UK Stratigraphical Framework Series: Lias Group

National Programme

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Laminated black mudstone from the Blue Lias Formation, Dorset

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Foreword & Summary

This report provides a high-level overview of the stratigraphy of the Lias Group for the main outcrop and subcrop area of southern and north-east England (Weald Basin, Wessex Basin, Somerset Basin, Worcester/Severn Basin, East Midlands Shelf and Cleveland Basin), and South Wales (Bristol Channel Basin). The report is intended to provide a broad geological context for any future investigations of this interval. The report does not include details of the Lias Group in Scotland.

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1 Introduction

1.1 BACKGROUND TO THE REPORT SERIES

This report on the Lias Group forms part of the UK Stratigraphical Framework Series (UKSFS) which aims to generate new information on the structure, stratigraphy and lithological 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. Cox et al. 1999), 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) 25 full-page figures at the rear and several appendices. The text includes an overview of data sources, methods, background information on the Lias Group 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 Lias Group strata and 262 boreholes which prove this interval in the subsurface.

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 Lias Group outcrops in the Wessex Basin.

Most of the boreholes used in the study were drilled for the purpose of hydrocarbon exploration and occur within the sedimentary basins of 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. Since June 2023 the North Sea Transition Authority (NSTA) has authorised the release of all the well data for onshore hydrocarbon boreholes held by BGS in the National Geoscience Data Centre (NGDC).

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). The geophysical logs vary widely in age, quality, and the suite of available log types.

1.3.2 Key outcrop sections and reference boreholes

Appendix B provides a list of key Lias Group outcrop sections and boreholes. BGS stratigraphical research boreholes (drilled during mapping programmes) are particularly important because these often combine core descriptions and biostratigraphy with geophysical logs. 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 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 sedimentary strata (Whittaker et al, 1985). Sonic logs are sometimes not available where Lias Group rocks were close to surface and the borehole was cased.

Gamma-ray instruments are sensitive to changes in the natural background gamma radiation and discriminate those 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 Lias Group 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. The UK Onshore Geophysical Library (https://ukogl.org.uk/) is a useful source for this information.

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.

1.3.4 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 elevation changes and ease comparison and correlation of specific units. All borehole correlation panels illustrated in this report are flattened on selected stratigraphical horizons rather than plotting at true depth relative 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).

1.3.5 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. In total 1220 markers were picked.

Table 1 List of markers and key to codes

Marker_Name	Unit_Below	Unit_Above	Type	Count
BLI_CHAM_N	Blue Lias Formation	Charmouth Mudstone Formation	N	148
CHAM_DYS_N	Charmouth Mudstone Formation	Dyrham Formation	N	147
PNG_BLI_N	Penarth Group	Blue Lias Formation	N	142
BDS_INO_N	Bridport Sand Formation	Inferior Oolite Group	N	115
MRB_WHM_N	Marlstone Rock Formation	Whitby Mudstone Formation	N	89
DYS_BNLS_N	Dyrham Formation	Beacon Limestone Formation	N	82
BNLS_DCC_N	Beacon Limestone Formation	Down Cliff Clay Coal	N	74
WHM_JURM_N	Whitby Mudstone Formation	Middle Jurassic Rocks (Undifferentiated)	N	64
DCC_BDS_N	Down Cliff Clay	Bridport Sand Formation	N	62
PNG_SMD_N	Penarth Group	Scunthorpe Mudstone Formation	N	61
DYS_MRB_N	Dyrham Formation	Marlstone Rock Formation	N	57
SMD_CHAM_N	Scunthorpe Mudstone Formation	Charmouth Mudstone Formation	N	36
CHAM_MRB_N	Charmouth Mudstone Formation	Marlstone Rock Formation	N	35
RMU_STA_N	Redcar Mudstone Formation	Staithes Sandstone Formation	N	13
CDI_WHM_N	Cleveland Ironstone Formation	Whitby Mudstone Formation	N	12
STA_CDI_N	Staithes Sandstone Formation	Cleveland Ironstone Formation	N	12
WHM_INO_N	Whitby Mudstone Formation	Inferior Oolite Group	N	10
WHM_NS_N	Whitby Mudstone Formation	Northampton Sand Formation	N	9
BNLS_BDS_N	Beacon Limestone Formation	Bridport Sand Formation	N	7
TRIA_BLI_U	Triassic Rocks (Undifferentiated)	Blue Lias Formation	U	7
TRIA_CHAM_U	Triassic Rocks (Undifferentiated)	Charmouth Mudstone Formation	U	4
WHM_BDS_N	Whitby Mudstone Formation	Bridport Sand Formation	N	4
BM_GAB_N	Belemnite Marl Member	Green Ammonite Member	N	3
LI_CK_U	Lias Group	Chalk Group	U	3
CL_BLI_U	Carboniferous Limestone Supergroup	Blue Lias Formation	U	2
MRB_BDS_N	Marlstone Rock Formation	Bridport Sand Formation	N	2
RZRU_BLI_U	Palaeozoic Rocks (Undifferentiated)	Blue Lias Formation	U	2
BAN_BLI_F	Blue Anchor Formation	Blue Lias Formation	F	1
CAMN_LI_U	Cambrian Rocks (Undifferentiated)	Lias Group	U	1
CARB_BLI_U	Carboniferous Rocks (Undifferentiated)	Blue Lias Formation	U	1
CHAM_BNLS_F	Charmouth Mudstone Formation	Beacon Limestone Formation	F	1
CHAM_CB_U	Charmouth Mudstone Formation	Cornbrash Formation	U	1
CHAM_INO_F	Charmouth Mudstone Formation	Inferior Oolite Group	F	1
CHAM_INO_U	Charmouth Mudstone Formation	Inferior Oolite Group	U	1
CHAM_JURM_U	Charmouth Mudstone Formation	Middle Jurassic Rocks (Undifferentiated)	U	1
CL_BLI_N	Carboniferous Limestone Supergroup	Blue Lias Formation	N	1
LI_JURM_N	Lias Group	Middle Jurassic Rocks (Undifferentiated)	N	1
LI_JURM_U	Lias Group	Middle Jurassic Rocks (Undifferentiated)	U	1
LI_LI_F	Lias Group	Lias Group	F	1
LI_LOCR_U	Lias Group	Lower Cretaceous Rocks (Undifferentiated)	U	1
MRB_DCC_N	Marlstone Rock Formation	Down Cliff Clay Coal (South Wales)" Member"	N	1
PNG_CHAM_N	Penarth Group	Charmouth Mudstone Formation	N	1
PNG_CHAM_U	Penarth Group	Charmouth Mudstone Formation	U	1
SSG_CHAM_U	Sherwood Sandstone Group	Charmouth Mudstone Formation	U	1
WHM_LOCR_U	Whitby Mudstone Formation	Lower Cretaceous Rocks (Undifferentiated)	U	1
				1220

1.3.6 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 to build the model (Table 2).

Table 2 List of datasets used in the modelling

Dataset	Description
Well markers	Borehole stratigraphical interpretation produced as part of this study
Shapefile of outcrop extent of onshore Lias Group	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/
Shapefile of 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 the Lias Group (and selected subdivisions) 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. Maps are presented using the scientific colour ramps of Crameri (2018) which are perceptually uniform and ordered to represent data without visual distortion.

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.

2 Lias Group: geological background

2.1 OVERVIEW

The Lias Group is a marine-mudstone dominated unit that encompasses the entire Lower Jurassic (ca. 26.7 Myr), together with the uppermost (Rhaetian) part of the Triassic and the lowermost (Aalenian) part of the Middle Jurassic. The rocks reach a maximum thickness of around 1 km in onshore UK and are mostly highly fossiliferous, with the frequent occurrence of ammonites permitting a high-resolution biostratigraphy of zones and subzones (Figure 2 and Appendix B). The Lias Group has long been recognised as a distinct stratigraphical unit that contrasts with the red mudstones of the Triassic below and the Middle Jurassic oolitic limestones and ‘estuarine’ sandstones above. The Lias probably takes its name from the Old French word ‘Liais’ referring to fine-grained, hard limestone which, particularly toward the base, interbeds with the marine mudstones.

In most parts of England, the marine mudstones of the Lias Group rest with a hiatus on an eroded top of the Rhaetian Penarth Group: an extensive sea-level fall has been postulated prior to the marine transgression that continued into the Early Jurassic (Hallam, 1990). The top of the Lias Group is also an erosive unconformity of variable duration, positioned at the base of the lowest limestone or sandstone of the Middle Jurassic Inferior Oolite Group, Ravenscar Group, Dogger Formation or West Sole Group. In the Cleveland Basin, the Lias Group was gently deformed and eroded during a widespread phase of Toarcian-Aalenian tectonism prior to the deposition of Middle Jurassic rocks. This regional unconformity is a distal expression of the 'Mid Cimmerian Unconformity' of the Central North Sea which relates to a transient phase of thermal doming, volcanism, relative sea-level fall and erosion (Underhill & Partington, 1993).

Throughout the Early Jurassic, fluctuating sea levels, climatic cycles and extensional tectonics associated with North Atlantic and Tethyan rifting modulated the deposition of mudstones, organic rich shales, limestones, siltstones, sandstones and ironstones (Cope, 2006; Bradshaw et al., 1992; Holloway, 1985). The high-resolution ammonite zonation shows that many of the major shifts in Lias Group lithology are broadly synchronous across different basins (Figure 2). The Lias Group includes the Toarcian Oceanic Anoxic Event (T-OAE) which is associated with a major extinction event, a large negative carbon isotope excursion, and the sequestration of carbon in marine basins to form organic-rich mudstones such as the Jet Rock in Yorkshire. Lias Group deposition is characterised by 'basin and swell' stratigraphic architecture, with thicker successions occupying fault-bounded basins separated by thinner successions across intervening structural highs (Figure 2).

Much of the UK was covered by a shallow sea during the Early Jurassic and the presence of small (but often thick) erosional outliers show that the Lias Group had a much wider distribution than the present outcrop and subcrop (Figure 3). Small island land-masses probably included eastern England (Anglo-Brabant Massif), SW England (Cornubia and the Mendips), SW Wales (Welsh Massif), and Scotland (Scottish Massif). There is a pattern of progressive overstep and thinning onto these massifs and the Lias Group has a strongly diachronous base that may rest unconformably on much older Mesozoic, Palaeozoic or Precambrian rocks (Barron, 2015). Where deposits of deeper shelf facies abut against inferred positive areas there is generally little change in facies (Hallam, 1992). Coupled with post-depositional erosion and the likely low-relief of land areas, this makes the identification of coastlines extremely difficult. Lias Group successions developed on the coast of South Wales and across the Radstock Shelf, north of the Mendip High, include facies reflecting highly condensed and/or near-shore, shallow water deposition (Simms, 2004). Thin basal conglomerates composed of limestone clasts are common where the Lias laps onto the London-Brabant Massif (Sumbler, 1996).

2.2 OUTCROP DISTRIBUTION

The main outcrop of the Lias Group extends across England, from the Dorset coast between Pinhay Bay and Bridport in the south-west, to the coast of Yorkshire between Robin Hood's Bay and Staithes in the north-east (Figure 1). There are also isolated outcrops on the coast of north Somerset, South Wales, Cheshire, the Solway Firth and in Scotland. While of huge importance, these outliers are not considered further because of project time-constraints, they are mostly limited in stratigraphical coverage, and they fall outside the main block of borehole data which is the primary focus of the work (Figure 1). Cox et al. (1999) and Simms et al. (2004) provide some information on the outliers.

2.3 SUBCROP DISTRIBUTION

East of its main outcrop belt, the Lias Group has an extensive subcrop in the Wessex, Pewsey, Worcester and Weald basins of southern England, the East Midlands Shelf and the Cleveland Basin (Figure 4). The continuity of subcrop across this area is broken by the Anglo-Brabant Massif, a major basement high which has only a partial cover of Lias Group. This results both from non-deposition of marine Lias Group on an emergent landmass and post-depositional erosion. The extent of Lias Group and younger strata across the Anglo-Brabant Massif was likely reduced by erosion during the latest Jurassic and early Cretaceous. The top of the Lias

Group was also eroded in the Toarcian during the relative sea-level fall associated with the Mid-Cimmerian Unconformity. The unconformity is commonly marked by pedogenically-modified Lias Group beneath Middle Jurassic deposits (Sumbler, 1996).

At subcrop, the elevation at which Lias Group is encountered reflects a combination of Jurassic-Cretaceous basin subsidence and Cenozoic basin inversion and uplift (Figure 4). The base of the Lias Group is present at greatest depth (around 2.5 km) in the Weald Basin and it occurs at around 1.8 km in the Portland-Wight Basin and 1.3 km in the Winterborne-Kingston Trough. The Worcester Graben forms a north-south trending structural low extending northwards from the Pewsey Basin, which forms a westward extension of the Weald Basin.

Across much of the Anglo-Brabant Massif and East Midlands Shelf the base of the formation occurs at relatively shallow (<0.5 km) depths. On the East Midlands Shelf the formation broadly strikes parallel to the coast and it dips gently offshore toward the Wolds Syncline, west of the Dowsing Fault Zone and Sole Pit Inversion. The Cleveland Basin forms a conspicuous trough north of (and parallel to) the Flamborough Fault Zone.

2.4 OVERALL THICKNESS PATTERNS

Information from 170 boreholes shows that the Lias Group (where 'complete') ranges from 22 m to 948 m thick with a median value of 251 m (Figure 5). The thickness patterns clearly relate to the location of rapidly subsiding fault-bounded basins and intervening highs during the Early Jurassic (Figure 6), which is identified as one of four major pulses of crustal extension in southern England (Chadwick, 1986). The recognition of Toarcian and Bajocian neptunian sills and dykes in the Wessex Basin-Mendip area provides further evidence of Early Jurassic extensional tectonic activity, which was probably driven by the early rifting phases of the Central Atlantic (Jenkyns & Senior, 1991).

The thickest deposits occur in the Portland-Wight Basin where the Lias Group reaches 948 m thick. Deposits up to 617 m thick occur in the Winterborne-Kingston Trough, a narrow graben structure to the north of the South Dorset High. Together these structural elements form the composite Wessex Basin, which is separated from the Weald Basin by a belt of relatively thin (200-300 m) Lias Group that extends from the Mendips to the Isle of Wight and includes the Cranborne-Fordingbridge High.

The Weald Basin, Pewsey Basin and Worcester Graben form a continuous curved belt where the Lias Group reaches a thickness of around 450-500 m (Figure 6). North and east of this belt the Lias Group thins rapidly onto the Anglo-Brabant Massif, across which the group is often less than 100 m thick or entirely absent.

Across the East Midlands Shelf the group is generally less than 250 m thick with a distinct trough of thicker deposits occurring in the saddle between the Anglo-Brabant Platform and the Market Weighton High (Figure 6). The term 'Grantham-Skegness Trough' is used here to denote this thicker zone. North of the Market Weighton High the Lias Group thickens to 434 m in the Cleveland Basin whose southern boundary is defined by the Flamborough Fault Zone. The Sole Pit Trough (bounded by the Dowsing Fault Zone) is a southern branch of the Cleveland Basin. Cameron et al. (1992) state that the Sole Pit Trough locally contains up to 744 m of Lias Group, but values of around 300 m are more typical.

Beyond the area covered by the map, high rates of fault-controlled subsidence are also inferred for the extremely thick (ca. 800 – ca. 2500 m) Lias Group successions proved in the Mochras Borehole and the adjacent Cardigan Bay Basin (Cope, 2006) (Figure 3). On the Somerset coast, an exceptionally thick Hettangian – Early Sinemurian Lias Group succession showing progressive up-section increases in ammonite zonal thicknesses, indicates very high rates of subsidence, contrasting with thinner and shallower water succession developed on the north side of the Bristol Channel along the South Wales coast (Simms, 2004).

2.5 LITHOSTRATIGRAPHY

Figure 7 shows the lithostratigraphy for the Lias Group that is relevant to this report and follows the rationalisation of stratigraphical nomenclature proposed by Cox et al. (1999). In this scheme, distinct regional stratigraphical classifications are recognised for the Wessex Basin (including Central Somerset Basin), the Worcester (Severn) Basin, the East Midlands Shelf and the Cleveland Basin. The revised lithostratigraphy represents a balance between the unification of units of broadly similar lithology and age while preserving clear local differences. On BGS 1:50,000 geological maps the lateral changes between broadly coeval units appear sharp (Figure 8), but in reality, are transitory and somewhat arbitrary between the end-member successions of Dorset and Yorkshire. The Cleveland Basin succession is generally regarded as more sandy and proximal to land than the Dorset outcrops.

Interbedded mudstone and limestone are common at the base of the Lias Group (Hettangian and lower Sinemurian) and these are included under the Blue Lias and Scunthorpe Mudstone formations. The 'Calcareous Shale' forms an analogous unit in the Cleveland Basin but Cox et al. (1999) rank it as a member of the Redcar Mudstone Formation. The Sinemurian-Pliensbachian Charmouth Mudstone grades upward from the Blue Lias through the progressive loss of limestone beds. The upper parts of the Charmouth Mudstone consist almost entirely of mudstones.

The late Pliensbachian to Toarcian Cleveland Ironstone, Marlstone Rock and Beacon Limestone formations are an important marker interval within the Lias Group. These transgressive condensed, iron-rich limestones often rest erosively on a shoaling succession of siltstones (Dyrham Formation) and sandstones (Staithes Sandstone Formation).

The most significant regional differences in the Lias Group occurs toward the top in the Toarcian which varies from dark laminated mudstone (Whitby Formation), to highly condensed limestone (Beacon Limestone Formation), and diachronous shallow marine sandstones (Bridport Sands).

The Lias Group was traditionally subdivided into three broad litho- and chrono-stratigraphical intervals, comprising Lower, Middle and Upper Lias (Cox, 1999). These included admixtures of long-established units like the Blue Lias (Lang, 1914, 1924), Marlstone Rock and Bridport Sand formations (Wilson et al., 1958), as well as more recent additions such as the Scunthorpe Mudstone and Redcar Mudstone formations (Brandon et al., 1990; Powell, 1984).

The Lias Group includes at least 47 formations, members and marker beds whose key lithological and palaeontological features are summarised in Appendix C. The characteristics of their boundaries are described in Appendix D. Most of these units are not referenced further.

2.6 DEPOSITIONAL ENVIRONMENT

Hallam (1992) summarises Lias Group mud-dominated deposition as 'deeper shelf', while noting that maximum water depths were probably not significantly in excess of 100 m in the shallow epicontinental seas of the British Isles. Other observations from Hallam (1992) include:

- Despite strong evidence for syn-depositional faulting, the absence of debris-flow deposits, turbidites and slumps indicates low depositional gradients. Tidal and wave energy were also likely low.
- The clays, composed almost entirely of illite, may contain a moderate proportion of silt and fine sand when in proximity to land or during regressive intervals.
- Low sedimentation rates correlate with an increase in the proportion of calcite in form of marls, microcrystalline limestone beds and nodules.
- Periodic variations in the oxygen content of bottom waters are signified by organic-rich black shales.
- Sandstones such as the Bridport Sands were deposited on a shallow, open shelf. The presence of hummocky cross-bedding in the Staithes Sandstone indicates the activity of periodic storms.

- Ironstones reflect intense chemical weathering on land under a tropical climate. Iron was reworked into shallow marine deposits during transgression.

2.7 BIOSTRATIGRAPHY

The biostratigraphy of the Lias Group is based on ammonites the preserved remains of which are generally abundant, although other types of fossils (e.g. bivalves, belemnites, brachiopods, echinoderms) can also be useful for recognising discrete intervals of strata within the succession. The standard biozonation of the Lias Group is shown in tabular form in Appendix C.

In addition to ammonite zones and subzones, a series of more refined ammonite subdivisions ('zonules' or 'biohorizons') has also been recognised in the Lias Group (Page, 2002, 2004, figs 1.3 – 1.7). These fine-scale biostratigraphical units are identified by characteristic assemblages of fossils, and are best considered as bioevent horizons between which gaps of uncertain duration exist (Page, 2004). These are not detailed or described further herein.

Zonal and subzonal nomenclature used in this text follows the conventions discussed by Cox (1990), in regarding Jurassic ammonite zones/subzones as chronostratigraphical units, referred to by species name with an initial capital letter written in non-italicized text.

Figure 2 shows the correlation of biozones between 13 key cored boreholes and outcrop sections in the Lias Group for the major depositional basins in southern England, Wales, the Midlands and north-east England. The following may be concluded:

- Biozonal patterns in the Lias Group show rapid lateral thickness changes, confirming published evidence (e.g. Cope, 2006) for the role of faulted blocks and basins as a control on patterns of expanded and condensed sedimentation.
- Most biozones in the Mochras Borehole (see inset on Figure 2) are hugely expanded compared to even the relatively thick Stowell Park Borehole succession in the Severn (Worcester) Basin, indicating both significant accommodation space and high sediment supply to this area. Together with the 617 m of Lias Group reported in a borehole at Prees (Warrington, 1997), and ca. 2500 m offshore in Cardigan Bay (Cope, 2006), these records indicate that very thick successions developed to the west of the current main outcrop margin of the Lias Group. Cardigan Bay and Mochras form the eastern termination of the much larger St George's Channel Basin.
- Biozones below the Ibex Zone (Hettangian-upper Pliensbachian) in the Weald Basin (at Warlingham) are relatively condensed, and similarly at the Dorset 'Jurassic Coast' outcrop sections compared to coeval deposits in the Somerset and Severn (Worcester) Basins.
- Pronounced thinning of biozones occurs towards the Mendip and Market Weighton structural highs. In the Dundry (Elton Farm) Borehole, just north of the Mendip High, this effect is seen below the Ibex Zone, but above this level expansion of biozones compared to adjacent basinal successions suggests changes in structural behaviour. The Dundry borehole is located in a small sub-basin to the north of the Radstock Shelf, on the north side of the Mendip High (Donovan & Kellaway, 1984), and indicates the potential for complex and variable sediment patterns in regions with sharply defined palaeoenvironmental gradients close to faults.
- Thinning of the Lias Group occurs on the flanks of the Anglo-Brabant Massif.
- The Lias Group is relatively thin but shows less lateral variability across the East Midlands Shelf, apart from close to the Market Weighton High.
- There is significant expansion of the Lias Group into the Cleveland Basin north of the Market Weighton High, but the succession is generally less expanded than the equivalent succession in the Worcester Basin.

- The typical Blue Lias facies of interbedded limestones and mudstones is diachronous; it terminates in the Early Bucklandi Zone in the Stowell Park Borehole, in the Semicostatum Zone in the Burton Row Borehole, and extends as high as the Ibex Zone in the Warlingham Borehole (Worssam & Ivimey-Cook, 1971).
- The Margaritatus Zone, broadly associated with the onset of deposition of the Dyrham Formation in southern England, is very significantly expanded in the south Dorset succession compared to the otherwise expanded Worcester Basin succession. Hesselbo & Jenkyns (1998) considered the Dorset succession to occupy a relatively distal basin setting, so expanded sedimentation in this area might indicate the filling of accommodation space in more proximal regions (closer to sediment sources).

2.8 SEQUENCE STRATIGRAPHY

The sequence stratigraphy of the British Lower Jurassic was described by Hesselbo and Jenkyns (1998) and Van Buchem and Knox (1998), the former based on outcrop information from the Wessex, Cleveland and Hebridean basins, and the latter based on outcrops and boreholes in the Cleveland Basin. The proposed relative sea-level curve for the British Lower Jurassic of Hesselbo & Jenkyns (1998) is shown in Figure 7. Key findings and comparisons that are useful for the conceptual understanding of the Lias Group are summarised below (comments in italics are observations made by the authors of this report):

2.8.1 Hesselbo & Jenkyns (1998)

- There are four large scale (2nd order) cycles (S1 – S4, Appendix A) that can be recognised across depositional basins. These are defined by sequence boundaries and maximum flooding surfaces identified in Appendix A.
- *Major regional lithostratigraphical subdivisions in different depositional basins are not consistently related to major sequence stratigraphy cycles. An exception is the base of the youngest cycle ('S4' Appendix A), which approximately corresponds to the incoming of sandier facies above the Charmouth / Redcar Mudstone formations* ("Upper Pliensbachian strata are largely arenaceous in the Wessex, Cleveland and Hebrides basins" (Hesselbo & Jenkyns, 1998). *Perhaps the general lack of synchroneity of facies change is a product of the different relative positions of basins with respect to sediment sources and highly variable rates of basin subsidence; factors that could significantly influence the timing of sea-level related facies changes in different basin settings*.
- In the Dorset succession, the top of the Blue Lias is hiatus caused by sediment starvation that is coincident with a maximum flooding surface, and the base of the Dyrham Formation is approximately coincident with a sequence boundary.
- The Semicostatum Zone (base of Charmouth Mudstone in Dorset) is globally a time of marine deepening. A hiatal surface at the top of the underlying Blue Lias in Dorset is interpreted as resulting from sediment starvation associated with sea level rise.
- On the East Midlands Shelf, the junction of the Scunthorpe Mudstone and Charmouth Mudstone appears to approximately coincide with a maximum flooding surface.
- The Dorset succession in the Wessex Basin is considered to be relatively distal to sediment sources, and tended to accumulate relatively thicker successions during long-term sea level fall (when proximal settings lacked accommodation space).
- The highly condensed Beacon Limestone Formation in the Wessex Basin is interpreted as a product of sediment starvation during a time of relative sea level highstand.
- The influx of northerly derived sand and silt in the Late Toarcian in the Dorset succession (Bridport Sand) is interpreted as representing a sea level highstand and fall that caused rapid sand progradation from north to south.
- The Cleveland Basin is generally interpreted as occupying a shelf to basin position that was equally prone to sediment accumulation during both long-term rises and falls in

relative sea level, although in the Early Toarcian and through the Middle Jurassic, the setting became much more proximal because of transient Central North Sea thermal doming.

- At a third-order scale, there may be multiple interpretations for how individual packages of sediment can be interpreted in terms of sequence stratigraphy. For example, in the Blue Lias, there is a widespread pattern of limestone-rich lower and upper parts, with a more mudstone-dominated interval between. This pattern can be interpreted as indicating deeper water for the mudstone-dominated interval, or sediment-starvation during accumulation of the limestone-rich intervals (maximum-flooding), with increased sediment supply accounting for the mudstone-rich interval (e.g. sediment progradation following sea level rise).
- At the third-order scale, it may be difficult to trace interpretations of sequence stratigraphy packages between basins because of significant variability in the accommodation space across different basin settings resulting from relative falls and rises in sea level [*perhaps a reflection of the distinctive structural compartmentalisation of basins that influenced Lias Group deposition*].

2.8.2 Van Buchem & Knox (1998)

- Three major (2nd Order) sequence stratigraphy cycles in the Hettangian – Pliensbachian interval (I – III of Appendix A).
- Six medium (3rd Order) sequence stratigraphy cycles (C1 – C6, Appendix A). Several of these cycles are inferred to be influenced by uplift/proximity of the Market Weighton structural block.
- Eustatic deepening inferred for mid Semicostatum Zone, slightly younger than the maximum flooding event identified at the base of the Semicostatum Zone by Hesselbo & Jenkyns (1998).
- Basal Jamesoni Zone eustatic deepening agrees with maximum flooding identified by Hesselbo & Jenkyns (1998).
- Deeper water conditions inferred for the upper Turneri Zone and basal Obtusum Zone disagree with identification of a sequence boundary by Hesselbo & Jenkyns (1998).
- There is an abrupt change from sandy facies to hemipelagic mud in the Taylori Subzone, corresponding with a maximum flooding surface identified by Hesselbo & Jenkyns (1998).
- Recognition of regression (related to regional uplift) in late Davoei and early Margaritatus zones is consistent with identification of a sequence boundary at the base of the Margaritatus Zone by Hesselbo & Jenkyns (1998).
- Low sedimentation rates and frequent horizons of iron-enrichment suggest that the Cleveland Basin succession is relatively incomplete.
- The sedimentation rate in the Pliensbachian in the Cleveland Basin is much higher than in the underlying Hettangian and Sinemurian, and rapid basin subsidence is inferred.
- Unusual thickness of Bucklandi Zone sediments in the Cleveland Basin coastal succession might indicate transport of sediment from Market Weighton high where this zone is not preserved.
- Late Sinemurian sedimentation is condensed and influenced by a lack of accommodation space.

2.9 GEOCHEMISTRY

Stratigraphical applications of geochemical data for the Lias Group are mainly focused on the following areas of research:

- Understanding the Toarcian Oceanic Anoxic Event (TOAE) – a large magnitude climate warming and mass extinction event, associated with widespread black shale deposition (e.g. McArthur et al., 2000; Littler et al., 2010; Reolid et al., 2021). This event has been intensively studied in the Cleveland Basin (Howarth, 1962; Knox, 1984; Little & Benton, 1995; Harries & Little, 1999; Danise et al., 2013, 2015; Thibault et al., 2018), where it occurs within the Whitby Mudstone Formation (Grey Shale and Mulgrave Shale members). Coeval Beacon Limestone Formation in the Wessex Basin does not preserve organic-rich sediment that is characteristic of the TOAE, but there is evidence from stable isotope data for the environmental perturbation associated with this event (Jenkyns & Macfarlane, 2022).
- For correlation and understanding the completeness of the stratigraphical record (Van Buchem et al., 1992; Price et al., 2016; Jenkyns et al., 2002).

2.10 CYCLOSTRATIGRAPHY

Parts of the Lias Group (particularly the Blue Lias and Charmouth Mudstone Formation) reveal regular cyclicity developed in thin, tabular interbeds of limestone and mudstone. The bed cyclicity has been tied to orbitally driven (Milankovitch) climate cycles, mostly at the scale of the long-eccentricity (405-kyr periodicity) or short-eccentricity cycle (100-kyr) (Weedon, 1985; Weedon et al., 1999; Weedon et al., 2019). Such information provides a 'floating' astronomical time scale which can be used to calibrate the duration of stages (Weedon et al., 2016).

2.11 GEOPHYSICAL LOG CHARACTERISTICS

Much of the work presented here is based on the stratigraphical interpretation of gamma-ray and sonic transit time logs. While many other log types are available, these are the most common in a UK onshore borehole dataset that spans many decades of drilling (see https://ukogl.org.uk). Cox et al. (1999) have previously acknowledged the high quality of stratigraphical information on the Lias Group that can be derived from commonly-available geophysical logs.

By way of introduction, the Winterborne Kingston borehole is used to illustrate the typical gamma-ray and sonic log characteristics of the Lias Group (Figure 9). Further discussion of regional variations is provided in following sections.

In terms of gamma-ray, the Lias Group is generally an interval of high response reflecting the abundance of mudstone within the stratigraphy. However, the gamma-ray curve is rarely constant, with most of the group showing isolated gamma-ray spikes or regularly-spaced, high amplitude serrations.

Higher than average gamma-ray values may reflect the presence of organic-rich 'hot shales' or intervals rich in glauconite or phosphate. In the Winterborne Kingston borehole two such intervals that probably relate to the presence of organic-rich shales occur at the base of the Charmouth Mudstone Formation within strata equivalent to the Sinemurian Shales-with-Beef and the Black Ven Marls (Figure 9).

Lower than average gamma-ray values reflect the presence of limestones or sandstones that are depleted in clays, glauconite and phosphate. In units such as the Blue Lias Formation, limestones typically appear as closely-spaced low gamma spikes (Figure 9). As limestone and mudstone beds become very close (<0.3 m) it may become difficult to resolve individual beds using the gamma-ray curve (which has limited vertical resolution) and the signal can become a convolution of the two lithologies.

Siltstones and sandstones (particularly in the uppermost Bridport Sands where present) can have a lower gamma-ray response and display funnel-shaped motifs reflecting episodes of shoreface progradation. However, the presence of glauconite and phosphate in the siltstones and sandstones can create higher gamma-ray responses than would be expected in an equivalent quartz-dominated sandstone. In this case, cross-referencing against sonic logs and cuttings descriptions is important.

The sonic transit time log is a powerful discriminator of limestone development in the Lias Group. Limestones have a fast sonic travel time relative to mudstones and in formations such as the Blue Lias and Bridport Sands produce a highly serrated profile with high frequency spikes (Figure 9). In the Charmouth Mudstone the spacing of sonic spikes increases and they may disappear entirely in the upper part of the formation where it primarily comprises mudstone. The sonic log is also important for picking the thin condensed limestones and ironstones of the Beacon Hill Limestone and Marlstone Rock. This unit forms an important marker for log correlation across all basins.

3 Regional trends in stratigraphy and thickness

3.1 WESSEX BASIN

The Wessex Basin (as defined here) is centred on Dorset and comprises a collection of fault-bounded basins and highs that lies to the southwest of a structural high that extends from the Mendips to the northern Isle of Wight (Figure 10). The two main sub-basins are the Winterborne-Kingston Trough, a narrow graben-like structure, and the Portland-Wight Basin (or Channel Basin), a major half graben bounded to the north by the segmented Abbotsbury-Purbeck-Wight Fault. This structure was inverted during the Tertiary to form the Purbeck Disturbance.

As a whole, the Wessex Basin is an area of thick (>350 m) Lias Group (Figure 10). In the Portland 1 borehole, which lies within the Portland-Wight Basin, the Lias Group reaches 949 m thick: the highest value in the examined borehole set (Figure 5).

The Lias Group thins across the Abbotsbury-Purbeck-Wight Fault so that it is typically around 450 m thick across the South Dorset High. The Jurassic Coast outcrop sections between Lyme Regis and Bridport are located on the western part of this platform where they are around 350 m thick: substantially thinner and more condensed than basinal successions to the south and north (Figure 11).

In the Winterborne-Kingston Trough the Lias Group reaches 653 m. This narrow basin is bounded to the north by the Cranborne-Fordingbridge High, a NW-SE trending belt of relatively thin (ca. 200 m) Lias Group.

Correlation between the outcrop section and basinal boreholes (Figure 11) shows that thickness differences are particularly marked in the lowermost (pre-Ibex Zone) parts of the succession. This includes the Blue Lias Formation and Sinemurian and lower Pliensbachian parts of the Charmouth Mudstone. The lower (Sinemurian) part of the Charmouth Mudstone includes organic-rich black shale intervals at outcrop which may correlate with exceptionally high gamma-ray intervals in the Winterborne Kingston borehole.

The frequency of limestones decreases above the Ibex Zone, while the proportion of silt and sand correspondingly increases through the upper parts of the Charmouth Mudstone (Green Ammonite Beds and Eype Clay) and Dyrham Formation. The thickness variations in this regressive interval are much less marked than below. Large thickness variations become re-established in the overlying Bridport Sand Formation (Figure 12), which may represent a second pulsed phase of basin extension and subsidence.

3.2 WORCESTER, PEWSEY AND WEALD BASIN

The Worcester, Pewsey and Weald basins form a curved belt of thick Lias Group that wrap around the western and southern faulted flanks of the Anglo-Brabant Massif (Figure 10). The Lias Group maintains a remarkably constant maximum thickness between the various depocentres at around 450-500 m.

The correlation panel in Figure 13 shows the relatively consistent geophysical log response across the various basins. In particular, the Blue Lias and Charmouth Mudstone Formation show a distinctive step-wise shift in log response that defines three intervals. The Blue Lias corresponds to the lowermost interval characterised by low, but highly serrated, gamma-ray and sonic transit time logs. The Blue Lias to Charmouth Formation boundary and the second interval is marked by a bulk increase in gamma-ray response and sonic transit time, while both curves still retain a serrated character. The uppermost interval is marked by a high gamma ray and high sonic transit time. Both curves are uniform, suggesting few interbedded limestones in a predominantly mudstone succession. The Charmouth Mudstone thus divides into two well-defined parts on the basis of geophysical logs.

The Charmouth Mudstone grades into the overlying Dyrham Formation by the inclusion of siltstone and sandstone. Gamma-ray curves show a succession of small funnel-shaped (coarsening-upward) motifs, which sometimes become thicker and more sandy upwards in the style of a progradational stacking pattern. This is capped by a variability well-defined gamma-ray and sonic spike corresponding to a thin Marlstone Rock.

The Bridport Sand Formation is sharply defined between the Marlstone Rock and the Inferior Oolite. The log response is variable but often 'coarsens-upwards' from a clayey base through a series of funnel-shaped gamma-ray profiles, similar to that observed in the Dyrham Formation. There is a clear thickening trend from the Worcester Graben into the central parts of the Weald Basin (Figure 13). A comparable thickening trend in the Bridport Sand also occurs from the Pewsey Basin into the Wessex Basin to the south, down the overall younging and progradational trend of this diachronous unit (Figure 14).

Figure 15 shows a north-south correlation across the Weald Basin, which is a graben-like structure between the London Platform and the Portsdown-Paris Plage High. The Lias Group thins abruptly across the complex splay of basin-bounding faults developed above the reactivated low-angle Variscan thrust (see seismic section on Figure 15). The borehole correlation panel shows that the thickest Lias Group occurs along the southern margin of the Weald Basin where faults dip and downthrow to the north. As seen in Dorset, the greatest thickness differential between highs and basin appears to be developed in the Blue Lias and lower (limestone-rich) part of the Charmouth Group.

3.3 ANGLO-BRABANT MASSIF (ABM)

3.3.1 London and eastern ABM

The Lias Group is entirely absent under large parts of London and surrounding counties to the north and east (Figure 6), likely a consequence of both non-deposition across an Early Jurassic land area and later erosion. A relative sea-level fall at the close of the Early Jurassic caused widespread erosion of Toarcian strata (Sumbler, 1996). Lower Jurassic and younger strata were also eroded from the ABM during latest Jurassic and early Cretaceous extensional faulting and uplift which stripped back parts of the ABM to the Palaeozoic core and redeposited material as the Wealden Group (Sumbler, 1996).

From the zero thickness contour, the Lias Group thickens progressively into surrounding basins. The base onlaps the ABM and is strongly diachronous.

3.3.2 South-east ABM

Figure 16 shows the progressive thinning of the Lias Group when traced eastwards onto the ABM in the area of the Kent Coalfield. Most of the Lias Group subdivisions persist as the overall group thins, until the eastern boundary fault is crossed toward the Paddlesworth Court borehole where thinning is severe. Counter to other subdivisions, the Marlstone Rock appears to thicken and shows stronger log responses moving from the basin centre toward the flanks of the massif.

3.3.3 Western ABM

A comparable progressive thinning is seen when moving from the Worcester Graben to the Anglo-Brabant Massif (Figure 17). Similar to above, the loss of subdivisions does not occur until the Lias Group becomes severely attenuated.

3.3.4 North-west ABM

Around Banbury, the ferruginous limestones of the Marlstone Rock reach their maximum thickness and are highly indurated, forming spectacular plateaus and cuesta-like landforms above the Charmouth Mudstone and Dyrham formations (Figure 18). The Marlstone Rock, a transgressive, condensed deposits containing chemically-precipitated iron, contrasts with other divisions of the Lias Group in thickening from basins to highs (Sumbler, 1996).

3.3.5 Northeast ABM

Further east on the Anglo-Brabant Massif (around Cambridge) a transect of closely-spaced Gas Council boreholes provides a particularly clear illustration of the progressive southward onlap of the ABM from the East Midlands Shelf (Figure 19). The Lias Group here consists of relatively evenly spaced limestone beds separated by mudstones. At outcrop the limestones are described as 'thin cementstone bands' or 'cementstone nodules' (Herbert et al., 2005) within a sequence of monotonous bluish grey clays.

Most of the succession below the Marlstone Rock is probably representative of the Charmouth Mudstone Formation. A thin cluster of limestones toward the base in northernmost boreholes may be representative of the uppermost part (Rugby Limestone Member) of the Scunthorpe Mudstone (Figure 19).

The Marlstone Rock is marked by a cluster of low gamma spikes and at outcrop in this area is described as shelly ironstone, oolite ironstone, siderite mudstone and grey micaeous silty clays (Herbert et al., 2005).

The Whitby Mudstone appears to be largely devoid of limestone beds (low gamma-ray spikes) and shows marked thinning toward the south beneath the Middle Jurassic Inferior and Great Oolite groups. At outcrop in this area, the beds are described as monotonous bluish grey clays containing only occasional cementstone or pyritic nodules (Herbert et al., 2005).

3.4 EAST MIDLANDS SHELF

Across the East Midlands Shelf the Lias Group consists largely of pale to dark grey mudstone, generally slightly calcareous, commonly silty and bioturbated (Kent, 1980). Thin limestones and siltstones are present as parts of numerous small-scale graded cycles (Kent, 1980). Fine-grained sandstone is occasionally present but, in contrast to other basins, sand-rich formations or members are absent. The East Midlands Shelf was an area of gradual subsidence cut off from sources of coarser siliciclastic sediment. Lias sedimentation terminated during the Toarcian and the region was uplifted and eroded, particularly near the Market Weighton High. The remnant Toarcian strata are mud dominated and do not shoal upwards into sandstones as seen in southern basins (Bridport Sand) or the Cleveland Basin (Blea Wyke Sandstone).

The Lias Group reaches a maximum thickness of 282 m in central parts of the East Midlands Shelf, thinning south onto the Anglo-Brabant Massif and north onto the Market-Weighton High (Figure 6). The Grantham-Skegness Trough forms a roughly west-east axis of thicker deposits. The Lias Group appears to thicken westward, away from the Sole Pit Trough. This may partly reflect uplift and back-tilting of the East Midlands Shelf along the Dowsing Fault Zone. Compaction and fault-related subsidence of concealed Carboniferous basins may also have contributed toward the slight thickening trend to the west (Figure 21).

The Lias Group is divided into the Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock and Whitby formations. The units form four relatively well-defined clusters in gamma-ray/sonic transit time cross-plots (Figure 20), reflecting variations in the proportion of mudstone, limestone and other components.

The Scunthorpe Mudstone contains numerous thin limestones and calcareous siltstones and includes the Frodingham Ironstone at the top. A thin bioclastic limestone at the base rests sharply on the underlying Penarth Group and is usually obvious as a distinct, broad spike of low gamma-ray and fast sonic transit time. The Frodingham Ironstone is around 5-10 m thick and composed of muddy ironstone and calcitic bioclast-rich oolitic ironstone (Berridge et al., 1994).

The Frodingham Ironstone does not have a clear individual log response but caps an interval of relatively low and highly-serrated sonic transit time.

In west-east section the Scunthorpe Mudstone maintains a consistent thickness of around 100 m across the Grantham-Skegness Trough (Figure 20). North-south orientated correlations show the marked thinning of the Scunthorpe Mudstone onto the Market Weighton High (Figure 22).

The Charmouth Mudstone generally lacks limestones but contains a ferruginous member, the Pecten Ironstone (Berridge et al., 1994). In geophysical logs the gamma ray generally shows a slight increase relative to the Scunthorpe Mudstone and the sonic travel time is slower and less uniformly serrated. In many boreholes the base of the Charmouth Mudstone is marked by a broad spike of high sonic transit time. As seen in basins south of the Anglo-Brabant Massif, some boreholes show a clear subdivision into a lower half with more frequent fast sonic spikes (limestones) and an upper half with a higher gamma response and slower sonic transit time. This upper mudstone-dominated part may thin and disappear away from the central Grantham-Skegness Trough. Such a stratigraphic trend is illustrated by Kent (1980, see his Fig. 6) where the 'Middle Lias Clay' is erosively cut out beneath the Marlstone Rock as the Market Weighton High is approached.

The Marlstone Rock generally ranges up to 10 m thick and includes variably ferruginous, calcareous sandstones and berthierine oolites with a fauna largely comprising brachiopods, bivalves and crinoids (Berridge et al., 1994). Fossils indicate normal marine salinity while cross-bedding and conglomeratic facies suggest high-energy, transgressive depositional environments. The Marlstone Rock has a serrated geophysical log response, but overall gamma ray values are typically low and the sonic transit time is faster than mudstones immediately below and above (Figure 20). In west-east section the Marlstone Rock appears to thicken onto the (possibly syn-depositionally uplifted) flanks of the Sole Pit Trough.

The Whitby Mudstone overlies the Marlstone Rock and is of variable thickness, partly depending on the depth of erosion below the Middle Jurassic. The maximum thickness is around 50 m and the thinning is particularly marked onto the Market Weighton High in the north (Figure 22) and the Anglo-Brabant Massif in the south (Figure 23). The Whitby Mudstone comprises silty mudstones, bituminous shales and laminated mudstones, which are more uniform than corresponding strata in the Cleveland Basin (Berridge et al., 1994). The gamma ray and sonic transit time are both significantly higher than the underlying Lias with the Whitby Mudstone forming a clear outlier in cross-plots (Figure 20).

3.5 CLEVELAND BASIN

North of the Market Weighton High, the Lias Group thickens abruptly into the Cleveland Basin (Figure 22), reaching 436 m thick in the Lockton 4 borehole (Figure 24). The Cleveland Basin was a small extensional basin, linked via the Sole Pit Basin, to the broader Southern North Sea Basin.

The eastern margin of the basin is cut by north-trending structures including the Peak Trough, an active graben during the Early Jurassic which preserves a thicker and more complete Early Jurassic succession.

Seismic evidence indicates that faults within the west-trending Flamborough Fault Zone do not show evidence of fault-controlled thickness variations until the late Jurassic (Kirby and Swallow, 1987). The southern margin of the Cleveland Basin in the Early Jurassic was probably a relatively unfaulted ramp between the stable Market Weighton Block and the subsiding Cleveland Basin.

Bounded to the west and north by the Pennine High and the Mid-North Sea High, the Lias Group in the Cleveland Basin has a higher sand content than elsewhere and, partly for this reason, has evolved a different lithostratigraphical nomenclature (Figure 7). The overall sequence of lithologies is, however, broadly similar to that found in other basins.

The base of the Lias Group (Hettangian and part of the Sinemurian) is characterised by interbedded mudstones and thin winnowed bioclastic limestones (the Calcareous Shales).

These are overlain by bioturbated quartz sand (Siliceous Shales) and dark grey to black hemipelagic mudstones of the Pyritous Shales and Ironstone Shales. All four of these units are included within the Redcar Mudstone Formation. As seen further south, the break between the basal carbonate (and sandstone) rich mudstones and the mudstones toward the middle of the Lias Group can be clearly seen on gamma-ray logs (Figure 24). Some of the highest gamma-ray spikes in boreholes such as Whenby 1 probably relate to the presence of organic rich shales.

The Redcar Mudstone Formation shoals upwards into the shoreface sands of the Staithes Sandstone Formation. This shoaling is broadly comparable in timing to the late Pliensbachian regression recorded in the Dyrham Formation of southern basins. It is marked by a progressive decrease in gamma-ray response from the peak values of the Ironstone/Pyritous Shales (Figure 24).

The Cleveland Ironstone is a thin condensed ironstone that is the partial correlative of the Marlstone Rock and Beacon Limestone.

The Whitby Mudstone is a sequence of organic rich shales and mudstones. The Cleveland Basin differs from the Wessex Basin in that the tenuicostatum to thouarsense zones are greatly expanded sequences of black shale contrasting with the highly condensed Beacon Limestone of Dorset.

The top of the Whitby Mudstone is erosively truncated by Middle Jurassic strata (Dogger Formation) and only within the Peak Trough does it extend and shoal upwards in the Blea Wyke Sandstone. This sandstone is age equivalent to the Bridport Sands of the Wessex Basin.

4 Summary and conclusions

- The Lias Group is a coherent unit of largely fine-grained marine deposits bounded by unconformities at the base and top.
- The thickness distribution of the Lias Group shows clear tectonic control. The thickest Lias Group are now found in the Portland-Wight Basin (Figure 25). Thicker deposits may have been formerly present in the uplifted and eroded basins of northwest Britain (e.g. Cheshire Basin).
- The Lias Group in the Weald, Pewsey and Worcester basins forms a tract where the maximum thickness and stratigraphy of the Lias Group is remarkably constant.
- The East Midlands Shelf is a distinct depositional province with limited sandstone.
- As a lithostratigraphical unit, the Charmouth Mudstone Formation conceals a clear and widely correlative two-fold division into a lower part containing limestone and an upper part dominated by relatively homogeneous mudstone. This may have geotechnical implications (e.g. slope stability) that necessitates formal subdivision of this unit.
- In the Wessex Basin organic rich shales occur toward the base of the group in the Sinemurian. The higher parts of the group are characterised by influxes of silt and sand and periods of extreme condensation.
- In the Cleveland Basin organic rich shales are distributed across the stratigraphy in the Sinemurian, Pliensbachian and Toarcian.

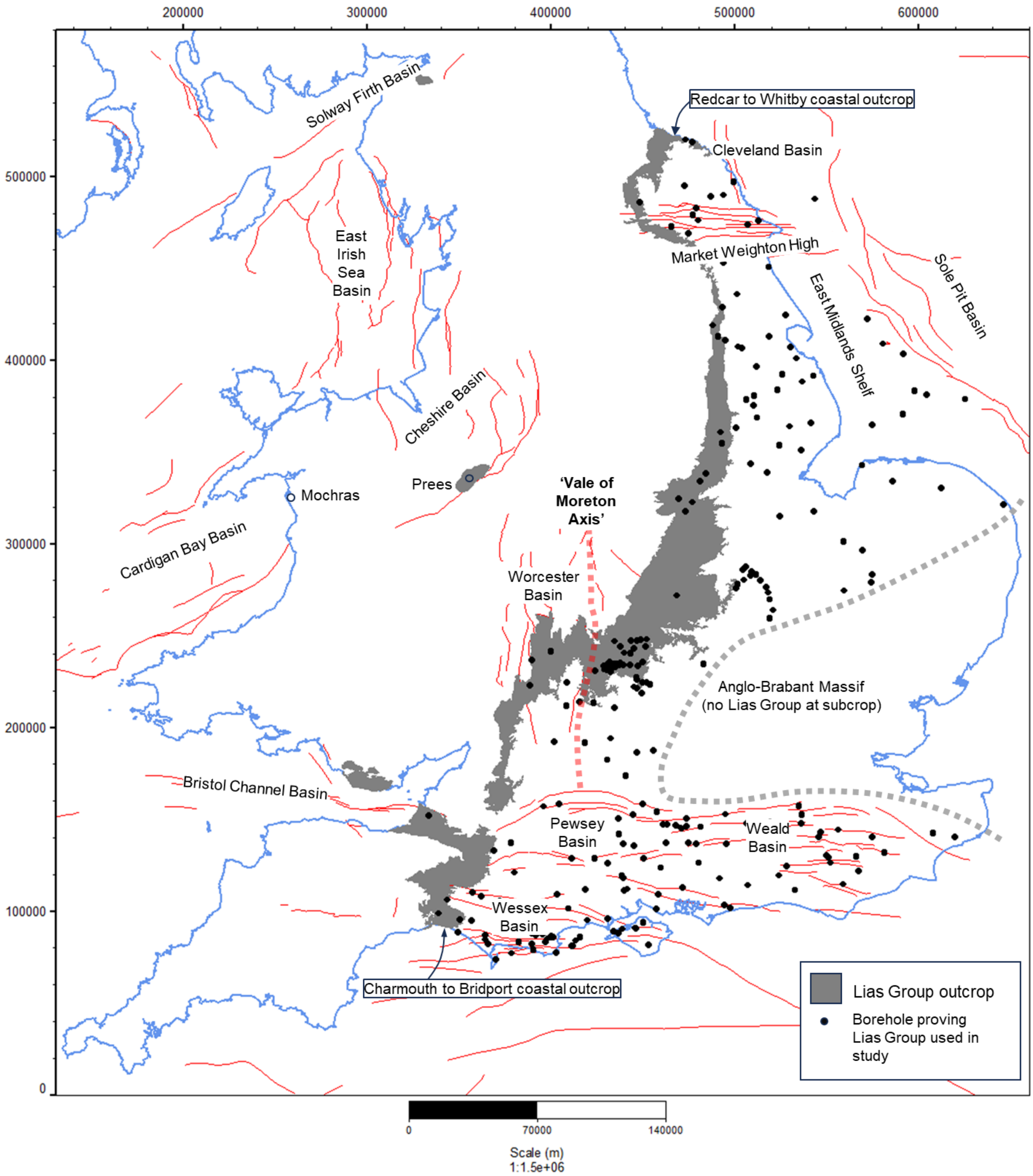

Figure 1 Lias Group outcrop and location of boreholes used in the study. Contains Ordnance Survey data © Crown copyright and database rights 2025

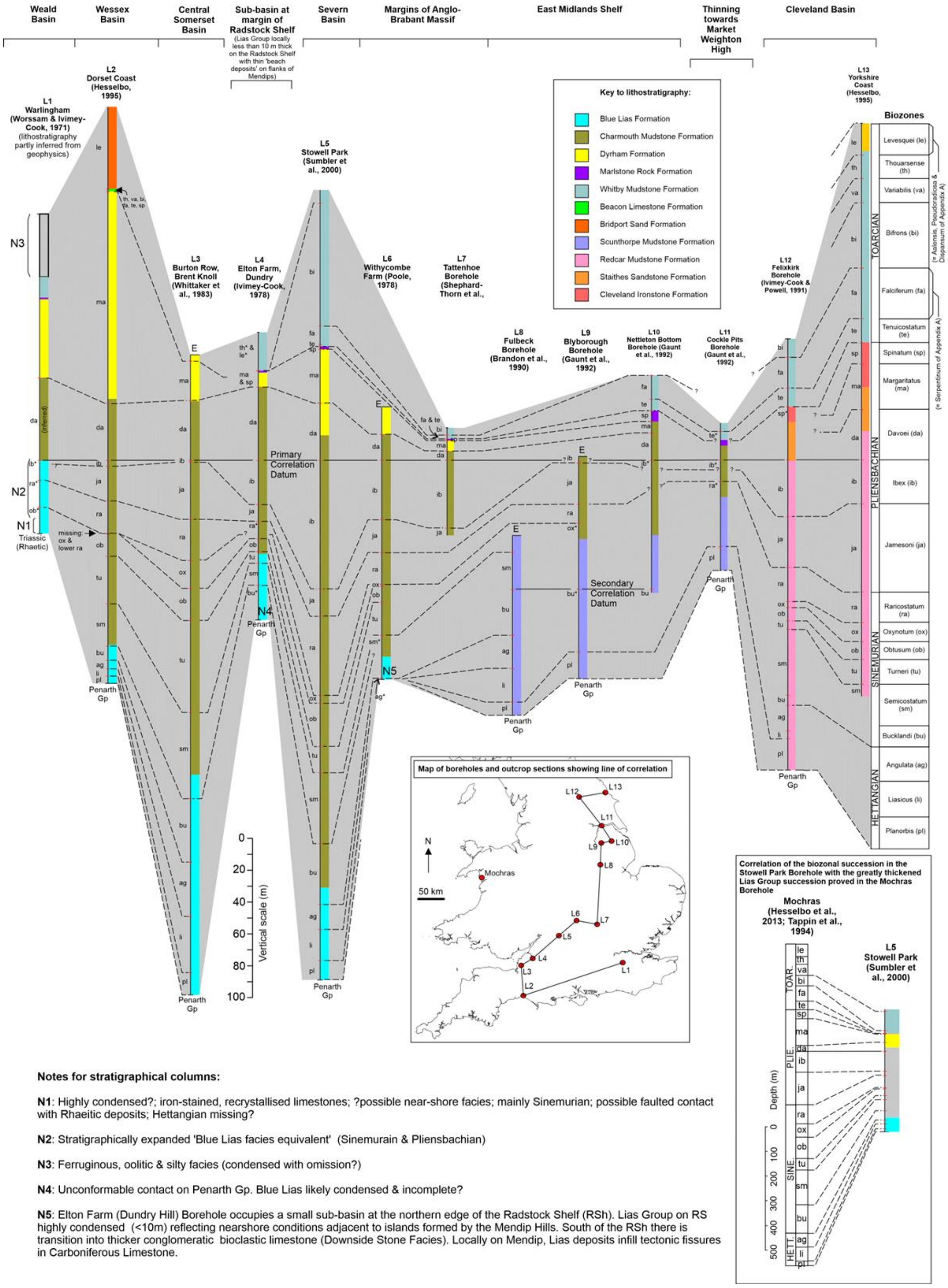

Figure 2 Biozonal correlation of key outcrop sections and cored boreholes. See map inset for locations. Contains Ordnance Survey data © Crown copyright and database rights 2025.

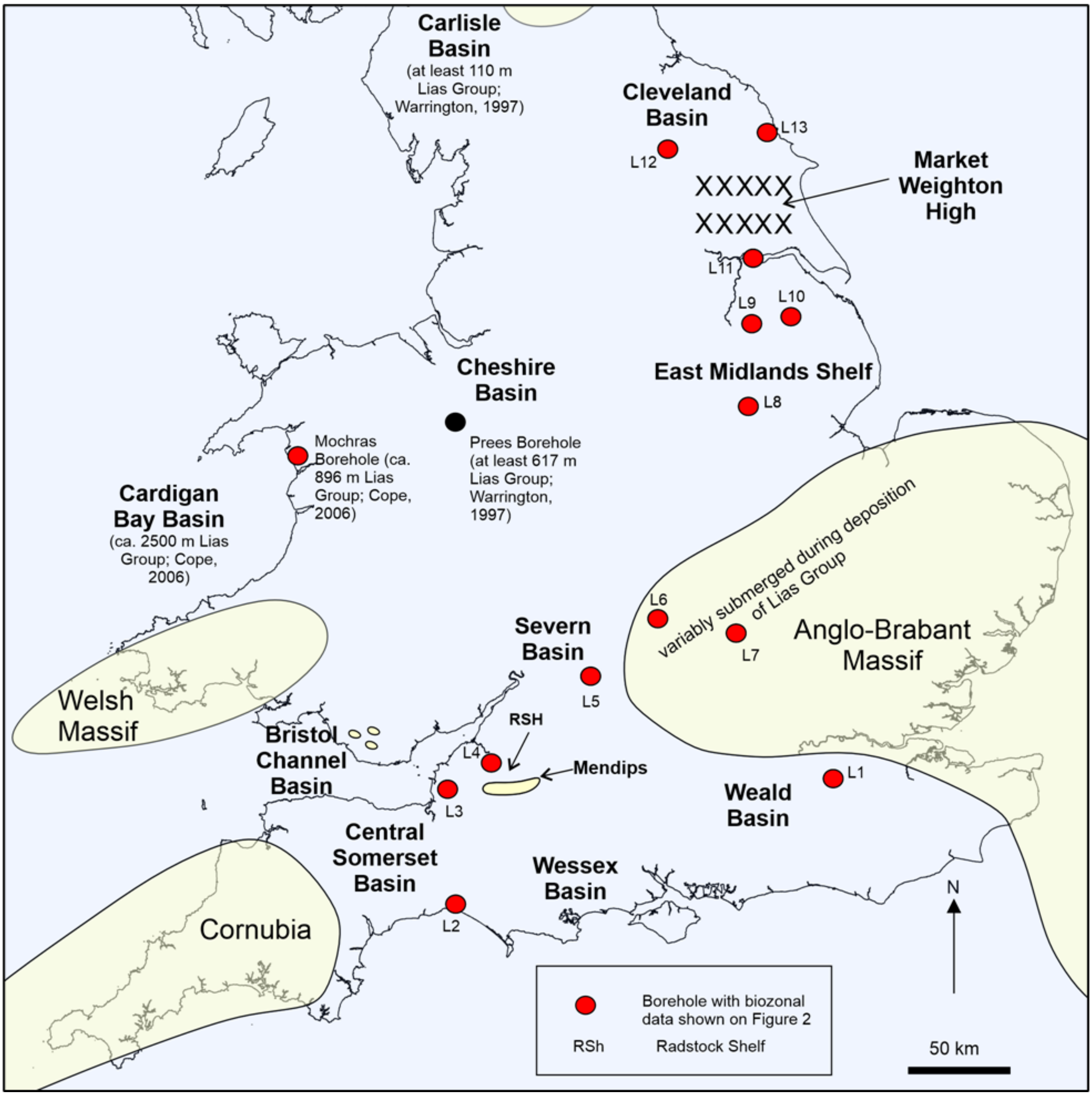

Figure 3 Palaeogeography and basin architecture for the Early Jurassic (Hettangian). Based on map J1 of Bradshaw et al. (1992) and fig. 1.2 of Simms et al. (2004). Extent of Market Weighton High based on Wright (2022). Contains Ordnance Survey data © Crown copyright and database rights 2025.

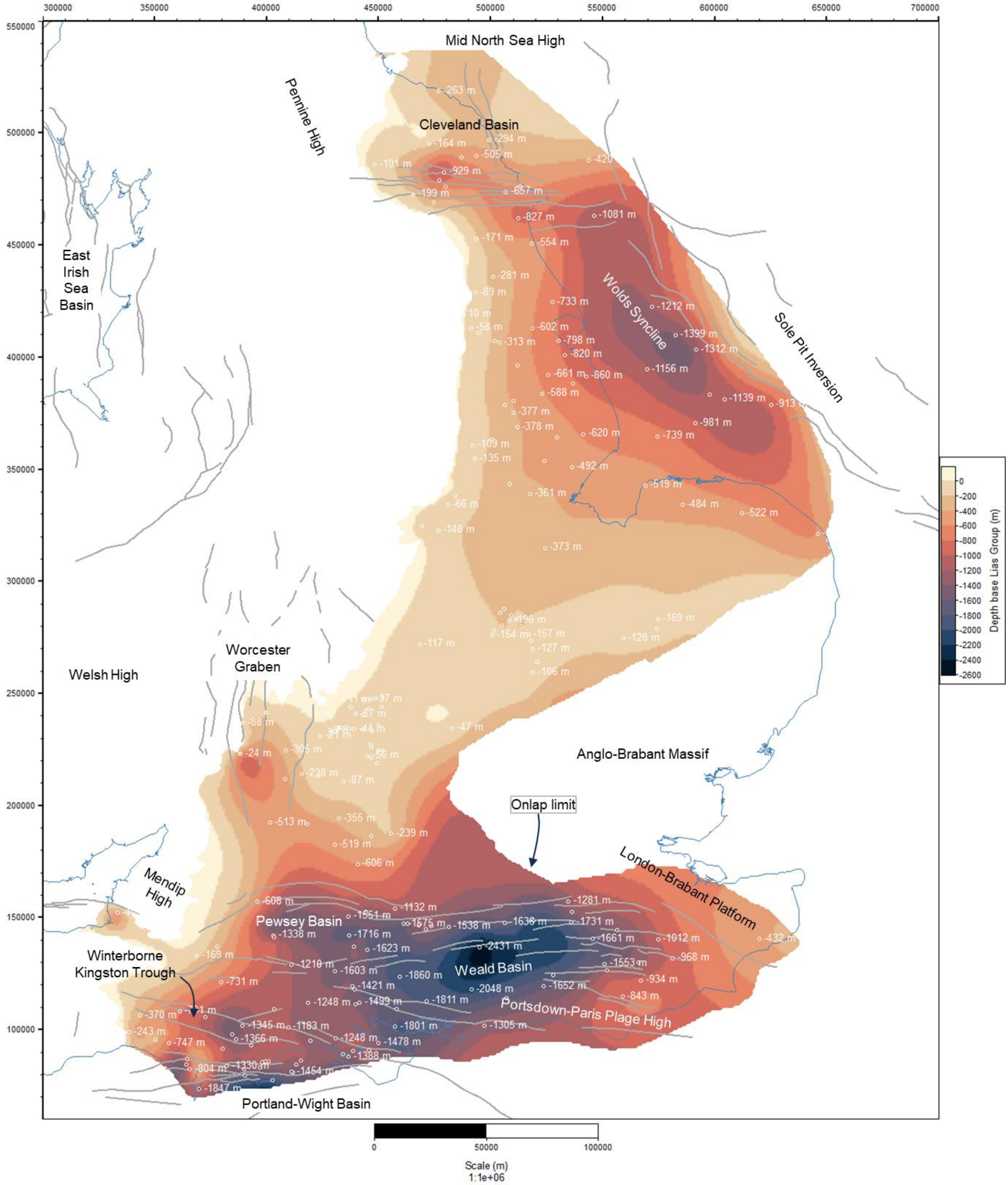

Figure 4 Map showing structure on the base of the Lias Group (equivalent to top of the Penarth Group where present). The map is interpolated from borehole data whose location is shown by white circles. Contains Ordnance Survey data © Crown copyright and database rights 2025.

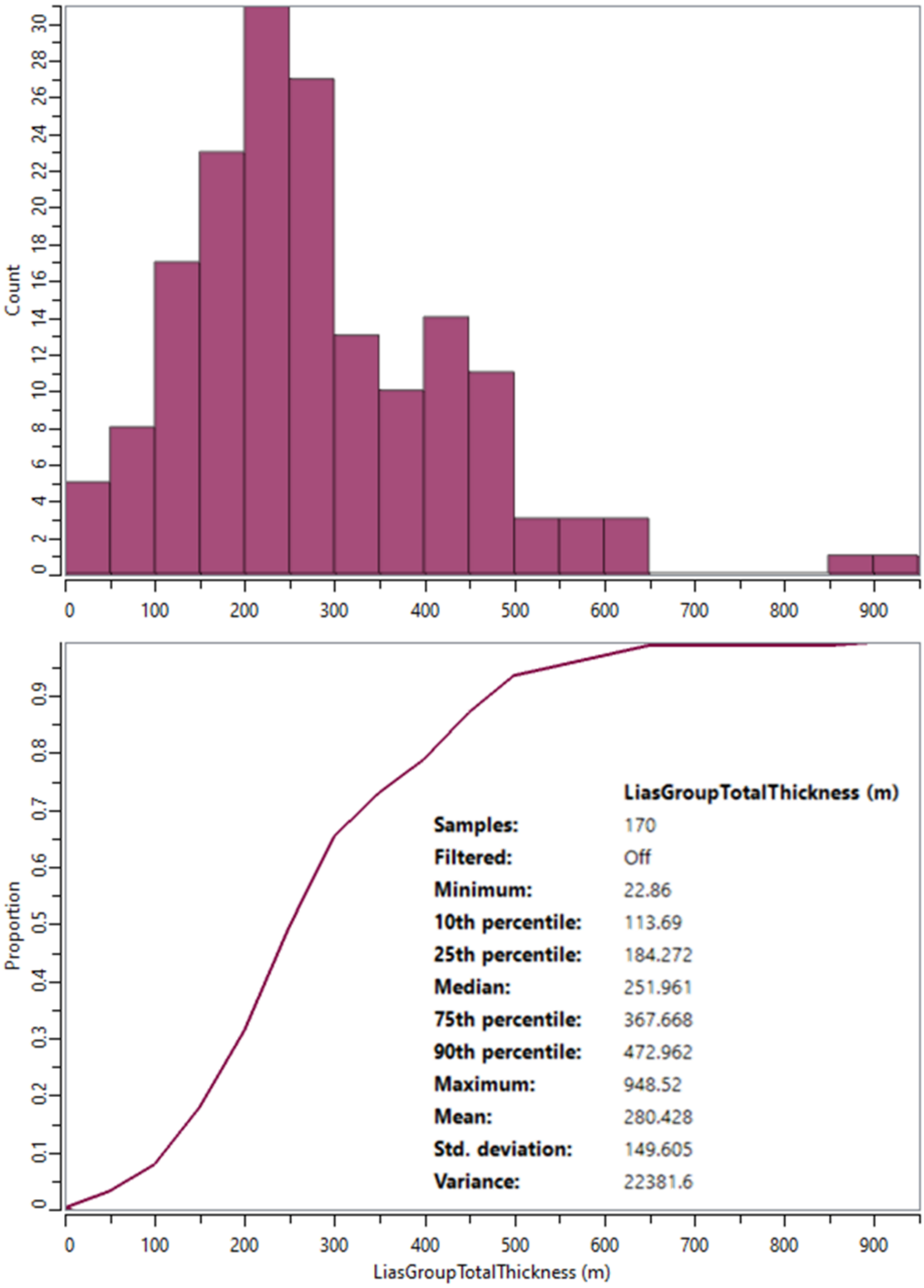

Figure 5 Distribution and summary statistics of Lias Group total thickness based on 170 boreholes where the ‘complete’ succession is present.

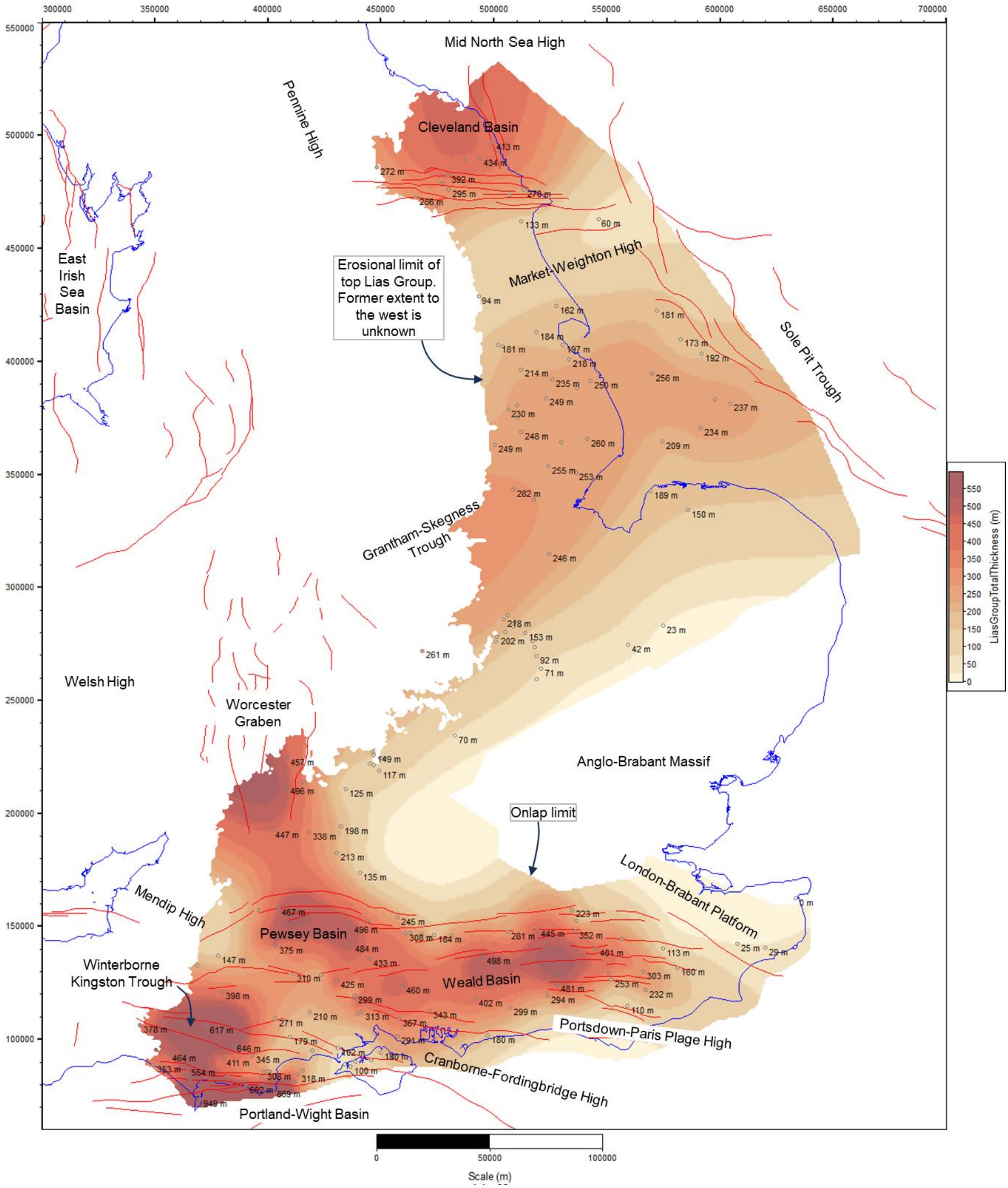

Figure 6 Map showing total thickness of the Lias Group. Map is interpolated from boreholes whose location and thickness value is shown as black circles. Contains Ordnance Survey data © Crown copyright and database rights 2025.

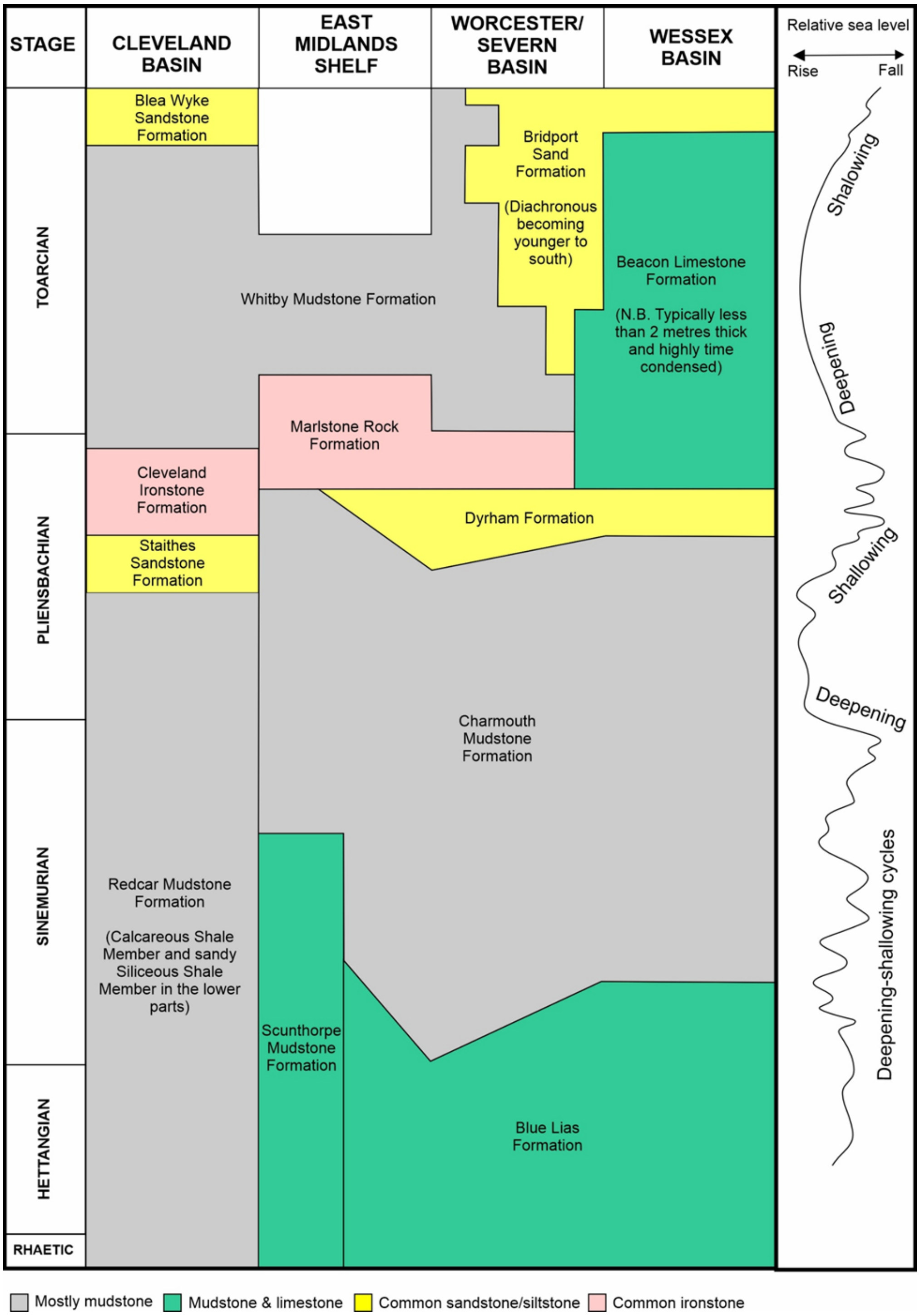

Figure 7 Lithostratigraphical subdivisions of the Lias Group (after Cox et al., 1999). Relative sea-level curve modified from Hesselbo & Jenkyns, 1998).

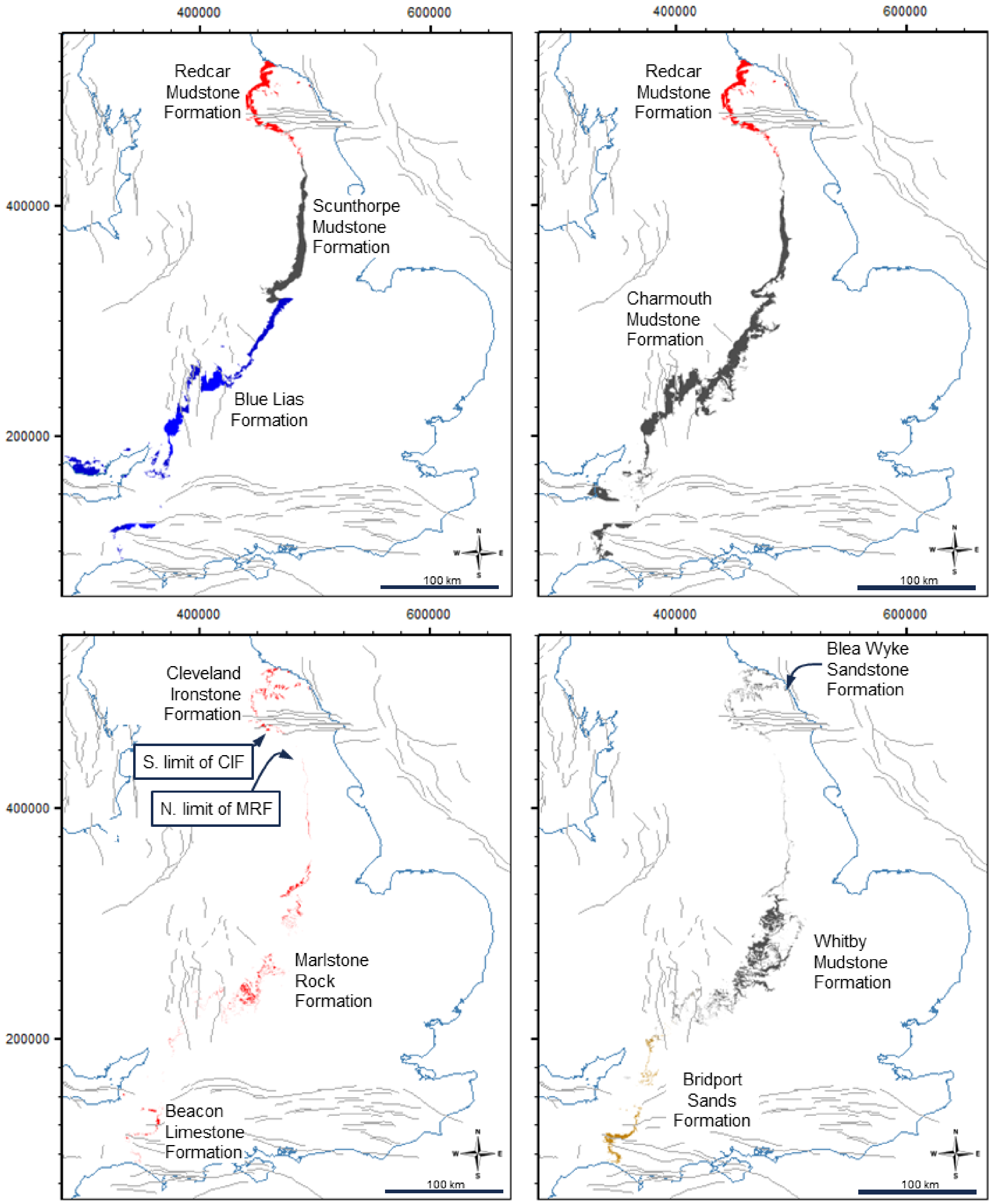

Figure 8 Polygons extracted from BGS 1:50000 scale geological maps (https://www.bgs.ac.uk/datasets/bgs-geology-50k-digmapgb/) showing the regionalisation of stratigraphical terms in the Lias Group. Each map shows selected Lias Group units that cover an approximately similar time interval but they do not imply that units are coeval. The geographical position of abrupt shifts in nomenclature is largely arbitrary. See Figure 7 for age ranges of lithostratigraphical units. Contains Ordnance Survey data © Crown copyright and database rights 2025.

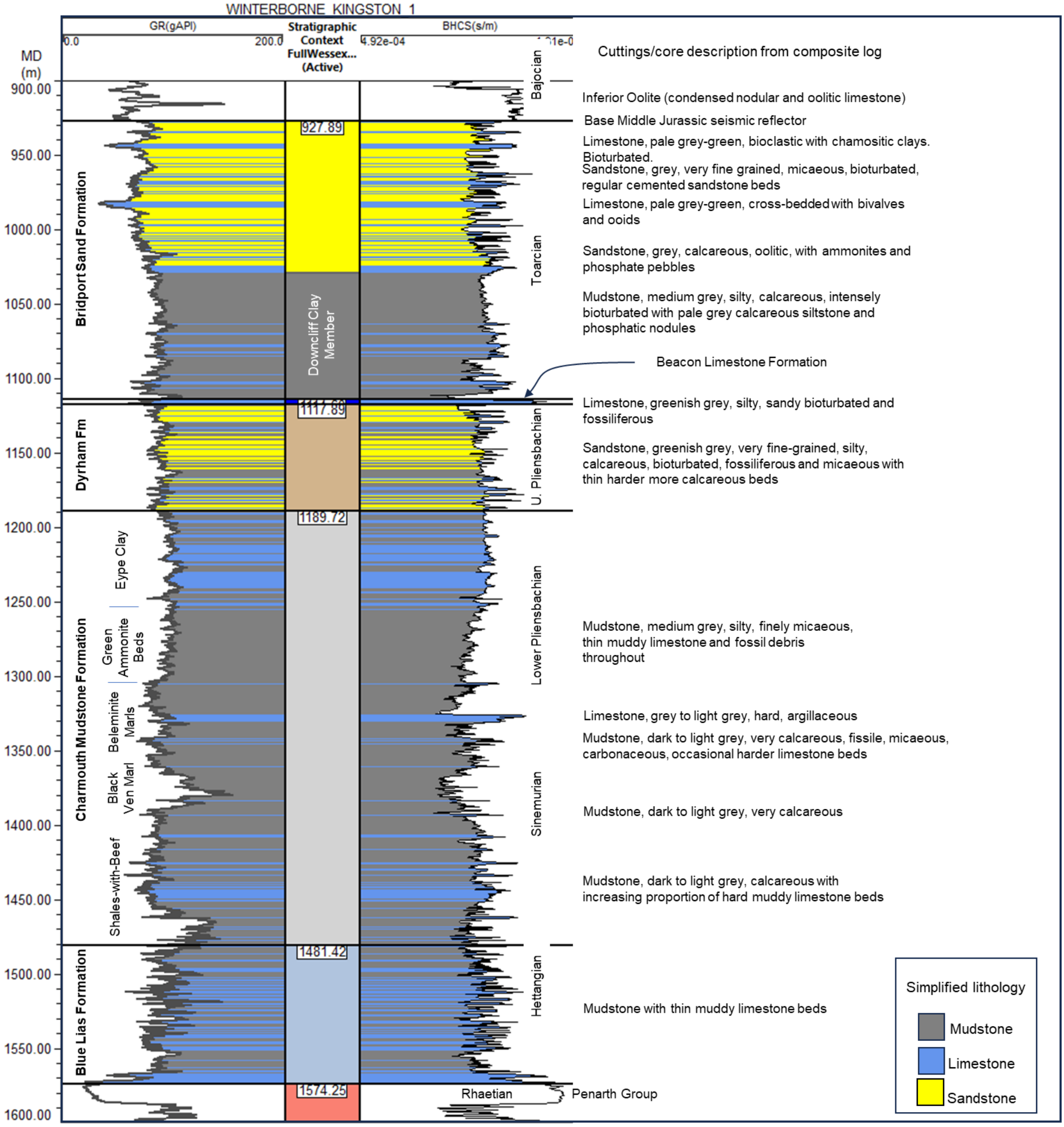

Figure 9 Lias Group stratigraphy and generalised lithology in the Wessex Basin stratigraphy exemplified by the Winterborne Kingston borehole.

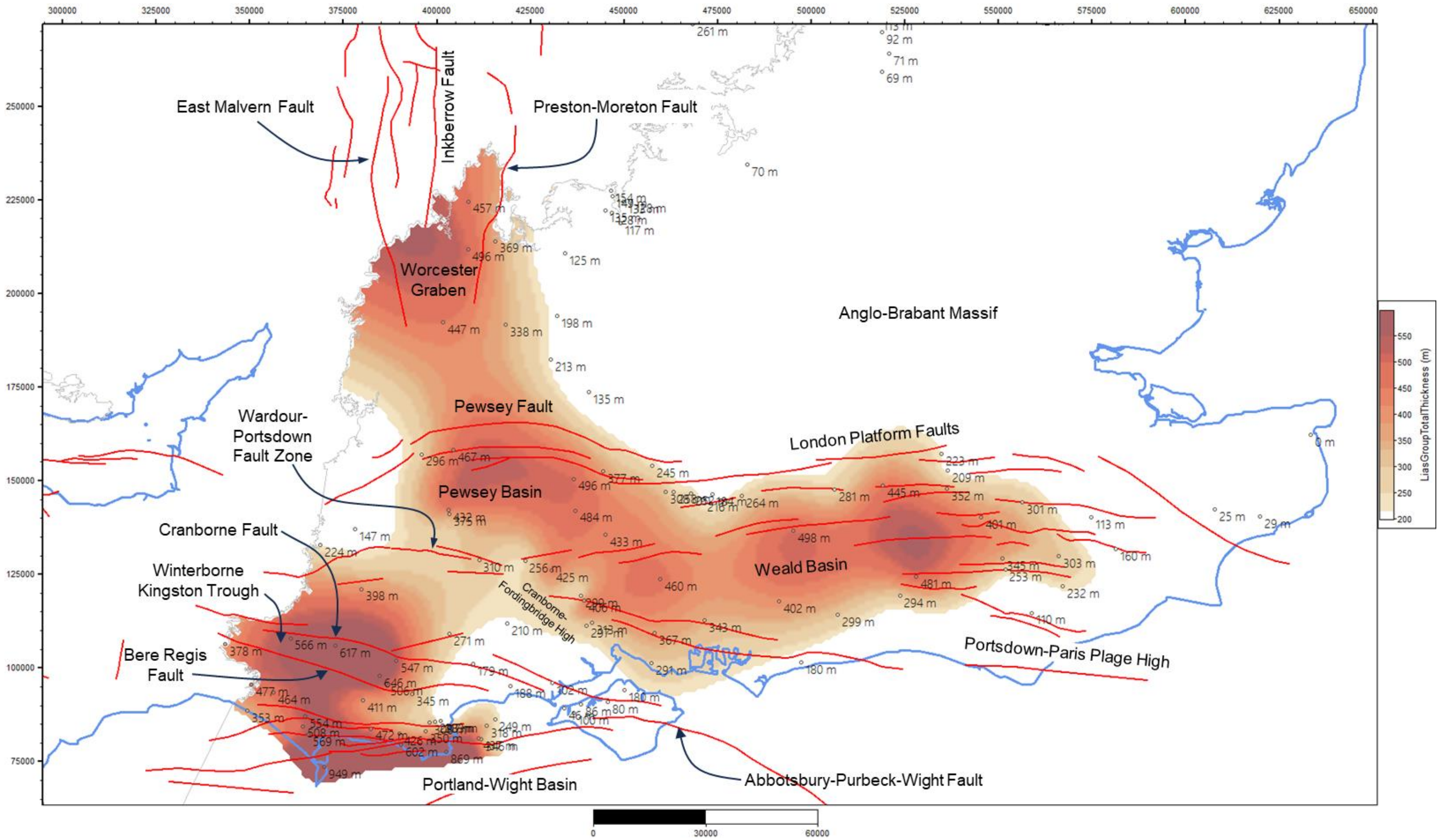

Figure 10 Map showing areas where the Lias Group exceeds 250 m in southern England. Areas of where the Lias Group is less than 250 m are not shown, highlighting the location of the main fault-controlled basins. Contains Ordnance Survey data © Crown copyright and database rights 2025.

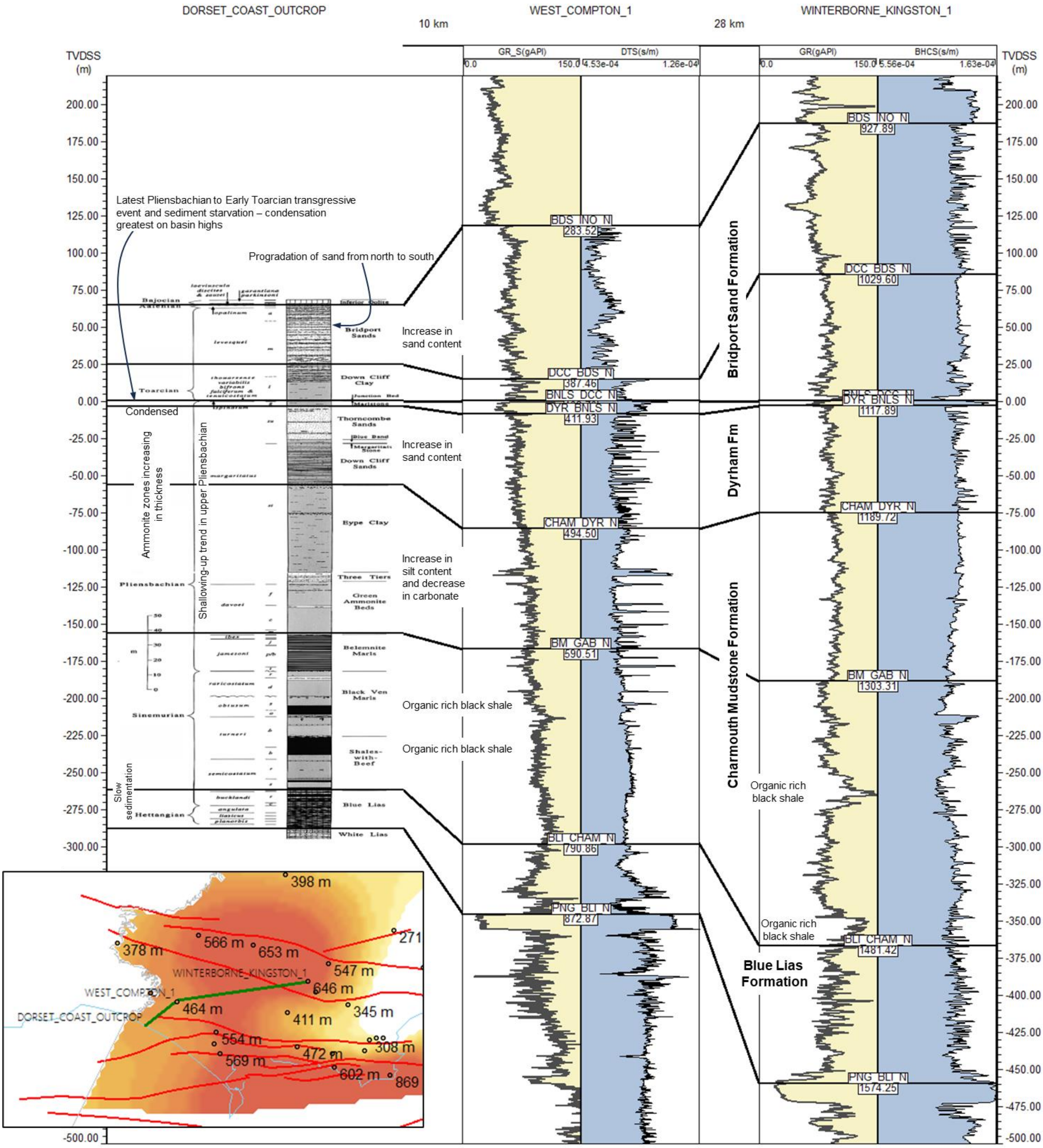

Figure 11 Correlation from the Dorset coastal outcrop to the Winterborne Kingston Borehole. Dorset coast outcrop section is adapted from Hesselbo and Jenkyns (1995). Contains Ordnance Survey data © Crown copyright and database rights 2025.

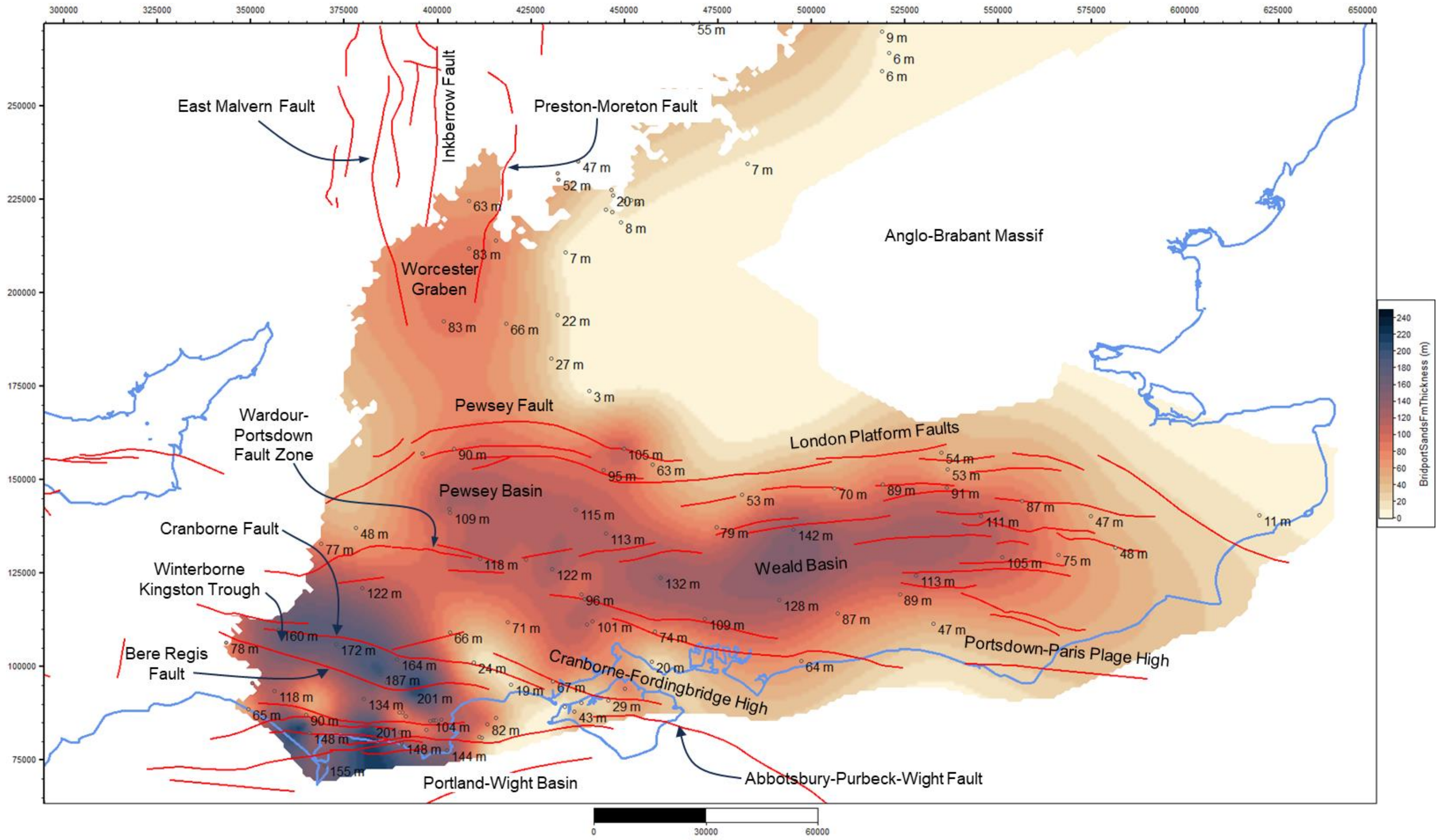

Figure 12 Thickness of the Bridport Sands Formation in southern England. Contains Ordnance Survey data © Crown copyright and database rights 2025.

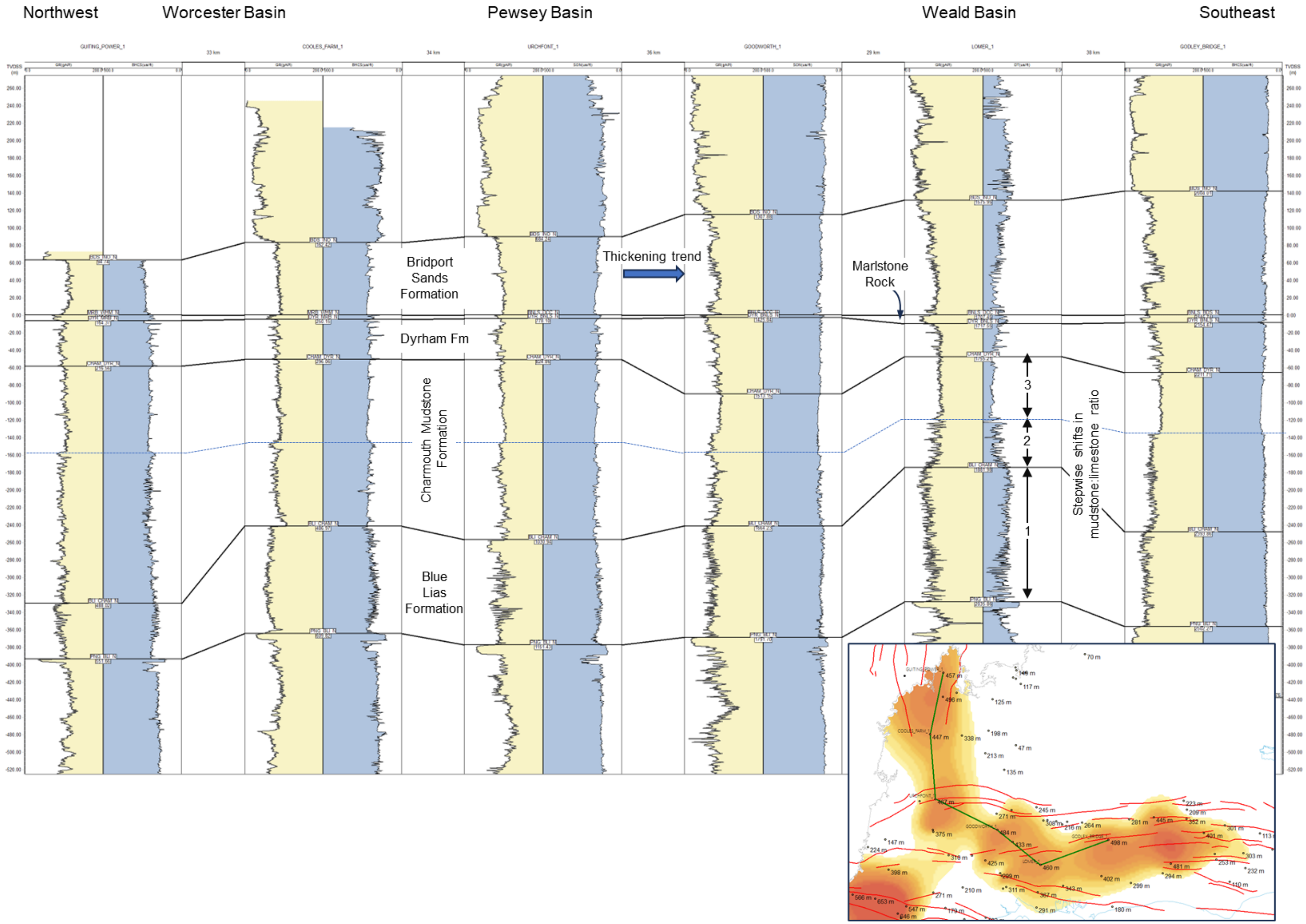

Figure 13 Correlation from the Worcester Graben to the Weald Basin. Note the stepwise subdivision of the Blue Lias and Charmouth Mudstone formations into three units (labelled 1-3), the uppermost of which is predominantly mudstone. Also note the west to east thickening of the Bridport Sands Formation (thick blue arrow).

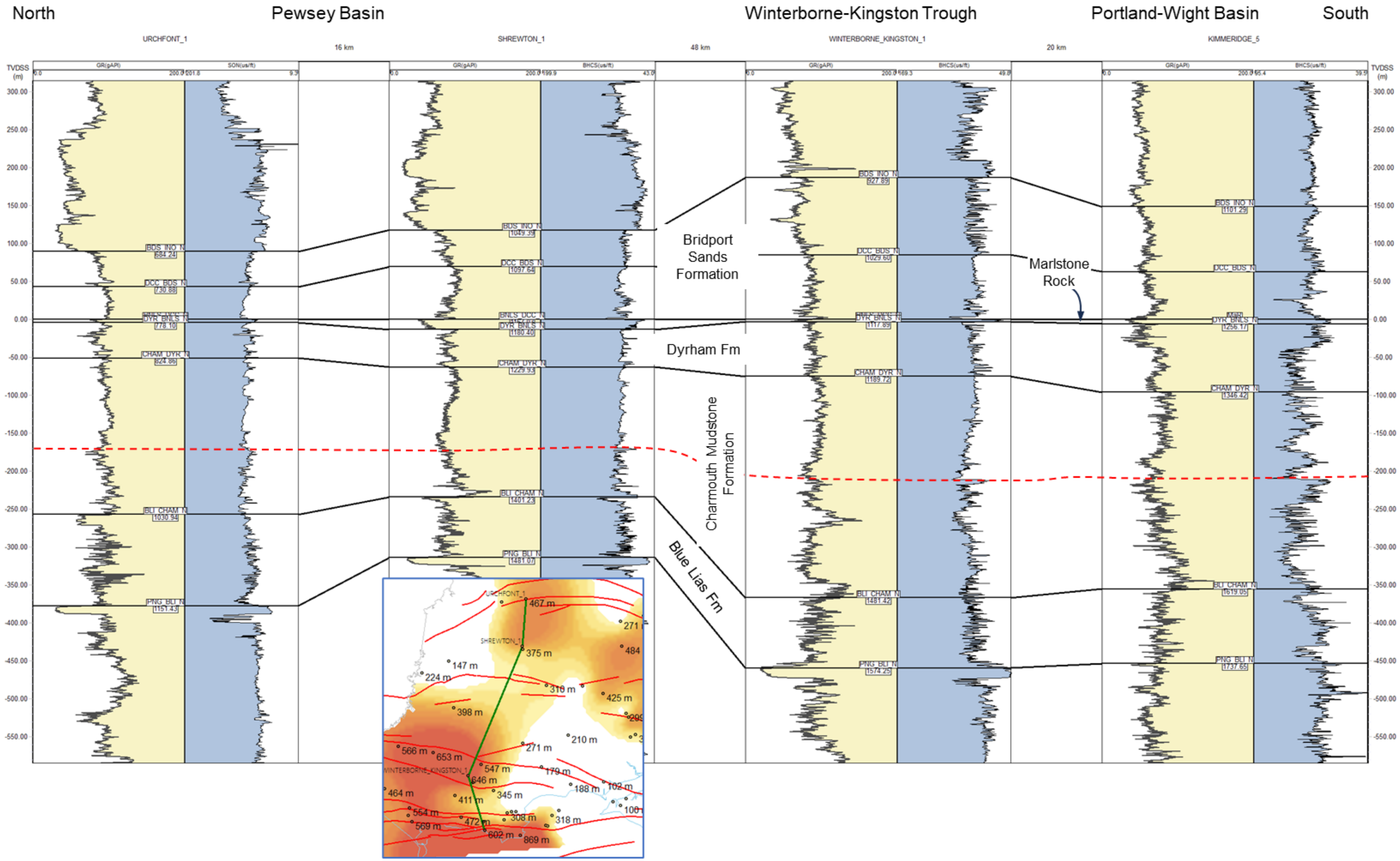

Figure 14 Correlation from the Pewsey Basin to the Wessex Basin. Note thickening into the Winterborne-Kingston Trough that is particularly marked in the lower (Sinemurian) half of the Charmouth Mudstone Formation.

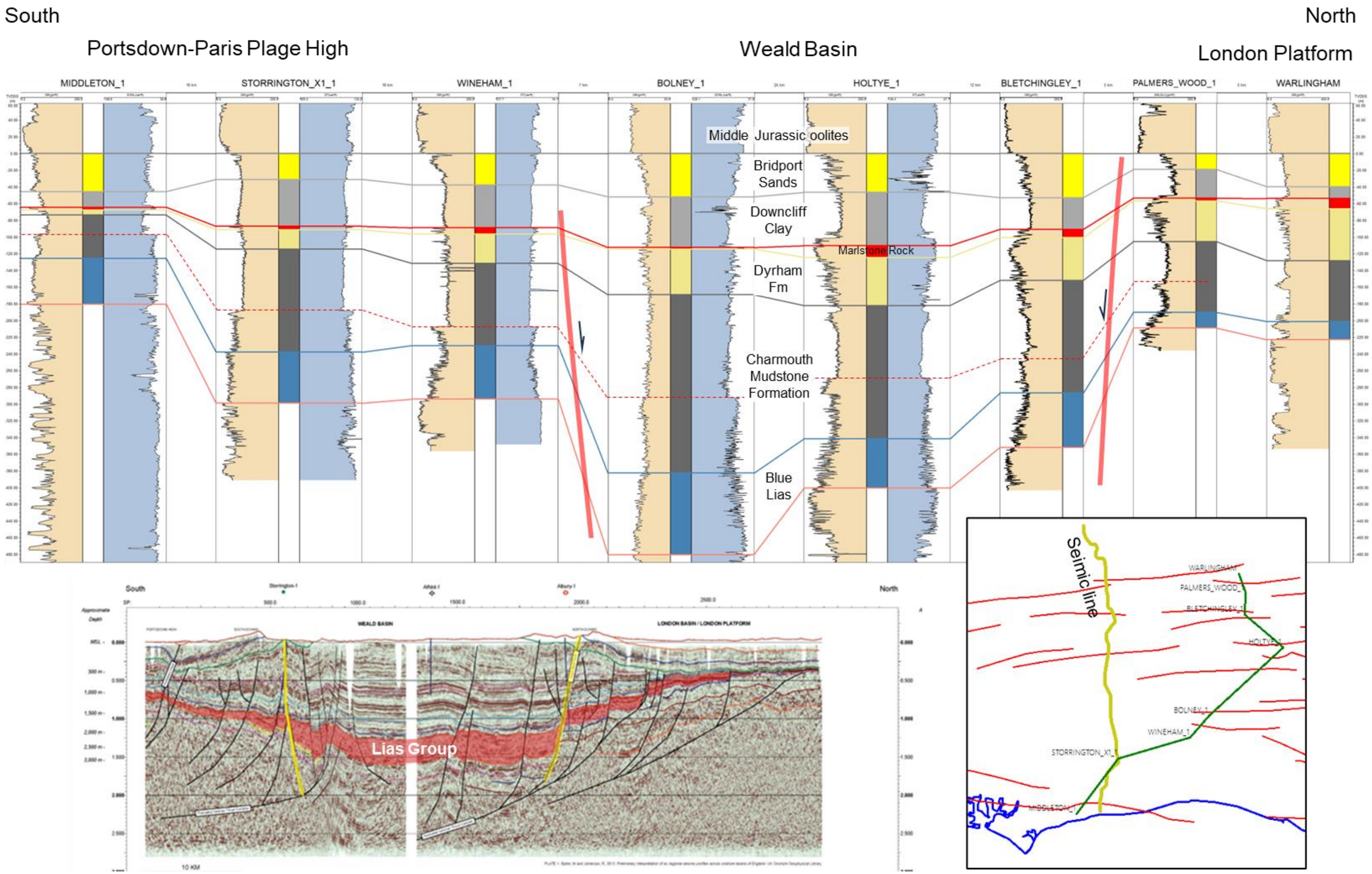

Figure 15 North-South correlation across the Weald Basin. Seismic section adapted from Butler, M. & Jamieson, R., 2013. **Preliminary Interpretation of Six Regional Seismic Profiles Across Onshore Basins of England.** UK Onshore Geophysical Library, digital publication, *https:// www.ukogl.org.uk. Contains Ordnance Survey data © Crown copyright and database rights 2025*

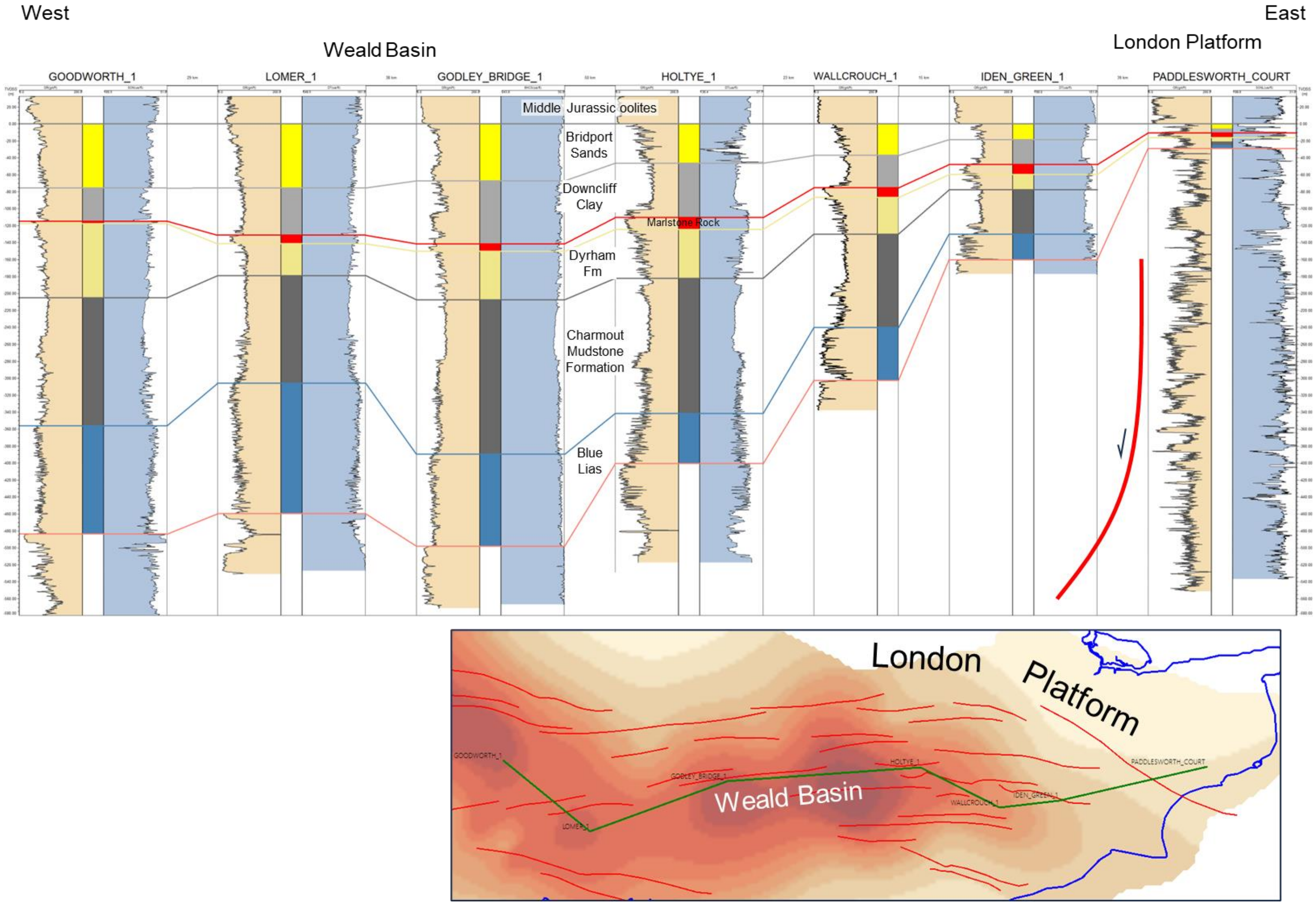

Figure 16 W-E correlation across the basin eastern bounding faults of the Weald Basin. Contains Ordnance Survey data © Crown copyright and database rights 2025.

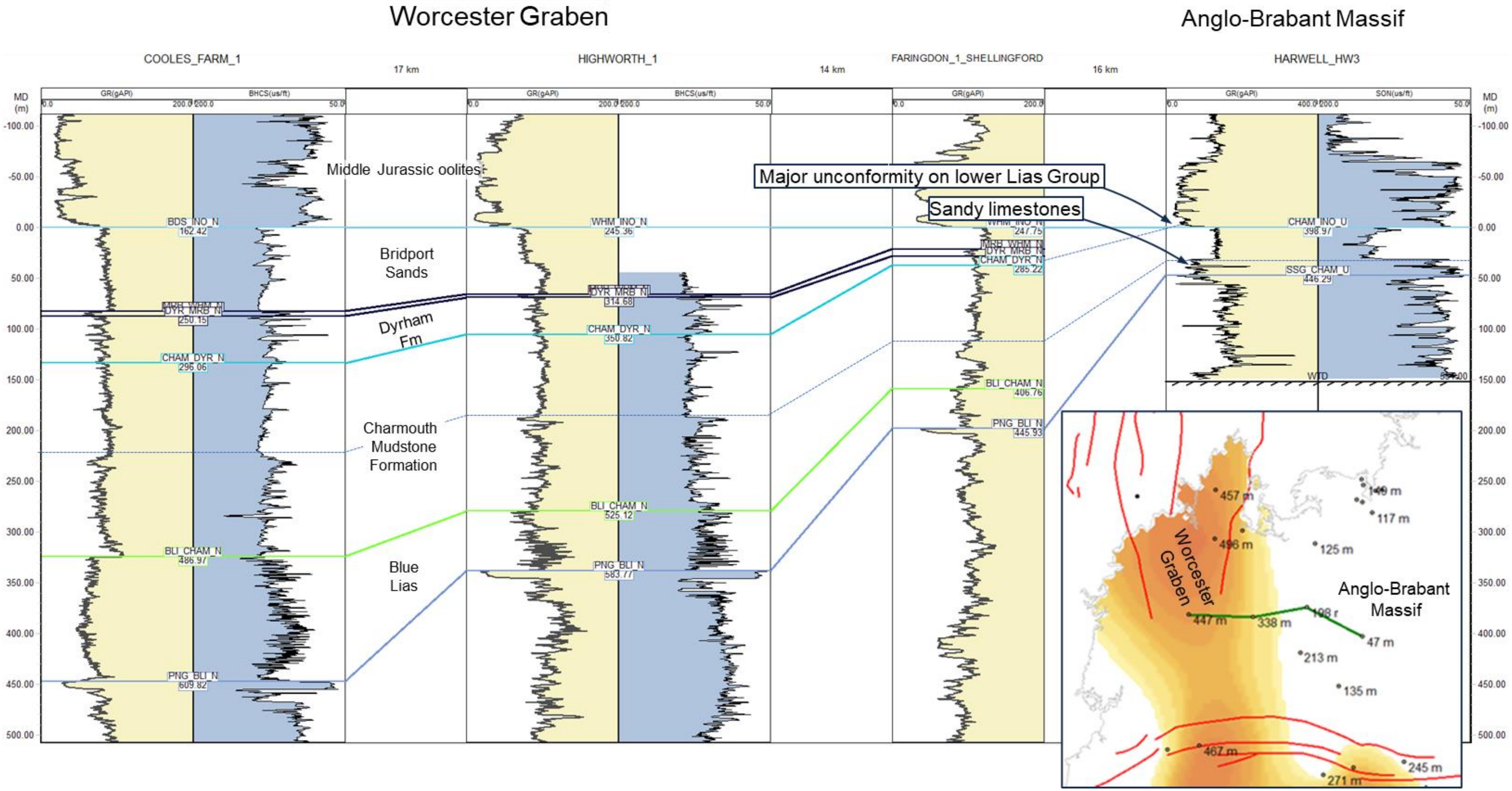

Figure 17 Worcester Graben to Anglo-Brabant Massif correlation. Lias Group subdivisions thin but remain present from basin to high, except in Harwell where the group is severely truncated beneath Middle Jurassic limestones of the Inferior Oolite Group. Contains Ordnance Survey data © Crown copyright and database rights 2025.

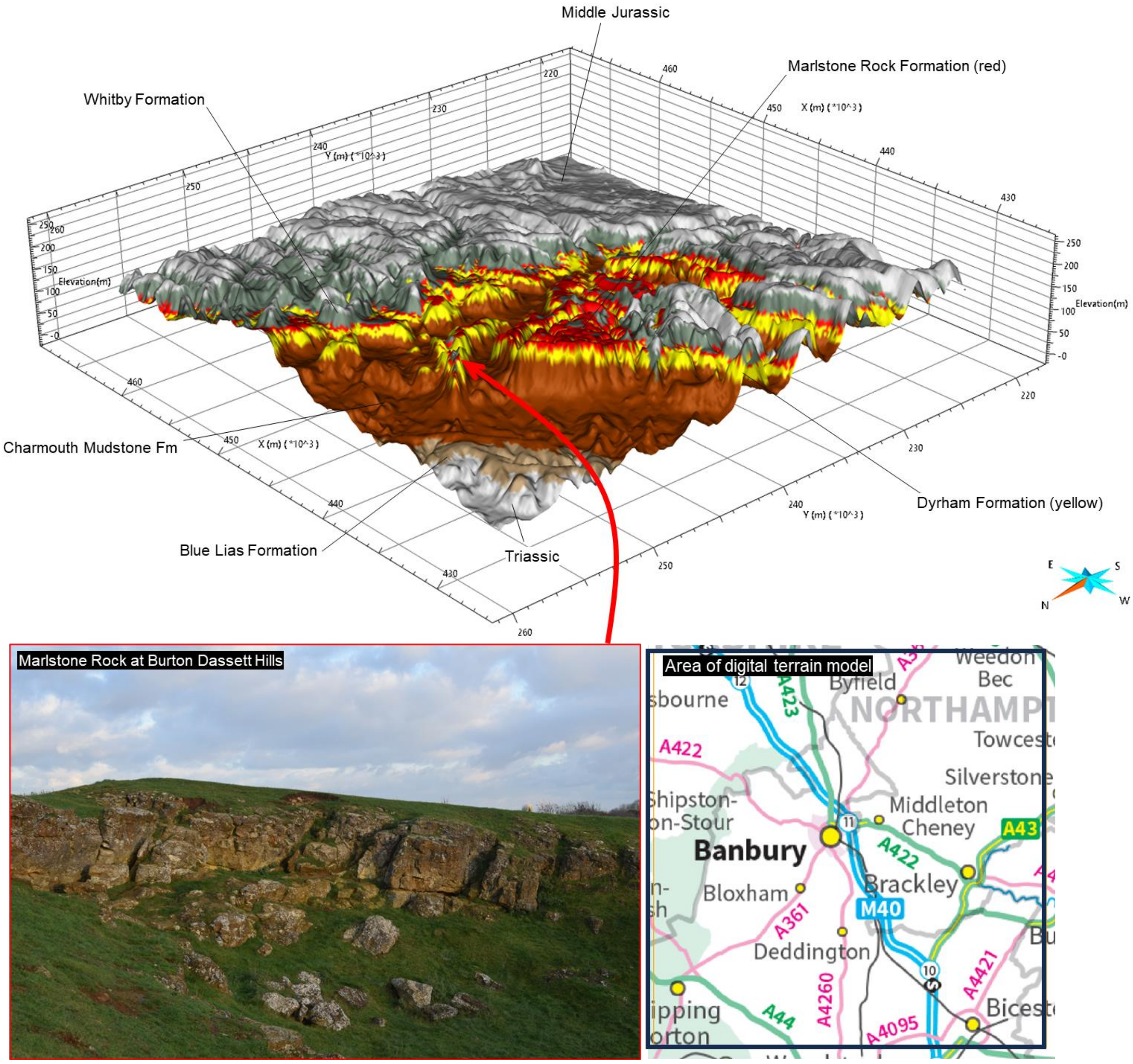

Figure 18 Field exposure of the Marlstone Rock at Dasset Hills, near Banbury. In this area the Marlstone Rock is up to 6 m thick and is a highly indurated ferrugineous limestone which has a major impact on the topography, capping plateaus and cuestas underlain by Charmouth Mudstone Formation. Contains Ordnance Survey data © Crown copyright and database rights 2025.

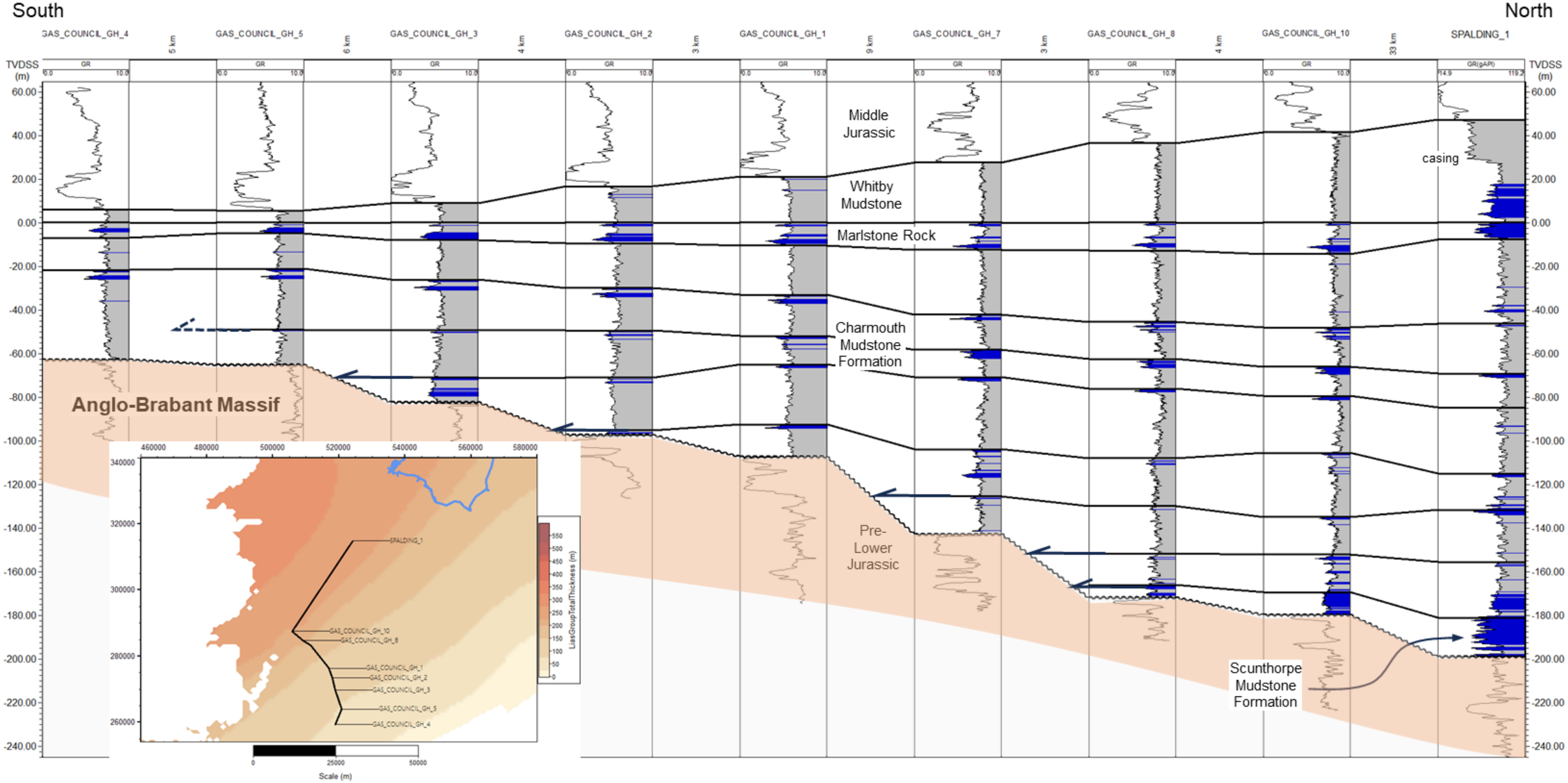

Figure 19 Transect of Gas Council boreholes (tied to Spalding 1) Lias Group which show spectacular onlap of the Lias Group onto the Anglo-Brabant Platform. The Whitby Mudstone Formation is eroded beneath the Middle Jurassic.

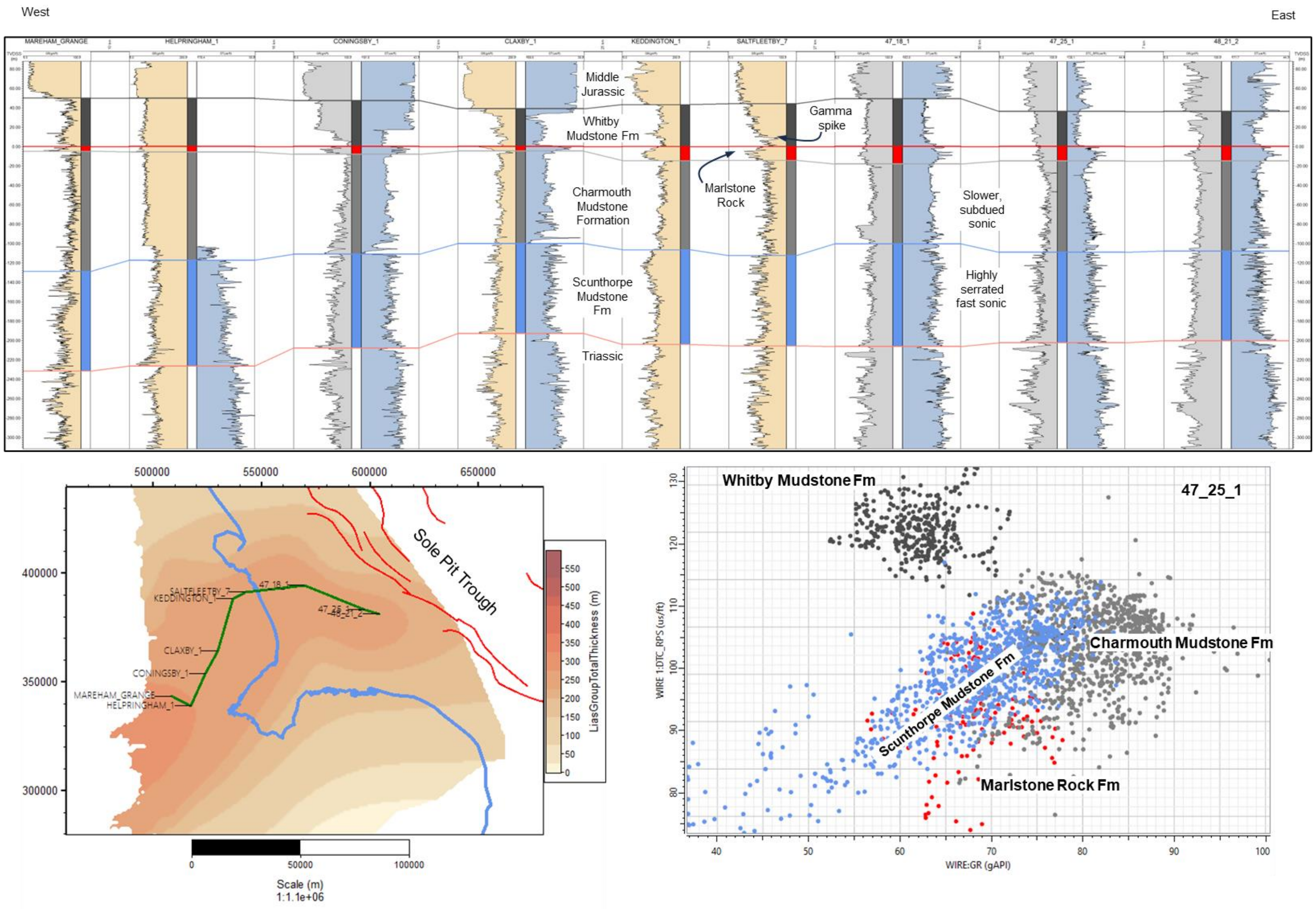

Figure 20 Lias Group of the central East Midlands Shelf including several offshore boreholes. The panel is orientated west-east along the axis of the thickest Lias Group in this area. Cross-plot of Lias Group sonic and gamma-ray for well 47/25-1 shows the relatively clear clustering and segregation of different formations. The Whitby Mudstone Formation forms a particularly marked outlying cluster. Contains Ordnance Survey data © Crown copyright and database rights 2025.

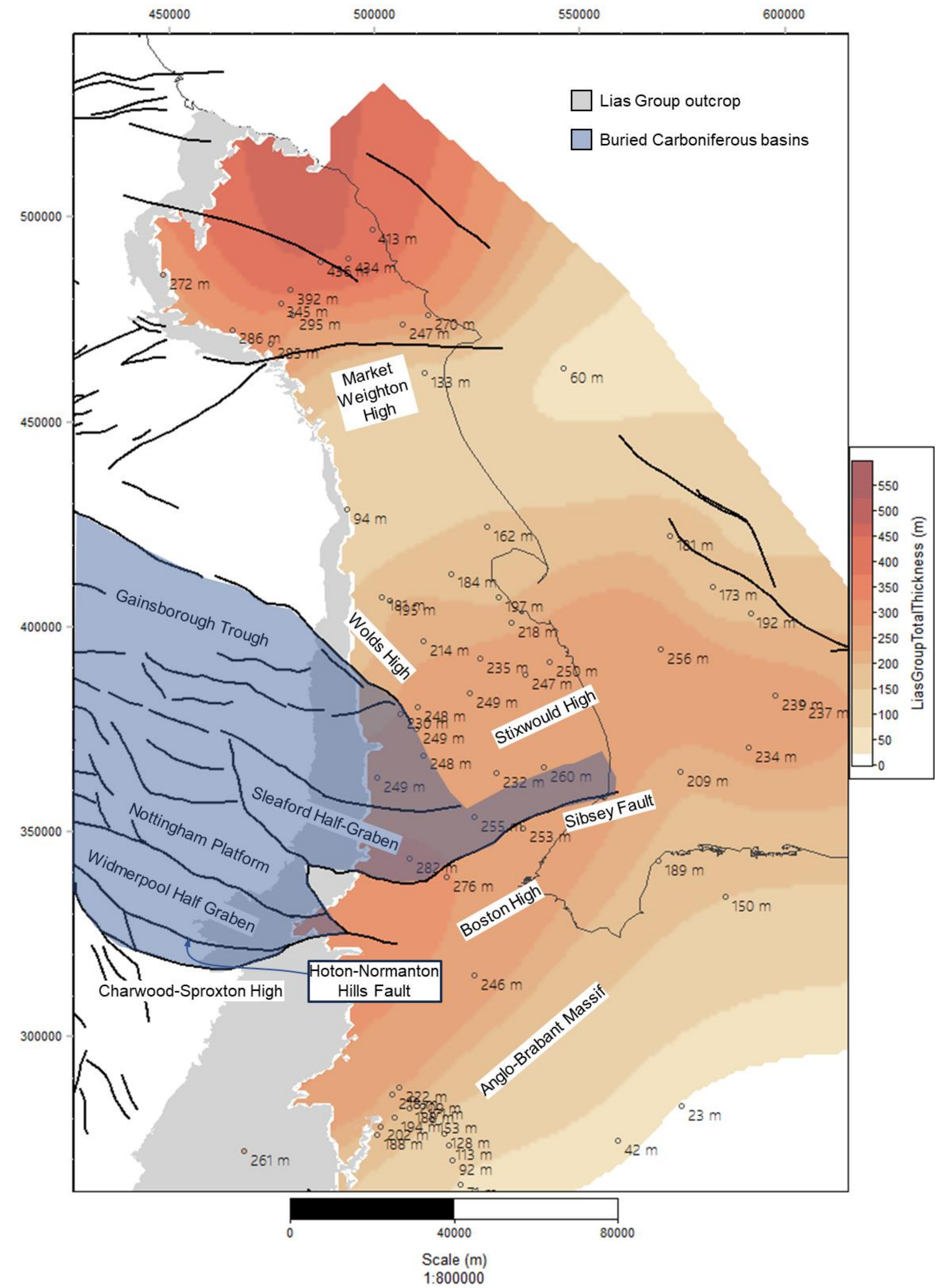

Figure 21 Map showing thickness distribution of Lias Group relative to the position of buried Carboniferous basins. Minor reactivation of basin-bounding faults (or simply compaction of thick Carboniferous basin-fills) may have some control on the slight thickening of the Lias Group to the west. Contains Ordnance Survey data © Crown copyright and database rights 2025.

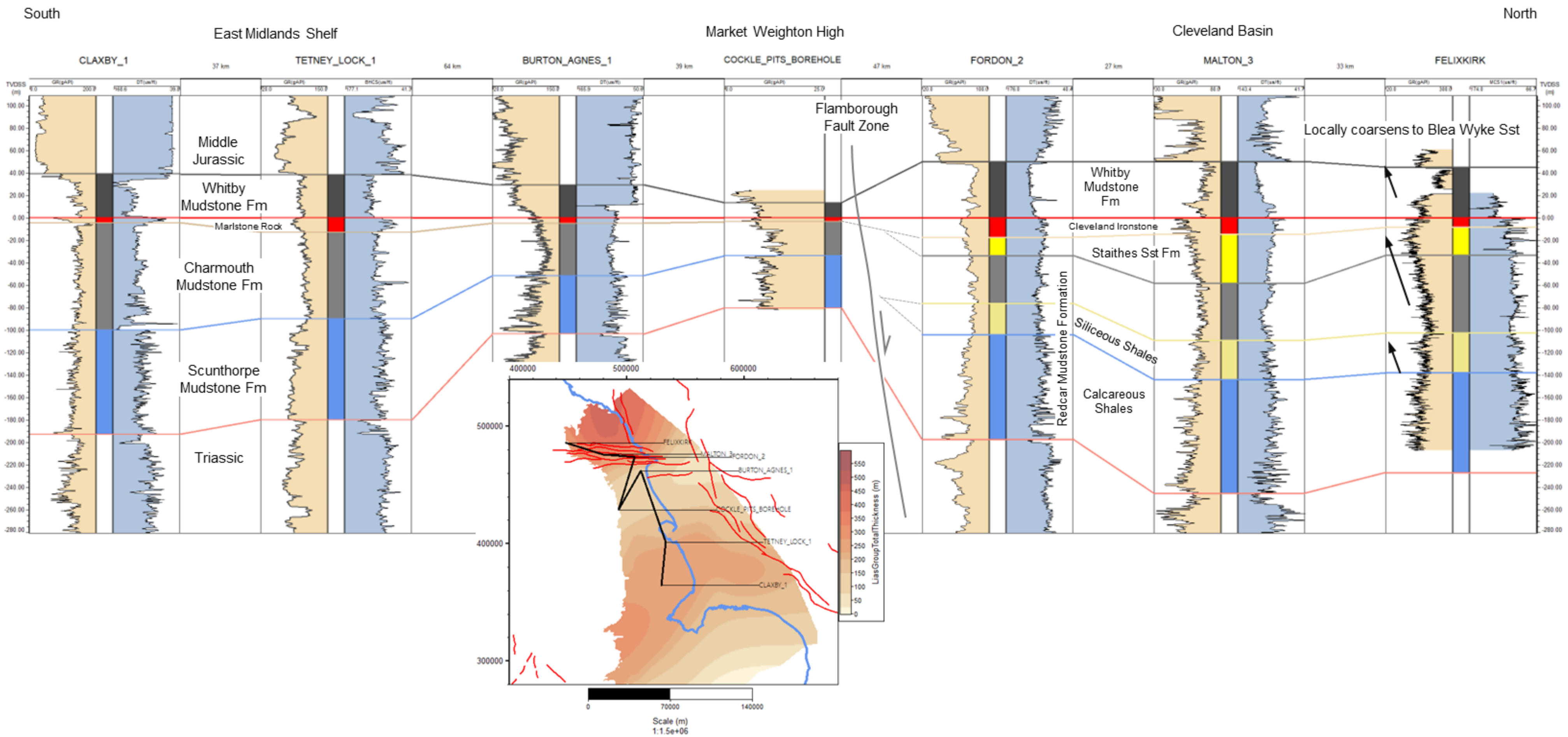

Figure 22 Correlation from the East Midlands Shelf to the Cleveland Basin. The Lias Group becomes highly attenuated across the Market Weighton High. The maximum thickness of the Lias Group is only marginally thicker in the Cleveland Basin than on the East Midlands Shelf. In the Cleveland Basin, the Lias Group includes three shoaling-up successions into sandstones. Thick sandstone bodies are not present on the East Midlands Shelf. Contains Ordnance Survey data © Crown copyright and database rights 2025.

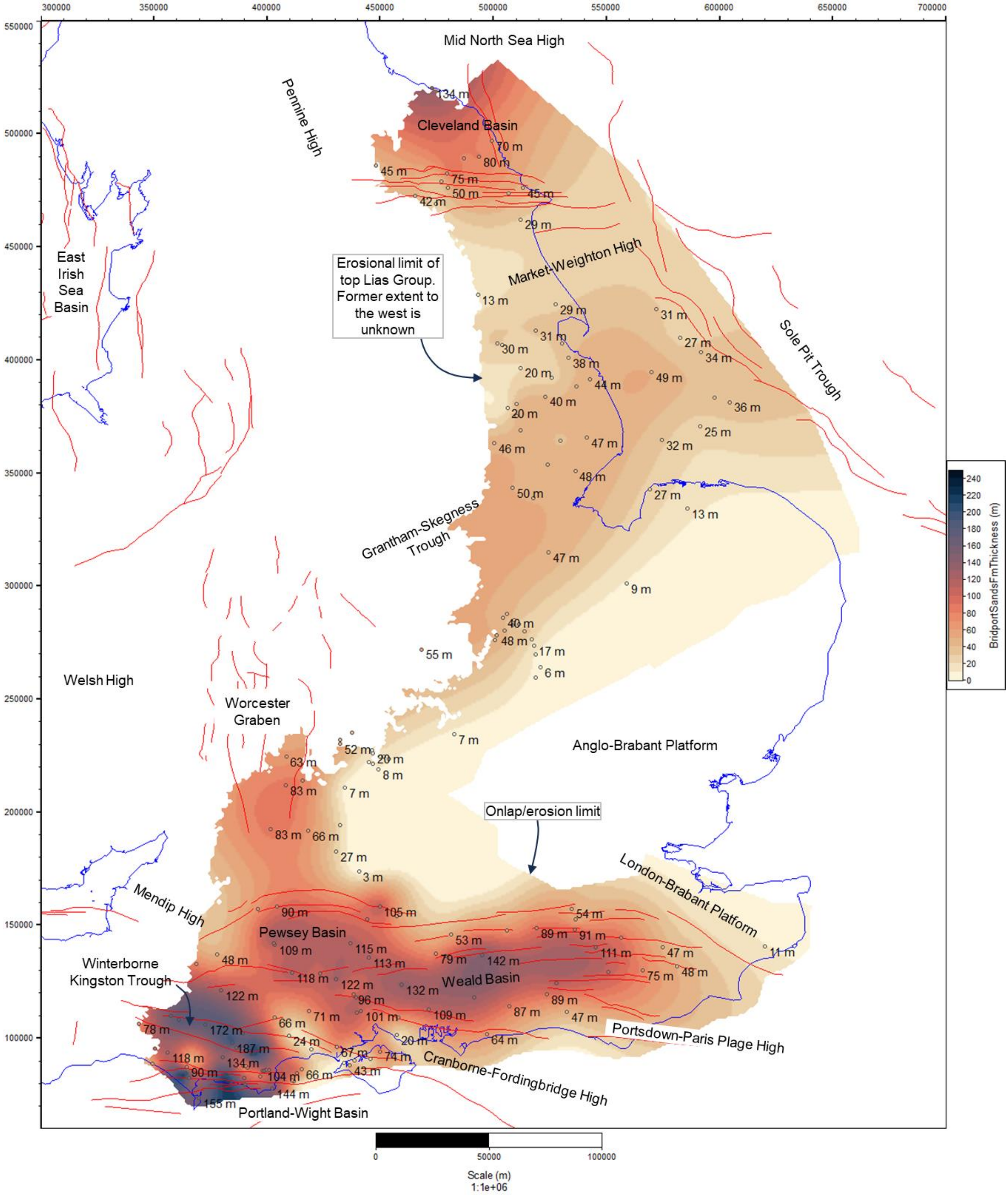

Figure 23 Thickness of Lias Group above the level of the Marlstone Rock. This includes the Bridport Sands Formation in the south and the Whitby Mudstone Formation/Blea Wyke Sandstone in the north. Contains Ordnance Survey data © Crown copyright and database rights 2025.

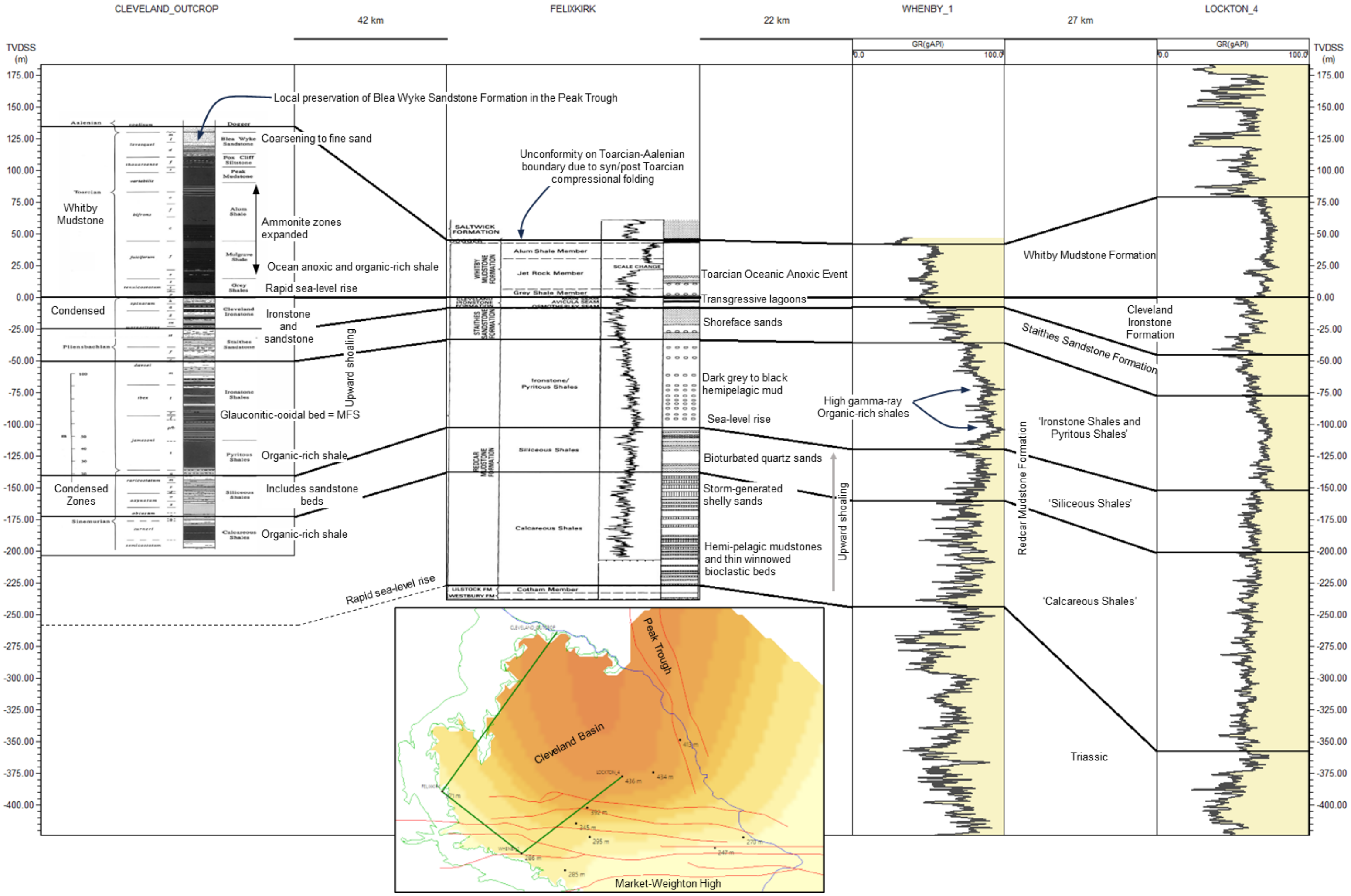

Figure 24 Correlation from outcrop to subsurface in the Cleveland Basin. Coastal outcrop section is adapted from Hesselbo and Jenkyns (1995). Contains Ordnance Survey data © Crown copyright and database rights 2025.

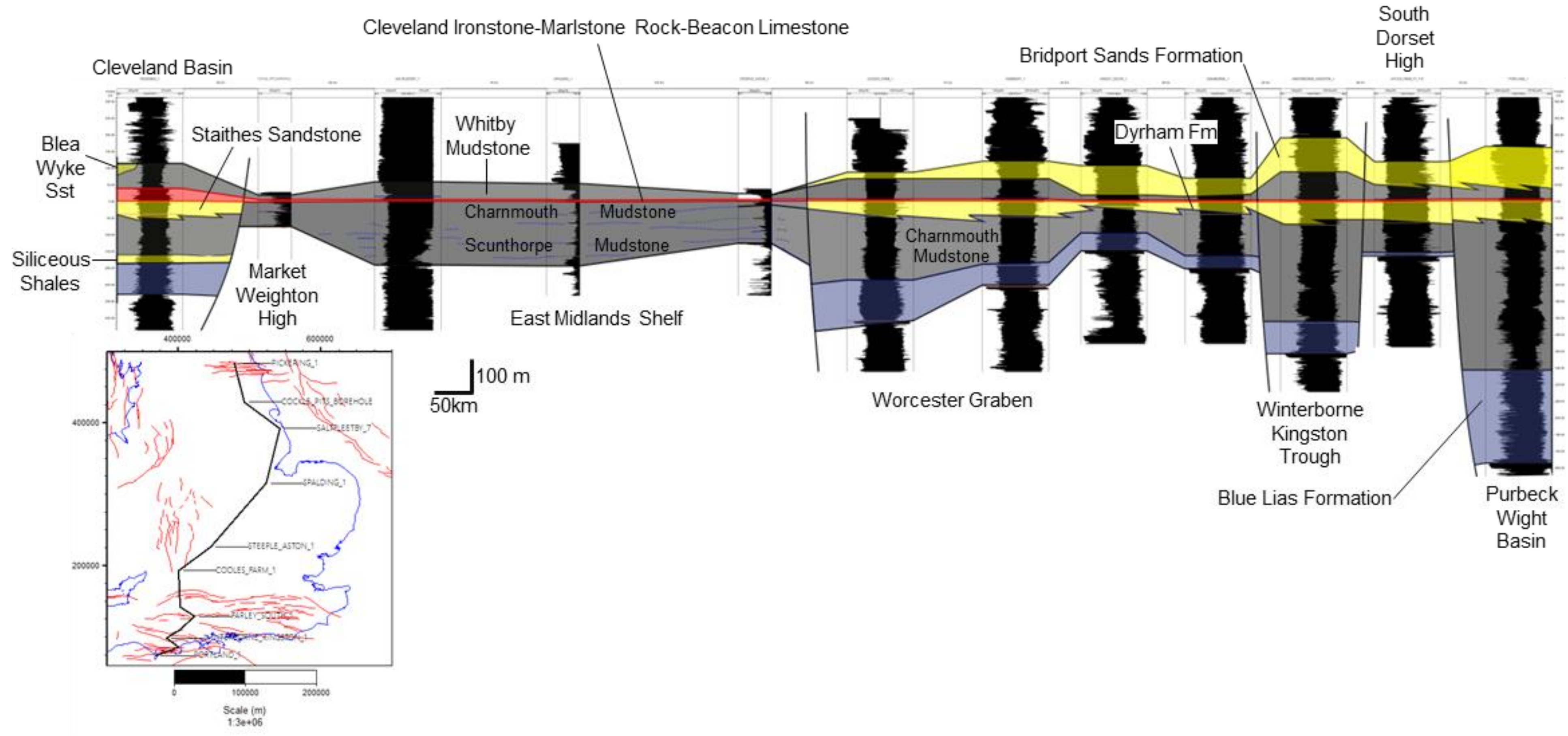

Figure 25 Summary stratigraphy showing major thickness and lithological trends in the Lias Group of southeast England. Contains Ordnance Survey data © Crown copyright and database rights 2025.

5 Appendix A – Lias Group Zones and Subzones

Biozonal subdivision of the Lias Group with major sequence stratigraphical surfaces (SB, MF) and numbered cycles (after Van Buchem & Knox (1998) and Hesselbo & Jenkyns (1998)). NB: Approximate positions of lithostratigraphical boundaries to biozones on East Midlands Shelf, and approximate position of SB and MF surfaces with respect to subzones. SB= Sequence Boundary; MF= Maximum Flooding Surface.

STAGE	ZONE	SUBZONE	SEQUENCE STRAT. (Van Buchem & Knox, 1998)	SEQUENCE STRAT. (Hesselbo & Jenkyns, 1998)		LITHOSTRATIGRAHY		
						Wessex Basin (Dorset Coast)	East Midlands Shelf (cored borehole composite)	Cleveland Basin (Yorkshire Coast)
Toarcian	Aalensis	Fluitans				Bridport Sand Fmn		Whitby Mudstone Fmn
		Mactra						
	Pseudoradiosa	Pseudoradiosa		SB				
		Levesquei			S4			
	Dispansum	Gruneri						
		Insigne						
	Thouarsense	Fallaciosum				Beacon Lst. Fmn.		
		Fascigerum						
		Striatulum						
		Bingmanni						
	Variabilis	Vitiosa						
		Illustris						
		Variabilis						
	Bifrons	Crassum						
		Fibulatum						
		Commune						
	Serpentinum	Falciferum		MF			Whitby Mudstone	
		Exaratum						
	Tenuicostatum	Semicelatum						
		Tenuicostatum						
		Clevelandicum						
		Paltus						
Pliensba	Spinatum	Hawskerense					Marlstone Rock Fmn	Cleveland Ironstone Fmn
		Apyrenum						

<table>
<tr><td rowspan="13"></td><td rowspan="3">Margaritatus</td><td>Gibbosus</td><td></td><td></td><td rowspan="2"></td><td rowspan="3"></td><td></td><td rowspan="19">Charmouth Mudstone Fmn</td><td rowspan="2"></td></tr>
<tr><td>Subnodosus</td><td rowspan="15">III</td><td rowspan="7">C6</td><td rowspan="2">Dyrham Fmn</td></tr>
<tr><td>Stokesi</td><td>SB</td><td rowspan="3">Staithes Sandstone Fmn</td></tr>
<tr><td rowspan="3">Davoei</td><td>Figulinum</td><td rowspan="9"></td><td rowspan="12">S3</td><td rowspan="24">Charmouth Mudstone Fmn</td></tr>
<tr><td>Capricornus</td></tr>
<tr><td>Maculatum</td><td rowspan="28">Redcar Mudstone Fmn</td></tr>
<tr><td rowspan="3">Ibex</td><td>Luridum</td></tr>
<tr><td>Valdani</td></tr>
<tr><td>Masseanum</td><td rowspan="8">C5</td></tr>
<tr><td rowspan="4">Jamesoni</td><td>Jamesoni</td></tr>
<tr><td>Brevispina</td></tr>
<tr><td>Polymorphus</td></tr>
<tr><td>Taylori</td><td>MF</td></tr>
<tr><td rowspan="17">Sinemurian</td><td rowspan="4">Raricostatum</td><td>Aplanatum</td><td></td></tr>
<tr><td>Macdonnelli</td><td>SB</td></tr>
<tr><td>Raricostatum</td><td rowspan="3"></td><td rowspan="8">S2</td></tr>
<tr><td>Densinodulum</td><td rowspan="9">II</td><td rowspan="5">C4</td></tr>
<tr><td rowspan="2">Oxynotum</td><td>Oxynotum</td></tr>
<tr><td>Simpsoni</td><td>MF</td></tr>
<tr><td rowspan="3">Obtusum</td><td>Denotatus</td><td rowspan="3"></td><td rowspan="14">Scunthorpe Mudstone Fmn</td></tr>
<tr><td>Stellare</td></tr>
<tr><td>Obtusum</td><td rowspan="6">C3</td></tr>
<tr><td rowspan="2">Turneri</td><td>Birchi</td><td>SB</td></tr>
<tr><td>Brooki</td><td rowspan="3"></td><td rowspan="10">S1</td></tr>
<tr><td rowspan="3">Semicostatum</td><td>Sauzeanum</td></tr>
<tr><td>Scipionianum</td><td rowspan="8">I</td></tr>
<tr><td>Lyra</td><td>MF</td></tr>
<tr><td rowspan="3">Bucklandi</td><td>Bucklandi</td><td rowspan="3">C2</td><td rowspan="6"></td><td rowspan="6">Blue Lias Fmn</td></tr>
<tr><td>Rotiforme</td></tr>
<tr><td>Conybeari</td></tr>
<tr><td rowspan="3">Hettangian</td><td rowspan="3">Angulata</td><td>Depressa</td><td rowspan="3">C1</td></tr>
<tr><td>Complanata</td></tr>
<tr><td>Extranodosa</td></tr>
</table>

	Liasicus	Laqueus							
		Portlocki							
	Planorbis	Johnstoni							
		Planorbis							

6 Appendix B - Key boreholes and localities

Locality	Key Lias Group Stratigraphy	Information Source(s)
Somerset Coast: Blue Anchor – Lilstock [ST 033 436 – ST 194 461]	Blue Lias Formation (very expanded succession)	Warrington & Ivimey-Cook (1995); Simms (2004)
South Wales Coast: Pant y Slade to Witches Point, Glamorgan [SS 870 741 – SS 890 726]	Blue Lias Formation (St Mary's Well Bay Member, Lavernock Shale Member, Porthkerry Member) Marginal facies = Sutton Stone & Southerndown Members	Warrington & Ivimey-Cook (1995); Simms (2004)
Dorset Coast: Pinhay Bay to West Bay, Bridport [SY 3173 9060 to SY 3470 8986]	Blue Lias Formation, Charmouth Mudstone Formation (Shales-with-Beef, Black Ven Marls, Belemnite Marls, Green Ammonite members), Dyrham Formation (Eype Clay, Down Cliff Sand, Thorncombe Sand members), Beacon Limestone Formation (Marlstone Rock, Eype Mouth Limestone members), Bridport Sand Formation (Down Cliff Clay Member)	Hesselbo & Jenkyns (1995); Simms (2004); Barton et al. (2011)
Yorkshire Coast: Robin Hood's Bay area to Staithes [NZ 9584 0412 to NZ 7830 1892]	Redcar Mudstone Formation (Calcareous Shale, Siliceous Shale, Pyritous Shale, Ironstone Shale members), Staithes Sandstone Formation, Cleveland Ironstone Formation (Penny Nab, Kettleness members), Whitby Mudstone (Grey Shale, Mulgrave Shale, Alum Shale, Peak Mudstone, Fox Cliff Siltstone members), Blea Wyke Sandstone (Grey Sandstone, Yellow Sandstone members)	Hesselbo & Jenkyns (1995); Simms (2004); Powell (2010)
Winterborne Kingston Borehole [SY 84700 97900]	Blue Lias, Charmouth Mudstone, Dyrham, Beacon Limestone, Bridport Sand formations	Rhys et al. (1981)
Tydd St Mary Borehole [TF 43070 17370]	Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Gallois et al. (1994)
Tattenhoe Borehole [SP 82890 34370]	Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Shephard-Thorn et al. (1994)
Cockle Pits Borehole [SE 93237 28644]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Gaunt et al. (1992)

Nettleton Bottom Borehole [TF 12520 98200]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Gaunt et al. (1992)
Blyborough (West Beck Lane) Borehole [SK 92041 94270]	Scunthorpe Mudstone Formation	Gaunt et al. (1992)
Disley Warren Pumping Station Borehole (M513 Near Scunthorpe) [SE 93666 13711]	Scunthorpe Mudstone Formation	Gaunt et al. (1992)
Worlaby Phase 2 Borehole [SE 99744 15961]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Richardson (1979); Gaunt et al. (1992)
Winestead 1 Borehole [TA 27410 24334]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Berridge et al. (1994)
Cleethorpes 1 Borehole [TA 30237 07090]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Berridge et al. (1994)
Tetney Lock 1 Borehole [TA 33187 00939]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Berridge et al. (1994)
Henfield 1 (Calcot Farm) Borehole [TQ 17990 14570]	Charmouth Mudstone Formation (inferred); Marlstone Rock Formation (inferred); Un-named micaceous mudstone & cross-bedded sandstone belonging to higher part of Lias Group	Young & Lake (1988)
Chilton Borehole [TR 27790 43460]	Un-named thin limestone/mudstone unit equivalent to combined Blue Lias & Charmouth Mudstone formations; Marlstone Rock Formation (inferred); un-named semi-nodular limestone belonging to higher part of the Lias Group.	Shephard-Thorn et al. (1988)
Hellingly 1 (Grove Hill) Borehole [TQ 60100 13580]	Charmouth Mudstone Formation (inferred); Marlstone Rock Formation (inferred); un-named siltstones, mudstones & sandy oolitic limestones equivalent belonging to the higher part of the Lias Group.	Lake et al. (1987)
Brightling 1 Borehole [TQ 67250 21820]	Charmouth Mudstone Formation (inferred), Marlstone Rock Formation (inferred); un-named mudstones, siltstones, sandstone and limestone belonging to the higher part of the Lias Group. The succession is repeated by faulting.	Lake et al. (1987)
Soham Borehole [TL 59280 74480]	Charmouth Mudstone Formation (inferred)	Gallois et al. (1988)
Wissington Estate Methwold 'C' Borehole [TL69300 96500]	Charmouth Mudstone Formation (inferred); Dyrham Formation (inferred); Marlstone Rock Formation (inferred)	Gallois et al. (1988)

Eriswell Borehole [TL 74250 78860]	Charmouth Mudstone Formation (inferred)	Bristow et al. (1989)
Harwell HW3 [SU 46801 86441]	Charmouth Mudstone Formation (inferred)	Gallois & Worssam (1983)
Felixkirk Borehole [SE 48343 85754]	Redcar Mudstone Formation (Calcareous Shale, Siliceous Shale, Pyritous Shale, Ironstone Shale members); Staithes Sandstone Formation; Cleveland Ironstone Formation; Whitby Mudstone Formation	Ivimey-Cook & Powell (1991)
Warlingham Borehole [TQ 34760 57190]	Blue Lias Formation (facies equivalent), Charmouth Mudstone (inferred); Dyrham Formation (inferred); Marlstone Rock Formation (inferred); un-named bituminous mudstone, silty mudstone & ferruginous limestone unit belonging to the upper part of the Lias Group.	Worssam & Ivimey-Cook (1971)
Llanbedr (Mochras Farm) Borehole [SH 55330 25940]	Detailed biozonal classification; no modern lithostratigraphical subdivision	Woodland (1971), Hesselbo et al. (2013)
St Fagans Borehole [ST11690 78130]	Blue Lias Formation (St Mary's Well Bay, Lavernock Shales, Porthkerry members)	Waters & Lawrence (1987)
Fulbeck Airfield FB5 [SK 90615 51788]	Scunthorpe Mudstone Formation (Barnstone, Barnby, Granby, Beckingham & Foston members)	Brandon et al (1990)
Thorpe By Water Borehole [SP 88570 96480]	Scunthorpe Mudstone, Charmouth Mudstone, Marlstone Rock, Whitby Mudstone formations	Brandon et al (1990)
Stowell Park (Yanworth) Borehole [SP 08350 11760]	Blue Lias (Saltford Shale, Rugby Limestone members), Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Sumbler et al. (2000)
Sherbourne 1 Borehole [SP15620 13930]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Sumbler et al. (2000)
Upton Burford Borehole [SP 23150 13130]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Sumbler et al. (2000)
Burton Row Brent Knoll Borehole [ST 33560 52080]	Blue Lias, Charmouth Mudstone, Dyrham formations	Whittaker et al. (1983)
Elton Farm (Dundry) Borehole [ST 56360 65890]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Ivimey-Cook (1978)
Twyning Borehole [SO 89430 36640]	Blue Lias Formation (Wilmcote Limestone, Saltford Shale, Rugby Limestone members); Charmouth Mudstone Formation	Hamblin et al. (1991)

Hollowell Borehole [SP 68331 71832]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Cox et al. (1999)
Upton Burford Borehole [SP 23150 13130]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Sumbler (1994); Cox et al. (1999)
Apley Barn Borehole [SP 34370 10660]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Cox et al. (1999)
Steeple Aston (IGS 1971) [SP 46870 25860]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone formations	Poole (1977); Cox et al. (1999)
Withycombe Farm Borehole [SP 43190 40170]	Blue Lias Formation (?condensed & incomplete); Charmouth Mudstone Formation, Dyrham Formation	Poole (1978); Cox et al. (1999)
Barby 1 Borehole [SP 54160 69570]	Charmouth Mudstone Formation; Dyrham Formation	Ambrose & Ivimey-Cook (1982); Cox et al. (1999)
Copper Hill Borehole [SK 97870 42650]	Scunthorpe Mudstone Formation, Charmouth Mudstone Formation; Dyrham Formation; Marlstone Rock Formation; Whitby Mudstone Formation	Berridge et al. (1999)
Bredon Hill 1 Borehole [SO 95770 39960]	Charmouth Mudstone Formation; Dyrham Formation; Marlstone Rock Formation; Whitby Mudstone Formation	Whittaker (1972); Cox et al. (1999)
Cooles Farm 1 Borehole [SU 01640 92140]	Blue Lias, Charmouth Mudstone, Dyrham, Marlstone Rock, Whitby Mudstone, Bridport Sand formations	Cox et al. (1999)
Hatton Lodge Borehole [SK 69328 24597]	Scunthorpe Mudstone Formation (Barnstone, Barnby, Granby, Beckingham & Foston members); Charmouth Mudstone Formation	Carney et al. (2004)
Melton Spinney Borehole [SK 76754 22556]	Scunthorpe Mudstone Formation (Barnstone, Barnby, Granby, Beckingham & Foston members); Charmouth Mudstone Formation	Carney et al. (2004)
Belvoir 1 Borehole [SK 80924 33979]	Scunthorpe Mudstone Formation (Barnstone, Barnby, Granby, Beckingham & Foston members); Charmouth Mudstone Formation	Carney et al. (2004)
Bolney 1 Borehole [TQ 28011 24269]	Blue Lias Formation, Charmouth Mudstone Formation (Shales-with-Beef, Black Ven Marls, Belemnite Marls, Green Ammonite Member), Marlstone Rock Formation, ?Whitby Mudstone Formation, ?Bridport Sand Formation (equivalent)	Gallois & Worssam (1993)
Trunch Borehole [TG 29330 34550]	Blue Lias Formation (inferred), Charmouth Mudstone Formation (inferred), ?Dyrham Formation	Detailed BGS archive core log registered as TG23SE/8

Southampton 1 (AKA Western Esplanade) Borehole [SU 41559 12018]	Blue Lias Formation, Charmouth Mudstone Formation (Shales-with-Beef, Black Ven Marls, Belemnite Marls, Green Ammonite Member), Drham Formation, Marlstone Rock Formation, Bridport Sand Formation	Edwards et al. (1987)
Wytch Farm X2 (X14) Borehole [SY 98040 85260]	Blue Lias Formation, Charmouth Mudstone Formation (Shales-with-Beef, Black Ven Marls, Belemnite Marls, Green Ammonite Member), Dyrham Formation, Marlstone Rock Formation, Bridport Sand Formation	Bristow et al. (1990)
Wytch Farm (Arne) G1 [SY 95750 87040]	Dyrham Formation, Marlstone Rock Formation, Bridport Sand Formation	Bristow et al. (1990)
Empingham SD6 Borehole [SK 94720 07370]	Marlstone Rock Formation; Whitby Mudstone Formation	Horton & Coleman (1977)
Empingham DG9 Borehole [SK 94476 07558]	Marlstone Rock Formation; Whitby Mudstone Formation	Horton & Coleman (1977)
Empingham DG2 [SK 93970 08250]	Marlstone Rock Formation; Whitby Mudstone Formation	Horton & Coleman (1977)
Glinton 1 Borehole [TF 15020 05260]	Blue Lias Formation, Charmouth Mudstone Formation, Marlstone Rock Formation, Whitby Mudstone Formation (inferred)	Annotated BGS archive log (registered TF10NE/1) based on examination of chippings by A Horton (1986)
Brown Moor Borehole [SE 81266 62043]	Redcar Mudstone Formation (Calcareous Shale, Siliceous Shale, Pyritous Shale, Ironstone Shale members), Staithes Sandstone Formation, Cleveland Ironstone Formation, Whitby Mudstone Formation (Grey Shales, Jet Rock, Bituminous Shales members)	Gaunt et al. (1980)
Thimbleby Borehole [SE 45410 94690]	Staithes Sandstone Formation, Cleveland Ironstone Formation, Whitby Mudstone Formation (Grey Shales, Jet Rock members)	Anon (1982)
Raisdale Borehole [NZ 53200 00120]	Cleveland Ironstone Formation; Whitby Mudstone Formation (Grey Shales Member)	Anon (1982)
Upwood Borehole [TL 24930 83040]	Blue Lias Formation; Charmouth Mudstone Formation; Dyham Formation; Marlstone Rock Formation; Whitby Mudstone Formation	BGS archived borehole log (registered TL28SW/1)
Harbury Quarry Borehole [SP 39220 58890]	Blue Lias Formation	Anon (1978)
Parsons Drove West Bridge Borehole [TF 37930 10520]	Whitby Mudstone Formation	Anon (1981)
Guiting Power 1 Borehole [SP 08550 24510]	Blue Lias Formation (Saltford Shale, Rugby Limestone members); Charmouth Mudstone,	Barron et al. (2002)

	Dyrham Formation, Marlstone Rock Formation, Whitby Mudstone Formation	
Ash Farm No. 1 Borehole [SP 20870 20870]	Blue Lias Formation; Charmouth Mudstone Formation	Barron et al. (2002)

7 Appendix C - Characteristic features of lithostratigraphical units in the Lias Group.

* The Marlstone Rock Member of the Beacon Limestone Formation becomes the Marlstone Rock Formation in areas where the Beacon Limestone Formation is absent (Cox et al., 1999, table 3).

Formation / Member	Parent Unit	Basin Distribution	Typical features	Maximum Thickness
Blea Wyke Sandstone Formation	Lias Group	Cleveland	Micaceous, fine-grained sandstone/silty sandstone	up to 18 m
Yellow Sandstone Member	Blea Wyke Sandstone Formation	Cleveland	Yellow-weathering, fine-grained sandstone	9 m
Grey Sandstone Member	Blea Wyke Sandstone Formation	Cleveland	Fine-grained, micaceous muddy sandstone with subordinate silty mudstone and sideritic concretions	7.8 – 9 m
Whitby Mudstone Formation	Lias Group	Worcester/Severn Basin, East Midlands Shelf, Cleveland Basin	Mudstone/siltstone, partly bituminous, with locally common limestone nodules.	up to 130 m
Fox Cliff Siltstone Member	Whitby Mudstone Formation	Cleveland Basin	Mudstone, siltstone, silty mudstone with ferruginous ooids, sideritic mudstone beds and concretions, and phosphatic nodules.	9.9 – 11.1 m
Peak Mudstone Member	Whitby Mudstone Formation	Cleveland Basin	Mudstone, micaceous and silty, with sideritic concretions and layers of phosphate nodules	12.6 m
Alum Shale Member	Whitby Mudstone Formation	Cleveland Basin	Mudstone, grey, non-bituminous, with common layers of grey calcareous concretions in lower and upper parts	13.2 – 40 m
Mulgrave Shale Member	Whitby Mudstone Formation	Cleveland Basin	Mudstone, dark grey, bituminous and pyritic, with common layers of grey calcareous concretions up to 4.5 m. Includes the 'Jet Rock' and 'Bituminous Shales'.	23 – 3 m
Grey Shale Member	Whitby Mudstone Formation	Cleveland Basin	Grey, shaly mudstone and siltstone, with layers of small calcareous and ferruginous nodules.	5 – 17 m
Cleveland Ironstone Formation	Lias Group	Cleveland	Mudstone/siltstone/silty sandstone with thin seams of ironstone.	up to 25 m
Staithes Sandstone Formation	Lias Group	Cleveland	Bioturbated argillaceous silty sandstone.	up to 30 m
Kettleness Member	Lias Group	Cleveland	Chamositic and sideritic oolitic ironstone. East and south-eastwards interfingers and transitions with/to siliciclastic silty shale, siltstone and subordinate fine sandstone	10 m

Penny Nab Member	Lias Group	Cleveland	Shale, siltstone and argillaceous silty sandstone with interbedded thin seams of chamositic and sideritic oolitic ironstone	19 m
Redcar Mudstone Formation	Lias Group	Cleveland	Fissile mudstone and siltstone, with thin beds of limestone in lower part and sandstone in upper part	up to 283 m
Ironstone Shale Member	Redcar Mudstone Formation	Cleveland	Mudstones with iron-rich silty laminations	64 m
Pyritous Shale Member	Redcar Mudstone Formation	Cleveland	Dark grey/black mudstones with pyrite nodules and beds of concretionary siderite	27 m
Siliceous Shale Member	Redcar Mudstone Formation	Cleveland	Mudstones with sandstone forming thin decimetre-scale bioturbated units, scour-infills, and discontinuous laminae	38 m
Calcareous Shale Member	Redcar Mudstone Formation	Cleveland	Mudstones with numerous oyster-rich limestone beds.	127 m
Scunthorpe Mudstone Formation	Lias Group	East Midlands Shelf (north)	Blocky/fissile mudstone with thin limestone/siltstone beds	up to 128 m
Frodingham Ironstone Member	Scunthorpe Mudstone Formation	East Midlands Shelf (north)	Repeated alternations of grainstone-dominated ironstone and muddy ironstone, including packstone, wackestone and mudstone.	up to 10.24 m
Foston Member	Scunthorpe Mudstone Formation	East Midlands Shelf (north)	Grey mudstones containing laterally persistent beds of limestone	30.07 m (type section)
Beckingham Member	Scunthorpe Mudstone Formation	East Midlands Shelf (north)	Shaly mudstones, with rare thin limestones	up to 24 m
Granby Member	Scunthorpe Mudstone Formation	East Midlands Shelf (north)	Calcareous mudstones with numerous thin, laterally persistent, shelly, bioclastic limestones occurring in groups	30.6 m
Barnby Member	Scunthorpe Mudstone Formation	East Midlands Shelf (north)	Calcareous mudstones with rare thin argillaceous limestones	22.05 m
Barnstone Member	Scunthorpe Mudstone Formation	East Midlands Shelf (north)	Alternating grey mudstones and limestones	up to 10 m
Bridport Sand Formation	Lias Group	Wessex - Weald	Micaceous silt and fine-grained sand with calcite cemented beds	up to 120 m
Down Cliff Clay Member	Bridport Sand Formation	Wessex - Weald	Grey, calcareous, bioturbated silicate mudstones, locally very finely sandy and micaceous.	up to 21 m (Dorset Coast); 121 m (inland Dorset)
Beacon Limestone Formation	Lias Group	Wessex	Ferruginous, ooidal/nodular/conglomeratic limestone	up to 5 m

Eype Mouth Limestone Member	Beacon Limestone Formation	Wessex	Hard, pinkish grey limestone, locally conglomeratic	up to 3.65 m
Marlstone Rock Member	Beacon Limestone Formation	Wessex	Shelly, brownish-grey and pink ferruginous limestone with ooids and sandstone pebbles. Conglomeratic base	ca. 1 m or less
Marlstone Rock Formation*	Lias Group	Worcester/Severn Basin, East Midlands Shelf, ?Weald Basin	Sandy, shelly ferruginous limestone with thin mudstone partings	up to 10 m
Dyrham Formation	Lias Group	Wessex Basin, Worcester Basin, southern part of East Midlands Shelf	Silty/sandy mudstone, with siltstone/sandstone interbeds and occasional thin, impersistent beds of limestone	up to 125 m
Thorncombe Sand Member	Dyrham Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Yellow-weathering silty very fine-grained sands, locally bioturbated and with hummocky cross-bedding.	23 m
Down Cliff Sand Member	Dyrham Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Interbedded muddy, very fine-grained sands and sandy mudstones.	up to 27 m
Eype Clay Member	Dyrham Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Pale grey, micaceous, variably silty mudstone with many small siderite nodules. Three units of fine-grained sandstone in basal part.	60 m
Charmouth Mudstone Formation	Lias Group	Wessex Basin, ?Weald Basin, Somerset Basin, Worcester/Severn Basin, East Midlands Shelf, Bristol Channel Basin	Mudstones (sometimes bituminous) with occasional limestones (more abundantly developed in some areas). Finely sandy beds at some levels and in upper part	up to 335 m
Pecten Ironstone Member	Charmouth Mudstone Formation	East Midlands Shelf	Ollitic ironstone with abundant *Pseudopecten equivalvis*	up to 2.2 m
Green Ammonite Member	Charmouth Mudstone Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Mudstones, with irregular limestones developed at three principal horizons	up to 31 m
Belemnite Marl Member	Charmouth Mudstone Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Pale grey and dark grey interbedded calcareous mudstones with abundant belemnites at many levels.	20 – 27 m
Black Ven Marl Member	Charmouth Mudstone Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Dark grey thinly interbedded mudstones and organic-rich mudstone, with a few thin beds of muddy limestone	43 m
Shales-with-Beef Member	Charmouth Mudstone Formation	Wessex Basin, Somerset Basin, Bristol Channel Basin	Dark grey laminated organic-rich shaly mudstone and dark grey mudstones with sporadic concretionary and tabular limestone bands. Abundant vertically	up to 32 m

			oriented fibrous calcite of diagenetic origin ('Beef').	
Blue Lias Formation	Lias Group	Wessex Basin, ?Weald Basin, Somerset Basin, Bristol Channel Basin, Worcester/Severn Basin, southern part of East Midlands Shelf	Interbedded argillaceous limestone and calcareous/bituminous mudstone	up to 140 m
Porthkerry Member	Blue Lias Formation	Bristol Channel Basin	Dominated by micritic limestones (0.05 – 0.3 m thick) with much thinner mudstone interbeds	up to 120 m
Lavernock Shale Member	Blue Lias Formation	Bristol Channel Basin	Grey calcareous mudstones with few, widely separated limestones	12 m
St Mary's Well Bay Member	Blue Lias Formation	Bristol Channel Basin	Interbedded fissile mudstone and thin limestone	16 – 18 m
Rugby Member	Blue Lias Formation	Worcester/Severn Basin	Interbedded muddy limestones and mudstones	up to 40 m
Saltford Shale Member	Blue Lias Formation	Worcester/Severn Basin	Grey, fissile/blocky calcareous mudstones with a few limestones	20 – 30 m typically (4.27 m in type section)
Wilmcote Member	Blue Lias Formation	Worcester/Severn Basin	Alternating limestones and mudstones	up to 11.9 m

8 Appendix D - Boundaries of the Lias Group

Geological Unit	Base/Top	Definition
Lias Group	Base	Non-sequential/unconformable contact with Penarth Group or older Permo-Triassic strata where this unit is eroded. In areas with very pronounced erosion across tectonic axes, strongly unconformable on older strata.
Lias Group	Top	Commonly a non-sequential contact with the overlying limestones of the Middle Jurassic Inferior Oolite Group. On East Midlands Shelf, contact with sandstone of the Northampton Sand Formation (or where eroded), mudstones of the Grantham Formation. In Cleveland Basin, non-sequential contact with Dogger Formation (ferruginous sandstone/ironstone/limestone/mudstone) or where this is absent, the Ravenscar Group (fluvio-deltaic sediments with plant remains).
Blea Wyke Sandstone Formation	Top	Unconformable contact with Middle Jurassic Dogger Formation/Ravenscar Group
Yellow Sandstone Member	Top	Unconformable contact with Middle Jurassic Dogger Formation/Ravenscar Group
Grey Sandstone Member	Top	Sharp upward colour-change from grey to yellow-weathering sandstones of the Yellow Sandstone Member
Whitby Mudstone Formation	Top	Eroded contact with limestones/sandstones of the Inferior Oolite Group (East Midlands Shelf) or Ravenscar Group/Dogger Formation (Cleveland Basin). In Worcester/Severn Basin, at lithological transition to predominantly sandy sediments of the overlying Bridport Sand Formation..
Fox Cliff Siltstone Member	Top	Upward transition from dark grey mudstone and siltstone, to paler burrow-mottled silt and sand-rich sediment of Blea Wyke Sandstone Formation
Peak Mudstone Member	Top	Sharp upward change from dark grey mudstone into muddy siltstone (Fox Cliff Siltstone Member)
Alum Shale Member	Top	Sharp upward change from grey shaly mudstone with common layers of calcareous concretions into dark grey micaceous and silty mudstone with sideritic concretions (Peak Mudstone Member)
Mulgrave Shale Member	Top	Contact of dark grey bituminous mudstone (with a double layer of sideritic concretions - Ovatum Bed) with overlying base of non-bituminous grey shaly mudstone (Alum Shale Member).
Grey Shale Member	Top	Contact of non-bituminous shaly mudstone withbase of bituminous mudstone with large concretions (Mulgrave Shale Member).
Cleveland Ironstone Formation	Top	Contact of highest ooidal ironstone OR row of hard sideritic nodules with overlying Whitby Mudstone.
Staithes Sandstone	Top	Upward transition from sandstone/siltstone to shaly mudstone with scattered sideritic nodules (Cleveland Ironstone Formation)

Penny Nab Member	Top	Non-sequential contact with the Pecten (ironstone) Seam of the Kettleness Member. In some areas this is also the upward change to more consistently developed oolitic ironstone facies of the Kettleness Member. Top probably not recognisable where Kettelness Member transitions into facies similar to Penny Nab Member.
Redcar Mudstone Formation	Top	Gradational contact with overlying sandstones and siltstones of Staithes Sandstone Formation
Ironstone Shale Member	Top	Gradational contact with overlying sandstones and siltstones of Staithes Sandstone Formation
Pyritous Shale Member	Top	No formally published definition. Inferred to be transition from pyritic and sideritic mudstone into mudstone with ferruginous silt bands.
Siliceous Shale Member	Top	No formal published definition. Inferred to be transition from mudstones with thin bioturbated sandstones into pyritic and sideritic mudstone.
Calcareous Shale Member	Top	No formal published definition. Inferred to be transition from mudstone with common oyster-rich limestone beds to mudstone with thin bioturbated sandstones.
Scunthorpe Mudstone Formation	Top	At top of Frodingham Ironstone, or where this is absent, at the erosive base of thin pebbly ferruginous oolite (Glebe Farm Bed) marking the base of the Charmouth Mudstone Formation.
Frodingham Ironstone Member	Top	Upward change from ironstone to grey, silty mudstone (Charmouth Mudstone).
Foston Member	Top	At erosive base of a ferruginous bed of oolitic wackestone (Glebe Farm Bed) at the base of the Charmouth Mudstone Formation. Where Frodingham Ironstone Member present, inferred to be marked by sharp transition into oolitic/muddy ironstone.
Beckingham Member	Top	Base of overlying ferruginous Stubton Limestones at base of Foston Member
Granby Member	Top	Top of highest limestone in unit
Barnby Member	Top	Base of lowest (unnamed) limestone bed in overlying Granby Member
Barnstone Member	Top	Top of highest limestone bed in Member.
Bridport Sand Formation	Top	Non-sequence at base of lowest limestone of the overlying Inferior Oolite Group
Down Cliff Clay Member	Top	Upward change from sandy mudstone to sands or sandstones of the higher (undivided) part of the Bridport Sand Formation
Beacon Limestone Formation	Top	Base of sands of the overlying Bridport Sand Formation
Eype Mouth Limestone Member	Top	Contact of hard limestone with sandy micaceous mudstone of the overlying Down Cliff Clay Member of the Bridport Sand Formation
Marlstone Rock Member	Top	No published definition, but inferred to be a textural change from sandy, ooidal limestone to fine-grained

		micritic limestone of the overlying Eype Mouth Limestone Member
Marlstone Rock Formation*	Top	At upward change to mudstone/nodular limestones of the Whitby Mudstone Formation.
Dyrham Formation	Top	At base of ferruginous limestone or ironstone of the Marlstone Rock Formation or Marlstone Member of the Beacon Limestone Formation.
Thorncombe Sand Member	Top	Base of limestones of the Beacon Limestone Formation
Down Cliff Sand Member	Top	Top of a slightly conglomeratic ferruginous limestone marker-bed (Margaritatus Stone) that caps the Down Cliff Sand Member, and contains the ammonite *Amaltheus margaritatus*
Eype Clay Member	Top	Upward transition from silty mudstone to sandy mudstone and muddy siltstone of the overlying Down Cliff Sand Formation. A sandstone marker-bed with remains of the brittle star *Palaeocoma milleri* (Starfish Bed) marks the position of this transition at the base of the Down Cliff Sand on the Dorset Coast.
Charmouth Mudstone Formation	Top	Sharp/gradational upward change to coarser siliciclastic deposits of the overlying Dyrham Formation. Where Dyrham Formation absent (East Midlands Shelf), marked by upward transition into ferruginous limestone of the Marlstone Rock Formation.
Pecten Ironstone Member (underlain and overlain by mudstones of the Charmouth Mudstone Formation)	Base/Top	Transition from Charmouth Mudstone to ironstone (base), and ironstone to Charmouth Mudstone (top)
Green Ammonite Member	Top	Base of lowest three beds of fine-grained sandstone that occur in the basal part of the Eype Clay Member.
Belemnite Marl Member	Top	Top of Belemnite Stone (an indurated concretionary marker-bed at the top of the Belemnite Marl Member with a rich fauna of bivalves, belemnites and ammonites)
Black Ven Marl Member	Top	At base of a marker-bed (‘Hummocky’= nodular limestone with irregular surfaces) at base of Belemnite Marl Member
Shales-with-Beef Member	Top	Top of Birchi Nodular (= concretionary limestone nodule bed; nodules up to 1 m, enclosed in ‘beef’ with well preserved specimens of the ammonite *Microderoceras birchi)*
Blue Lias Formation	Top	At the base of the Charmouth Mudstone Formation, coinciding with marked upward decrease in abundance of limestone beds, and marked decrease in their individual thickness and lateral persistence.
Porthkerry Member	Top	Erosion surface marking the local top of the preserved Jurassic succession.
Lavernock Shale Member	Top	Upward transition into mudstones with >50% limestone
St Mary’s Well Bay Member	Top	Marked by a thick limestone (the ‘Dual Bed’) at the top of the St Mary’s Well Bay Member, above which

		there is a decrease in the proportion of limestone compared to mudstone.
Rugby Member	Top	Placed at top of highest limestone of the limestone/mudstone sequence
Saltford Shale Member	Top	Placed at the base of the interbedded argillaceous limestone/mudstone succession of the Rugby Member
Wilmcote Member	Top	Placed at the top of the highest limestone, at the transition to the mudstone dominated succession of the Saltford Shale

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