGS is present in the Isle of Wight within the Portland-Wight Basin. From the western Weald depocentre, the LGS thins toward the South Dorset High, forming a well-defined wedge of Aptian-Albian strata (Figure 12).

The localised areas of thickening shown by the LGS, reflect two distinct phases of LGS deposition that comprise two contrasting lithofacies. These phases are separated by a sequence boundary, the 'Intra-Aptian Unconformity', which biostratigraphically occurs at the base of the upper *martinioides*-lower *tardefurcata* Zone (Ruffell, 1992).

The first depositional phase is formed by the Atherfield Clay and Hythe/Ferruginous Sands formations, which are mainly found within localised deep clastic basins (Weald and Portland-Wight basins) (Figure 13). Areas outside these basins were mostly regions of non-deposition/post-depositional erosion. These open marine, bioturbated and glauconitic shelf sandstone and mudstone deposits show relatively little evidence of tidally influenced deposition (Wells, 2010).

The second phase is coincident with the base of the Sandgate Formation in the Weald Basin, a *nutfieldiensis* Zone transgressive unit which overlies the Intra-Aptian sequence boundary (Ruffell, 1992). The Sandgate Formation marks the beginning of a significant increase in sediment deposition and the widespread onlap onto basin margins. In marginal areas, it includes reworked clasts and fossils of Hythe Formation in a basal pebbly bed above an often-pronounced unconformity (Rawson, 2006). In the centre of the Weald Basin, where there is a near continuous sedimentary succession from the Late Jurassic to Early Cretaceous, this Intra-Aptian Unconformity corresponds with the transgressive base of the Sandgate Formation above the Hythe Formation, and likely represents a relatively minor disconformity. Away from basin centres, an often-significant time-gap exists between Late Aptian-Albian deposits and onlapped bedrock of Jurassic age (Ruffell, 1992). This can be seen in the Strat A1 and Cliffe at Hoo boreholes which shows a thin development of Sandgate and Folkestone formations (Figure 14).

The base of the Sandgate Formation also marks a significant change in facies with sedimentary structures indicating strong tidal activity in shallow marine estuaries and embayments. These reach a peak in the spectacular tidal cross-bedding and related structures of the Woburn Sand (Figure 7), Folkestone and Sandrock formations (Figure 8). Consequently, the Sandgate Formation is a heterolithic, muddy, glauconitic unit which changes laterally in facies and contains numerous component members (Bargate Sandstone Member, Rogate Member, Easebourne Member, Selham Ironshot Sands Member, Fittleworth Member, Pulborough Sandrock Member and Marehill Clay Member). This variable lithological character is reflected in the typical variability of its geophysical log response (see **3.2.4** above).

The Leighton Buzzard Trough (or Bedfordshire Straits) lay to the north-west of the London-Brabant Massif and is represented by a restricted marine embayment (Yoshida et al, 2004). This opened to the south-west into the Pewsey Basin. At least during the deposition of the Woburn Sands Formation, there is little evidence that the Leighton Buzzard Trough had a north-easterly connection across the London-Brabant Massif with the East Midlands Shelf and Southern North Sea (Wells et al, 2010).

3.4 THICKNESS TRENDS IN THE GAULT FORMATION

The thickness map shows the development of three northwest-southeast trending belts (Figure 15). In the most south-western belt (Hampshire and South Dorset) the Gault Formation is typically around 30m thick, increasing to around 50m to the northeast. The Gault Formation reaches its' maximum thickness of around 80-100m in a central belt which extends from Surrey toward Oxfordshire. North-eastwards from this thick belt, the Gault Formation thins to around 50m. The thinning trend continues toward north Norfolk where the Gault Formation transitions laterally to the muddy carbonates of the Hunstanton Formation.

The Gault Formation is an outer shelf mud (Rawson, 2006) with thinning to the southwest largely the result of a lateral facies changes into the prograding sands of the Upper Greensand Formation. To the northeast, thinning is likely related to limited accommodation space across the London-Brabant Massif. The northwest - southeast trending isopachs (across the predominant west-east structural grain) and the presence of thick deposits beyond the limits of the Weald Basin, suggest that there was relatively minor structural control on its' deposition.

3.5 THICKNESS TRENDS IN THE UPPER GREENSAND FORMATION

Figure 16 shows that the maximum thickness (around 80m) of the Upper Greensand Formation (UGS) occurs in the western part of the outcrop, between the Vale of Wardour and the Vale of Pewsey. From here, thick UGS occurs along an axis which extends under Salisbury Plain towards Andover. Further to the northeast, the UGS thins progressively until it disappears at outcrop just northeast of Monks Riseborough in the Chilterns. South of the Vale of Wardour, across Dorset and Hampshire the UGS ranges between 15-40m.

It is thought that the shallow marine siliclastic UGS prograded across southern England in Mid to Late Albian times. Biostratigraphy confirms the diachronous nature of the boundary between the UGS and the Gault Formation (Ruffell, 1991). From west to east, away from the influence on accommodation control exerted by the London-Brabant Massif, the UGS shows a very clear pattern of thinning as the Gault Formation becomes thicker (Figure 17).

4 The East Midlands Shelf and adjacent areas

Throughout much of the Aptian and Albian, the East Midlands Shelf was a distinct depositional province, separated (at least partially) from the linked depocentres of the Leighton Buzzard Trough, Wessex, Weald and Portland-Wight basins by a probable low-lying topographic region between the northwest margin of the London-Brabant Massif and the southern margin of the Pennine Massif. This barrier was most evident during the Aptian, separating muddy and shallow marine environments on the East Midlands Shelf from the high-energy, sand-rich tidal basins to the south (Wells et al. 2010). With increasing sea-level rise during the Albian, the influence of the barrier decreased, with progressive onlap of the London-Brabant Massif by the Carstone and Gault formations.

The East Midlands Shelf links northward to the Cleveland Basin, with the Market Weighton High and Flamborough Fault Zone forming the boundary between the two areas. To the east, the East Midlands Shelf extends offshore to the Dowsing Fault Zone, which forms the boundary to the Sole Pit Trough.

4.1 STRATIGRAPHICAL UNITS

Two main Aptian-Albian units are present across the onshore East Midlands Shelf, the cross-bedded sandy deposits of the Carstone Formation (Lower Albian) and the overlying pink to brick red impure carbonates of the Hunstanton Formation (Middle-Late Albian). In southern Lincolnshire and around The Wash a few metres of Skegness Clay Formation and Sutterby Marl Formation are the only strata representative of the Aptian (Figure 1).

In the Cleveland Basin, Aptian-Albian strata include the uppermost parts of the Speeton Clay Formation. These have comparable and correlative units along the margins of the Sole Pit Trough, in the uppermost part of the Valhall Formation and the overlying Carrack Formation, units that relate to nomenclature applied in the Southern North Sea (Lott & Knox, 1994). A summary description of the main units and their depositional environments is given in Table 4.

Table 4 List of lithostratigraphical units that include Aptian and Albian strata on the East Midlands Shelf and adjacent areas.

Unit	Lithologies	Depositional environment
Hunstanton Formation	Rubbly to massive chalks with marl bands; typically, pink to brick-red (due to disseminated haematite), but locally the upper part is grey due to secondary alteration of the iron minerals. The lower part of the formation is commonly weakly sandy. Generally sharp lower and upper boundaries.	Benthonic calcitic invertebrates are typical of shallow water with stromatolites indicating depths within the photic zone (Jeans, 1980).
Carrack Formation (offshore East Midlands Shelf only)	Dark grey, essentially non-calcareous, marine mudstones. Thin sandy beds and phosphatic pebbles may occur which may produce gamma-ray spikes.	Restricted marine basin with periodic bottom-water oxygen depletion and transgressive phases.
Carstone Formation	Medium to coarse sandstone, pebbly, glauconitic, and stained brown by limonitic cement. Pebbly and conglomeratic toward margins and at the base. Clasts include reworked Lower Cretaceous ammonites. Glauconite may be present and *Arenicolites* and *Skolithus* burrows are locally present. Erosive base. Sedimentary structures include trough and swaley cross-stratification.	Transgressive deposit deposited on a storm-dominated shoreface at water depths of 30-40m (Cseh and Andrews, 2019)
Speeton Clay Formation	Mudstones, calcareous mudstones and black shales. Occasional concretionary limestones and phosphatic nodules and glauconitic mudstones at omission surfaces. Common belemnites and planktonic foraminifera, occasional ammonites. Becoming more carbonate rich in the uppermost Aptian-Albian beds.	Relatively shallow marine (<100m) regressive sequence with changing depositional conditions that varied in bottom water oxygenation. Becoming more confined and reducing toward the top (Dypvik 1984).
Valhall Formation (offshore East Midlands Shelf only)	Mudstones, chalky mudstones and thin limestones. Uppermost Aptian strata comprise a unit of pale hard chalky mudstone with a lower gamma-ray response.	Hemipelagic muds in an offshore, low-energy oxygenated marine setting.
Sutterby Marl Formation	Thin, pale grey calcareous mudstone. Bioturbated with diverse macrofauna, including ammonites, belemnites, bivalves, brachiopods, rare echinoids and corals, together with coccoliths, foraminifera and ostracods.	Shallow marine, low energy environment
Scunthorpe Mudstone Formation	Grey and dark grey mudstone with ammonites and phosphatic nodules.	Shallow marine, low energy environment with variable oxygenation

4.2 RELATIONSHIP BETWEEN THE EAST MIDLANDS SHELF AND THE LEIGHTON BUZZARD TROUGH

The relationship between the stratigraphy of the Leighton Buzzard Trough and the East Midlands Shelf is shown in Figure 18, which correlates boreholes from Tring 1 to Skegness. In the Tring 1 and Ashwell 1 boreholes, Woburn Sands Formation are present beneath the Gault Formation which coarsens upwards into weakly developed Upper Greensand Formation. Northward toward Lakenheath 1, the Woburn Sands Formation are absent and a thin bed of glauconitic, ferruginous coarse-grained sand (Carstone Formation) rests unconformably on Jurassic mudstones. Around Ely, Gallois (1988) has shown that the Carstone Formation has an erosive contact with the Woburn Sands Formation and is therefore stratigraphically younger. The Carstone is overlain by a relatively thin succession of Gault Formation in the Marham and Gayton boreholes. Further north toward Skegness, the Gault Formation has been replaced laterally by the impure carbonates of the Hunstanton Formation, which grade upwards from the Carstone into the overlying Chalk Group. Further south onto the London-Brabant Massif, the Aptian-Albian is often only comprised of Gault Formation resting directly on Palaeozoic basement (e.g., the Stowlangtoft borehole).

4.3 THICKNESS TRENDS

Figure 5 shows the thin development of Aptian-Albian deposits across the East Midlands Shelf relative to the southern basins. Onshore, the combined Aptian-Albian sequence generally does not exceed 20m and thins to 1m north of the Humber Estuary, across the Market Weighton High. Aptian-Albian deposits thicken abruptly across the Flamborough Fault Zone into the Cleveland Basin, where they form the upper part of the Speeton Clay Formation. The total thickness here varies rapidly in response to syndepositional faulting, reaching a maximum thickness of around 100m in boreholes west of the outcrop at Speeton cliffs (Rawson, 2006). In offshore parts of the East Midlands Shelf, on the flanks of the inverted Sole Pit Basin, Aptian-Albian deposits reach around 60m thick.

4.4 CLEVELAND AND SOLE PIT BASINS – RELATIONSHIP TO OFFSHORE SOUTHERN NORTH SEA STRATIGRAPHY

To the north and east of the East Midlands Shelf, Aptian-Albian strata thicken into the Cleveland Basin and offshore into the Sole Pit Trough. The successions are thicker and more mud-rich, and biostratigraphical subdivision relies primarily on foraminifera, supplemented by geophysical log characteristics (Crittenden, 1987).

The stratigraphical relations are shown in a correlation panel from Fordon 1 in the Cleveland Basin to Borehole 49/25-1 in the Southern North Sea (Figure 19). In this region Aptian-Albian strata are around 100m thick and overlie a thick pre-Aptian Lower Cretaceous succession, which in the Cleveland Basin, includes strata assigned to the lower part of the Speeton Clay Formation. In the Southern North Sea (SNS), Aptian-Albian deposits are partly included within and underlain by the Valhall Formation. The base of the Aptian is primarily picked on foraminiferal biostratigraphy, but particularly in the SNS, this coincides with a distinctive low gamma-ray bulge which Crittenden (1987) graphically describes as the 'Aptian belly'. This corresponds to a currently unnamed package of calcareous mudstones at the top of the Valhall Formation. These Aptian calcareous mudstones are probably distinctive enough in lithology, biostratigraphy, and geophysical log response to merit their own stratigraphic name, as occurs in the Dutch sector of the SNS, where they are termed the Lower Holland Marl Member. These are overlain by mudstones of the Carrack Formation and carbonates of the Hunstanton Formation which, as in other parts of the East Midlands Shelf, show a progressive upward decline in gamma-ray response.

5 Conclusions

- Lower Cretaceous Aptian-Albian strata of the Lower Greensand and Selborne Groups form a coherent transgressive, siliciclastic marine deposit between the Wealden Group (and related deposits) and the Chalk Group.
- The deposits vary widely in thickness and facies development as basin geometries evolved during marine transgression, with increased connection with oceanic areas to the south.
- The distribution and thickness patterns of the Lower Aptian parts of the succession (Hythe Formation-Ferruginous Sands Formation) appear strongly controlled by the Late Jurassic-Early Cretaceous predominantly east – west tectonic fabric created by extension. By the Albian, these appear to exert relatively little influence on the thickness and distribution patterns of the Selborne Group. The Aptian-Albian transgressive succession thus plays an important role in infilling and erasing the tectonic topography generated during the deposition of the Wealden Group and older Jurassic units.
- The Intra-Aptian Unconformity is key to understanding the unusual thickness distribution of the Lower Greensand Group. Depocentres in the Weald Basin and Portland-Wight Basin contain a thick succession of Lower Greensand Group strata which can reach over 200m. This contrasts with thinner LGS (typically 10 – 30m) in areas away from the

expanded successions, where the younger part of the LGS Group (Sandgate and Folkestone formations) transgress a wider area, truncating older LGS intervals.

- The Gault Formation transgresses the London-Brabant Massif and is thickest in a belt from Bedfordshire to the Weald. Thickness belts cut across the orientation of the major basin bounding faults and there appears to have been little tectonic control on its deposition.
- Upper Greensand Formation is thickest in the Pewsey Basin and thins north eastwards.
- The well-known diachroneity of the Gault and Upper Greensand formations is reflected in their thickness relationships.
- An understanding of the spatial extent and distribution of the Lower Greensand Group is crucial in the context of its role as a regionally important principal aquifer. The Lower Greensand Group is also potentially important in open loop geothermal systems and as a storage reservoir for other fluids (e.g., hydrogen).

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7 References

The 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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8 Appendix 1 List of key boreholes and localities

Locality Please note: Locations given as British National Grid references, except the offshore boreholes which are given by decimal Latitude and Longitude coordinates.	**Key Lower Cretaceous Stratigraphy**	**Reference(s)**
Portsdown 1 Borehole [BNG: 463800, 0106520] BGSID: 420261	Upper Greensand Fm Gault Fm Lower Greensand Group	Taitt & Kent (1958)
Sompting Borehole [BNG: 516600, 0106350] BGSID: 577579	Lower Greensand Group, undivided Folkestone Fm Atherfield Clay Fm	Young and Monkhouse (1980) Simpson (1985)
Chale Bay, Isle of Wight Cliff section between Shepherd's Chine [SZ 4466, 7982] and Whale Chine [SZ 4684, 7825].	Carstone Fm Sandrock Fm Ferruginous Sands Fm Atherfield Clay Fm	Simpson (1985) Hopson et al (2008) Ruffell & Wach (2020)
Coastal exposures around Mill Point [TR 2218 3525 to TR 2177 3527], Folkestone. Bognor Common Quarry [TQ 0080 2135], West Sussex. Sunken Lane near Nutbourne [TQ 0731 1922], Sussex.	Hythe Formation	Ruffel (1992b) Hopson et al (2008)
Exposures at Warminghurst [TQ 1170 1675], and Nutbourne [TQ 07311922], and Bognor Common Quarry [TQ 0080 2135].	Hythe Formation	Ruffell (1992b)
Hoes Farm borehole, near Petworth [BNG: 498080,0119620] BGSID: 434522	Hythe Formation	Ruffell (1992b) Bristow et al (1987)
The town of Sandgate [TR 20 35] on the coast near Folkestone, and in the West Cliff [TR 235 364] at Folkestone	Sandgate Formation	Hopson et al (2008)
East Cliff [TR 24 36], Folkestone, Kent.	Folkestone Formation	Hopson et al (2008)
Type area around Woburn district from Clophill [TL 08 38] to Leighton Buzzard [SP 91 25]; including present day quarries located within this district.	Woburn Sands Fm	Hopson et al (2008)
Warlingham borehole [BNG: 534760,157190] BGSID: 595131	Upper Greensand Fm Gault Fm Lower Greensand Group: Folkestone Fm Sandgate Fm Hythe Fm Atherfield Clay Fm	Whittaker et al (1985) Gallois et al (2016)
Hunstanton borehole (BGS) [BNG: 568570, 0340780] BGSID: 509712	Hunstanton Fm Carstone Fm	Whittaker et al (1985)
Marchwood borehole [BNG: 439910, 111180] BGSID: 406071	Upper Greensand Fm Gault Fm Lower Greensand Fm	Whittaker et al (1985)
Glyndebourne borehole [BNG: 544200, 0111410] BGSID: 695385	Gault Formation	Hopson et al (2001) Hopson et al (2008)
Type area of the district around Selborne, Hampshire	Upper Greensand Fm Gault Fm	Hopson et al (2008) Gallois et al (2016)
Copt Point Cliff Section [TR 241 364] at Folkestone, Kent	Upper Greensand Fm Gault Fm	Hopson et al (2008) Gallois et al (2016)
Selborne 1 borehole [BNG: 473200, 134940] BGSID: 426353	Upper Greensand Fm Gault Fm	Hopson et al (2001).
Selborne 2 borehole [BNG: 475400, 134350] BGSID: 426321	Gault Fm	Hopson et al (2001).
Selborne 3 borehole	Gault Fm	Hopson et al (2001).

[BNG: 475830, 134000] BGSID: 426322		
Mundford C Borehole [BNG: 576762, 0291290] BGSID: 551477	Gault Fm	Hopson, et al (2008) Gallois et al (2016)
Arlesey Brickpit Borehole [BNG: 518870, 0234630] BGSID: 529016	Woburn Sands Fm Gault Fm	Hopson et al (2008) Gallois et al (2016)
Offshore borehole 99/16-1 [Decimal lat and long: 50.386227, -0.96313]	Lower Greensand Group laterally equivalent to: Carstone Fm Sandrock Fm Ferruginous Sands Fm Atherfield Clay Fm	Ruffell & Wach (1991) Ruffell & Wach (2020)
Offshore borehole 98/11-1 [Decimal lat long: 50.653694, 1.832000]	Upper Greensand Fm Gault Formation Lower Greensand Group	Ruffell & Wach (1991)
Wilmingham borehole, Isle of Wight [BNG: 436623, 87790] BGSID: 454853	Upper Greensand Fm Gault Formation Lower Greensand Group	Ruffell & Wach (1991) Gallois et al (2016
Lockerley borehole [BNG: 430671, 125910] BGSID: 406622	Upper Greensand Fm Gault Formation Lower Greensand Group	Ruffell and Wach (1991)
Shrewton borehole [BNG: 406230, 143520] BGSID: 399183	Upper Greensand Fm Gault Formation Lower Greensand Group	Ruffell and Wach (1991)
Hunstanton cliffs, Norfolk [TF 6735 4175]	Gault Fm Hunstanton Fm Carstone Fm	Gallois et al (2016) Hopson et al (2008)
Fobbing borehole, Essex [BNG: 571270, 184350] BGSID: 748709	Gault Fm Folkestone Fm Sandgate Fm	Gallois et al (2016) Owen (1971)
Cliffe Marshes 6 borehole, Essex [BNG: 571850, 178580] BGSID: 717474	Gault Fm Folkestone Fm Sandgate Fm	Gallois et al (2016)
Bushey borehole, Hertfordshire [BNG: 511950, 0195770] BGSID: 582476	Gault Fm Lower Greensand Group	Gallois et al (2016)
Yarnbury 1 borehole [BNG: 403357, 0141053] BGSID: 399209	Upper Greensand Fm	Bristow et al (1999)
Dorset and East Devon Coast World Heritage Site, coastal section	Upper Greensand Fm Gault Fm	Gallois & Owen (2019)

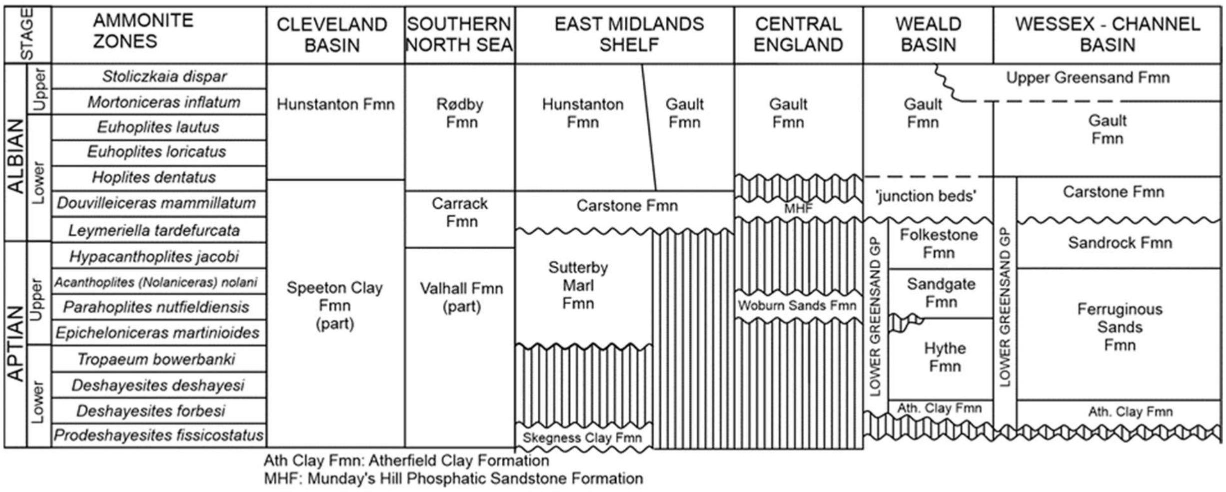

Figure 1 Ammonite zonation and regional correlation of the Lower Greensand and Selborne groups. Based on Rawson (2006, Figure 15.4) with some modification.

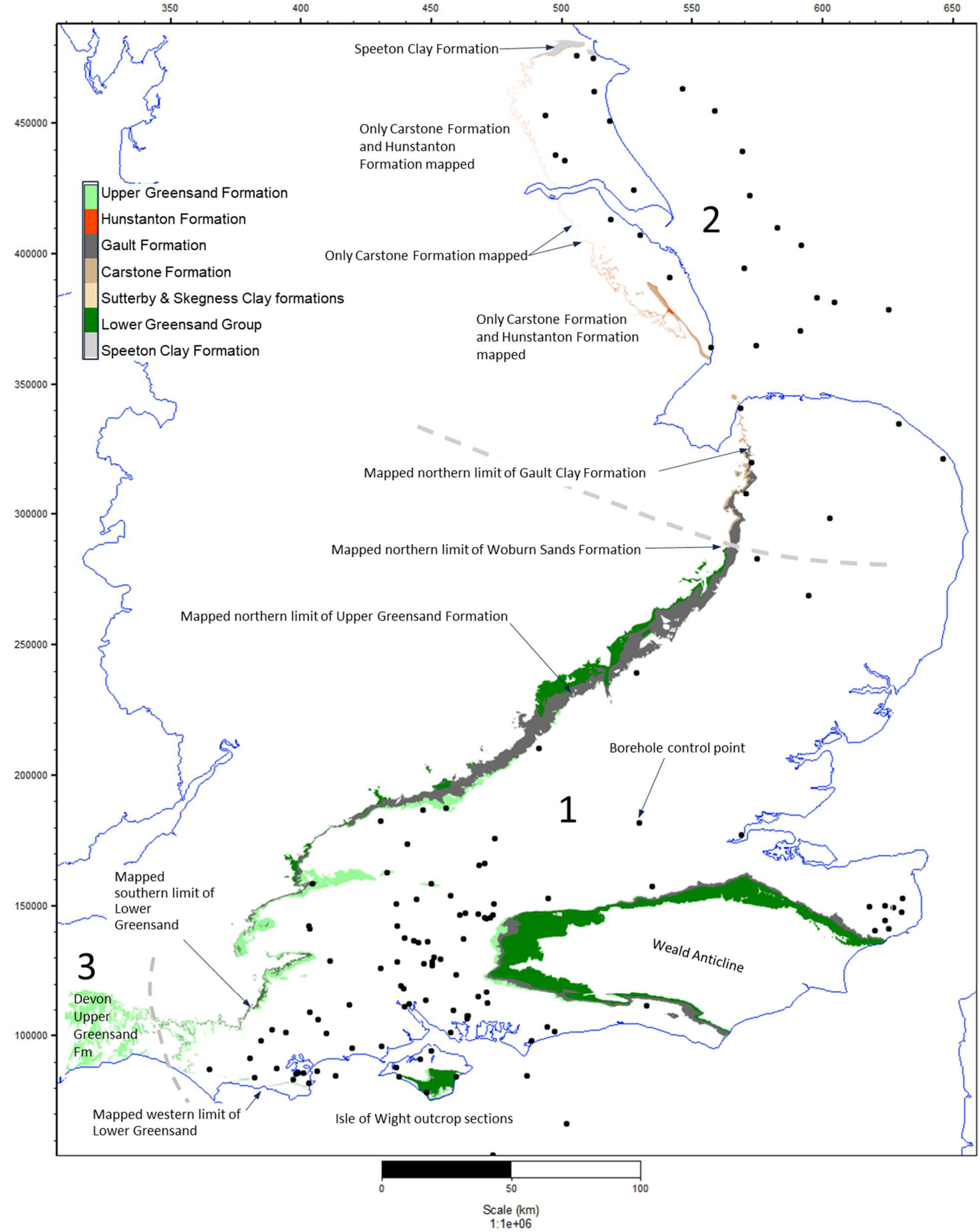

Figure 2 Mapped distribution of Aptian-Albian deposits from BGS Geology 50K. Outcrop distribution reflects the interaction of original depositional trends and major episodes of Cenozoic uplift and basin inversion. The map shows the three main depositional provinces, (1) Channel Basin, Wessex Basin, Weald Basin, Leighton Buzzard Trough (2) East Midlands Shelf, Cleveland Basin (3) Devon (not covered in this report). Black dots indicate boreholes used in the study.

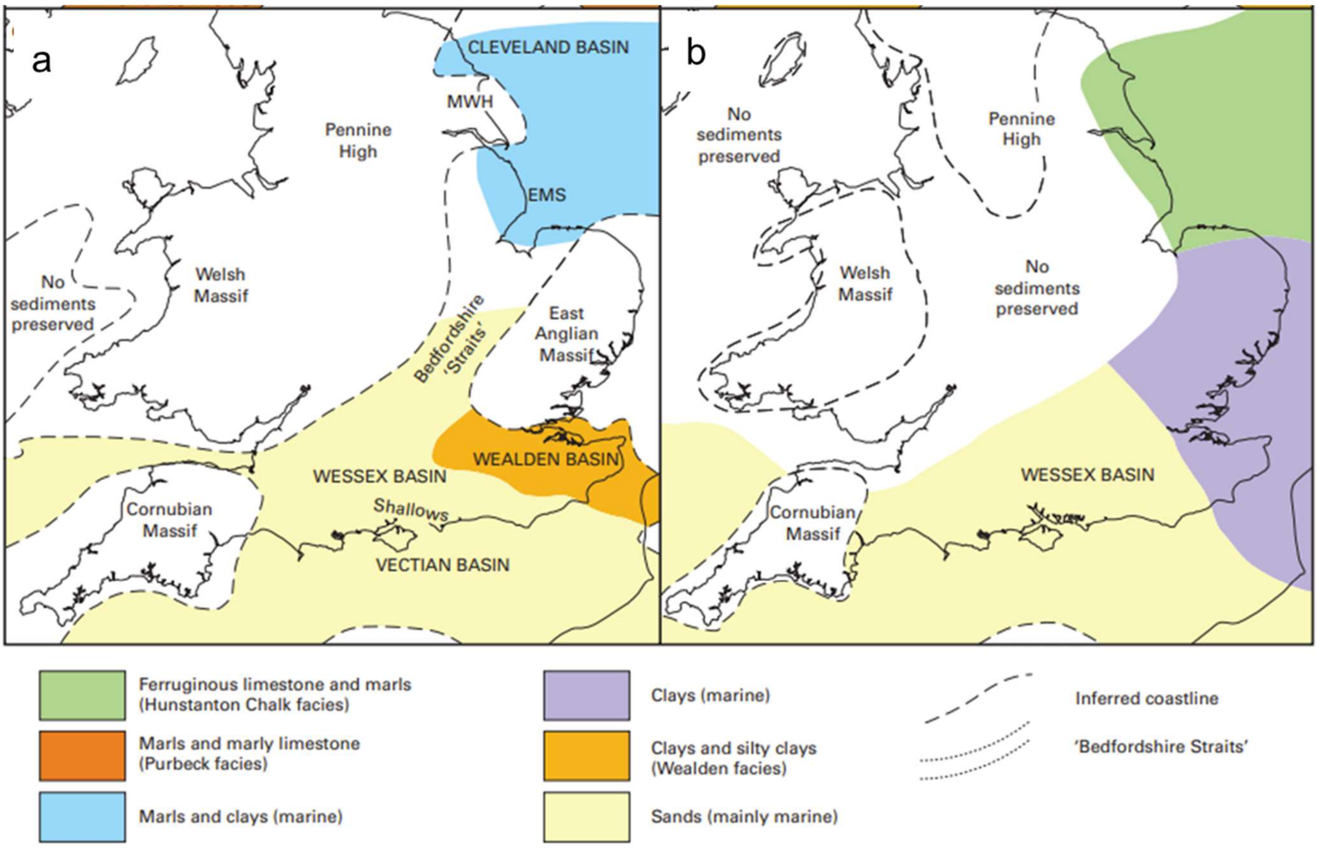

Figure 3 Simplified palaeogeographic maps during the (a) Late Aptian and (b) Late Albian (modified from Hopson, 2008 and Rawson, 1992). There is uncertainty over the original depositional limits of Aptian-Albian strata. The 'Bedfordshire Straits' was probably a 'blind' embayment with no link to the East Midlands Shelf during the Aptian.

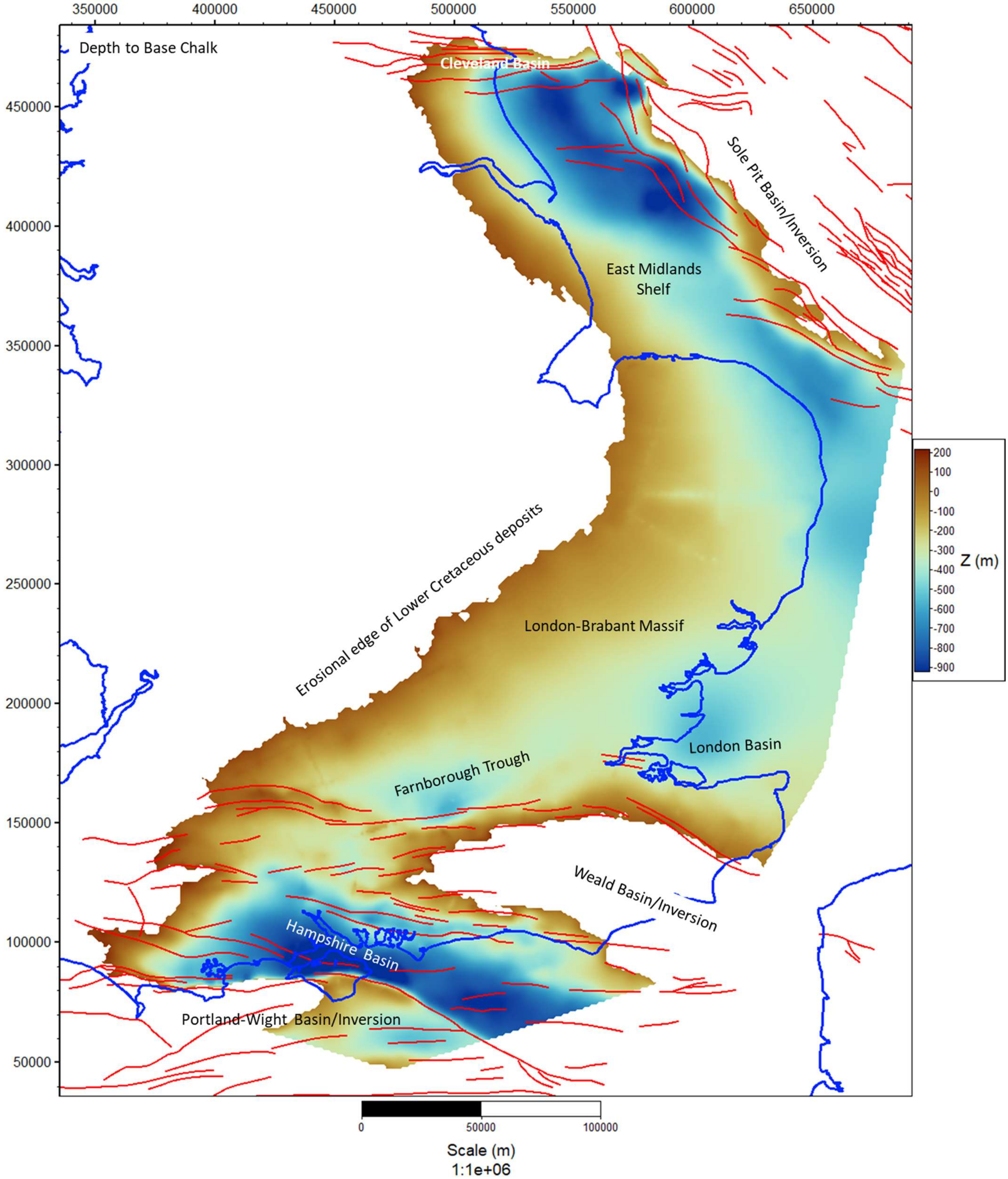

Figure 4 Map showing depth to the top of the Aptian-Albian (Base Chalk Group) and the subcrop area of Aptian-Albian strata across SE England. The structure is strongly controlled by the effects of Palaeogene compression and basin inversion. Former Lower Cretaceous depocentres have been uplifted (e.g. Channel Basin) and extensively eroded (e.g. Weald Basin). Former Lower Cretaceous depositional highs are now deep structural synclines (e.g. Hampshire Basin).

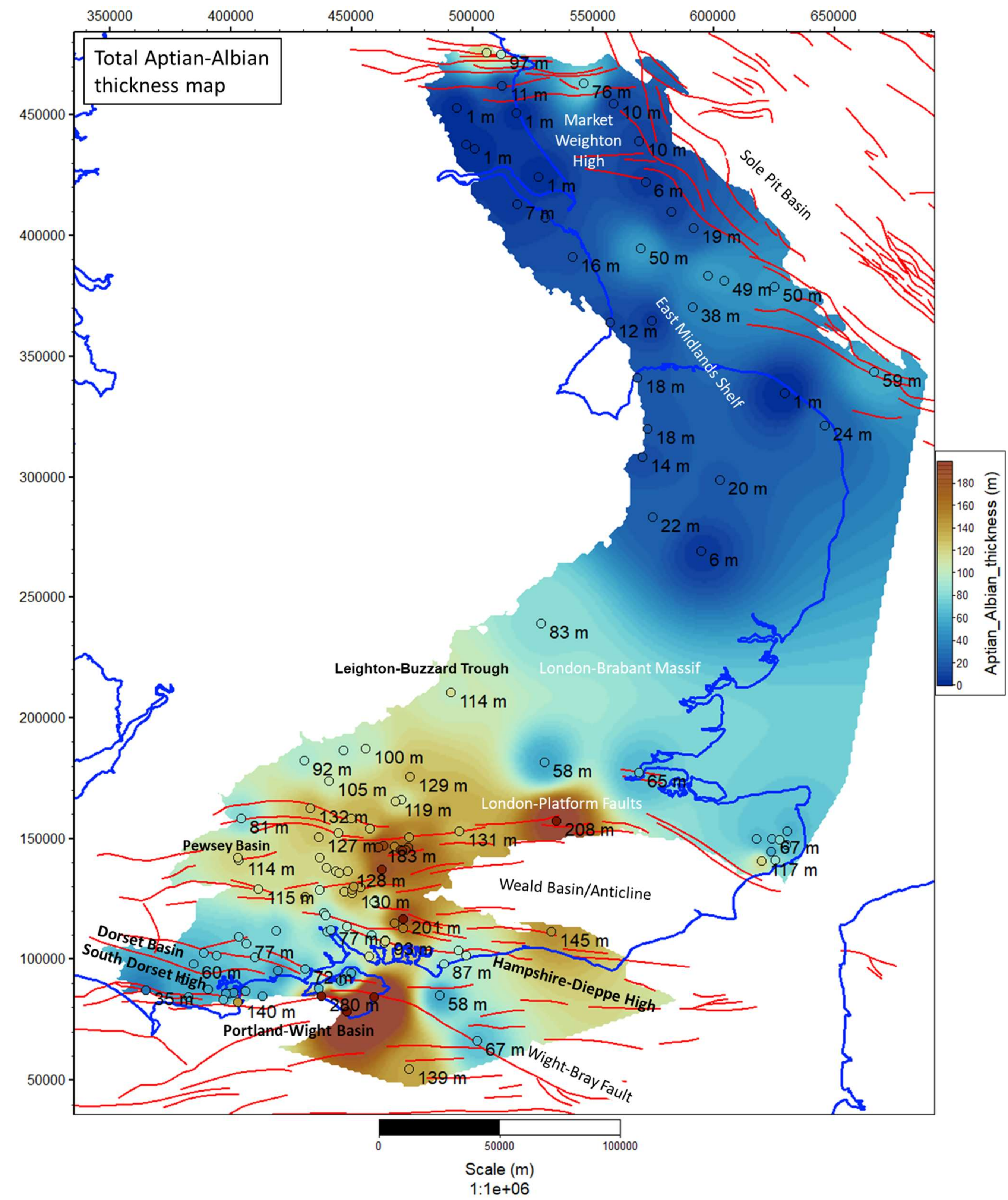

Figure 5 Map showing total thickness of Aptian-Albian deposits. Circles show borehole locations with selected thickness values shown. Aptian-Albian strata are thin (<20 m) across most of the East Midlands Shelf and the East Anglian London-Brabant Massif. Thick deposits occur around the periphery of the Weald Basin (where the Lower Cretaceous has been uplifted and eroded) and on the Isle of Wight/Channel Basin. These areas are separated by relatively thin deposits across the South Dorset-Hampshire-Dieppe High.

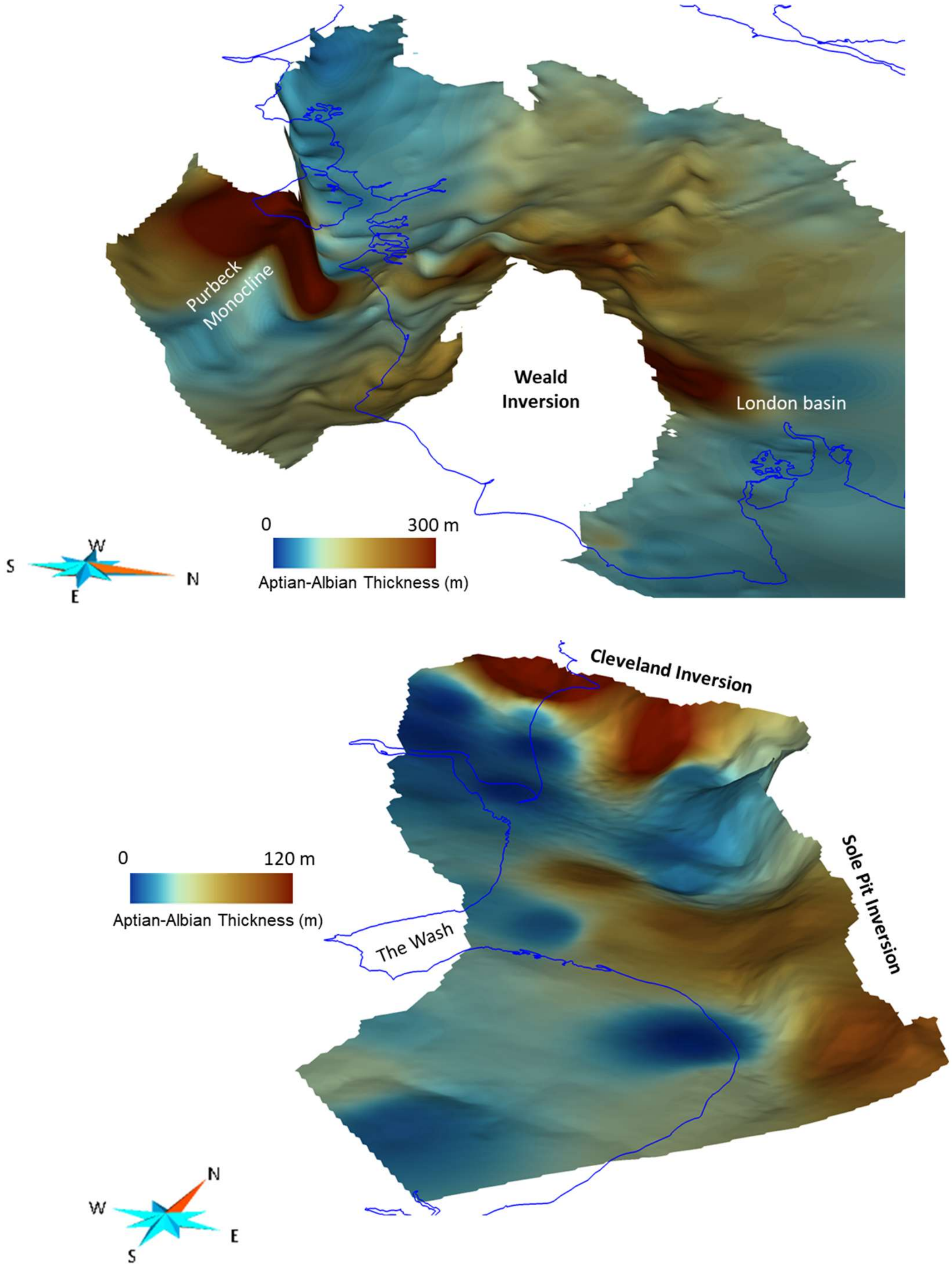

Figure 6 Perspective views showing the present structure of the top Aptian-Albian in southern England (above) and the East Midlands Shelf (below). The structural models are painted with the total thickness of Aptian-Albian deposits and show the correspondence of present structural highs with thick Lower Cretaceous deposits. In southern England the thickest deposits are found around the western nose of the Weald Anticline and in the inverted Channel Basin. On the East Midlands Shelf the thickest deposits are found on the steep flanks of the Cleveland and Sole Pit inversions. Surfaces are shown with x15 vertical exaggeration.

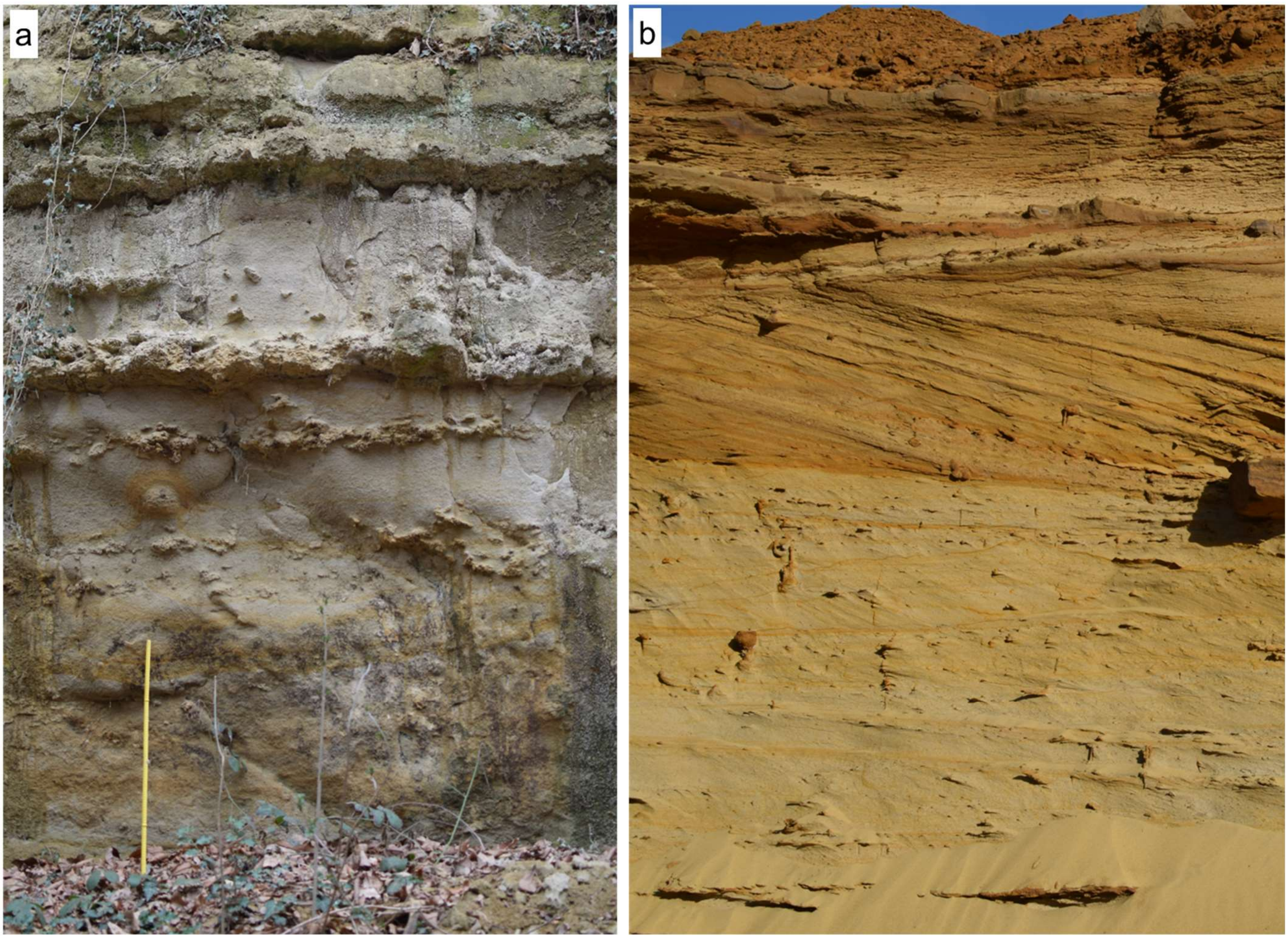

Figure 7 Photographs showing contrasting Lower Greensand Group sandstone facies. (a) Bioturbated, glauconitic, carbonate cemented sands of the Hythe Formation in the southern Weald Basin (BGS image P1038692). (b) Cross-bedded quartz-rich sands of the Woburn Sand Formation in the Leighton Buzzard Trough (BGS image P1038691).

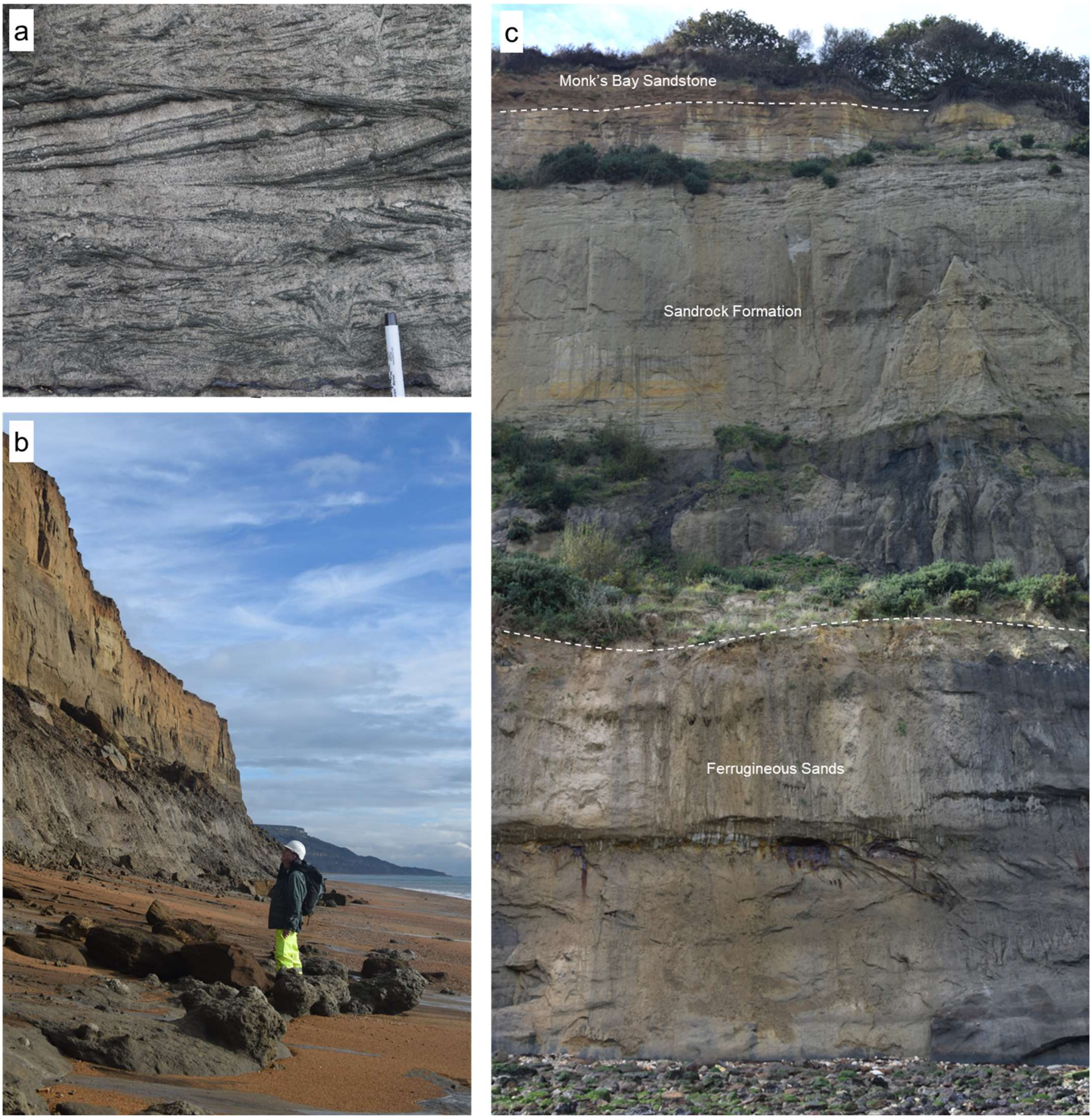

Figure 8 Outcrop photographs from the Isle of Wight. (a) Cross-bedding with mud drapes and tidal bundles in the Sandrock Formation (Monks Bay, Bonchurch) (BGS image P1038694). (b) The sharp contact between the Ferruginous Sands Formation and the Atherfield Clay Formation (Chale Bay) (BGS image P1038695). (c) Sandrock Formation sandwiched between the Ferruginous Sands and the Monk's Bay Sandstone. Cliff is approximately 70 m high (Knock Cliff, Shanklin) (BGS image P1038693).

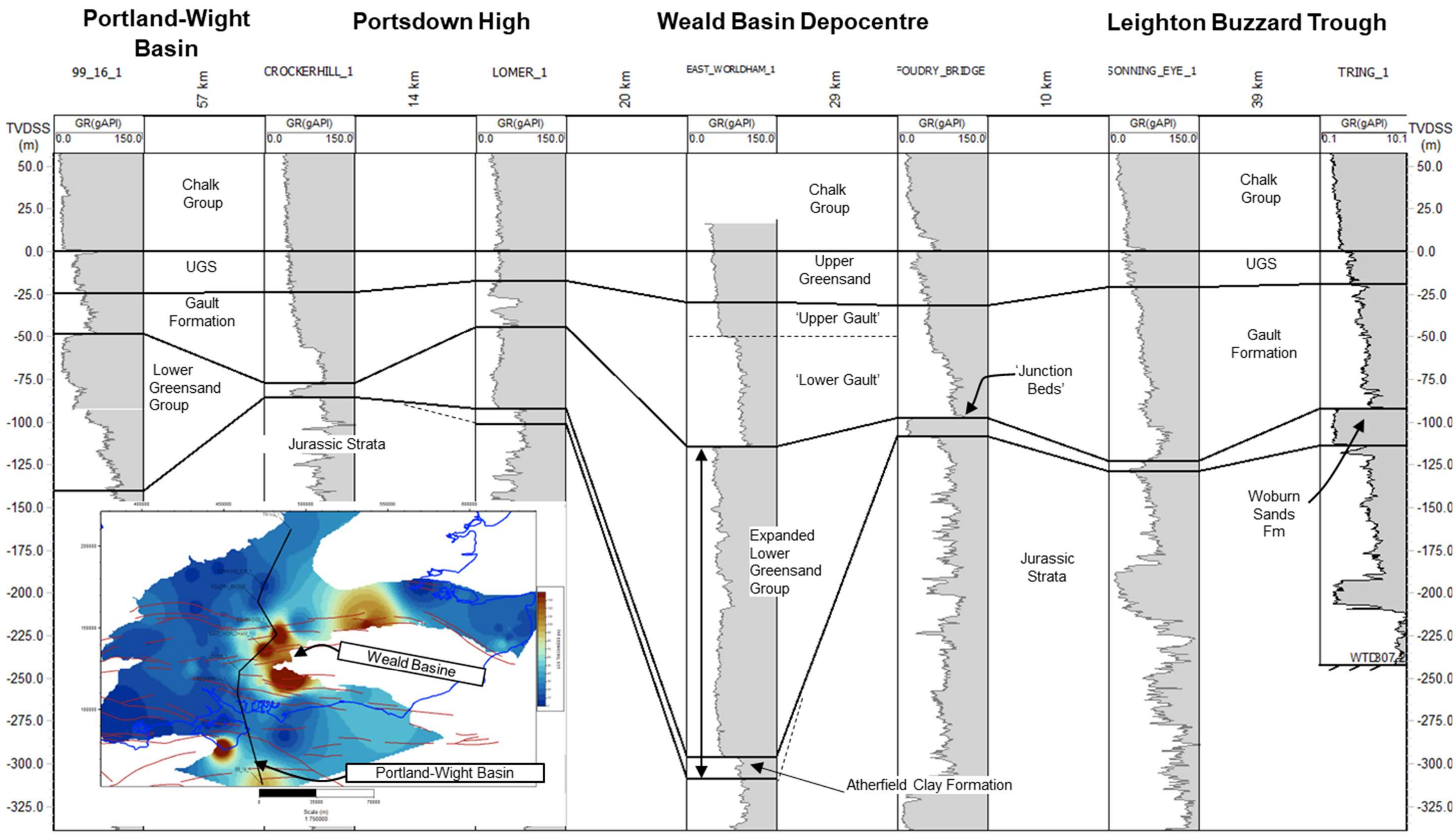

Figure 9. South-North correlation panel from the 99_16_1 borehole to the Tring 1 borehole. The section shows representative and contrasting stratigraphies in different basinal settings.

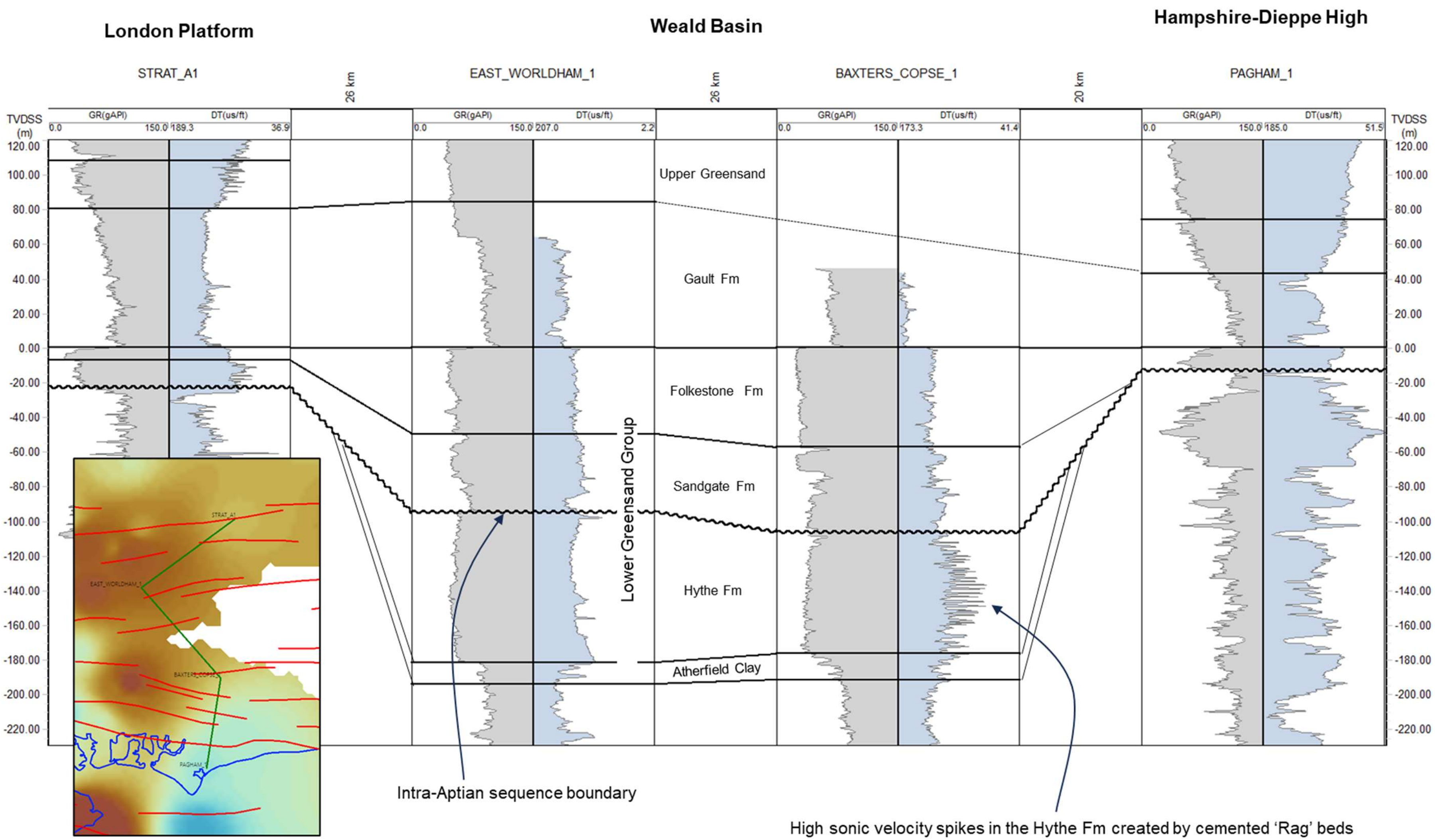

Figure 10 North-south Correlation panel from Strat A1 on the London Platform to Pagham 1 on the Hampshire-Dieppe High. East Worldham and Baxters Copse are within the Weald Basin and show abrupt thickening of the LGS associated with the presence of Hythe Formation and Atherfield Clay. Note the high frequency sonic spikes in the Hythe Formation of the Baxters Copse borehole created by carbonate-cemented sandstone beds (often referred to as 'Rag') which are common in the southwestern part of the Weald Basin. Above the intra-Aptian sequence boundary (wavy line) units begin to onlap adjacent highs.

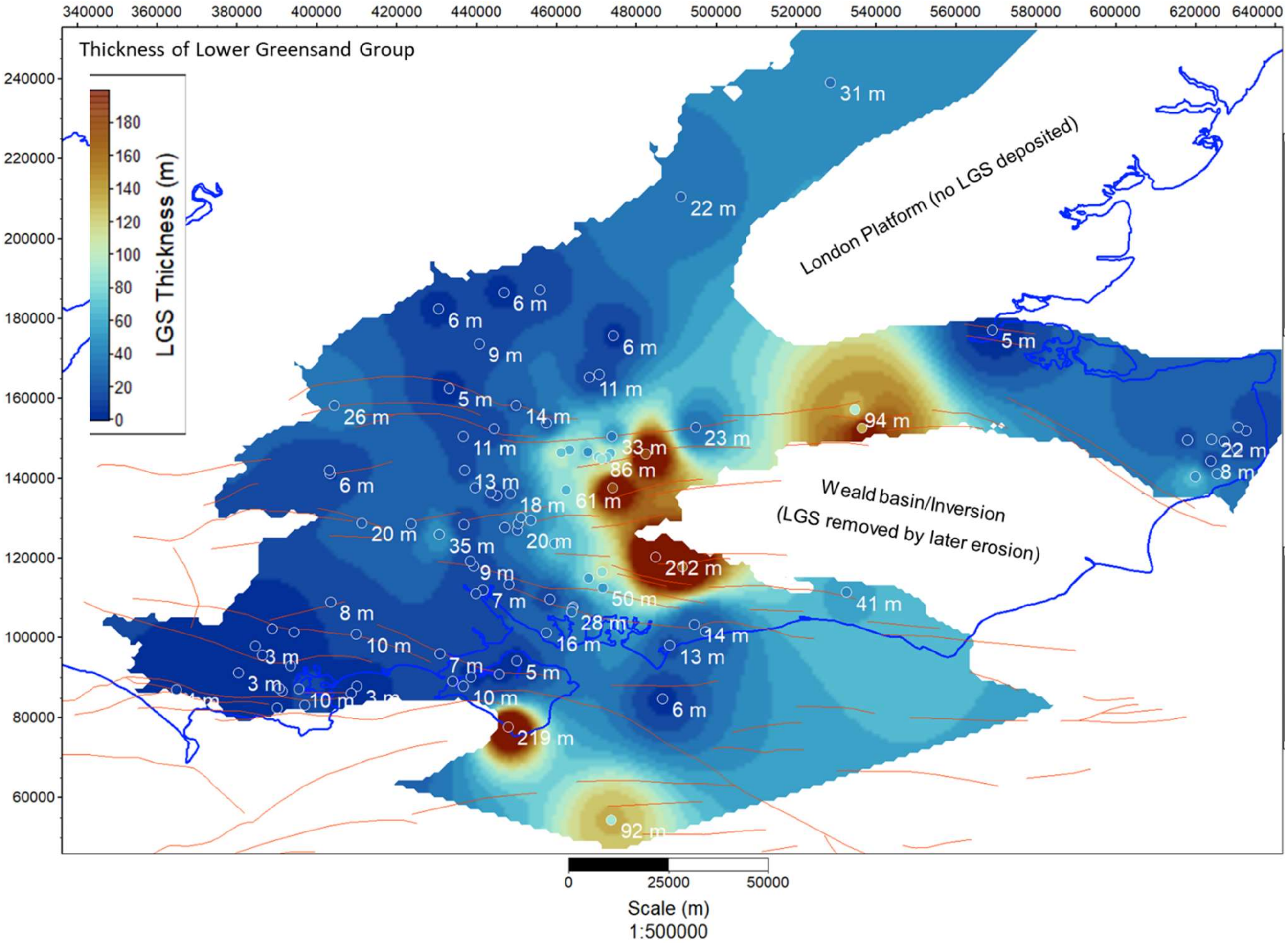

Figure 11 Map showing thickness of the Lower Greensand Group (covering interval base Gault to base Atherfield Clay formations, where present). Note the marked and highly localised thickening of the Lower Greensand Group at the western end of the Weald Basin. This is created by the presence of the Atherfield Clay and Hythe Formation, which have a restricted, basin-centric, distribution. Surrounding thinner successions are largely represented by younger Lower Greensand deposits (*nutfieldiensis-mammillatum* biozone) which progressively onlapped areas peripheral to the main basins. A comparable situation is found in the Isle of Wight where thick Atherfield Clay and Ferruginous Sands Formation are present in the Portland-Wight Basin but missing across the Dorset-Hampshire High to the north.

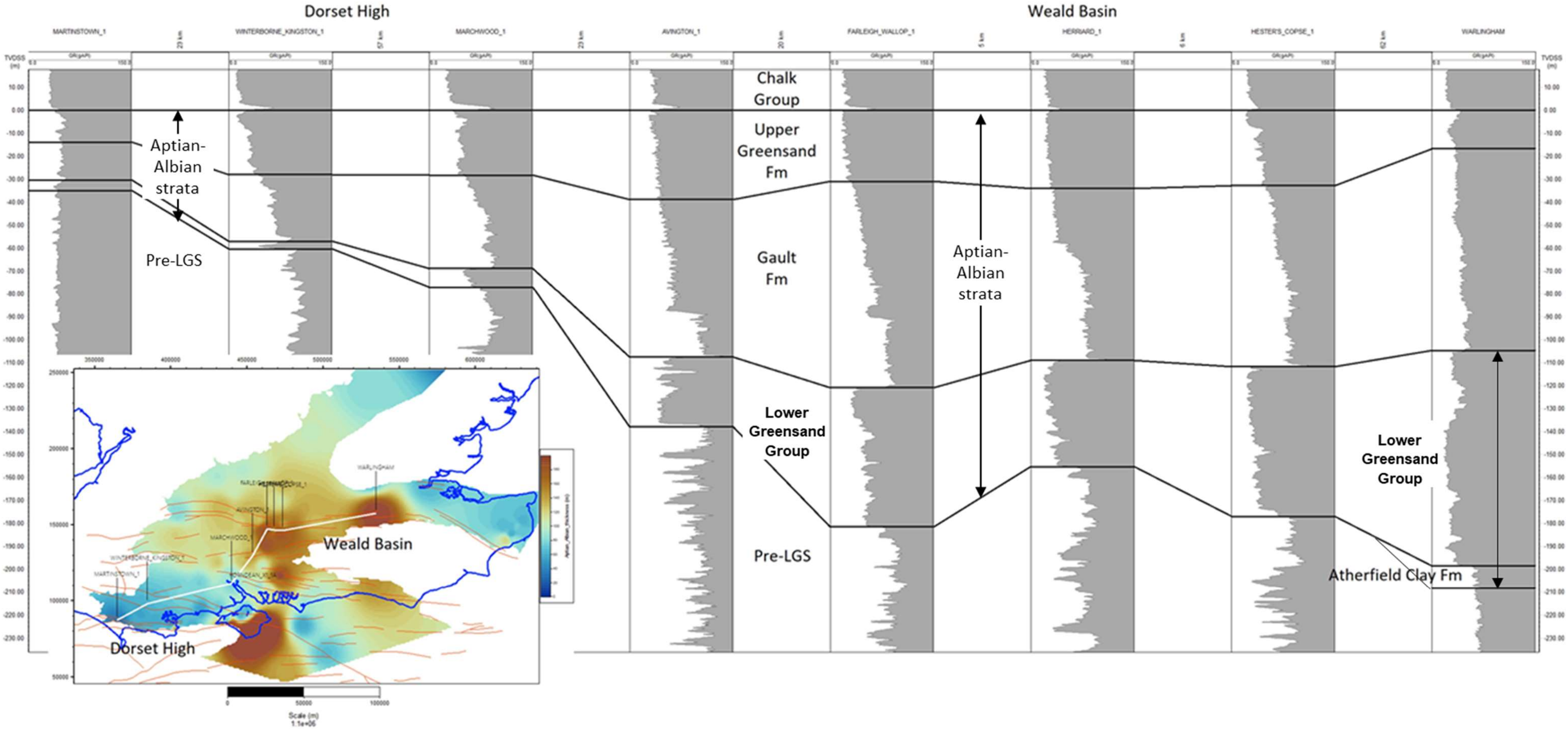

Figure 12. South-west to north-east correlation panel from Martinstown 1 on the South Dorset High to the Warlingham borehole in the Weald Basin. Aptian-Albian strata form a wedge-shaped unit with large thickness variation in the Lower Greensand Group and Gault Formation. The Upper Greensand is a more uniform thickness and grades upward from the underlying Gault, with a progressive decrease in gamma-ray value. This contrasts with the generally sharp lower and upper of the Lower Greensand Group. The boreholes are flattened on the base of the Chalk Group.

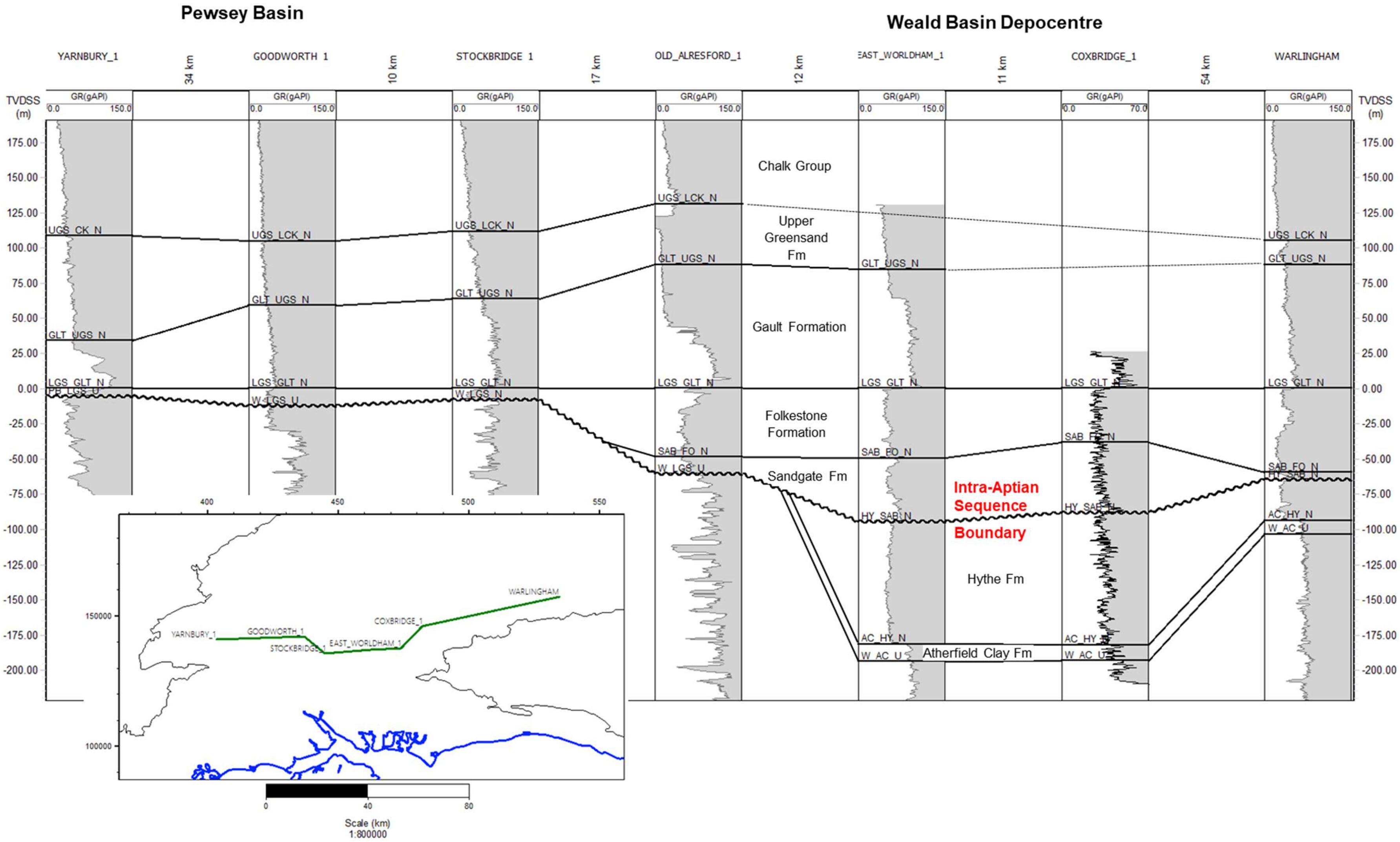

Figure 13 West-east correlation panel from Yarnbury 1 in the Pewsey Basin to Warlingham in the Weald Basin. Note the abrupt increase in thickness in the Lower Greensand Group between Old Alresford and East Worldham created by the presence of Atherfield Clay and Hythe Formation. An intra-Aptian sequence boundary separates these basin-centric pre-*nutfieldiensis* units from overlying LGS, which onlaps and expands across adjacent highs. This trend, driven by eustatic sea-level rise and regional post-rift thermal subsidence continues into the Gault Formation and above.

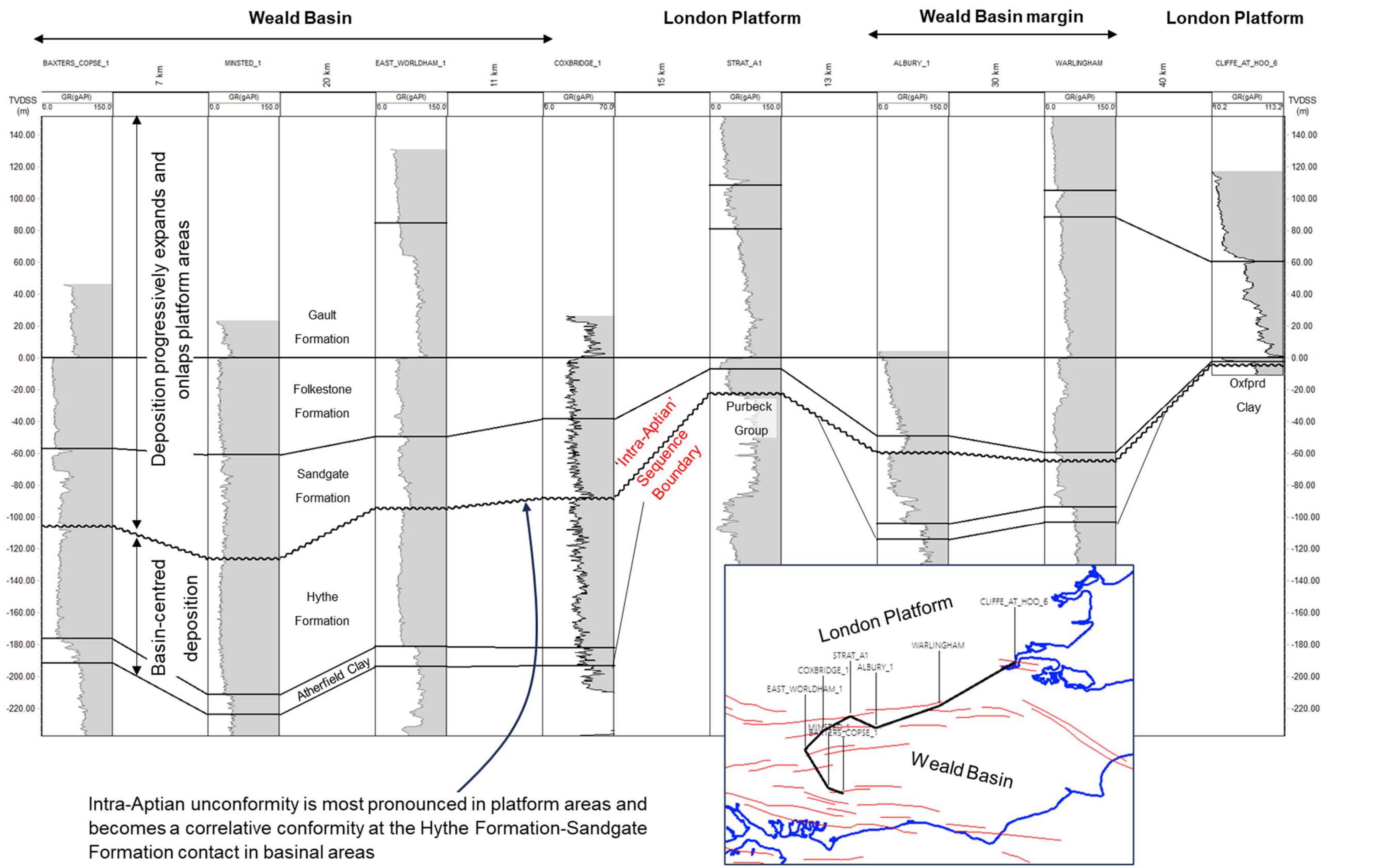

Figure 14 Correlation panel from the Weald Basin onto the London Platform showing onlap of basin margins above the intra-Aptian unconformity

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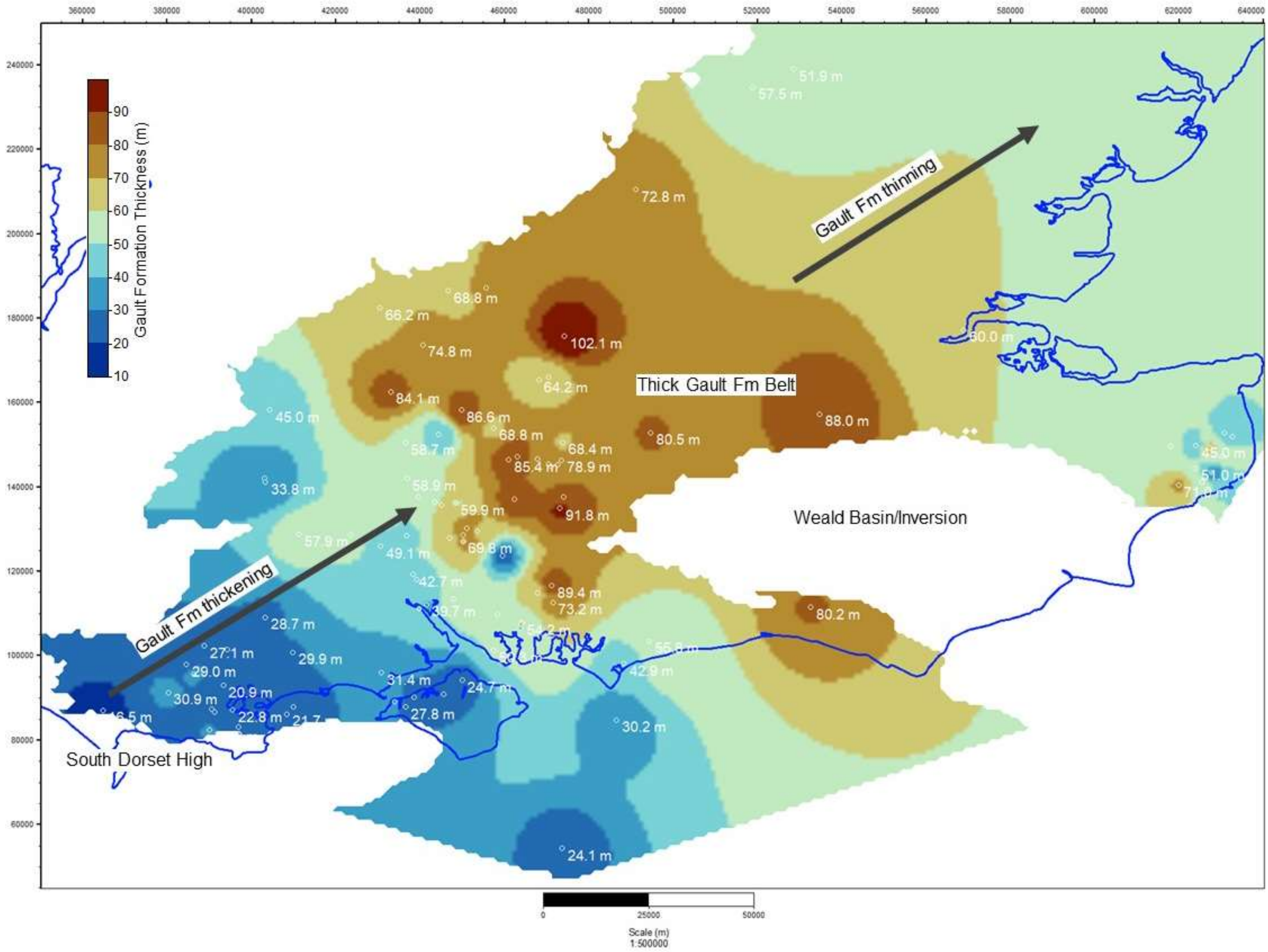

Figure 15 Map showing thickness of the Gault Formation and the development of three distinct NW-SE trending belts. Note that the trend of the belts (isopach contours) cuts along the regional west-east trending structural grain of southern England.

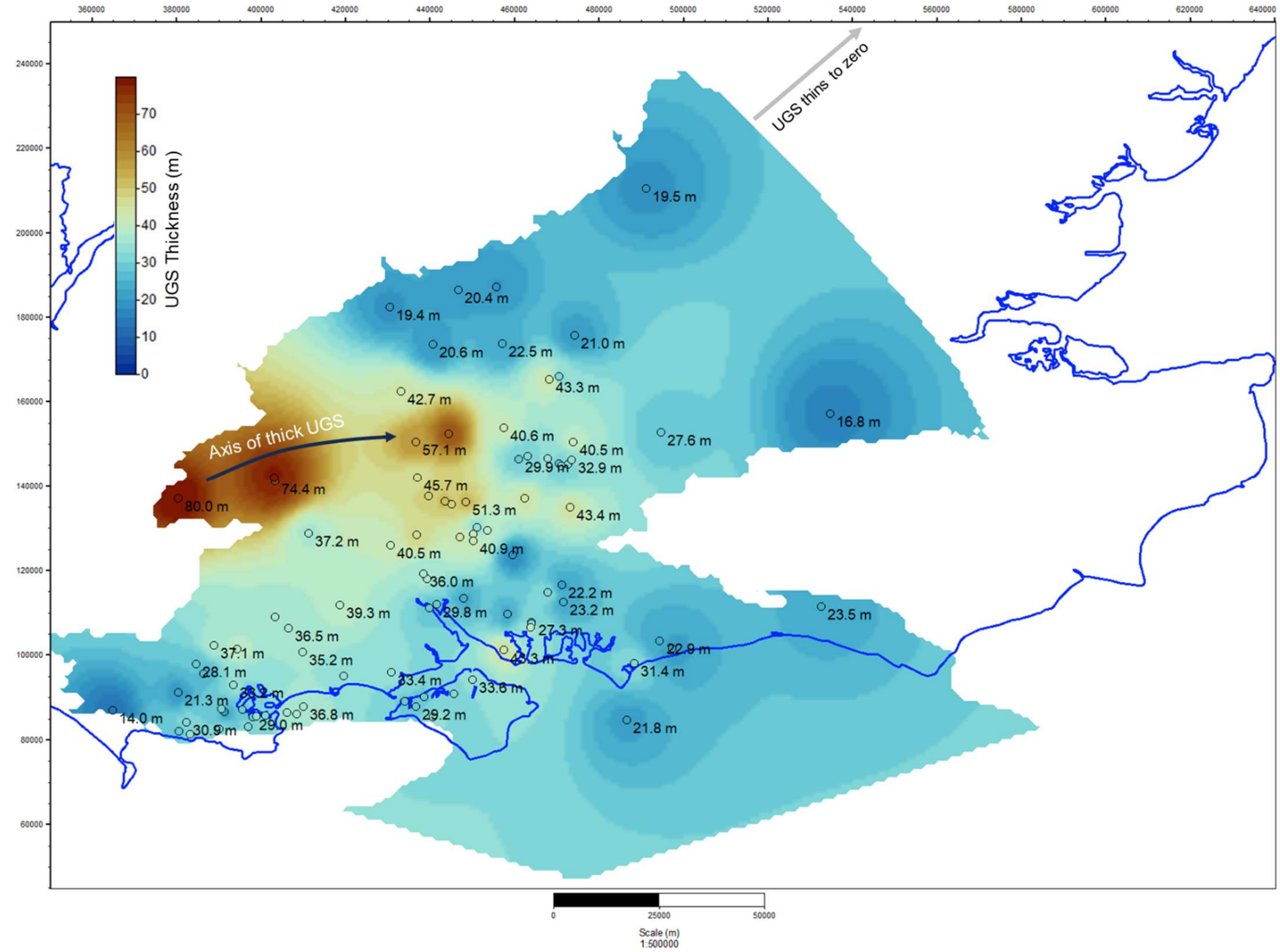

Figure 16 Map showing thickness of the Upper Greensand Formation (UGS) with a distinct axis of thick UGS extending under Salisbury Plain toward Andover.

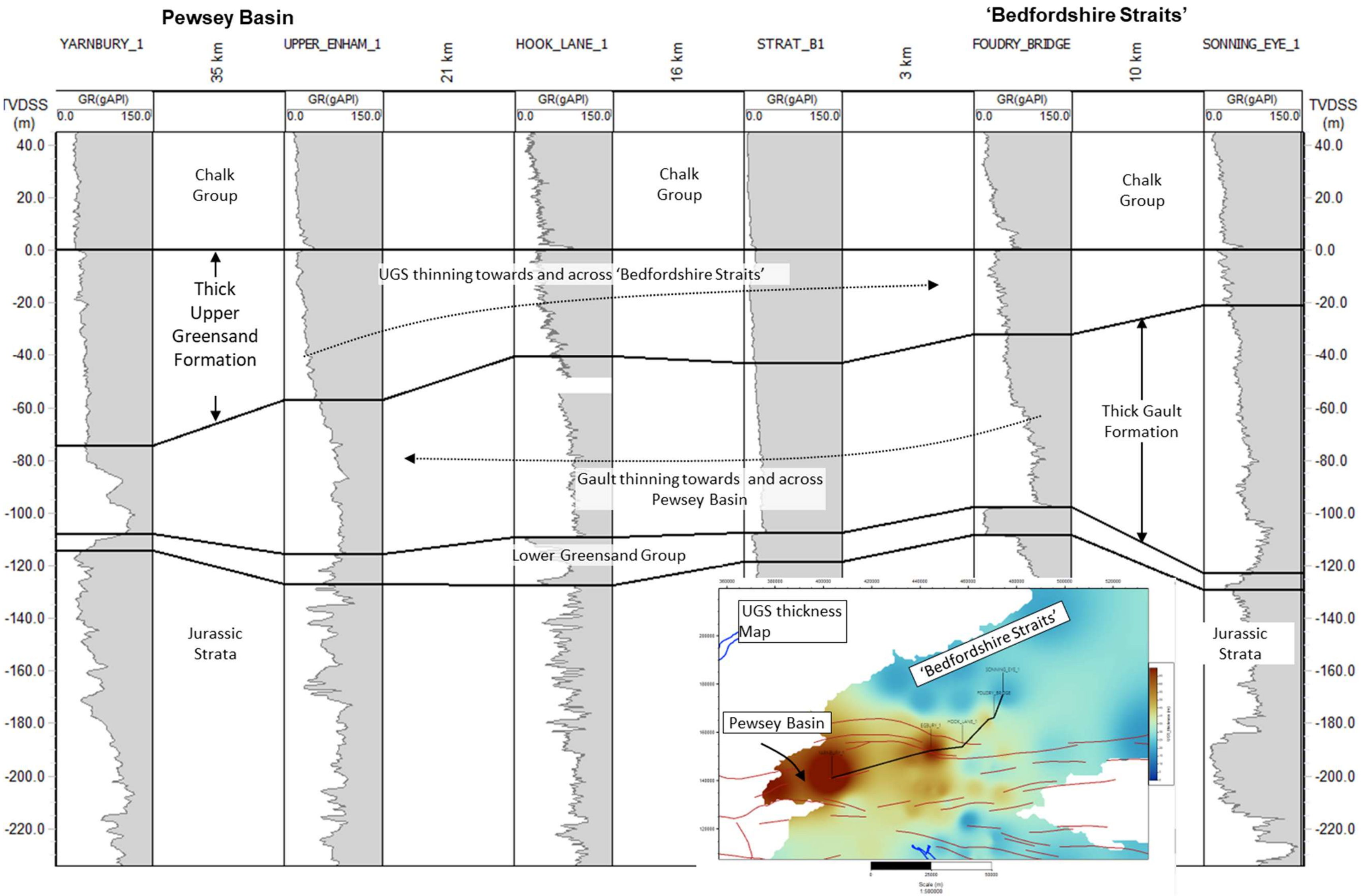

Figure 17 Correlation panel showing the diachronous boundary between Gault and Upper Greensand formations. Note the eastward thinning of the Upper Greensand and the corresponding eastward thickening of the Gault Formation. The Lower Greensand Group maintains a relatively constant thickness.

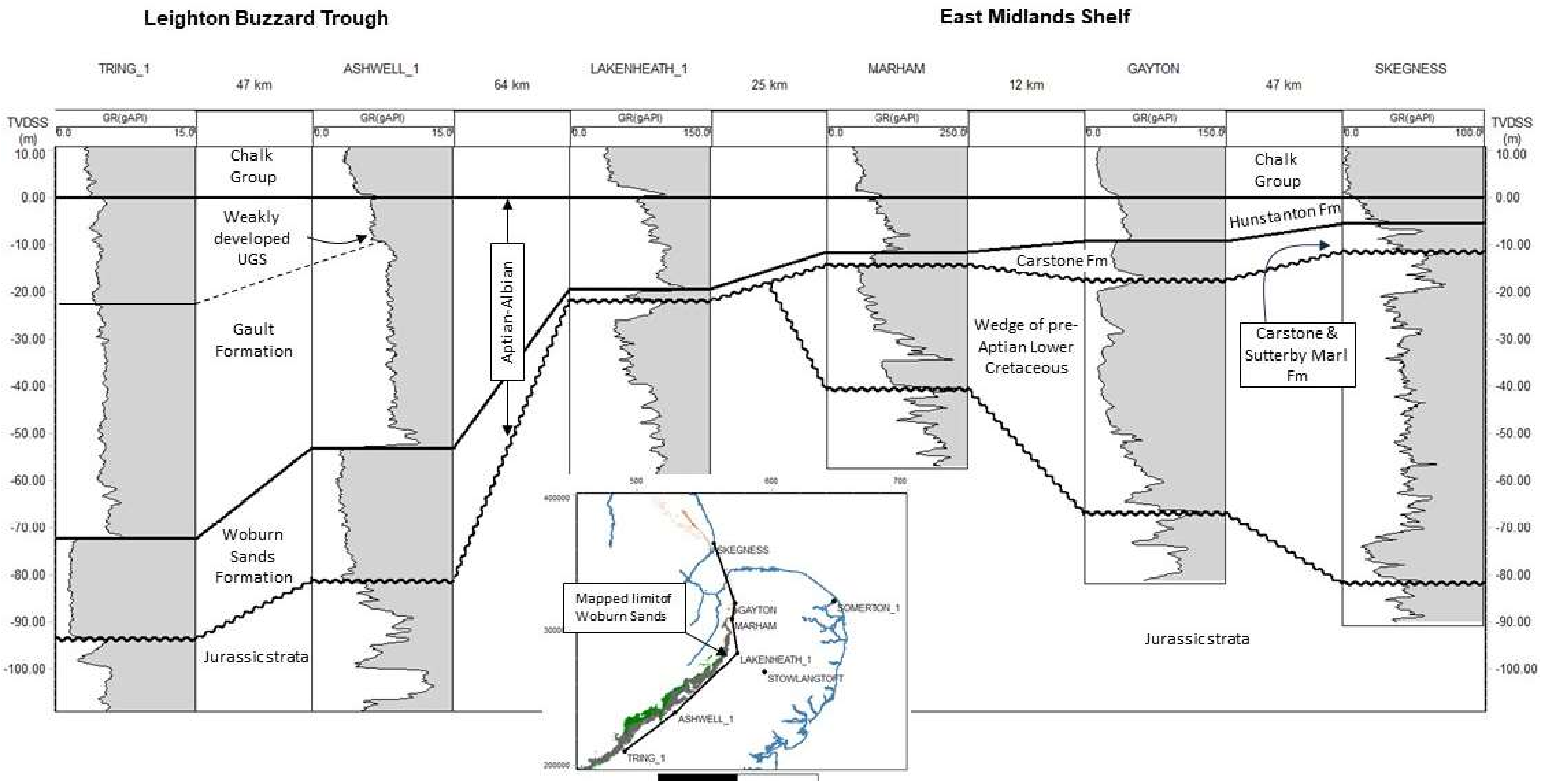

Figure 18 Correlation panel from the Tring 1 to the Skegness borehole which bridges the divide between the distinct depositional provinces of the Leighton Buzzard Trough and the East Midlands Shelf. In the Tring 1 and Ashwell 1 boreholes, Woburn Sands Formation are present beneath Gault Clay which coarsens upwards into weakly developed Upper Greensand Formation. Northward toward Lakenheath 1 the Woburn Sands are absent and a thin bed of glauconitic, ferruginous coarse-grained sand (Carstone Formation) rests unconformably on Jurassic mudstones. The Carstone Formation is overlain by a relatively thin succession of Gault Formation in Marham and Gayton. Further north toward Skegness, the Gault Formation has been replaced laterally by the impure carbonates of the Hunstanton Formation which grade upwards from the Carstone Formation into the overlying Chalk Group. Boreholes in the correlation panel are flattened on the base of the Chalk Group.

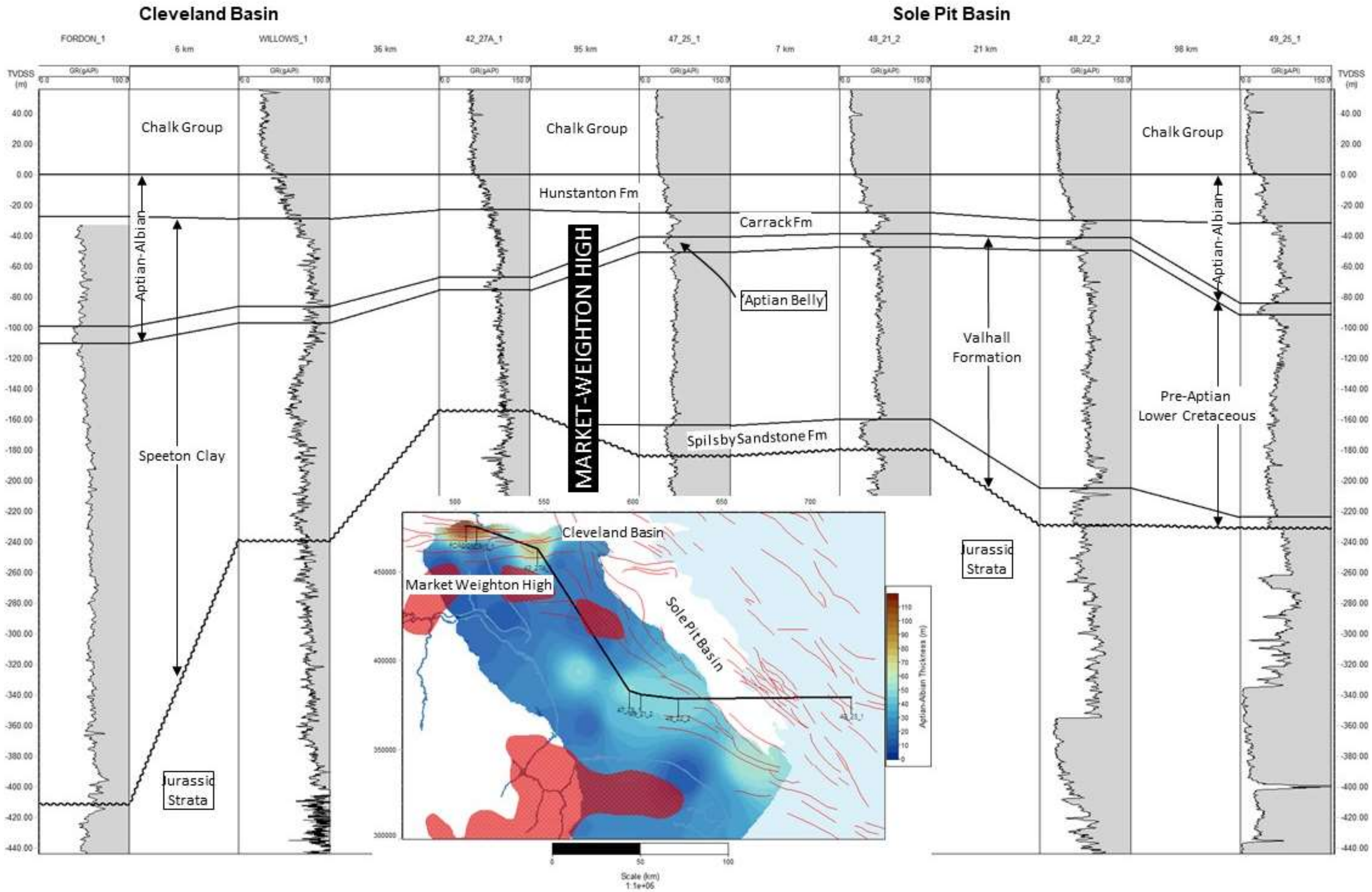

Figure 19 Correlation panel from Fordon 1 in the Cleveland Basin to 49/25-1 in the Southern North Sea (SNS). In these basinal areas, Aptian-Albian strata reach around 100 m thick. They overlie a thick pre-Aptian Lower Cretaceous succession, which in the Cleveland Basin, includes strata assigned to the lower part of the Speeton Clay. In the SNS, Aptian-Albian deposits are partly included within and underlain by the Valhall Formation. The base of the Aptian is primarily picked on foraminiferal biostratigraphy, but particularly in the SNS this coincides with a distinctive low gamma bulge which Crittenden (1987) graphically describes as the 'Aptian belly'. This corresponds to a package of calcareous mudstones at the top of the Valhall Formation. These are overlain by mudstones of the Carrack Formation and the Hunstanton Formation. Wells are flattened on the base of the Chalk Group.