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A Newell

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Gypsum nodules within the Red Rock Member of the Wessex Basin, Branscombe, Devon

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Contents

Contents ... v

Foreward and summary ... xii

1 Introduction ... 13
- 1.1 Background to the Report Series ... 13
- 1.2 Report structure and associated datasets ... 13
- 1.3 Methods ... 14

2 Mercia Mudstone Group: geological background ... 17
- 2.1 Overview ... 17
- 2.2 Outcrop distribution ... 18
- 2.3 Subcrop distribution ... 18
- 2.4 lithoStratigraphy ... 18
- 2.5 Broad lithofacies associations and depositional environments ... 19
- 2.6 The MMG in the context of regional events ... 20
- 2.7 present Structure of top MMG ... 20
- 2.8 Regional thickness trends ... 21

3 Regional trends in stratigraphy ... 21
- 3.1 Wessex Basin ... 21
- 3.2 Somerset Basin to southern flanks of the Pewsey Basin ... 24
- 3.3 Eastern fringe of MMG outcrop: Pewsey Basin to IOW High ... 24
- 3.4 Worcester graben ... 25
- 3.5 English Midlands ... 26
- 3.6 Anglo-Brabant Massif (ABM) ... 27
- 3.7 southern north sea ... 28
- 3.8 East Midlands Shelf (EMS) ... 29
- 3.9 Cheshire BASIN and East Irish Sea Basin ... 31

3.10 Summary and conclusions ... 33

List of figures

Figure 1 Map showing onshore and offshore outcrop of Mercia Mudstone Group, major faults, basins/highs and distribution of boreholes used in the study. Faults are a sub-selection from BGS (1996). OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024. ... 36

Figure 2 Map showing the distribution of borehole correlation panels (thick black lines) illustrated in the report relative to MMG outcrop and subcrop limits. OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024. ... 37

Figure 3 Sketch palaeogeographical map for the middle and late Triassic when a vast complex of terrestrial, paralic and shallow marine environments occupied a central position within the Pangean Supercontinent between the Boreal Sea and Tethys Ocean. Rift basins were interspersed with broad basement highs which where progressively onlapped during the Triassic. Summer monsoons from the Tethys Ocean periodically brought moisture into the hot arid interior. Marine gateways between remnant Variscan uplands allowed incursion of marine waters into the Germanic Basin where marine carbonates of the Muschelkalk were deposited. Coastlines created using QGIS and GPlates Web Map Service at time step

240Ma using the MULLER2019 model. https://gws.gplates.org/reconstruct/coastlines/?time=140&model=MULLER2019 38

Figure 4 Generalised chronostratigraphy of the MMG in different locations across the UK. Note the diachronous base of the MMG with younging toward the south where sandy fluvial facies of the Sherwood Sandstone Group persisted into the Ladinian. Coloured double-headed arrows show the revised/current lithostratigraphical scheme of Howard et al. (2008) which recognises two main mudstone intervals below (Sidmouth Mudstone Formation) and above (Branscombe Mudstone Formation) the Arden Sandstone Formation (where this is present). Where thick Ladinian-Carnian halites replace the Arden Sandstone these are included in the Sidmouth Mudstone Formation. The Tarporley Siltstone Formation and Blue Anchor Formation are comparatively thin transitional units into the Sherwood Sandstone Group (below) and the Penarth Group (above). In the Southern North Sea, strata equivalent to the onshore MMG are termed the Haisborough Group which is divided into three formations. SSG=Sherwood Sandstone Group, NH=Northwich Halite, DH=Droitwich Halite, ASF=Arden Sandstone Formation. 39

Figure 5 Comparison of the MMG lithostratigraphical schemes of Howard et al. (2008) and Gallois (2001) with the modified version developed and used in the compilation of this report. The applicability of this scheme to the East Irish Sea Basin, East Midlands Shelf and Southern North Sea is debatable where the stratigraphy is modified by, for example, additional thick units of halite. 40

Figure 6 Comparative MMG stratigraphy across four basins. Correlation lines do not imply physical continuity of units or time-equivalence but emphasise the general tri-partite subdivision of the MMG into a lower-part (Anisian) dominated by mudstone; a mid-part (Ladinian-Carnian) dominated by halite (in basin centres) and an upper-part (Norian) dominated by mudstone and anhydrite/gypsum. The Norian mudstones (Triton Formation/Branscombe Mudstone Formation) that cap the MMG are relatively thin but cover a stage of anomalously long duration (18.9 Ma). Rapid rates of deposition in pre-Norian MMG strata probably reflect syndepositional extensional tectonics and high rates of evaporite precipitation. Chronostratigraphy is based on various sources and should be regarded as uncertain and approximate. 41

Figure 7 Top and base of the MMG in Devon. The top near Seaton [SY266895] (above) is a transition from red and green coloured mudstones of the uppermost Branscombe Mudstone Formation, through the grey carbonates and mudstones of the Blue Anchor Formation into dark grey pyritic mudstones of the lowermost Penarth Group (not present in this exposure). The base seen near Sidmouth [SY129873] is a transition from the sandstones of the Otter Sandstone Formation into red mudstones of the MMG. These uppermost Otter Sandstone Formation comprise muddy, micaeous meandering channel deposits (Newell, 2018a) which are probably Tarporley Siltstone equivalent. 42

Figure 8 Towering cliffs (around 160 m high) of Sidmouth Mudstone Formation at Salcombe Hill near Sidmouth in Devon [SY136874]. The reddish brown mudstones are thickly bedded and largely structureless. The hilltop is formed by Cretaceous Upper Greensand lying unconformably on Triassic MMG. 43

Figure 9 Photograph above shows the base of the Dunscombe Mudstone Formation (as used in this report) at Higher Dunscombe Cliff in south Devon (SY152876). The white arrow marks a change from relatively homogeneous red brown mudstones into red brown and grey mottled mudstones. Gypsum becomes common and laminated/cross-laminated siltstone and sandstone occurs. Grey laminated mudstones are developed. Sandstones may reach several metres thick and show cross-bedding, convolute bedding and bioturbation (left) suggesting deposition in freshwater lacustrine deltas during the Carnian Pluvial Episode (Porter and Gallois, 2008). See the following Figure 10 for an additional view of this cliff and further explanation. 44

Figure 10 Virtual outcrop model (VOM) constructed from drone imagery of Higher Dunscombe Cliff showing the modified base of the Dunscombe Mudstone Formation as used in this report. This includes 27 m of grey and reddish brown mudstones (sometimes brecciated), gypsum and cross-laminated sandstones and siltstones assigned to the Little Weston

Mustone Member of Gallois (2001). These rest sharply on the massive red brown mudstones of the Sidmouth Mudstone Formation. The Lincombe Member sandstone body is 47 m above this horizon. Thicknesses are measured from the VOM. 45

Figure 11 Red brown structureless mudstones of the Branscombe Mudstone Formation overlying the 'Red Rock Gypsum Member' at Branscombe Beach, south Devon [SY202881]. Masses of nodular gypsum (primary texture) are connected by veins of fibrous gypsum probably formed as natural hydraulic fractures a result of overpressure in the low permeability mudstones by tectonic compression (and possible anhydrite hydration) during basin inversion and uplift (Meng et al., 2017). 46

Figure 12 The main facies associations found in the Mercia Mudstone Group with snippets showing typical gamma-ray (left track) and sonic transit time (right track) responses......... 47

Figure 13 Summary of major events in the Germanic Middle and Late Triassic (Bachmann et al., 2010b) as a context for understanding controls on the UK MMG/Haisborough Group. UK sequences illustrated using boreholes from the East Midlands Shelf and Sole Pit Basin. Periodically marine conditions of the 'Muschelkalk' were replaced by deltaic, hypersaline and nonmarine environments of the Ladinian-Norian 'Keuper'. 48

Figure 14 Structure map on the top of the MMG interpolated from borehole data whose locations are shown by a black circle. Only areas with a cover of Penarth Group and younger Jurassic rocks have been gridded. MMG within deep basins straddle the structural high created by the Anglo-Brabant Massif. Map uses OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024. 49

Figure 15 Map of total MMG thickness in metres. Borehole values are interpolated only where full sequences are preserved beneath Penarth Group. Thickness values are posted against borehole locations – in the East Irish Sea Basin most of these values represent erosionally-truncated MMG which accounts for the variability. The thickest MMG occurs in the north-west, with around 1300 m in the Cheshire Basin and probably a comparable (or greater) maximum thickness deposited in the East Irish Sea Basin. Thick successions (ca. 900 m) were also deposited in the Portland-Wight Basin. Note the thin to absent MMG of the Weald Basin which did not subside significantly until the Jurassic and Early Cretaceous. Map uses OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024. 50

Figure 16 Correlation between MMG type-section outcrops in south Devon (Gallois, 2001) and boreholes in the Dorset Basin, where the Dunscombe Mudstone Formation includes thick halite. The definition of the Dunscombe Mudstone Formation is extended in this report to include the Little Weston Mudstone Member of Gallois (2001). 51

Figure 17 NE to SW correlation panel across the Wessex Basin from the Cranborne-Fordingbridge High to the southern limits of the Portland-Wight Basin. Note fault control on halite distribution. The Branscombe Mudstone Formation is greatly expanded in the Winterborne-Kingston Trough. 52

Figure 18 South to north panel from southern margin of the Portland-Wight basin into the main depocentre adjacent to the Abbotsbury-Purbeck-Wight (A-P-W) Fault Zone. Thick developments of halite adjacent to the fault pass southwards into dolomitic-anhydritic muds, sands and siltstones. Note the abrupt decrease in gamma ray values at the top of the Sidmouth Mudstone Formation as this interval is entered. Note the presence of sandstones in the Branscombe Mudstone Formation in borehole 98/23 -1 probably related to the proximity of the Central English Channel High. Lithological annotations are taken from cuttings descriptions on composite logs. 53

Figure 19 South to north panel from southern margin of the Portland-Wight basin into the main depocentre adjacent to the Abbotsbury-Purbeck-Wight (A-P-W) Fault Zone. Thick developments of halite adjacent to the fault at Portland show rapid thinning (across a fault) to the south in 97/19 -1. Further south in 97/24 -1A the lateral equivalent of the Dorset Halite includes sandstones and anhydritic or calcareous mudstones. Note the presence of micaeous sandstones in the Sidmouth Mudstone Formation of 97/24 -1A and a well-developed anhydrite marker in the Branscombe Mudstone Formation, a correlative of the Red Rock Gypsum Member at outcrop (see Figure 10). 54

Figure 20 West to east correlation panel in the Portland-Wight Basin. Thick halites (of variable thickness) occur with the depocentre of the Portland-Wight Basin adjacent to the Abbotsbury-Purbeck-Wight (A-P-W) Fault Zone. Eastward the Dorset Halite correlates with dolomitic siltstones interbedded with sandstones and anhydritic mudstone in 98/16-1 and 98/18-1. Closer to the basin margin in 99/16-1 the MMG becomes dominated by sandstones and breccias. 55

Figure 21 West-East panel along the axis of the Winterborne-Kingston Trough and stepping onto the Cranborne-Fordingbridge High. Halites are present within the graben structure at Mappowder and Winterborne Kingston. These pass laterally into sandstones on the Cranborne-Fordingbridge High at Hurn. The Red Rock Gypsum Member is a strongly developed log marker consisting of anhydrite (at depth) in a mudstone matrix with dolomite and gypsum. In Mappowder and Winterborne Kingston, this anhydrite marker is overlain by a 70 m thick unit of hard blocky siltstones with much fine angular quartz (possible loess deposits). This unit forms a prominent 'bench' on the gamma-ray log with an apparently sharp change into overlying claystones (corresponding to the top of Lott Unit D (Lott et al., 1982)). 56

Figure 22 West to east correlation panel from the Dorset Basin onto the South Dorset High showing progressive thinning of the MMG. The Sidmouth Mudstone is a remarkably uniform silty mudstone despite thinning. Low gamma-ray spikes at the top are associated with white, hard limestones (interpreted as calcrete) in West Compton 1; coarse, subrounded sand grains in Nettlecombe 1; and halite in Coombe Keynes 1 The Dunscombe Mudstone Formation thins eastward and passes from halite into mudstones with anhydrite, dolomite and sandstone. In the Branscombe Mudstone, anhydritic silty mudstones occur above and below a well-developed anhydrite marker bed. In West Compton there is evidence of halite above and below the anhydrite marker. 57

Figure 23 Correlation panel from Burton Row in the Somerset Basin toward Stockbridge 1, south of the Pewsey Basin. In the Somerset Basin, the Sidmouth Mudstone is a thick red silty claystone/siltstone which shows a progressive upward decrease in gamma-ray value into evaporitic siltstones at the top (Whitaker and Green, 1983). The Dunscombe Mudstone (Somerset Halite) is composed of four main halite intervals which are thin relative to those in the Portland-Wight Basin. Eastwards, correlative Dunscombe Mudstone comprises anhydritic mudstone whose main distinguishing feature is a high sonic transit time. The Branscombe Mudstone is a succession of red mudstones, siltstones and sandstones split into two parts by the Red Rock Gypsum. This is strongly developed in the Yarnbury 1 borehole, less so in Burton Row. In the lower part of the Branscombe Mudstone, dolomitic contorted siltstones in the Burton Row and sandstones in Yarnbury 1 are likely correlatives of the Carnian North Curry (Arden) Sandstone seen at outcrop (Dawson et al., 2022). In the upper part of the Branscome Mudstone, the 'gamma-ray-maximum' marker seen to the south is clearly seen in Goodworth 1.. 58

Figure 24 North-south correlation panel toward the eastern limits of the MMG subcrop from Goodworth 1 to Wilmingham 1 on the Isle of Wight. Here individual MMG formations start to loose clear identity. The Sidmouth Mudstone is thin relative to basinal settings but can still be recognised as a blocky mudstone or siltstone with a uniform sonic travel time and a relatively high, upward decreasing gamma-ray response (e.g. see Wilmingham 1). The Dunscombe Mudstone is subtlety marked by the appearance of dolomites, anhydrite and sandstones. Gamma ray and sonic logs may show slightly greater serration because of the heterogeneity. The slow sonic zone that distinguishes the Dunscombe Mudstone in Goodworth 1 becomes more difficult to recognise southwards. The main marker within the Branscombe Mudstone (and the MMG as a whole) is formed by the 'Red Rock Gypsum' (an anhydrite at depth). Above this anhydrite marker the Branscombe Mudstone shows the widely-developed pattern of upward increasing gamma-ray to a maxima (GR Max), followed by an upward decrease toward the base of the Blue Anchor Formation. Note the considerable expansion of the Branscombe Mudstone interval (particularly below GR Max) in the Wilmingham 1 borehole on the Isle of Wight, possibly reflecting eastward propagation of the Winterborne-Kingston Trough (WKT). 59

Figure 25 South to north section along the axis of the Worcester Graben (Sherbourne 1 steps east of the eastern bounding fault with thinning of MMG). Note the overall thickening from south to north. In the Worcester Graben the MMG below the Blue Anchor Formation was conventionally divided into 3 main parts: the Lower Keuper Marl, Keuper Saliferous Beds and the Upper Keuper Marl (Poole and Williams, 1981). This was later revised into two main parts (Eldersfield and Twyning Mudstone) separated by the Arden Sandstone (Barclay et al., 1997). A three-part subdivision is suggested by the sonic log. As seen elsewhere, the Sidmouth Mudstone has a typically short transit time and a relatively high gamma-ray response. Fine serrations in the gamma-ray log probably represent an alternation of blocky red brown mudstones and fine-grained sandstones (Milroy et al., 2019). The Dunscombe Mudstone is represented an interval of high sonic transit time (from soft mudstones and evaporites) which can be correlated between boreholes. These facies are lateral correlatives of the Droitwich Halite proven in the Saleway Borehole (Poole and Williams, 1981). Caliper logs may show irregular borehole enlargement (e.g. see Guiting Power 1). The Branscombe Mudstone marks a return to low and relatively uniform sonic transit times. The anhydrite marker bed seen in Yarnbury 1 can be tracked northward to Cooles Farm 1 but becomes indistinct thereafter. The Arden Sandstone occurs in the lower part of the Branscombe Mudstone, but a sandstone identified (in the borehole record) as the Arden Sandstone appears in the Dunscombe Mudstone in the Stowell Park borehole. 60

Figure 26 Correlation from the eastern footwall of the Worcester Graben into the Triassic basin complex of the English Midlands. The Tarporley Siltstone becomes a readily identifiable unit of thin sandstones and mudstones (around 40 m thick) from the Home Farm borehole northwards. The Sidmouth Mudstone is predominantly red brown mudstone with relatively high (but finely serrated) gamma-ray response (micaeous) and uniform high sonic velocity. It thickens markedly (to 140 m) into Hanbury 1 in the Needwood Basin. The Dunscombe Mudstone is marked by a zone (around 60 m thick) of highly perturbed sonic transit time with many high (slow) values. In the cored Home Farm borehole this interval is marked by many intervals of brecciated mudstones with evaporites and thin sandstone units (Old et al., 1987). The Dunscombe Mudstone correlates with the Stafford Halite (and overlying evaporitic mudstones) in the Hanbury 1 borehole. The Arden Sandstone forms the top of the Dunscombe Mudstone Formation. The Branscombe Mudstone is thin (around 40 m) across the Moreton Morell, Home Farm and Asfordby Hydro boreholes of the English Midlands and comprises mudstones and gypsum/anhydrite generally concentrated into (often named, e.g. Tutbury Gypsum) beds toward the middle. 61

Figure 27 Correlation panel from the Worcester Graben across the northern flank of the Anglo-Brabant Massif. The MMG thins abruptly across the eastern bounding fault of the Worcester Graben between Sherbourne 1 and Upton Burford. Boreholes such as Withycombe Lane show a notably sandy development of Tarporley Siltstone equivalent strata that (lithostratigraphically) are usually included within Sherwood Sandstone Group. These include marine bivalves, ostracods and the brachiopod Lingula. Toward the east in Spalding and Wiggenhall the MMG thins and becomes conglomeratic toward the base. Inset photograph shows MMG infilling high relief topography developed on Precambrian volcanics in the area of Bardon Hill, Charnwood Forest [SK453128]. It is speculated that footwall uplift and back-tilting along the eastern flanks of the Worcester Graben may have diverted coarse clastics from the Anglo-Brabant Massif northwards rather than into the Worcester Graben.. 62

Figure 28 Correlation panel from the Anglo-Brabant Massif (ABM) into the Sole Pit Trough. Lithological notes from composite logs (cuttings). High on the ABM, near the limits of MMG onlap, it consists mainly of thin pebbly sandstones and conglomerates with some dolomitic cement. The attribution of these to the MMG is on assumed conformity to overlying Jurassic strata but there is no independent dating evidence (Lee et al., 2015). From Somerton 1, the MMG forms an eastward thickening (onlapping) wedge of mudstones and evaporites. Three thick halite bodies are developed in the Sole Pit Trough (49/21-2): the Röt Halite, Muschelkalk Halite and Keuper Halite. The lowermost two are contained with the Dowsing

Formation. The halites do not extend into 53/01-2 west of the Dowsing Fault where the Dowsing Formation consists of grey-green and red-brown mudstone and sandstone with common dolomite. The sonic velocity is serrated but high. In the Sole Pit Basin (49/21-2), the Dudgeon Formation transitions upwards from mudstone and thin halites into thick halites. On the shelf (53/01-2), mudstones with dolomite and anhydrite at the base of the Dudgeon Formation pass upwards in mudstones and dolomitic sandstones. An interval of slow sonic occurs toward the top of the Dudgeon Formation in 52/05-11. In the Sole Pit Trough, halites are sharply overlain by mudstones and anhydrites of the Triton Formation. The Keuper Anhydrite Member within the Triton Formation can be readily correlated, thinning westwards onto the shelf. 63

Figure 29 Correlation panel from the East Midlands Shelf (EMS) into the Sole Pit Basin. Note the abrupt thickening of the MMG across the Dowsing Fault Zone. The three main halites show a trend of increasingly basin-centric deposition (Cameron et al., 1992). The Röt Halite can be readily correlated from basin onto shelf. The Muschelkalk (and particularly Keuper) halites have a more restricted distribution within the Sole Pit Trough. Muschelkalk (late Anisian) equivalent strata on the EMS have been identified using biostratigraphy in Tetney Lock 1 (Geiger and Hopping, 1968). These strata occur just below an abrupt increase in sonic transit time ('sonic break') which can be correlated across the East Midlands Shelf (see Figure 29). In the absence of reliable biostratigraphy, is difficult to know how much of the MMG mudstone overlying the sonic break is representative of the Ladinian-Carnian Dudgeon Formation versus the overlying Carnian-Norian Triton Formation. The sonic break (and associated hard dolomitic limestones) could represent an interval of missing MMG when deposition shifted into the Sole Pit Basin. 64

Figure 30 Correlation panel from the Asfordby Hydo borehole to Cleethorpes 1, providing a southwest to northeast transect across the East Midlands Shelf. The log tracks show sonic transit time logs which have been clipped to the stratigraphical range of the MMG and normalised in the range [0,1]. Logs are plotted back-to-back to visually accentuate trends. The MMG shows a clear 2 part subdivision that is particularly marked in boreholes northeast from Coningsby. The 'sonic break' boundary between the two parts is marked by a thin high velocity zone of dolomite cemented sandstones and mudstones. Logs are coloured with sonic transit time with brown fast (small travel time) and green slow (large travel time). The panel is flattened on the 'sonic break'. 65

Figure 31 Correlation panel showing normalised gamma ray and sonic transit time logs across the MMG interval of the East Midlands Shelf. Inset is a cross-plot of gamma ray against sonic transit time which highlights two (overlapping) two subdivisions. The lower subdivision (grey dots) has a generally high gamma ray and low sonic transit time (fast). The upper subdivision (red dots) has a generally lower gamma ray and longer sonic transit time (slow). The 'sonic break' marker identified here occurs just above gamma-ray marker of Balchin & Ridd (1970) which is shown in Tetney Lock 1 and can be identified in most boreholes. This occurs around the Anisian-Ladinian according to dating in the Tetney Lock borehole (Geiger & Hopping, 1968) or within the Ladinian (mid Gunthorpe Formation) in the Asfordby Hydo borehole (Carney et al. 2004). 66

Figure 32 Borehole lithology information extracted from composite logs and plotted on the panel. These are a summary of cuttings descriptions with the exception of Asfordby Hydro (core). In the interval below the sonic break, micaeous sandstones in proximal (southwest) locations (the Sneinton/Tarporley Siltstone Formation) pass northeast into mudstones and dolomite. The sands appear to be diachronous/progradational and capped by hard dolomite cemented lithologies which probably corresponds with the Plains Skerry of Elliott (1961). Above the sonic break mudstones become soft, blocky and contain gypsum and/or anhydrite. The Cotgrave and Hollygate sandstones of the Edwalton Formation may represent a second progradational phase. The mudstones and anhydrite/gypsum of the Cropwell Bishop Formation caps the MMG succession. 67

Figure 33 Distribution of sedimentary features across the stratigraphy of the MMG on the East Midlands Shelf (mostly based on borehole and outcrop observations in Nottinghamshire by Elliot, 1961). Thinly laminated micaeous sandstones with ripples, mudstone clasts and salt pseudomorphs are common in the lower half. Gypsum-rich mudstone is more common in the upper half. The succession of lettered subdivisions (A-G) of the MMG recognised in boreholes by Gaunt et al. (1992) are shown on the right. These reflect the MMG in a more basinward setting around the Humber Estuary. 68

Figure 34 Correlation panel from the Cheshire Basin into the East Irish Sea Basin (EISB). In the Cheshire Basin a thick package of halite (and interbedded mudstone) occurs between the Bollin Mudstone and the Brooks Mill Mudstone. The Tarporley Siltstone forms an exceptionally thick arenaceous unit at the base. Northwards into the EISB the Tarporley Siltstone is replaced by mudstones and halites (Fylde Halite and Rossall Halite). The Blackpool Mudstone (=Bollin Mudstone) forms a remarkably consistent unit across the EISB. Together with the overlying Dowbridge Mudstone, the Blackpool Mudstone encloses a thick interval of halites and mudstones. As in the Cheshire Basin, the evaporites divide into two halite-rich intervals (Mythrop/Northwich and Preesall/Wilkesley) separated by a more mudstone-rich part. Note that this stratigraphy/correlation differs from that offered by Wilson (1990) and Jackson et al. (1997). 69

Figure 35 High resolution correlation of the Mythrop Halite across 3 boreholes in the EISB. Note that the panel is flattened (expanded/contacted to an equal thickness) on both lower and upper contacts to remove thickness variations due to structure and aid correlation. Depths on top and base markers are given in metres (different scales apply to each borehole depending on thickness). Halite-mudstone units are classified into three types (Mud=mostly mudstone; Thick Salt=mostly halite; Mixed = multiple thin interbeds of mudstone and halite). Regardless of thickness, many of the units can be correlated across large horizontal distances (distance between boreholes given in km). Descriptive statistics for bed thickness of mudstone and halite in 110/03B-6A are given in the inset table (unit is metres except count). 70

Figure 36 Extended correlation of previous figure toward Prees 1 in the Cheshire Basin where the relationship and correlation of individual halite units becomes less clear. 71

Figure 37 Correlation of the Preesall Halite, where halites are thicker and mudstones are thinner relative to the underlying Mythop Halite. Note the remarkable correlation of even thin mudstones between widely spaced boreholes in the East Irish Sea Basin. This does not extend to the Cheshire Basin (Prees 1) where the halite units appear thinner with a higher frequency of interbedded mudstone. The panel is flattened (expanded/contacted to an equal thickness) on both lower and upper contacts and different thicknesses of strata are present in each borehole. 72

List of tables

Table 1 List of markers (ordered by frequency) and key to codes 16

Table 2 List of datasets used in the modelling 17

Foreward and summary

This report forms part of the UK Stratigraphical Framework Series (UKSFS) and provides an overview of the stratigraphy of the Mercia Mudstone Group across southern UK, extending offshore into the English Channel, East Irish Sea Basin and Southern North Sea. The work is based on interpretation of borehole geophysical logs and published records of cored boreholes. The emphasis of the report is on regional structure, thickness and facies trends in the Mercia Mudstone Group, and should provide a framework for site-specific geological investigations that require understanding of this stratigraphical interval.

1 Introduction

1.1 BACKGROUND TO THE REPORT SERIES

This report on the Mercia Mudstone Group (MMG) forms part of the UK Stratigraphical Framework Series (UKSFS) which aims to generate new information on the structure, stratigraphy and facies (lithology) trends within UK bedrock geology units (formations or groups) of sedimentary origin. The emphasis of the report series is primarily (but not exclusively) on onshore UK geology and on stratigraphical trends across the entire spatial 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. (Howard et al., 2008), BGS Memoirs and in the BGS Lexicon of Named Rock Units (www.bgs.ac.uk). The findings may however prove useful in guiding future formal revisions of lithostratigraphical nomenclature and correlation.

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) 36 full-page figures at the rear. The figures have extended captions so that, to some extent, they summarize key information in the text. The text includes an overview of data sources, methods, essential (but minimal) background information on the Mercia Mudstone 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 MMG outcrop and 262 boreholes which prove the group in the subsurface (Figure 1).

Outcrop information was sourced primarily from BGS memoirs, maps and reports, and the wider published literature (see references). In addition, field visits were undertaken to key Mercia Mudstone Group outcrops in the Wessex Basin, Worcester Graben and East Midlands Shelf. Core from the East Irish Sea Basin was viewed to aid understanding of the halite bodies.

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.

Away from prospective basins (for example, on the Anglo-Brabant Massif) water boreholes and those drilled for stratigraphical research (primarily by BGS mapping programs) are important sources of information. 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 Geophysical log interpretation

Natural gamma-ray and sonic transit time 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 MMG rocks were close to surface and the borehole was cased.

Gamma-ray instruments are sensitive to changes in the natural background gamma emitted by potassium, thorium and uranium and their decay chains. In the MMG, mudstones rich in detrital mica are generally high in radioactivity because of an abundance of potassium. A suite of Mg-rich early diagenetic clay minerals (including sepiolite, palygorskite and smectite) associated with evaporitic facies in the MMG can have lower bulk gamma-ray values. Halite is readily distinguished by uniformly low gamma-ray values. Quartz-rich sandstones have variable gamma-ray responses with values intermediate between halite and mudstones.

Sonic logs record changes in the transit time of sonic waves through the rock, and as such serve as a proxy for changes in density. The sonic log is shown here to be a powerful tool for stratigraphical subdivision of the MMG, particularly in identifying intervals of weak, brecciated mudstone that appear to occur lateral to halite bodies. The sonic log is also useful for identifying key anhydrite marker beds characterised by low transit times.

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.

1.3.3 Lithological determinations from geophysical logs

Most of the borehole correlation panels in the report show gamma-ray and sonic logs that are ‘filled’ with a lithological classification. In all cases the lithology has been determined using simple cut-off values on one or both logs (see Newell et al. (2021) for a discussion of the method). The interpreted lithologies should be regarded as highly simplified versions of reality whose aim is solely to assist in the visualisation of facies trends and borehole correlation. They are not intended as a full petrophysical investigation, which normally requires a much broader suite of geophysical logs. The lithological classification of the MMG has been undertaken on a formation-by-formation basis such that in a single borehole some formations may be classified and others not, depending on the need to help demonstrate a particular geological observation.

The stratigraphy of the MMG sometimes consists of thinly interbedded or intermixed lithologies (e.g. halite and mudstone). The signal received from a geophysical log (whose vertical resolution may only be 0.3-1.0 m) will therefore be a convolution of different lithologies that might be difficult to interpret. Log interpretations always were 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.

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 (Figure 2) are flattened on selected stratigraphical horizons rather than plotting at true depth relative to Ordnance Datum. Scales on the correlation panels are in metres and show positive and negative depths away from the flattened horizon which is set at zero. Measured depths (in metres below borehole datum) which can be directly related to original borehole descriptions (e.g. composite logs) are shown on most stratigraphical markers.

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 890 markers were picked.

Table 1 List of markers (ordered by frequency) and key to codes

MARKER	FREQUENCY	MARKER_BELOW	MARKER_ABOVE	TYPE	UNIT_NAME_BELOW	UNIT_NAME_ABOVE
MMG_PNG_N	130	MMG	PNG	N	Mercia Mudstone Group	Penarth Group
SSG_MMG_N	115	SSG	MMG	N	Sherwood Sandstone Group	Mercia Mudstone Group
BCMU_BAN_N	69	BCMU	BAN	N	Branscombe Mudstone Formation	Blue Anchor Formation
SIM_DUM_N	57	SIM	DUM	N	Sidmouth Mudstone Formation	Dunscombe Mudstone Formation
DUM_BCMU_N	55	DUM	BCMU	N	Dunscombe Mudstone Formation	Branscombe Mudstone Formation
BAN_PNG_N	38	BAN	PNG	N	Blue Anchor Formation	Penarth Group
OS_SIM_N	34	OS	SIM	N	Otter Sandstone Formation	Sidmouth Mudstone Formation
OMS_MMG_N	15	OMS	MMG	N	Ormskirk Sandstone Formation	Mercia Mudstone Group
BNS_DWDL_N	12	BNS	DWDL	N	Bunter Sandstone Formation	Dowsing Formation
BLMU_MSA_N	11	BLMU	MSA	N	Blackpool Mudstone Member	Mythop Halite Member
MSA_CLMU_N	11	MSA	CLMU	N	Mythop Halite Member	Cleveleys Mudstone Member
RSA_BLMU_N	11	RSA	BLMU	N	Rossall Halite Member	Blackpool Mudstone Member
BMS_MMG_N	10	BMS	MMG	N	Bromsgrove Sandstone Formation	Mercia Mudstone Group
TPSF_RDCF_N	10	TPSF	RDCF	N	Tarporley Siltstone Formation	Radcliffe Member
AS	9	AS	AS	N	Arden Sandstone Formation	Arden Sandstone Formation
CLMU_PRSA_N	8	CLMU	PRSA	N	Cleveleys Mudstone Member	Preesall Halite Member
TPSF_SIM_N	8	TPSF	SIM	N	Tarporley Siltstone Formation	Sidmouth Mudstone Formation
ANMU_RSA_N	6	ANMU	RSA	N	Andsell Mudstone Member	Rossall Halite Member
ORS_MMG_U	6	ORS	MMG	U	Old Red Sandstone Supergroup	Mercia Mudstone Group
CARB_SSG_U	5	CARB	SSG	U	Carboniferous Rocks (Undifferentiated)	Sherwood Sandstone Group
DEV_MMG_U	5	DEV	MMG	U	Devonian Rocks (Undifferentiated)	Mercia Mudstone Group
DGSL_TTHY_N	5	DGSL	TTHY	N	Dudgeon Formation	Triton Formation
FYHA_ANMU_N	5	FYHA	ANMU	N	Fylde Halite Member	Andsell Mudstone Member
HAI_PNG_N	5	HAI	PNG	N	Haisborough Group	Penarth Group
PRSA_DOMU_N	5	PRSA	DOMU	N	Preesall Halite Member	Dowbridge Mudstone Formation
BNS_HAI_N	4	BNS	HAI	N	Bunter Sandstone Formation	Haisborough Group
DEV_SIM_U	4	DEV	SIM	U	Devonian Rocks (Undifferentiated)	Sidmouth Mudstone Formation
DWDL_DGSL_N	4	DWDL	DGSL	N	Dowsing Formation	Dudgeon Formation
MMG_LI_N	4	MMG	LI	N	Mercia Mudstone Group	Lias Group
ORD_MMG_U	4	ORD	MMG	U	Ordovician Rocks (Undifferentiated)	Mercia Mudstone Group
APRZ_MMG_U	3	APRZ	MMG	U	Proterozoic To Palaeozoic Rocks (Undifferentiated)	Mercia Mudstone Group
CL_MMG_U	3	CL	MMG	U	Carboniferous Limestone Supergroup	Mercia Mudstone Group
HBSF_TPSF_N	3	HBSF	TPSF	N	Helsby Sandstone Formation	Tarporley Siltstone Formation
TTHY_PNG_N	3	TTHY	PNG	N	Triton Formation	Penarth Group
CL_SIM_U	2	CL	SIM	U	Carboniferous Limestone Supergroup	Sidmouth Mudstone Formation
SAL_MMG_U	2	SAL	MMG	U	Salop Formation	Mercia Mudstone Group
WHT_BMI_N	2	WHT	BMI	N	Wilkesley Halite Member	Brooks Mill Mudstone Formation
BMI_PNG_N	1	BMI	PNG	N	Brooks Mill Mudstone Formation	Penarth Group
BOM_NWHF_N	1	BOM	NWHF	N	Bollin Mudstone Member	Northwich Halite Member
BYM_WHT_N	1	BYM	WHT	N	Byley Mudstone Member	Wilkesley Halite Member
CL_BCMU_U	1	CL	BCMU	U	Carboniferous Limestone Supergroup	Branscombe Mudstone Formation
COME_MMG_N	1	COME	MMG	N	Coal Measures Supergroup	Mercia Mudstone Group
LCM_MMG_U	1	LCM	MMG	U	Lower Coal Measures Formation	Mercia Mudstone Group
NWHF_BYM_N	1	NWHF	BYM	N	Northwich Halite Member	Byley Mudstone Member
ORS_TRIA_U	1	ORS	TRIA	U	Old Red Sandstone Supergroup	Triassic Rocks (Undifferentiated)
PNG_LI_N	1	PNG	LI	N	Penarth Group	Lias Group
SSG_MMG_F	1	SSG	MMG	F	Sherwood Sandstone Group	Mercia Mudstone Group
SSG_STAH_N	1	SSG	STAH	N	Sherwood Sandstone Group	Stanah Member
STAH_FYHA_N	1	STAH	FYHA	N	Stanah Member	Fylde Halite Member
TCB_MMG_U	1	TCB	MMG	U	Tremadoc Beds	Mercia Mudstone Group
TEG_TRIA_U	1	TEG	TRIA	U	Temeside Group	Triassic Rocks (Undifferentiated)
TRIA_PNG_N	1	TRIA	PNG	N	Triassic Rocks (Undifferentiated)	Penarth Group
UDEV_MMG_U	1	UDEV	MMG	U	Upper Devonian Rocks (Undifferentiated)	Mercia Mudstone Group
VOLC_TRIA_U	1	VOLC	TRIA	U	Unnamed Volcanic Rocks Of Any Age	Triassic Rocks (Undifferentiated)
DHA_BCMU_N	16	DHA	BCMU	N	Dorset Halite	Branscombe Mudstone Formation
PERM_SIM_U	1	PERM	SIM	U	Permian (Undifferentiated)	Sidmouth Mudstone Formation
MMG_TRUNCATED	18	MMG	TRUNCATED	U	Mercia Mudstone Group	Truncated
SIM_DHA_N	17	SIM	DHA	N	Sidmouth Mudstone Formation	Dorset Halite

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 which are listed in 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 Mercia Mudstone 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 Mesozoic 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 MMG (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 Mercia Mudstone Group: geological background

2.1 OVERVIEW

The MMG of the UK is a Middle to Upper Triassic succession of mudstones, evaporites, sandstones, dolomites and minor breccia/conglomerate that (onshore) ranges up to around 1300 m thick. The group is predominantly (but not exclusively) a continental red-bed deposit sandwiched between the coarser fluvial deposits of the Sherwood Sandstone Group and the paralic to marine deposits of the Penarth and Lias groups. Correlation of the MMG in different parts of the UK is primarily on lithological criteria with sporadic control provided by sparse macrofossils and palynoflora (Warrington and Ivimey-Cook, 1992).

The depositional environment of the MMG has been the subject of long debate, particularly on the relative influence of continental versus marine processes on halite precipitation (Taylor, 1983; Wilson, 1993; Wright and Sandler, 1994). This remains largely unresolved and the MMG seems to have been deposited in a hybrid setting that has no real modern analogue. During the Triassic, continents were amalgamated (but in the early stages of rifting) and a vast system of low gradient mudflats, saline pans, alluvial plains and sabkhas lay between the Tethys Ocean and the Boreal Sea (Figure 3). The climate was predominantly dry and hot at the palaeolatitude of the UK, but with seasonal monsoons (and marine flooding) emanating from the Tethys Ocean (Bachmann et al., 2010b; Geluk et al., 2018). Shallow saline water bodies (from either a marine or terrestrial source) may have been mosaiced and stratified with freshwater wedges formed by runoff along the flanks of broad, low relief areas of exposed land (Allison and Wright, 2005). Only some of the MMG is the result of subaqueous deposition, because there is much evidence that wind-blown silt in the form of angular quartz shards or clay aggregates are a substantial dryland component of the MMG (Jefferson et al., 2002; Mao et al., 2021). Phases of extensional tectonics and rifting, progressive onlap of basement highs, sea-level change, and major climatic perturbations such as the Carnian Pluvial Episode (Simms and Ruffell, 2018) all played a part in introducing stratigraphical variability into the MMG (Hounslow and Ruffell, 2006).

2.2 OUTCROP DISTRIBUTION

Outcrop of the MMG extends as a irregular, near-continuous belt from Devon to Yorkshire (Figure 1). Broad areas of outcrop occur around Bristol and the Mendip Hills, extending westwards into south Wales and the Bristol Channel. Extensive outcrops of MMG occur in the English Midlands, from where the outcrop branches northwest into the Cheshire Basin and East Irish Sea Basin, and northeast onto the East Midlands Shelf and Southern North Sea. Small seafloor outcrops of MMG occur within the inverted Sole Pit Trough of the Southern North Sea.

2.3 SUBCROP DISTRIBUTION

From the main Devon-Yorkshire outcrop tract, the MMG generally dips southeast beneath a younger Mesozoic and Cenozoic cover. Boreholes show that it onlaps the flanks of the Anglo-Brabant Massif (Pharaoh, 2018) and was not deposited across a large part of this high (Figure 1), or much of the Weald Basin immediately to the south, which only became a rapidly subsiding depocentre later in the Jurassic (Newell et al., 2024) and Early Cretaceous (Cripps et al., 2024).

2.4 LITHOSTRATIGRAPHY

The MMG has a complex lithostratigraphy with an abundance of local named subdivisions in different parts of the UK and onshore-offshore variation that even exists at group level (Warrington et al., 1980) (Figure 4).

Driven by the needs of modern Geographical Information Systems (GIS) delivery of geological data, Howard et al. (2008) proposed a unifying lithostratigraphical scheme for the MMG. This was partially based on the work of Gallois (2001) on outcrop in south Devon (Figure 5).

Howard et al. (2008) rationalise the onshore lithostratigraphy of the MMG into five main formations which in ascending order are: the Tarporley Siltstone, Sidmouth Mudstone, Arden Sandstone, Branscombe Mudstone and Blue Anchor (Figure 5). Not all of these formations are present everywhere and under this scheme their lithological composition may vary considerably. For example, the Sidmouth Mudstone Formation may be predominantly mudstone or locally encompass thick halite deposits (Figure 4).

The key difference between this scheme and that of Gallois (2001) was the abandonment of the Dunscombe Mudstone Formation, which covered an array of distinctive fluvial, freshwater lacustrine and salina facies which were widely developed during the Carnian Pluvial Episode (Figure 5).

The lithostratigraphical scheme developed and used in this report represents a variation on the schemes of Howard et al. (2008) and Gallois (2001). The 'Dunscombe Mudstone Formation' is reinstated but covers a slightly larger stratigraphic range than that defined by Gallois (2001). The report has not sought to introduce another variant on MMG lithostratigraphy but this has proven necessary for clear communication of the findings of the work. In many boreholes, the Dunscombe Mudstone is an essential container to carry the heterolithic assemblage of red-grey mudstones, evaporites and sandstone that dominate mid-parts of the MMG. It also allows the Sidmouth Mudstone Formation to refer only to a coherent body of red-brown mudstones and siltstones which can be recognised toward the base of the MMG across most basins (Figure 6). More details are provided in following sections, but the units used (informally) in this report are summarised below in ascending order:

Tarporley Siltstone Formation a fine-grained micaeous sandstone at the base of the MMG, often bioturbated and interbedded with mudstone. A sometimes problematic unit because as the grain-size and proportion of sandstone increase (typically toward southern source areas) it switches from the lowermost Mercia Mudstone Group to the uppermost Sherwood Sandstone Group (Figure 7).

Sidmouth Mudstone Formation a cohesive body of red brown, thick-bedded, generally structureless mudstone (Figure 8). It may contain regularly spaced dolomitic siltstones and minor gypsum/anhydrite and typically has an extremely uniform (but finely serrated) gamma-ray and sonic log response (Figure 6).

Dunscombe Mudstone Formation an extremely heterolithic unit that here corresponds to the combined Dunscombe Mudstone Formation and Little Weston Mudstone Member of Gallois (2001) (Figure 9 and Figure 10). In basin depocentres it is often dominated by interbedded halite and mudstone (Figure 6). On basin margins, it passes into reddish brown and grey mudstones which are often laminated or highly brecciated, cross-laminated siltstones and fine-grained, cross-bedded sandstones, mapped in the Midlands as the Arden Sandstone Formation (Figure 9). It may contain thin intervals of dark grey mudstone and a high proportion of swelling clays. Halite voids/pseudomorphs and gypsum/anhydrite are often present. Halite bodies have characteristically low gamma-ray and uniform sonic log responses. Laterally equivalent evaporitic-brecciated mudstones have highly variable gamma-ray signatures and sonic logs indicate slow velocities. Caliper logs often indicate intervals of wash-out, possibly from weak brecciated rock where salt has been removed syn- or post depositionally. This unit appears to have major geotechnical differences from the Sidmouth Mudstone Formation.

Branscombe Mudstone Formation a cohesive unit of reddish brown massive mudstone and dolomitic siltstone. May contain thin sandstones in the lower half. A widely-correlative gypsum/anhydrite marker (including the Red Rock Gypsum, Tutbury and Newark Gypsum, Keuper Anhydrite) occurs toward the middle of the formation (Figure 11).

Blue Anchor Formation predominately grey mudstones and dolomites, often laminated (Figure 7). Can be preceded by an interval of striped red and grey interbedded mudstone (Haven Cliff Mudstone Member of Gallois (2001)). Overlain by pyritic black shales of the Westbury Formation (Penarth Group), it could be argued that the Blue Anchor Formation has more sedimentological affinity with the Penarth Group than the Mercia Mudstone Group. Alternating carbonates and mudstones produce a distinctive highly serrated gamma ray and sonic trace.

The utility of these formations breaks down somewhat in the East Irish Sea Basin and Southern North Sea where thick halites are developed throughout the MMG and local stratigraphical schemes are possibly preferable. In the southern North Sea, the Haisborough Group is the direct equivalent of the MMG and is conventionally divided into three formations, Dowsing Formation, Dudgeon Formation and Triton Formation (Figure 6). These broadly mirror the lithological trends of the MMG in having a central halite-rich unit sandwiched between mudstones above and below. In the southern North Sea, a basal halite unit (Röt Halite) also occurs which is a lower Anisian correlative of the Tarporley Siltstone Formation. Halites also occur at this level in the East Irish Sea Basin. In the Cheshire Basin, and East Irish Sea Basin, the MMG stratigraphy is similar to elsewhere but separate nomenclature has evolved (Figure 6).

2.5 BROAD LITHOFACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

Figure 12 summarises the major lithofacies associations of the MMG and their typical log responses. As recognised elsewhere these broadly subdivide into ‘dry’ and ‘wet’ environments.

Thick uniform intervals of reddish brown mudstone and siltstone probably represent significant inputs of wind-blown dust into (at least periodically) dry basins (Arthurton, 1980; Jefferson et al., 2002; Mao et al., 2021). These facies reach peak development in the Sidmouth (Anisian-Ladinian) Formation.

Laminated reddish brown and grey coloured mudstones, ripple cross-laminated and cross-bedded sandstones represent sub-aqueous deposition. Common bioturbation indicates the local development of freshwater lakes (Porter and Gallois, 2008). These facies reach a peak in the Dunscombe Mudstone Formation, which was deposited during the wet climatic perturbation of the Carnian Pluvial Episode (Simms and Ruffell, 2018).

Halite was precipitated within shallow salt-lakes, usually developed in rapidly subsiding faulted depocentres where subsidence outpaced clastic infill and brines were supplied by marine flooding/aerosols or continental sources, which may have included reworked older evaporites

(Arthurton, 1980; Taylor, 1983). Halite intervals occur throughout the lower part of the MMG but typically reach peak development (in terms of unit/bed thickness and purity) in the Carnian (Figure 6).

Calcite, dolomite, gypsum/anhydrite and halite also precipitated within the sediment pile from saturated groundwaters at shallow depths, replacing and displacing the matrix (Spötl and Wright, 1992). Analogous to the trends recognised by Ortí et al. (2017) in the Triassic evaporites of Iberia, muddy sabkha-type environments appeared to have formed broad aprons around more localised salt-lakes.

Fluvial sandstones, conglomerates and breccias were deposited adjacent (and across) exposed Palaeozoic massifs.

2.6 THE MMG IN THE CONTEXT OF REGIONAL EVENTS

The regional events surrounding deposition of the MMG are easier to decipher in the Germanic Basin where the Muschelkalk carbonates clearly identify episodes of Tethyan marine inundation (Bachmann et al., 2010a). Figure 13 summarises some of the key information that can be translated across to successions in eastern England.

The Anisian 'Muschelkalk' represents peak marine influence in the Germanic Basin. This starts with the Röt Halite which can be traced onto the East Midlands Shelf and correlated beyond, into the English Midlands, using evidence (e.g. presence of Lingula) for marine conditions in the Tarporley Siltstone Formation (Warrington and Pollard, 2021). The Lower, Middle and Upper Muschelkalk record oscillating marine and non-marine conditions, with thick salt bodies such as the Muschelkalk Halite forming when tectonics and eustatic falls in sea-level combined to restrict Tethyan water exchange converting the southern North Sea into a salina (Bachmann et al., 2010b).

In the Germanic Basin, marine conditions of the Muschelkalk were replaced by deltaic, hypersaline and nonmarine environments of the Keuper Group in the Ladinian. Extrapolating this to the MMG would suggest that the bulk of the post-Anisian strata (including thick Carnian salt deposits) were deposited with minimal marine influence under sabkha or playa conditions. Across NW Europe, the Carnian was a very active phase of extensional tectonics and the thickness and volume of accumulated halite may relate more to the development of many long-lived fault-bounded depressions than greater marine influence (Arthurton, 1980).

The Norian Arnstadt Formation of the Germanic Basin is interpreted as a post-rift cover that drapes across earlier syn-rift deposits (Bachmann et al., 2010b). It follows that Norian strata (Triton Formation, Branscombe Mudstone, Brooks Mill Mudstone and Dowbridge Mudstone) are some of the most uniform and readily correlative units in the MMG. Marker beds of anhydrite (or gypsum) within these Norian strata appear to have remarkable lateral continuity.

2.7 PRESENT STRUCTURE OF TOP MMG

The present structure on the top of the MMG (where preserved beneath Penarth Group) is shown in Figure 14. It reflects the combined effects of Triassic (and younger) episodes of basin subsidence with major episodes of Cretaceous and Cenozoic uplift and erosion which acted both regionally and locally (Holford et al., 2005). Regional uplift was particularly focussed in and around the East Irish Sea Basin where the MMG is truncated at rock head over large areas.

MMG occurs at greatest depth (>2 km) in the Weald Basin and in the Portland-Wight Basin. From these basins it generally becomes shallower toward outcrop in the west, with local deeper pockets in the Winterborne Kingston Trough and Pewsey Basin. The Quantock-Cranborne-Isle of Wight High cuts diagonally across southern England (Figure 14)

In the Worcester Graben the top of the MMG increases in depth from north to south. MMG occurs at shallow depth across the Anglo-Brabant Massif before starting a steady eastward descent into offshore regions of East Midlands Shelf. MMG occurs at depth within the Cleveland Basin.

2.8 REGIONAL THICKNESS TRENDS

Figure 15 shows a map where the total thickness of the MMG has been computed from borehole information. Borehole thickness values have been gridded and interpolated where the 'full' MMG succession is present beneath Penarth Group. Thickness values are posted against borehole locations (but not gridded) where the top of the MMG is truncated (e.g. in the Midlands and East Irish Sea Basin).

Within the studied borehole set, the greatest thickness of MMG onshore is found in the Prees 1 borehole in the Cheshire Basin (1341 m). Further north, the East Irish Sea Basin contains MMG that locally reaches or exceeds 2 km thick, the majority of boreholes here are erosively truncated (and unconformably overlain by Quaternary deposits) at various levels with the MMG.

Deposits of MMG in the range 500-1000 m occur within the Portland-Wight Basin and the Winterborne-Kingston Trough which both lie within the composite Wessex Basin. This area is bounded to the northeast by Quantock-Cranborne-Isle of Wight High where the MMG is generally <200 m.

The Worcester-Pewsey basins form a broadly contiguous north-south trending belt of MMG which ranges up to 450 m thick. From the Pewsey Basin the MMG thins rapidly to east. The Weald Basin, which became a rapidly subsiding depocentre in the Jurassic and early Cretaceous, had not yet developed.

The MMG thins across the northern flank of the Anglo-Brabant Massif where it onlaps Palaeozoic and older rocks. It is entirely absent from large parts of this long-lived basement high whose nucleus was created by subduction-related magmatism in Ediacaran time and was little affected by later crustal extension (Pharaoh, 2018).

Across the East Midlands Shelf the MMG maintains a reasonably constant thickness in the range 200-250 m. This thickness increases rapidly to around 800 m or more across the Dowsing Fault Zone into the Sole Pit Trough where thick evaporites occur in the Late Triassic deposits (Cameron et al., 1992).

3 Regional trends in stratigraphy

3.1 WESSEX BASIN

The 'Wessex Basin' is a composite structure that includes two main depocentres southwest of the Quantock-Cranborne-Isle of Wight High: the linear graben of the Winterborne-Kingston Trough and the much larger Portland-Wight Basin which extends across a large part of the English Channel to the south of the Purbeck-Wight Fault Zone (Figure 14).

The Wessex Basin includes the most continuously exposed Middle and Late Triassic succession in northwest Europe in south Devon (Gallois, 2001) where the succession is around half as thick compared to the main depocentre under the Isle of Portland. The outcrop lacks the thick halite deposits present in basinal areas to the east but provides informative exposures of coeval facies developed at basin margins (Figure 16).

The stratigraphy of the MMG in the Wessex Basin is essentially a sandwich of halite-rich facies (and their basin-margin lateral equivalents) between two intervals of relatively homogeneous red brown mudstone. Figures 15-21 provide a series of borehole correlation panels which detail vertical and lateral trends in MMG stratigraphy. These are discussed below under formation headings.

3.1.1 Tarporley Siltstone Formation

A sandy facies is not generally included at the base of the MMG in the Wessex Basin. The shift from the Sherwood Sandstone Group (Otter Sandstone Formation) is generally abrupt both at outcrop (Figure 7) and in *some* boreholes where gamma-ray values increase sharply at the base of the MMG (Figure 16).

The precise boundary between the SSG and the MMG is not always clear however, and evidence from both outcrop and boreholes points toward a candidate Tarporley Siltstone equivalent. In borehole geophysical logs the top of the Sherwood Sandstone is often marked by a distinct interval of relatively high and serrated gamma-ray response that contrasts with the lower, uniform values below (Figure 17). At outcrop, fine-grained micaeous sandstone interbedded with mudstone occurs at the top of the Otter Sandstone Formation and were deposited in a meandering channel-floodplain setting which contrasts with the underlying Otter Sandstone Formation (amalgamated braid-plain facies) from which they are separated by an erosion surface (Newell, 2018a). More work is required to understand the relationship between this unit and the Tarporley Siltstone further to the north.

3.1.2 Sidmouth Mudstone Formation

The Sidmouth Mudstone Formation forms the base of the MMG in the Wessex Basin and as used here extends to the base of Little Weston Mudstone at outcrop (Gallois, 2001) (Figure 5). It is an mostly an exceptionally monotonous succession of structureless red mudstones that form large (and unstable) cliffs to the east of Sidmouth (Figure 8). The mudstones are generally silty and the presence of siltstones and sandy siltstones is frequently mentioned in cuttings descriptions on borehole composite logs. Outsize rounded quartz grains are sometimes mentioned in cuttings descriptions supporting the conclusion that much of the Sidmouth Mudstone Formation is of aeolian (loessic) origin (Mao et al., 2021). Nodular gypsum and anhydrite occur throughout.

In boreholes the top of the formation often includes a change toward mudstones and muddy sandstones that are dolomitic, anhydritic and can include grey shales (Figure 16). This is marked by a progressive decrease in gamma-ray values toward the top of the Sidmouth Mudstone Formation, which below is mostly characterised by a uniform, high (but finely serrated) pattern. The sonic log generally shows uniformly low transit times in what is one of the most distinctive and sharply defined units in the MMG.

The Sidmouth Mudstone Formation reaches a maximum thickness of around 220 m, thinning abruptly across faults and onto basin margins (Figure 17). It is around 130 m thick at its spectacular outcrop section east of Sidmouth (Figure 8). The unit thins progressively toward the Central English Channel High (Figure 18).

3.1.3 Dunscombe Mudstone Formation

In the Wessex Basin, the Dunscombe Mudstone Formation has a sharp contact with the Sidmouth Mudstone Formation, although the progressive inclusion of more anhydrite, dolomite, sandstone and grey mudstones at the top of the latter appears to herald its arrival.

In the northern (deepest) part of the Portland-Wight Basin and in the Winterborne-Kingston Trough the Dunscombe Mudstone Formation comprises thick halite deposits (Figure 17). The halite is interbedded with mudstone in nested cycles of multiple scales. The entire halite-mudstone interval reaches 463 m thick in the Portland 1A borehole and has sharp lower and upper boundaries (Figure 20). The thickness varies rapidly and is clearly fault-controlled.

Halite is absent at outcrop of the Dunscombe Mudstone Formation and in many boreholes. At outcrop, the incoming of the Dunscombe Mudstone Formation is marked by a colour change from uniform red brown toward grey, purple and reddish brown mudstones which often contain gypsum nodules and halite moulds or pseudomorphs. Mudstones are often brecciated, possibly as a result of evaporite dissolution and collapse (Old et al., 1987). These facies were probably deposited as sulphate sabkhas and mudflats which bordered the salinas forming in the most rapidly subsiding parts of the basin. Analogous relationships have been described from the Middle and Late Triassic of Iberia (Ortí et al., 2017). Grey laminated organic-rich mudstones also occur in association with bioturbated, cross-bedded sandstones and indicate the local or periodic development of freshwater lakes and fluvio-lacustrine deltas (Porter and Gallois, 2008). The apparent conflict between the coexistence of freshwater and saline water bodies could be explained by bodies of freshwater developing close to exposed fault blocks and upland massifs. These may even have formed wedges with a stratified relationship to contiguous saline bodies (Allison and Wright, 2005).

In many boreholes throughout the Wessex Basin, the non-halite facies of the Dunscombe Mudstone Formation is recorded in cuttings as a heterolithic assemblage of red brown and grey mudstone, sandstone, anhydrite and dolomite. The unit generally has a low gamma-ray response relative to the Sidmouth Mudstone below and the Branscombe Mudstone above (Figure 20). This may partly reflect an abundance of Mg-rich authigenic clays (Jeans, 2006). Both gamma-ray and sonic log may show greater variability relative to the very uniform response of the underlying Sidmouth Mudstone Formation. Grey microcrystalline dolomites are widely reported from boreholes at the level of the Dunscombe Mudstone Formation and may have precipitated as groundwater dolocretes (Wright and Sandler, 1994), which are also described from the Upper Triassic of the Paris Basin (Spötl and Wright, 1992). Sandstones are particularly common toward the southern (Figure 19) and eastern (Figure 20) periphery of the Portland-Wight Basin.

The Dunscombe Mudstone Formation reaches a maximum thickness of around 460 m in the Portland 1A borehole. At outcrop, strata assumed here to be lateral equivalents are around 75 m thick. Large differential thicknesses and the abrupt partitioning of halite-rich and halite-poor facies can be related to a pulse of extensional tectonics in the Carnian that appears to be synchronous across much of northwest Europe (Bachmann et al., 2010a).

The abundance of fluvial sandstone and lacustrine deposition points toward a wetter environment relative to the Sidmouth Mudstone Formation. There is now strong global evidence for elevated pluvial activity during the Carnian (Simms and Ruffell, 2018). Magnetostratigraphy suggests the Carnian starts at the base of the Little Weston Mudstone and thus covers the extended interval of the Dunscombe Mudstone Formation as used in this report (Hounslow and Gallois, 2023).

3.1.4 Branscombe Mudstone Formation

The base of the Branscombe Mudstone Formation is either: (1) a sharp switch from halite-dominated strata to mudstones, or (2) a return to monotonous red silty mudstones (with scattered gypsum/anhydrite) from the heterogeneous and multicoloured deposits of the Dunscombe Mudstone Formation.

In the eastern Portland-Wight Basin the Branscombe Mudstone Formation is marked by a (largely) progressive upward increase in gamma-ray response to a maxima, then a progressive decrease toward the base of the Blue Anchor Formation (Figure 18). In some boreholes (98/23-1) the Branscombe Mudstone is rich in sandstones with angular grains (probable fluvial) close to the Central English Channel High (Figure 18).

Further west, an ‘anhydrite marker bed’ breaks the continuity of the Branscombe Mudstone Formation (Figure 19). This correlates with the spectacular Red Rock Gypsum which occurs at outcrop near Branscombe (Gallois, 2001; Gallois, 2004) (Figure 11). Above the gypsum/anhydrite marker the gamma-ray rapidly increases toward the maximum gamma-ray marker.

In the Dorset Basin and Winterbourne-Kingston Trough the Red Rock Gypsum marker is strongly developed. In some boreholes (best exemplified by Winterbourne Kingston 1) the gamma-ray does not show a smooth transition toward the maximum value but includes a secondary shoulder which corresponds to the Marker D identified by Lott et al. (1982). The thickness between the Red Rock Gypsum and Marker D varies in proportion to total thickness of the member. Large differential thicknesses suggest relatively strong extensional activity during its deposition.

3.1.5 Blue Anchor Formation

The Blue Anchor Formation is well developed throughout the Wessex Basin with a base marked by the start of a highly serrated gamma-ray and sonic profile (Figure 21).

3.2 SOMERSET BASIN TO SOUTHERN FLANKS OF THE PEWSEY BASIN

The Somerset Basin is a narrow graben-like structure between the Mendips and the Quantocks (Figure 14). It represents an onshore extension of the Bristol Channel Basin and passes eastwards into the Pewsey Basin (Glen et al., 2005).

In the Somerset Basin the succession is known from the Burton Row cored borehole (Whitaker and Green, 1983) where the MMG is 483 m thick. The MMG thins to the east along boreholes located in a complex area of down-to-the-south half grabens between the Pewsey Basin and the Cranborne-Fordingbridge High (Figure 23).

3.2.1 Sidmouth Mudstone Formation

In the Burton Row borehole the Sidmouth Mudstone exhibits a similar character to the Wessex Basin comprising blocky red siltstones and mudstones with a high gamma ray and low sonic transit time. Sandy strata at the base are probably correlative with the Tarporley Siltstone, while the top exhibits a funnel shaped profile with an increase in evaporites signalling the arrival of the main Somerset Halite. The Sidmouth Mudstone thins rapidly to the east in the Yarnbury and Goodworth boreholes but still exhibits its characteristic log responses.

3.2.2 Dunscombe Mudstone Formation

In the Burton Row borehole the Dunscombe Mudstone comprises four main halite bodies. Brecciated admixtures of mudstone and halite are also reported in the borehole description (Whitaker and Green, 1983). The total thickness of halite is thin (58 m) relative to boreholes on the southern side of the Cranborne-Fordingbridge High such as Winterborne Kingston (185 m). Traced eastwards the halite interval correlates with evaporitic mudstones whose main distinguishing feature in the Yarnbury 1 and Goodworth 1 boreholes is a interval of variable but generally high sonic transit time (Figure 23).

3.2.3 Branscombe Mudstone Formation

The Branscombe Mudstone Formation is 237 m thick in the Burton Row Borehole. An interval of 'hard contorted dolomitic siltstones' in the lower part is described as the lateral equivalent of the Arden Sandstone Formation in the borehole description. It may correlate with an interval of fine-medium grained sandstone in the Yarnbury borehole which lies below a strongly developed anhydrite marker (Red Rock Gypsum Member) (Figure 23*)*. A similar stratigraphy is seen in the Goodworth 1 borehole. The anhydrite marker is weakly developed in the Burton Row borehole.

Above the anhydrite marker, the Branscombe Mudstone Formation consists of red mudstones which show the characteristic increase and decrease in gamma-ray value. The Goodworth 1borehole provides a particularly clear example with a well defined gamma-ray maximum.

3.3 EASTERN FRINGE OF MMG OUTCROP: PEWSEY BASIN TO IOW HIGH

Figure 24 shows a N-S section across the relatively thin (around 200 m) MMG that occurs as its eastern limit is approached in southern England. The MMG here is more uniform than elsewhere with very minor differences between formations.

3.3.1 Sidmouth Mudstone Formation

The Sidmouth Mudstone is less than 50 m thick but is developed in the usual facies of blocky claystone, siltstone and sandstone, with dolomitic cements noted in cuttings descriptions. The sonic transit time is consistently low and uniform while the gamma-ray often shows a slight decrease from base to top.

3.3.2 Dunscombe Mudstone Formation

The Dunscombe Mudstone is just under 50 m thick and consists of claystone which is often described as anhydritic, dolomitic and occasional with fine-grained friable sandstone. In these marginal locations it contains no recorded halite beds. The geophysical log response is unremarkable and it can be picked only on a slight increase in sonic transit time and a higher amplitude response relative to the underlying Sidmouth Mudstone. In many boreholes the difference between the Sidmouth Mudstone and Dunscombe Mudstone are slight.

3.3.3 Branscombe Mudstone Formation

The Branscombe Mudstone is the thickest of the four MMG formations at around 140 m. A strongly developed anhydrite marker bed (often associated with dolomite) divides the formation into two approximately equal parts. Below the marker, mudstones with common anhydrite have a generally constant gamma-ray and sonic response. In some boreholes (e.g. Lockerley 1) the difference in response between this interval and the underlying Dunscombe Mudstone is minimal. Above the anhydrite marker the Branscombe Mudstone is more distinctive with the signature rise and fall in gamma-ray response toward a maximum. Cuttings descriptions tend not to suggest a major change in lithology from the lower part of the formation consisting of blocky red-brown claystone and siltstone with scattered anhydrite throughout.

3.3.4 Blue Anchor Formation

The Blue Anchor Formation maintains a constant thickness of around 25 m and has a typically highly serrated gamma-ray and sonic response.

3.4 WORCESTER GRABEN

The Worcester Graben is a linear north-south trending basin whose development during the latest Carboniferous breached the Welsh-Anglo-Brabant Massif (Glover and Powell, 1996) and created a conduit for the northward flow of Triassic rivers and sediments from the Armorican Massif (Newell, 2018b).

Along the main axis of the graben the MMG is around 300-400 m thick (Figure 25), thinning rapidly onto the footwalls of bounding faults. In the northern part of the graben around Droitwich the base of the MMG is unproven but it probably reaches 625 m thick and includes the Droitwich Halite (Poole and Williams, 1981).

Outcrops and borehole core of the MMG in the southwestern part of the Worcester Basin along the Severn Estuary have been described in detail by Milroy et al. (2019). The outcrops are largely representative of thin marginal successions.

The MMG of the Worcester Graben has evolved its own stratigraphical nomenclature with the Eldersfield Mudstone Formation and Twyning Mudstone Formation below and above the Arden Sandstone Formation (Barclay et al., 1997).

3.4.1 Sidmouth Mudstone Formation

The Sidmouth Mudstone ranges up to around 225 m thick in basinal successions and comprises blocky mudstones and siltstones with anhydrite and occasional sandstone. As seen further south, the gamma-ray log is relatively constant and in some boreholes decreases slightly from base to top (Figure 25). The sonic log is uniform (e.g. Urchfont 1) or in some boreholes (e.g. Cooles Farm 1) finely serrated with a moderate amplitude in parts (Figure 25). In Guiting Power 1 the caliper log indicates local hole enlargement from weakly indurated intervals.

At outcrop and in cored boreholes, Milroy et al. (2019) show that the Sidmouth Mudstone is an alternation of thick (10-15 m) intervals of blocky claystone with carbonate/sulphate nodules and thin intervals (1-2 m) of ripple cross-laminated siltstones and sandstones. The mudstones are interpreted as alluvial/lacustrine origin while the sandstones reflect sheet-floods during seasonal high-intensity rain events.

3.4.2 Dunscombe Mudstone Formation

At Droitwich (Saleway borehole) the Dunscombe Mudstone corresponds to the Droitwich Halite which Poole and Williams (1981) show is an alternation of halite beds up to 12 m thick and blocky reddish brown mudstones with abundant halite nodules and veins.

South of Droitwich where halite is absent, the Dunscombe Mudstone corresponds to an interval of soft anhydritic mudstones. The interval is clearly defined on sonic logs (e.g. Cooles Farm 1) by a highly serrated response that is generally much slower than mudstones above and below (Figure 25). Caliper logs (e.g. Guiting Power 1) may indicate associated borehole enlargement. In the cored Home Farm borehole located to the northeast (Figure 26), high sonic transit times are associated with zones of brecciated and sheared mudstone with listric surfaces coated with gypsum. Much of the rock appears to have been fragmented and recemented reflecting cycles of evaporite (probably including former halite) dissolution and rock collapse into voids (Old et al., 1987).

In addition to mudstone and anhydrite, borehole cuttings returns indicate the occasional presence of sandstone and dolomite. In the Stowell Park borehole thin sandstones within the Dunscombe Mudstone are correlated with the Arden Sandstone Formation (Figure 25). In other boreholes (e.g. Sherbourne 1) sandstones attributed to the Arden Sandstone appear within the lower half of the Branscombe Mudstone.

3.4.3 Branscombe Mudstone Formation

The Branscombe Mudstone corresponds to the 'Upper Keuper Marl' of the Droitwich area where it overlies halites. It ranges up to approximately 175 m thick. As seen further south, an anhydrite marker bed (often associated with dolomite) splits the formation into two parts. The anhydrite marker is clear in some boreholes (e.g. Cooles Farm 1) but less so in others (e.g. Guiting Power 1) (Figure 25). Mudstones below the marker bed generally seem to be more anhydritic than those above.

3.4.4 Blue Anchor Formation

In geophysical logs the Blue Anchor Formation has a much weaker development than seen in the Wessex Basin to the south.

3.5 ENGLISH MIDLANDS

The Worcester Graben merges northward into a number of linked Permo-Triassic extensional basins across the English Midlands (Knowle, Hinckley, Needwood, Stafford) (Figure 26). Across much of this area the Triassic stratigraphy is eroded at rock head and incomplete. Outliers of Penarth Group in the Needwood Basin suggest that the MMG attained total thicknesses of around 300 m. Here the MMG includes halite, which is not present elsewhere in the region for reasons of non-deposition or later erosion (Poole and Williams, 1981).

The Midlands form an important junction in the Triassic basin network, which bifurcates northwest into the Cheshire Basin and the East Irish Sea Basin (where the MMG rapidly thickens to 1.3 km), and northeast onto the East Midlands Shelf and Southern North Sea (Figure 1). A panel from Sherbourne 1 to Hanbury 1 shows both the continuity and changes in MMG stratigraphy (Figure 26).

3.5.1 Tarporley Siltstone Formation

In the Midlands, the Tarporley Siltstone Formation becomes a clearly identifiable unit of thinly interbedded micaeous sandstones and mudstones with gypsum nodules, distinct from the amalgamated sandstones of the Sherwood Sandstone Group. Gamma-ray logs show a highly serrated pattern with evidence of a funnel-shaped (progradational) trend in some boreholes (e.g. Home Farm). The thickness is around 30 m. The unit is noteworthy for the presence of Lingulide brachiopods which provide evidence of marine influence in the lowermost parts of the MMG (Warrington and Pollard, 2021) .

3.5.2 Sidmouth Mudstone Formation

The Sidmouth Mudstone is a unit of relatively homogeneous reddish brown mudstones and dolomitic siltstone with a characteristic uniform fast sonic log and uniform but finely serrated gamma-ray response. A rapid thickening of this interval is observed into the Hanbury 1 borehole of the Needwood Basin (Figure 26).

3.5.3 Dunscombe Mudstone Formation

In the Needwood Basin, the Dunscombe Mudstone includes the Stafford Halite, the main body of which is 30 m thick in the Hanbury 1 borehole (Figure 26). In the nearby cored Bagot's Park borehole 'Saltiferous Mudstones' were described over an interval of 50 m, suggesting the upper boundary of the Dunscombe Mudstone Formation could be placed higher than the main halite body revealed by the gamma-ray log of Hanbury 1.

The cored Home Farm borehole (Old et al., 1987) provides a good example of facies development where halites are absent. Here the Dunscombe Mudstone includes a heterogeneous association of mudstone breccias, common gypsum and thin sandstones. Sandstones at the top of the Dunscombe Mudstone in the Home Farm and Asfordby Hydro boreholes are correlated with the Arden Sandstone Formation (Old et al., 1987; Carney et al., 2004).

As seen in the Worcester Graben, the Dunscombe Mudstone Formation is marked by an interval showing strong perturbations in the sonic log with slow transit times probably related to mudstone breccias which may have formed marginal to major salt lakes, a similar scenario to that described from the Blackpool region (Wilson, 1990).

3.5.4 Branscombe Mudstone Formation

The Branscombe Mudstone forms a relatively thin (ca. 40) unit across the English Midlands compared to the Worcester Graben. However, as seen further south a gypsum/anhydrite unit occurs toward the middle of the formation which corresponds to the Tutbury Gypsum and other named units.

3.6 ANGLO-BRABANT MASSIF (ABM)

3.6.1 Western and northern flank of the ABM

The MMG thins rapidly across the eastern boundary faults of the Worcester Graben onto the Anglo-Brabant Massif (Figure 27). Across much of this long-lived structural high the MMG is thin or entirely absent and the Palaeozoic and older basement rocks were probably a source of much clastic sediment for the MMG. Quarries around Charnwood Forest (e.g. Bardon Hill) show the spectacular development of high-relief erosional topography on the top basement surface that was progressively infilled and onlapped by the MMG (Figure 27).

Across the Anglo-Brabant Massif, the MMG is typically thin (<150 m) and sandy. A correlation from Cooles Farm 1 to Wiggenhall 1 shows that MMG successions on the ABM do no split readily into the four formations identified within the much thicker successions of the Worcester Graben (Figure 27).

In the Upton Burford and Withycombe Farm boreholes, sandstones with ostracods and *Lingula* occur at the base (Warrington and Pollard, 2021). These coarser-grained lateral correlatives of the Tarporley Siltstone Formation are generally included within the Sherwood Sandstone Group. They grade upwards into mudstones which generally show a progressive increase in gamma-ray response. The Arden Sandstone occurs at an approximately mid-way point in the succession of mudstones and has been used as division between the Sidmouth Mudstone Formation below and Branscombe Mudstone Formation above (Howard et al., 2008).

Further east, in Spalding 1 and Wiggenhall 1, the MMG includes conglomerates and pebbly sandstones with igneous and metamorphic clasts suggesting proximity to source.

3.6.2 Eastern and southern flank of the ABM

The Soham and Ellingham 1 boreholes provide examples of MMG successions close to the southern onlap limits of the MMG onto the ABM (Figure 28). Here it becomes thin, pebbly and conglomeratic with dolomite cements. In the absence of dating there is sometimes uncertainly over whether such deposits represent proximal Triassic deposits or Devonian Old Red Sandstone (Lee et al., 2015).

3.7 SOUTHERN NORTH SEA

The MMG thickens rapidly off the eastern margin of the ABM into the Sole Pit Trough of the Southern North Sea (Figure 28). The Dowsing Fault forms an important boundary here and further to the north where it demarcates the eastern edge of the East Midlands Shelf. The MMG thickens progressively northward from the ABM onto the East Midlands Shelf (Figure 15).

3.7.1 Offshore lithostratigraphical terminology

In the Southern North Sea the term Haisborough Group is used in place of Mercia Mudstone Group (Cameron et al., 1992). The Haisborough Group divides into three main formations Dowsing Formation, Dudgeon Formation and Triton Formation. Lithologically and chronostratigraphically these have much in common (but also significant differences) with the Sidmouth Mudstone, Dunscombe Mudstone Formation and Branscombe Mudstone Formation of the onshore MMG.

3.7.2 Dowsing Formation (c.f. Sidmouth Mudstone Formation)

In the Sole Pit Trough, the Anisian Dowsing Formation contains two thick halite units which are thought to be the product of temporary marine influxes which travelled westwards across the Anglo-Dutch Basin (Figure 28). The halites themselves are interpreted as parts of 'drying-up' regressive sequences which are topped out by muddy anhydritic sabkha deposits (Cameron et al., 1992).

Only the lowermost Röt Halite can be correlated across the Dowsing Fault Zone and onto the East Midlands Shelf (Figure 29). The Muschelkalk Halite (and overlying Keuper Halite of Dudgeon Formation) have a smaller areal extent presumably related to accelerating tectonic subsidence and increasingly focussed deposition in hanging-wall basins (Cameron et al., 1992).

Laterally the halite-rich Dowsing Formation correlates with dolomitic and anhydritic mudstones which thin onto the Anglo-Brabant Massif (Figure 28). An abundance of dolomite cementation probably accounts for the relatively fast sonic velocity. This facies and log response compares closely with the Sidmouth Mudstone Formation.

3.7.3 Dudgeon Formation (c.f. Dunscombe Mudstone Formation)

The Dudgeon Formation reaches a maximum thickness of 350 m at the southern end of the Sole Pit Trough (Cameron et al., 1992). Monotonous red-brown and green mudstones occur at the base and often produce a marked increase in sonic transit time. Elsewhere the base of the Dudgeon Formation is a somewhat arbitrary pick between the top of the Muschelkalk Halite and the first thick halites of the Dudgeon Formation (Cameron et al., 1992). Above the basal mudstones, halite beds increase in thickness and frequency into the main Keuper Halite Member of approximate Carnian age (Figure 29).

In the southern Sole Pit Trough the halite-rich Dudgeon Formation east of the Dowsing Fault Zone passes laterally into red-brown and grey-green mudstone with anhydrite and some dolomite (Figure 28). Black shales are occasionally recorded in cuttings descriptions: these have also been described from Carnian-age MMG in the Wessex Basin. Dolomitic sandstone was described from the top of the Dudgeon Formation in borehole 53/01-2. The variable range of facies creates a more variable (and often slower) sonic log response than the dolomitic mudstones of the Dowsing Formation.

Further north, correlating the Dudgeon Formation from the Sole Pit Basin onto the East Midlands Shelf is more problematic (Figure 29). Röt and Muschelkalk (Dowsing Formation) equivalent strata make up over half the MMG of the East Midlands Shelf, leaving a relatively thin succession of Dudgeon and Triton formation equivalents. As discussed in more detail below, a major sonic break within the MMG stratigraphy of the East Midlands Shelf may represent partial omission or condensation of Dudgeon Formation during a phase of rapid extensional tectonic when most deposition shifted east of the Dowsing Fault into the Sole Pit Trough.

3.7.4 Triton Formation (c.f. Branscombe Mudstone Formation)

The Triton Formation is around 220 m thick in the Sole Pit Trough and comprises monotonous red mudstones at the base with relatively sparse anhydrite. The lower boundary with the Dudgeon Formation is obvious on the top Keuper Halite Member where this is present. In halite-free sequences, the Dudgeon-Triton boundary is more cryptic and might be most clearly seen in the sonic log as either an increase in travel time above dolomitic mudstones and sandstones (e.g. 53/01-2) or a decrease in transit time (e.g. 52/05-11) (Figure 28).

An interval with abundant anhydrite/gypsum occurs toward the middle of the Triton Formation and is termed the Keuper Anhydrite Member (Figure 28). Correlatives of this important gypsum/anhydrite marker are widespread across the UK.

The uppermost part of the Triton Formation are predominantly grey-green in colour and are lateral equivalents of the Blue Anchor Formation (Cameron et al., 1992).

3.8 EAST MIDLANDS SHELF (EMS)

The EMS is an area of relatively simple (generally east-dipping) structure located west of the Dowsing Fault Zone and north of the Anglo-Brabant Massif (Figure 14). Presently, the Flamborough Fault Zone and Market Weighton High form an abrupt northern boundary between the EMS and the Cleveland Basin. Thickness patterns, however, indicate that these were not significant controls on sedimentation in the Triassic (Newell, 2023). The Pennine-Charnwood High formed at least a partial topographic barrier between the southwestern EMS and the Needwood, Hinckley and Knowle basins (Newell, 2023). Within the MMG, there is a general decrease in the sand-content and increase in the proportion of dolomite from southwest (close to the Anglo-Brabant Massif) to northeast across the East Midlands Shelf. The overall thickness of the MMG remains relatively constant at 200-250 m (Figure 15). The Hardegsen Unconformity separates the Sherwood Sandstone Group from the Mercia Mudstone Group and at least in part is a sharp aeolian deflation surface with a lag of wind-facetted pebbles.

3.8.1 Two-fold sonic velocity subdivision of the MMG

Sonic logs reveal a fundamental two-fold subdivision of the MMG on the EMS which is not seen in any other UK Triassic basin (Figure 30). This is most clearly demonstrated using back-to-back presentation of sonic transit time logs that have been extracted and normalised in the range (0,1) for the MMG interval. The two parts are of approximately equal thickness with the lower half showing short transit times (fast sonic velocities) and the upper half showing a large increase in sonic transit time (slow velocities). The pinched waistline of the back-to-back logs at the boundary between the two parts indicates a sharp boundary underlain by a high-velocity lithology. The contrast between the two parts increase down the structural dip (and depositional pathway) from southwest to northeast. The contrast is most marked north of the Coningsby 1 borehole (Figure 30).

3.8.2 Gamma ray expression of subdivisions

The two subdivisions are less marked on gamma-ray logs but there are differences nonetheless (Figure 31).

The lowermost sonic subdivision (fast) has a higher overall gamma-ray response. Many boreholes (e.g. Apley 1) show a trend of upward-decreasing gamma-ray value in the lower subdivision from a position near the base of the MMG.

The actual base of the MMG is often marked by an extremely high gamma-ray spike, overlain by a 5-10 m thick interval of low gamma-ray values. These perturbations correlate with the transgressive-regressive cycle of the Lower Röt Mudstone and Röt Halite.

Toward the top of the lower subdivision, just below the sonic break identified here, is a broad gamma-ray spike which corresponds with the gamma-ray marker of Balchin and Ridd (1970). The position of this GR marker is shown on Tetney Lock 1 on Figure 31 and it can be correlated across many boreholes

The upper sonic subdivision generally has a low and relatively constant gamma-ray response. Conspicuous gamma-ray lows are seen in proximal (southern) boreholes (e.g. Asfordby Hydro) and relate to the presence of thin sandstones (Cotgrave and Hollygate members). Toward the top, low gamma-ray spikes (associated with high sonic velocities) are created by bedded gypsum (e.g. Coningsby 1).

A cross-plot of normalised gamma-ray and normalised sonic transit time shows the general clustering of the two subdivisions into fast sonic/high gamma-ray (lower part) and slow sonic/low gamma-ray (upper part). There is clearly much overlap and spread in the loose clusters (Figure 31).

3.8.3 Mapping lithology and lithostratigraphy onto the geophysics

The Asfordby Hydro borehole is cored and described in detail in Carney et al. (2004). Lithological information for other boreholes have been extracted from cuttings descriptions on composite logs (available from https://ukogl.org.uk/) and shown on Figure 32.

3.8.3.1 Lower fast sonic division

The lower sonic division divides into a number of lithological parts. At the base high and low gamma-ray values are associated with grey mudstones and sandstones which may be 'speckled black' (with organic material?) and include anhydrite and dolomite.

This is followed by a thicker interval of mudstone which distally includes dolomite and proximally includes siltstone and sandstone. The progressive upward decreasing (funnel-shaped) gamma-ray trace seen in most boreholes is associated with the incoming of sandstones and siltstones. In proximal boreholes (e.g. Asfordby Hydro) this corresponds to the micaeous sandstones of the Sneinton (Tarporley) Formation.

The sonic spike at the top of the lower MMG division appears to relate to descriptions of hard dolomitic limestone, siltstone and mudstone. It may correlate with the Plains Skerry of Elliott (1961) and with the top of the Diseworth Sandstone Member mapped on the Loughborough sheet 141 (A. Howard, pers. comm). In the Tetney Lock 1 borehole the interval just below the sonic break yielded palynomorphs of uppermost Anisian age that indicated equivalence to the Muschelkalk (Geiger and Hopping, 1968).

The lowermost fast sonic division can be equated to the all of Elliot's (1961) MMG units below the Plains Skerry (Carlton, Radcliffe, Waterstones and Woodthorpe). Elliot (1961) neatly maps the distribution of sedimentary features in the MMG around Nottingham and these are summarised in Figure 33. It also maps to subdivisions A-D of Gaunt et al. (1992) (Figure 33). An abundance of potassium-rich mica probably accounts for the high gamma response while the common occurrence of dolomite cemented mudstones and siltstones accounts for the fast sonic velocity.

The fast sonic division has a close correspondence with the Sidmouth Mudstone Formation and the dolomitic Dowsing Formation of the southern North Sea.

3.8.3.2 Upper slow sonic division

Above the sonic break, mudstones predominate. These are described as soft and blocky and may contain gypsum and anhydrite and minor dolomite in distal boreholes (e.g. Cleethorpes 1).

Higher in the succession traces of sandstone and sand lenses are recorded in distal boreholes, often in two intervals separated by mudstone and anhydrite (e.g. Cleethorpes 1). In proximal boreholes (e.g. Asfordby Hydro) these expand to form the two thin sandstone intervals of the Cotgrave Sandstone and the Hollygate Sandstone. These are separated by sandy clays rich in smectites. Swelling clays are also recorded from this interval in the some boreholes (e.g. Saltfleetby 1).

Above the uppermost sandstone, mudstone with anhydrite (or gypsum) is widely recorded in boreholes, corresponding to the Cropwell Bishop Formation. Norian-age palynomorphs have been recovered from the Tetney Lock 1 borehole (Geiger and Hopping, 1968) confirming equivalence with the Triton Formation of the southern North Sea.

The uppermost slow sonic division can be mapped to the Harlequin, Edwalton and Trent formations of Elliot (1969) and units E, F and G of Gaunt et al. (1992). An abundance of gypsum/anhydrite and Mg-rich swelling clays (particularly in the Edwalton Formation) probably accounts for the relatively low overall gamma-ray response. A much lower proportion of dolomite may account for the slower sonic velocity.

The slow sonic division broadly corresponds with the combined Dunscombe and Branscombe mudstone formations (and Blue Anchor Formation). A lower boundary for the Branscombe Mudstone could be picked at the top of the Hollygate Member, where this can be recognised in proximal boreholes. It corresponds to the Dudgeon and Triton formations of the southern North Sea.

It is possible (but unknown) that the sonic break and associated hard dolomitic limestone represent a break in deposition and a significant time-gap. This could have occurred because of active movement on the Dowsing Fault Zone which shifted deposition basinwards into the Sole Pit Basin.

3.9 CHESHIRE BASIN AND EAST IRISH SEA BASIN

The Cheshire Basin is an asymmetrical half-graben and one of the deepest rift basins in the UK with a preserved fill of over 4.5 km of Permo-Triassic red beds and locally Jurassic marine strata (Plant et al., 1999). It links northward with the East Irish Sea Basin (EISB) a complex systems of extensional basins and highs controlled by N-S, NE-SW and NW-SE faults (Knipe et al., 1993). The coastline of the Lake District broadly defines the eastern margin of the EISB in the north (Figure 1). In the south, the Permo-Triassic deposits of the Blackpool region represent an onshore extension of the EISB (Wilson, 1990; Wilson and Evans, 1990). Across the EISB, several episodes of kilometre-scale uplift and erosion in the Cretaceous and Palaeogene (Holford et al., 2005) has left a fragmentary Triassic record biased toward older deposits locally preserved in deep tectonic pockets.

3.9.1 Stratigraphical nomenclature

3.9.1.1 Existing lithostratigraphy

The stratigraphical nomenclature of the MMG of the Cheshire Basin and East Irish Sea Basin has evolved separately, despite their proximity and close similarity in thickness and facies succession (Figure 34). Jackson et al. (1997) provide a detailed overview of the existing nomenclature for the EISB, while Evans et al. (1993) provide a good description of MMG stratigraphy in the Cheshire Basin. In these existing schemes each major shift in lithology (mostly to either mudstone- or halite-dominated) is generally designated as a formation.

3.9.1.2 Revised lithostratigraphy

Howard et al. (2008) attribute the bulk of the MMG in the EISB (west Lancashire onshore portion) to their definition of the Sidmouth Mudstone Formation in the revised MMG scheme. This includes all of the major halite units in the EISB. In the Cheshire Basin, the Sidmouth Mudstone Formation similarly extends to the top of the Wilkesley Halite Member and is thus an extremely thick and heterogeneous unit. Where preserved, the mudstone-dominated interval toward the top of the MMG (above the main halite intervals) is correlated with the Branscombe Mudstone Formation. This corresponds to the Brooks Mill Mudstone in the Cheshire Basin.

A possible alternative scheme considered here is that in the EISB, strata correlative with the Sidmouth Mudstone Formation (in the more restricted sense defined in this report) extend only to the top of the Blackpool Mudstone (or correlative Bollin Mudstone of the Cheshire Basin). The main halite-bearing interval comprising the Mythop Halite, Cleveleys Mudstone and Pressall Halite in the EISB could be classified as Dunscombe Mudstone Formation. The terminal mudstones of the MMG are ascribed to the Branscombe Mudstone Formation (often below a thin Blue Anchor representative). The earliest halite units (Fylde and Rossall halites) are likely to be lateral correlatives of the Tarporley Siltstone Formation (Figure 34). A south to north change in facies and stratigraphy (Figure 34) reflects a proximal to distal gradient, with marine influence probably coming from the north. Given the additional halites, a local stratigraphy may still offer the simplest solution for subdividing the MMG in the Cheshire and East Irish Sea basins.

3.9.2 Tarporley Siltstone Formation

In the Cheshire Basin, the basal part of the MMG includes sandy facies which are classified as Tarporley Siltstone Formation. The 213 m thick funnel-shaped gamma-ray profile in the Prees 1 borehole suggests a coarsening-upward (progradational) trend (Figure 34). Outcrop studies in the Cheshire Basin incorporating detailed analysis of the trace fossils suggest a shallow tidally-influenced environment of channels and sandflats (Ireland et al., 1978), coincident with peak marine influence in the Muschelkalk of the Germanic Basin (Geluk et al., 2018). Sandstone dominated parts of the Tarporley Siltstone (Malpas Member) contain abundant wind-blown grains (Wilson, 1993) suggesting a trend toward fully terrestrial arid environments.

Northwards, into the EISB, mudstones at the base of the MMG (sometimes with dolomite and a basal anhydrite) pass upwards into the Rossall Halite (Figure 34). The funnel-shaped gamma-ray profile (e.g. 110/14-3) mimics the trend seen in the Tarporley Siltstone of the Cheshire Basin and represents desiccation of the former marine-influenced basin. Further north still, an additional halite body (Fylde Halite) underlies the Ansdell Mudstone in what is probably a base-lapping succession migrating toward the south under relative sea-level rise.

3.9.3 Sidmouth Mudstone Formation

The sandstones (Cheshire Basin) and halites (EISB) of the Tarporley Siltstone are sharply overlain by the Bollin Mudstone, and its lateral correlative, the Blackpool Mudstone (Figure 34). In the Prees 1 borehole, 226 m were proven and a similar thickness is seen in many boreholes in the EISB, with some localised thinning (e.g. 110/03B-6A) (Figure 34).

This is one of the most readily identifiable intervals in the MMG of the EISB area comprising mudstones with a relatively high but finely serrated gamma-ray response and a low sonic transit time. The uniformity of response is similar to that seen in the Sidmouth Mudstone of the Wessex Basin and elsewhere (Figure 6).

The mudstones are mostly reddish brown and structureless with some laminated mudstones which increase in abundance toward the top (Wilson, 1993). A few low gamma-ray spikes occur toward the top and (as also seen in the Wessex Basin) and appear to herald salina development and the accumulation of major halite bodies above. Dolomitic siltstones occur toward the top in the Cheshire Basin (Wilson, 1993).

3.9.4 Dunscombe Mudstone Formation

Thick halites appear sharply in the MMG stratigraphy above the Blackpool/Bollin mudstones (Figure 34). They are generally developed in two distinct intervals separated by a unit where the proportion of mudstone increases markedly and may exceed the proportion of interbedded halite. The total thickness of the Dunscombe Mudstone (as used here) reaches 1338 m in 110/03-2 compared to 683 m in the Cheshire Basin.

The mudstone-rich interval that separates the two major halites is termed the Cleveleys Mudstone in the EISB and the Byley/Wych Mudstone in the Cheshire Basin. This mudstone differs from the Bollin/Blackpool Mudstone in having a high proportion of laminated facies (Wilson, 1993), thin halites and grey colouration, a feature often recognised and recorded in cuttings descriptions from wells in the EISB.

Below the Cleveleys Mudstone is the Mythop Halite (Northwich Halite in the Cheshire Basin) which is composed of approximately equal proportions of mudstone and halite in a unit that reaches 445 m thick in 110/03-2. Halite beds are thin and relatively widely spaced. Dual flattening the Mythop Halite on the base and top (to remove thickness variations due to structure) reveals a remarkable level of correlation across large distances in the EISB (Figure 35). Packages of thick salt, thinly interbedded mudstone and salt, and thick mudstone appear synchronously developed across the basin despite crossing major fault structures (Figure 35). The fidelity of the correlation does not extend to the same degree into the Cheshire Basin, although the same broad packages may be present (Figure 36), suggesting this was an independent depositional system.

Above the mudstone is the Preesall Halite which reaches 597 m thick in 110/03-2. Apart from the greater thickness, this differs from the Mythop Halite in comprising much thicker intervals of halite relative to mudstone (Figure 37). Dual flattening the Preesall Halite on base and top also reveals a remarkable level of correlation of the thin mudstones across large distances in the EISB. The Preesall Halite is (considered here) a correlative of the Wilkesley Halite in the Cheshire Basin (Figure 34). The proportion of mudstone increases southward into the Cheshire Basin, breaking up the halite bodies into thinner units. Thin sandstones have also been reported (Wilson, 1993) and the increase in the siliciclastic component probably represents the greater proximity to source areas.

Jackson et al. (1997) correlate the Wilkesley Halite with a thick halite body they term the Warton Halite. The Warton Halite is considered here to be the same unit as the Preesall Halite which may have been mis-identified in borehole 110/13-8 (Jackson et al. 1997, their figure 3). Pending further investigation, only two (Mythop and Preesall) and not three (Mythop, Preesall and Warton) major halite bodies appear to occur above the Blackpool Mudstone (Figure 34). This mirrors the stratigraphy in other basins where two major halites are present above the Sidmouth Mudstone: Northwich and Wilkesley halites in the Cheshire Basin; Muschelkalk and Keuper halites in the southern North Sea, two unnamed halites in the Portland 1A borehole of the Wessex Basin (Figure 6).

The depositional environment of the halite bodies has long been a topic of debate, ranging from shallow continental salt pans to deep salt lakes and lagoons recharged by marine flooding (Wilson, 1990). Extensive evidence for displacive halite growth within sediment piles, palaeosols and shallow-water or wind-blown deposits suggests acid shallow lakes in an arid continental environment (Andeskie et al., 2018). The long-range correlations of thin halites shown here indicate that while lakes were shallow they extended laterally for many tens of kilometres.

3.9.5 Branscombe Mudstone Formation

In the Cheshire Basin, around 200 m of mudstone lie between the top of the Wilkesley Halite and the Penarth Group (Wilson, 1993). Most of this is assigned to the Brooks Mill Mudstone, with around 20 m metres of Blue Anchor Formation at the top where the mudstones become predominantly greenish grey. The Brooks Mill Mudstone mostly comprises structureless reddish brown mudstone (Wilson, 1993). Gypsum/anhydrite is common as nodules and beds, particularly toward the middle of formation as seen in coeval Norian MMG elsewhere (e.g. Keuper Anhydrite Member of the Triton Formation). Thin sandstone beds occur toward the base. Wilson (1993) tentatively correlates sandstones that occur around 35 m above the Wilkesley Halite in the Wilkesley borehole of the Cheshire Basin with the Hollygate Sandstone of Nottinghamshire.

In the EISB there is highly variable preservation of the uppermost MMG beneath the Quaternary unconformity. In borehole 110/03B -6A the composite log records around 365 m of blocky red brown and green grey mudstone preserved above the top of the Preesall Halite (Figure 34). Thin halite beds are present at the base passing up into good traces of anhydrite. This unit is wholly assigned here to the Dowbridge Mudstone Formation.

3.10 Summary and conclusions

- Geophysical log based correlations show that in most basins the MMG can be divided into 3 main intervals – these are named using a slightly modified version of the scheme of Gallois (2001). This is not a new concept, the MMG having long been subdivided in lower and upper ‘marls’ separated by ‘saliferous beds’ (Poole and Williams, 1981).
- The Sidmouth Mudstone Formation (as used in this report) is a coherent body of reddish-brown mudstone, often rich in silt and dolomite, at the base of the MMG. The mudstones are generally structureless and much of the material may be of loessic origin (Mao et al., 2021). The unit is readily identified in geophysical logs by a high-gamma ray

response (reflecting an abundance of K-rich mica) and low sonic transit time reflecting strong cementation. Closer to marine environments, in the Southern North Sea and East Irish Sea basins, the Sidmouth Mudstone Formation includes halite bodies. Closer to source areas, the base of the MMG includes the sandy facies of the Tarporley Siltstone Formation. At present, this unit is often vaguely defined, shifting between the SSG and the MMG as it becomes more or less sand-prone.

- The Dunscombe Mudstone Formation is lithologically variable. Its recognition is simplest in basinal areas where it includes thick halite bodies, often developed in two discrete intervals. Where halite is absent, the Dunscombe Mudstone Formation is still identifiable by the presence of laminated reddish brown and greenish grey mudstones, siltstones and fine sandstones, mudstone clast breccias and occasional dark grey claystones. In geophysical logs, it is often marked by a zone of variable but often high sonic transit time values probably reflecting weak brecciated mudstones which may have contained evaporites. The Dunscombe Mudstone Formation represents a major perturbation in Late Triassic climate (associated with the Carnian Pluvial Event) and a time of accelerated tectonic extension.
- The Branscombe Mudstone Formation marks a return to structureless reddish brown anhydritic/gypsiferous mudstone. Its base is readily recognisable in basinal areas where it rests sharply on halite. Elsewhere it can be recognised by a shift in sonic transit time. Beds of anhydrite and gypsum often occur toward the middle of the formation and are broadly correlative to the Keuper Anhydrite of the Triton Formation in the southern North Sea. These appear to be of great lateral extent and, as long recognised, make excellent marker beds for correlation. The Branscombe Mudstone Formation grades upwards into the Blue Anchor Formation, arguably this uppermost unit of the MMG has more affinity with the overlying Penarth Group.
- Howard et al. (2008) place considerable emphasis on the Arden Sandstone Formation as a key marker within the MMG subdividing Sidmouth Mudstone below from Branscombe Mudstone above. There is no doubt that, at outcrop, the Arden Sandstone often forms the most conspicuous topographical feature which allows mapped subdivision of the MMG. In the subsurface, however, the thin Arden Sandstone can often not be recognised with confidence. Boreholes also show that multiple sandstones can occur within the Dunscombe Mudstone and in the lower part of the Branscombe Mudstone. It is here not considered here a good unit on which to base subdivision of the Mercia Mudstone Group, not least because it results in the amalgamation of vastly different lithologies (e.g. mudstone and halite) into a greatly expanded Sidmouth Mudstone Formation.
- The MMG of the East Midlands Shelf breaks the general ‘rule’ that the MMG falls into 3 main parts. The sonic log in particular shows that the MMG here sharply subdivides into two parts. A lower ‘fast part’ composed of dolomitic mudstones and an upper ‘slow part’ composed of mudstones and sulphates. Sandstones of the Sneinton Formation/Tarporley Siltstone, Cotgrave Member and Hollygate/Arden Sandstone Member prograding from south to north are superimposed on this general stratigraphy. The sonic break is extremely abrupt and marked by a dolostone in eastern parts of the shelf which may have formed in response to tectonic activation of the Dowsing Fault Zone and a shift in the main locus of deposition into the rapidly subsiding Sole Pit Basin.

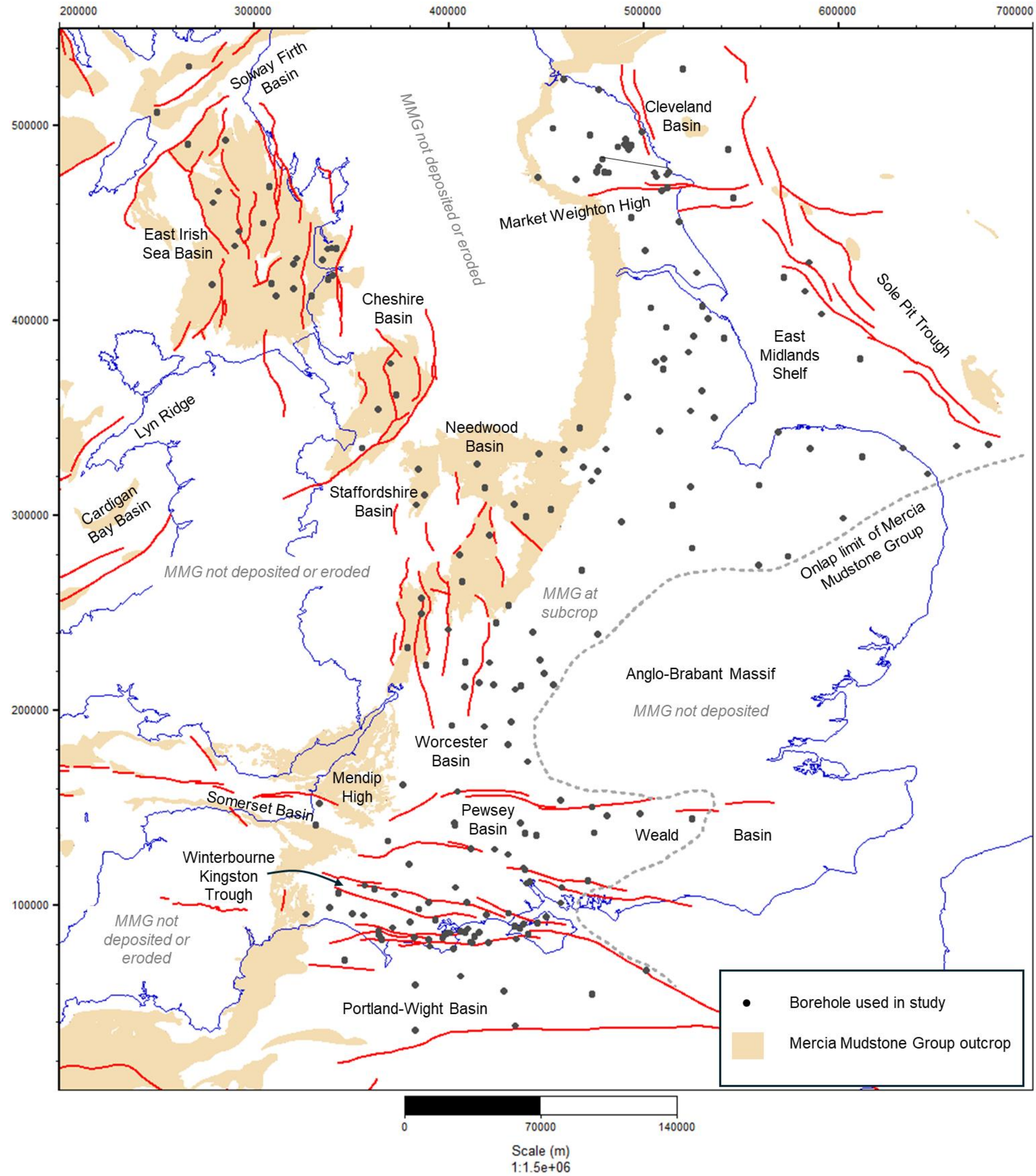


Figure 1 Map showing onshore and offshore outcrop of Mercia Mudstone Group, major faults, basins/highs and distribution of boreholes used in the study. Faults are a sub-selection from BGS (1996). OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024.

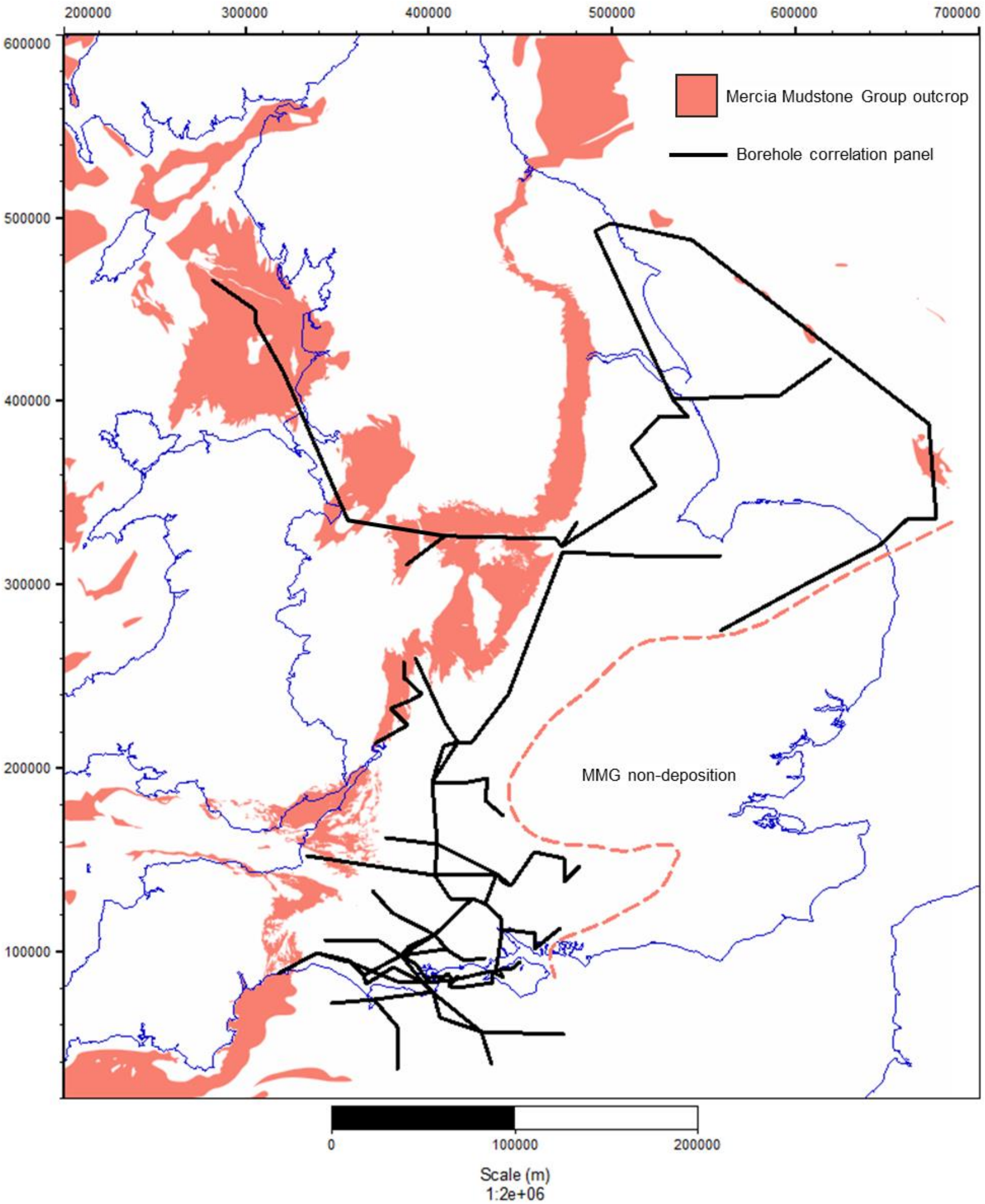


Figure 2 Map showing the distribution of borehole correlation panels (thick black lines) illustrated in the report relative to MMG outcrop and subcrop limits. OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024.

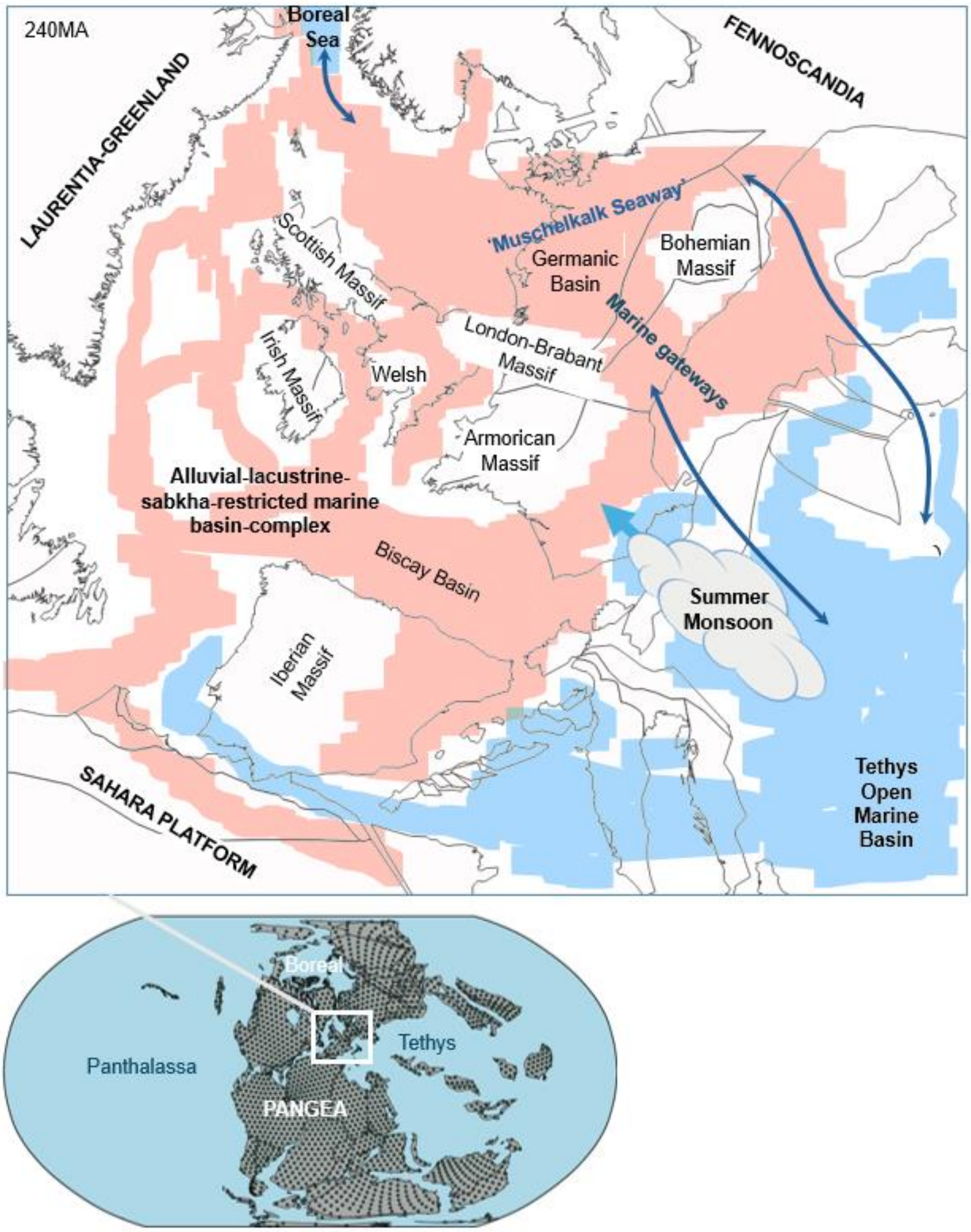


Figure 3 Sketch palaeogeographical map for the middle and late Triassic when a vast complex of terrestrial, paralic and shallow marine environments occupied a central position within the Pangean Supercontinent between the Boreal Sea and Tethys Ocean. Rift basins were interspersed with broad basement highs which where progressively onlapped during the Triassic. Summer monsoons from the Tethys Ocean periodically brought moisture into the hot arid interior. Marine gateways between remnant Variscan uplands allowed incursion of marine waters into the Germanic Basin where marine carbonates of the Muschelkalk were deposited. Coastlines created using QGIS and GPlates Web Map Service at time step 240Ma using the MULLER2019 model. https://gws.gplates.org/reconstruct/coastlines/?time=140&model=MULLER2019

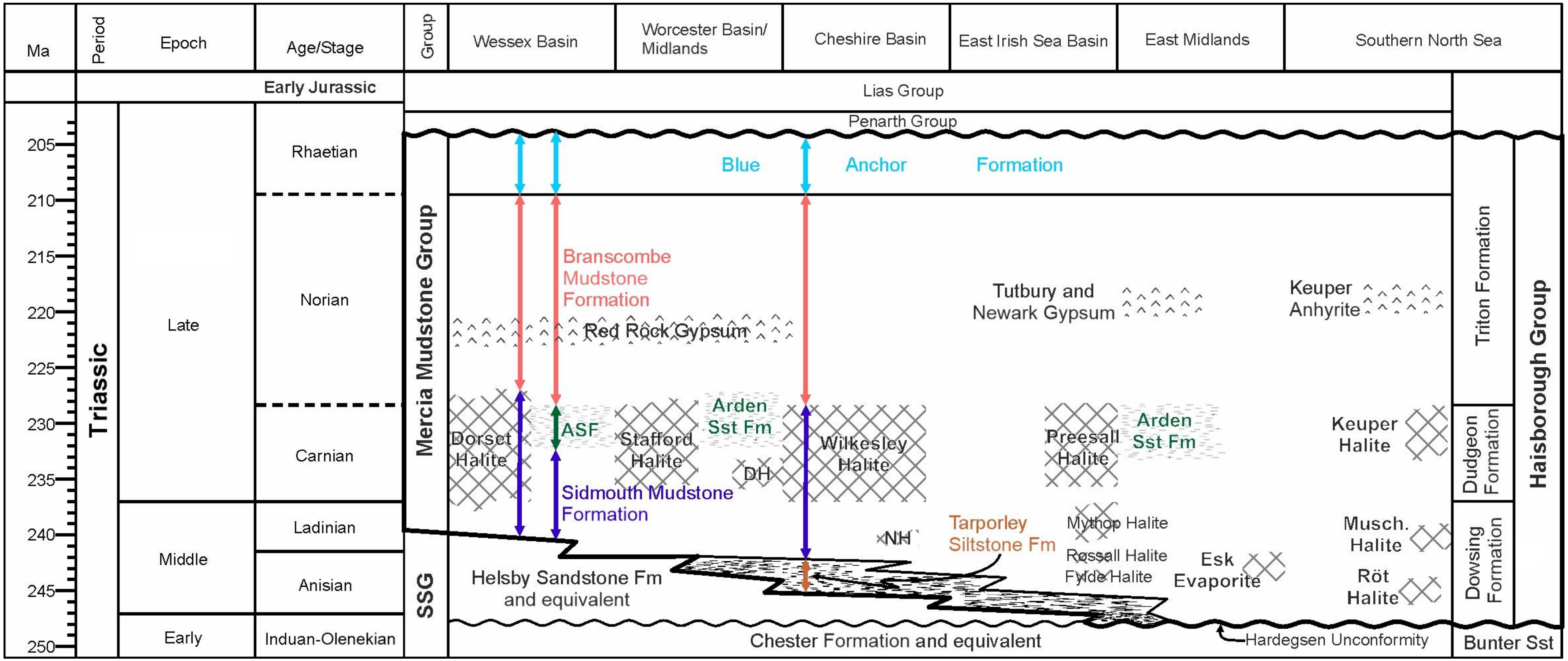
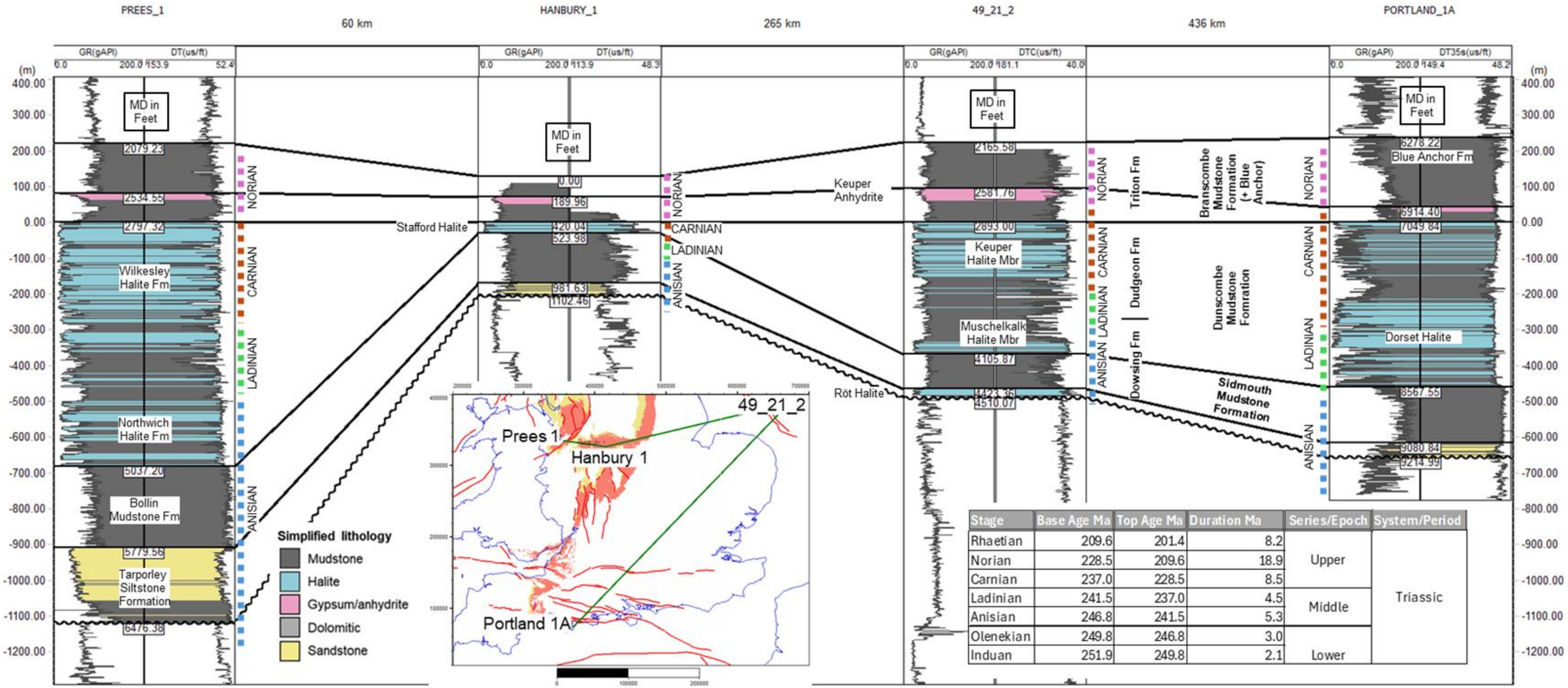


Figure 4 Generalised chronostratigraphy of the MMG in different locations across the UK. Note the diachronous base of the MMG with younging toward the south where sandy fluvial facies of the Sherwood Sandstone Group persisted into the Ladinian. Coloured double-headed arrows show the revised/current lithostratigraphical scheme of Howard et al. (2008) which recognises two main mudstone intervals below (Sidmouth Mudstone Formation) and above (Branscombe Mudstone Formation) the Arden Sandstone Formation (where this is present). Where thick Ladinian-Carnian halites replace the Arden Sandstone these are included in the Sidmouth Mudstone Formation. The Tarporley Siltstone Formation and Blue Anchor Formation are comparatively thin transitional units into the Sherwood Sandstone Group (below) and the Penarth Group (above). In the Southern North Sea, strata equivalent to the onshore MMG are termed the Haisborough Group which is divided into three formations. SSG=Sherwood Sandstone Group, NH=Northwich Halite, DH=Droitwich Halite, ASF=Arden Sandstone Formation.

	Howard et al. (2008)	Gallois (2001)		As used in this report	Key features
Mercia Mudstone Group	Blue Anchor Formation	Blue Anchor Formation	**(Member subdivisions)**	Blue Anchor Formation	Grey mudstones and dolomitic carbonates
	Branscombe Mudstone Formation	Branscombe Mudstone Formation	Haven Cliff Mudstone Member	Branscombe Mudstone Formation	Primarily massive reddish-brown mudstones, often with high silt component. Dispersed gypsum/anhydrite and dolomite. Concentration of thick gypsum/anhydrite beds at some levels.
			Seaton Mudstone Member		
			Red Rock Gypsum Member		
			Littlecombe Shoot Mudstone Member		
	Arden Sandstone Fm	Dunscombe Mudstone Formation	Lincombe Hill Member	Dunscombe Mudstone Formation	Heterogeneous association of red and grey mudstones, finely laminated mudstones, brecciated mudstones, bioturbated sandstones, thick halite in basinal areas
	Sidmouth Mudstone Formation	Sidmouth Mudstone Formation	Little Weston Mudstone Member		
			Hook Ebb Mudstone Member	Sidmouth Mudstone Formation	Primarily massive reddish-brown mudstones, often with high silt component. Dispersed gypsum/anhydrite and dolomite.
			Salcombe Mouth Member		
			Salcombe Hill Member		
			Sid Mudstone Member		
	Tarporley Siltstone Fm			Tarporley Siltstone Formation	Sandstones, siltstones and mudstones

Figure 5 Comparison of the MMG lithostratigraphical schemes of Howard et al. (2008) and Gallois (2001) with the modified version developed and used in the compilation of this report. The applicability of this scheme to the East Irish Sea Basin, East Midlands Shelf and Southern North Sea is debatable where the stratigraphy is modified by, for example, additional thick units of halite.



Stage	Base Age Ma	Top Age Ma	Duration Ma	Series/Epoch	System/Period
Rhaetian	209.6	201.4	8.2	Upper	Triassic
Norian	228.5	209.6	18.9		
Carnian	237.0	228.5	8.5		
Ladinian	241.5	237.0	4.5	Middle	
Anisian	246.8	241.5	5.3		
Olenekian	249.8	246.8	3.0	Lower	
Induan	251.9	249.8	2.1		

Figure 6 Comparative MMG stratigraphy across four basins. Correlation lines do not imply physical continuity of units or time-equivalence but emphasise the general tri-partite subdivision of the MMG into a lower-part (Anisian) dominated by mudstone; a mid-part (Ladinian-Carnian) dominated by halite (in basin centres) and an upper-part (Norian) dominated by mudstone and anhydrite/gypsum. The Norian mudstones (Triton Formation/Branscombe Mudstone Formation) that cap the MMG are relatively thin but cover a stage of anomalously long duration (18.9 Ma). Rapid rates of deposition in pre-Norian MMG strata probably reflect syndepositional extensional tectonics and high rates of evaporite precipitation. Chronostratigraphy is based on various sources and should be regarded as uncertain and approximate.

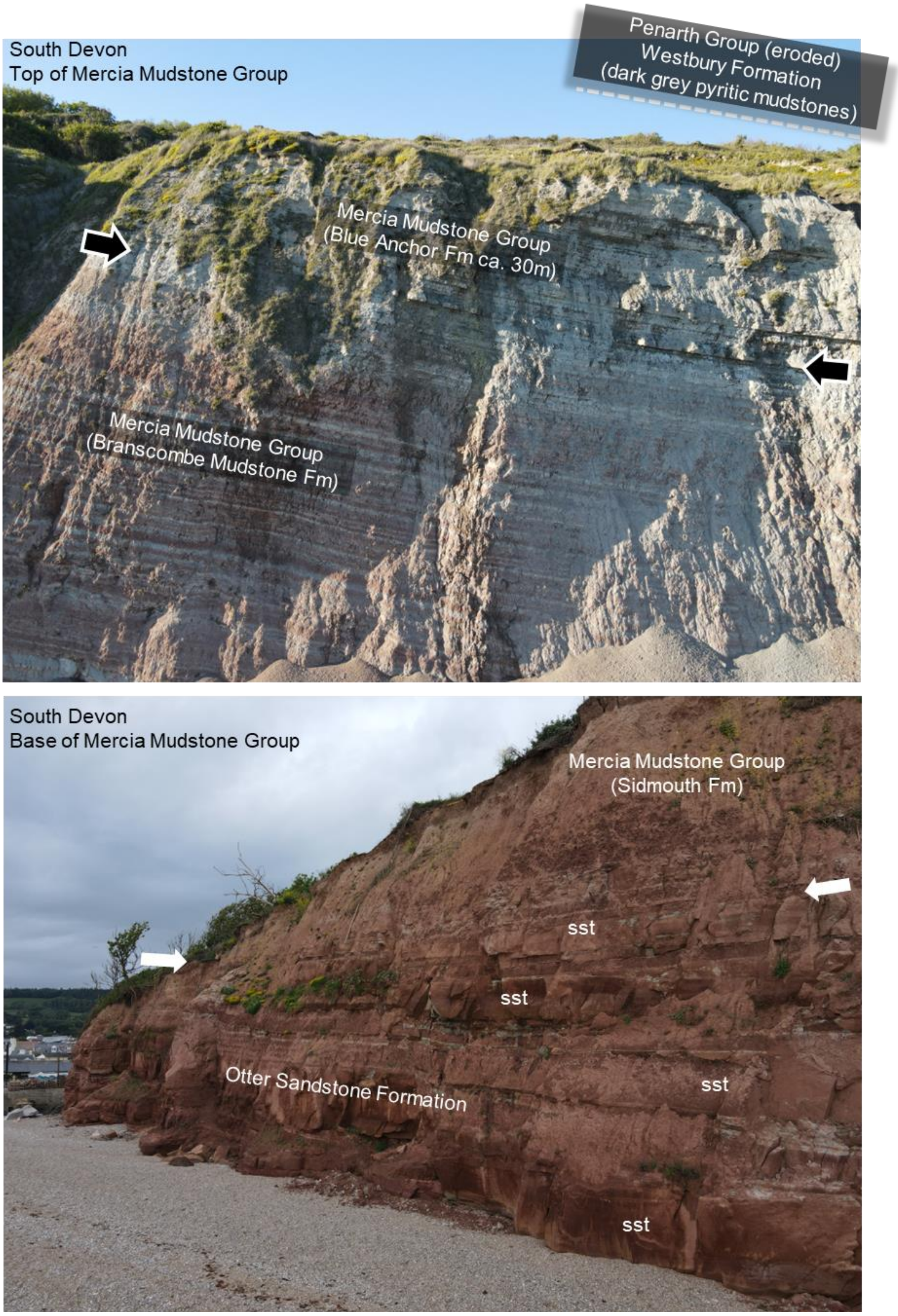


Figure 7 Top and base of the MMG in Devon. The top near Seaton [SY266895] (above) is a transition from red and green coloured mudstones of the uppermost Branscombe Mudstone Formation, through the grey carbonates and mudstones of the Blue Anchor Formation into dark grey pyritic mudstones of the lowermost Penarth Group (not present in this exposure). The base seen near Sidmouth [SY129873] is a transition from the sandstones of the Otter Sandstone Formation into red mudstones of the MMG. These uppermost Otter Sandstone Formation comprise muddy, micaeous meandering channel deposits (Newell, 2018a) which are probably Tarporley Siltstone equivalent.

Figure 8 Towering cliffs (around 160 m high) of Sidmouth Mudstone Formation at Salcombe Hill near Sidmouth in Devon [SY136874]. The reddish brown mudstones are thickly bedded and largely structureless. The hilltop is formed by Cretaceous Upper Greensand lying unconformably on Triassic MMG.

Figure 9 Photograph above shows the base of the Dunscombe Mudstone Formation (as used in this report) at Higher Dunscombe Cliff in south Devon (SY152876). The white arrow marks a change from relatively homogeneous red brown mudstones into red brown and grey mottled mudstones. Gypsum becomes common and laminated/cross-laminated siltstone and sandstone occurs. Grey laminated mudstones are developed. Sandstones may reach several metres thick and show cross-bedding, convolute bedding and bioturbation (left) suggesting deposition in freshwater lacustrine deltas during the Carnian Pluvial Episode (Porter and Gallois, 2008). See the following Figure 10 for an additional view of this cliff and further explanation.

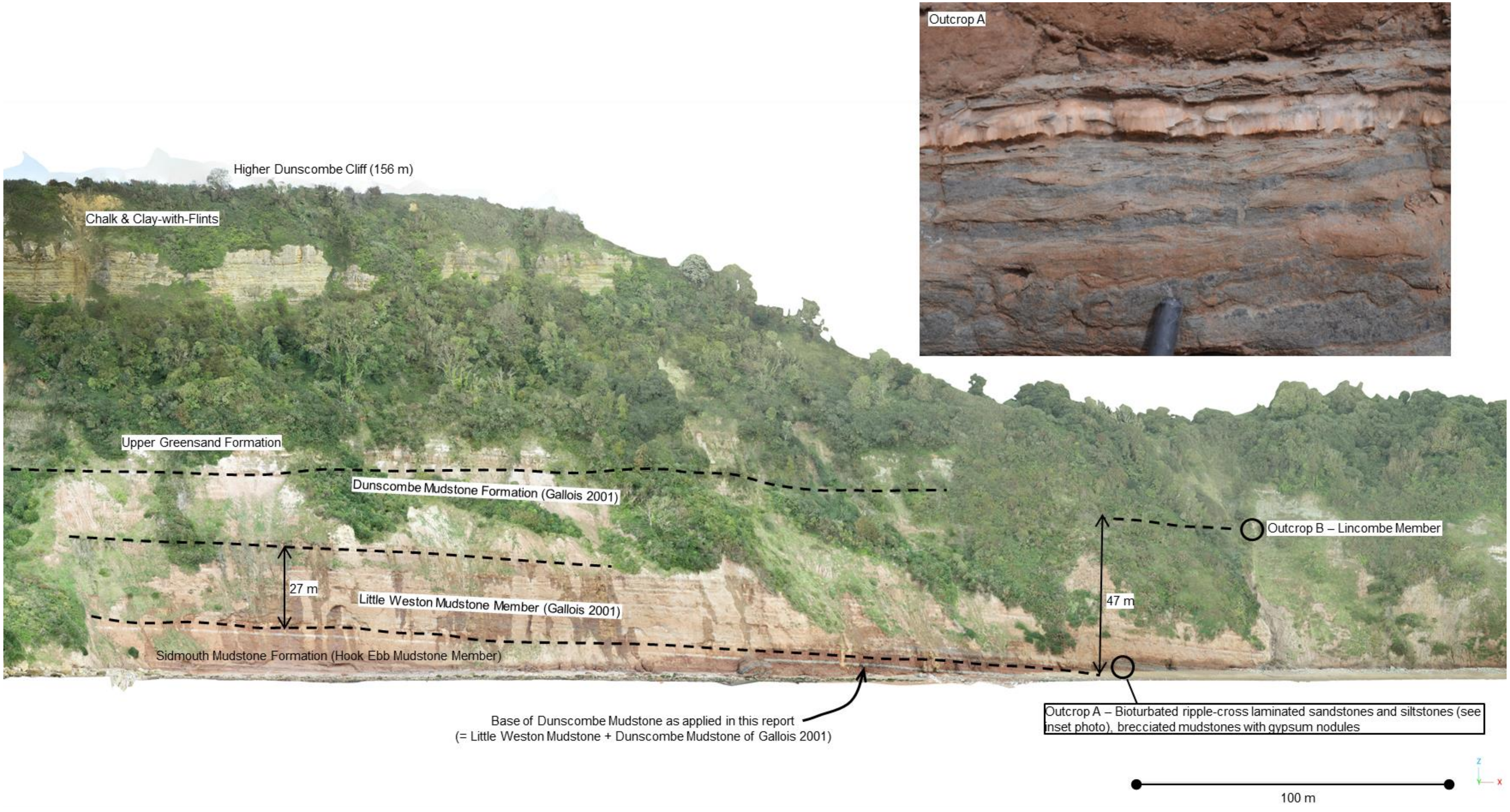


Figure 10 Virtual outcrop model (VOM) constructed from drone imagery of Higher Dunscombe Cliff showing the modified base of the Dunscombe Mudstone Formation as used in this report. This includes 27 m of grey and reddish brown mudstones (sometimes brecciated), gypsum and cross-laminated sandstones and siltstones assigned to the Little Weston Mustone Member of Gallois (2001). These rest sharply on the massive red brown mudstones of the Sidmouth Mudstone Formation. The Lincombe Member sandstone body is 47 m above this horizon. Thicknesses are measured from the VOM.

Figure 11 Red brown structureless mudstones of the Branscombe Mudstone Formation overlying the 'Red Rock Gypsum Member' at Branscombe Beach, south Devon [SY202881]. Masses of nodular gypsum (primary texture) are connected by veins of fibrous gypsum probably formed as natural hydraulic fractures a result of overpressure in the low permeability mudstones by tectonic compression (and possible anhydrite hydration) during basin inversion and uplift (Meng et al., 2017).

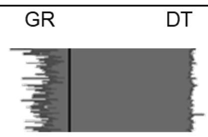
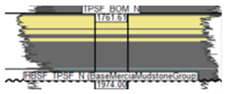
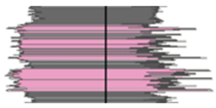
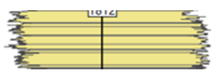
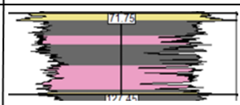
Facies Association	Description and interpretation	Gamma ray Sonic transit time snippet
Massive silty claystones and siltstones	Reddish brown silty claystones and siltstones. Generally massive. Occasional gypsum nodules. High (but often finely serrated) gamma-ray values and uniform low sonic travel time. Thickly bedded, massive character makes interpretation difficult. Silt component suggests a high primary or reworked aeolian dust component	
Halite and mudstone	Halite in beds of various thickness. Generally interbedded with mudstones (often laminated and brecciated). Halite has a very low gamma response and uniformly lower sonic transit time relative to interbedded mudstone. Halite often show a displacive texture with remnants of former mudstone matrix between crystalline halite masses. Salt precipitation in shallow saline lakes subject to periodic desiccation	
Dolomitic limestone and mudstone	Interbedded dolomitic mudstones and siltstones, red, green, grey and black mudstones. Massive to finely laminated, halite casts and gypsum. Mostly at the top of the MMG (Blue Anchor Formation). Characteristically serrated gamma ray and sonic log motif. Sabkhas, freshwater lakes, greater evidence of marine influence toward the top	
Sandstones	Sandstones, siltstones and mudstones. Commonly laminated, cross-laminated and cross-bedded, bioturbated. In some units (Tarpoley Siltstone Formation) the (optimally) marine brachiopod *Lingula* is present. Can form the top of the coarsening-up cycle or funnel-shaped profile on gamma-ray logs or interbeds within muddy evaporite sequences. Fluvio-lacustrine or fluvio-marine delta	
Anhydrite	Anhydrite (or gypsum) interbedded with mudstone. Bedded, nodular, convolute and chicken-wire textures. Low gamma-ray and fast sonic. Evaporitic sabkha-type settings	
Breccias and pebbly sandstones	Matrix to clast supported breccia, conglomerate and gravelly sand. Mudstone interbeds. Basin-marginal fans and canyon-fills cut into basement	
Brecciated mudstones	Heterolithic association of brecciated mudstone, evaporites and thin cross-laminated sandstones. Variable gamma and highly serrated sonic. Sonic can show thick intervals of unusually slow response. Caliper logs can show borehole enlargement resulting from intervals of unusually weak rock. This association is a lateral correlative of thick halite-bearing intervals. Represents an array of lake-margin facies with chaotic brecciated facies possibly resulting from salt dissolution.	

Figure 12 The main facies associations found in the Mercia Mudstone Group with snippets showing typical gamma-ray (left track) and sonic transit time (right track) responses.

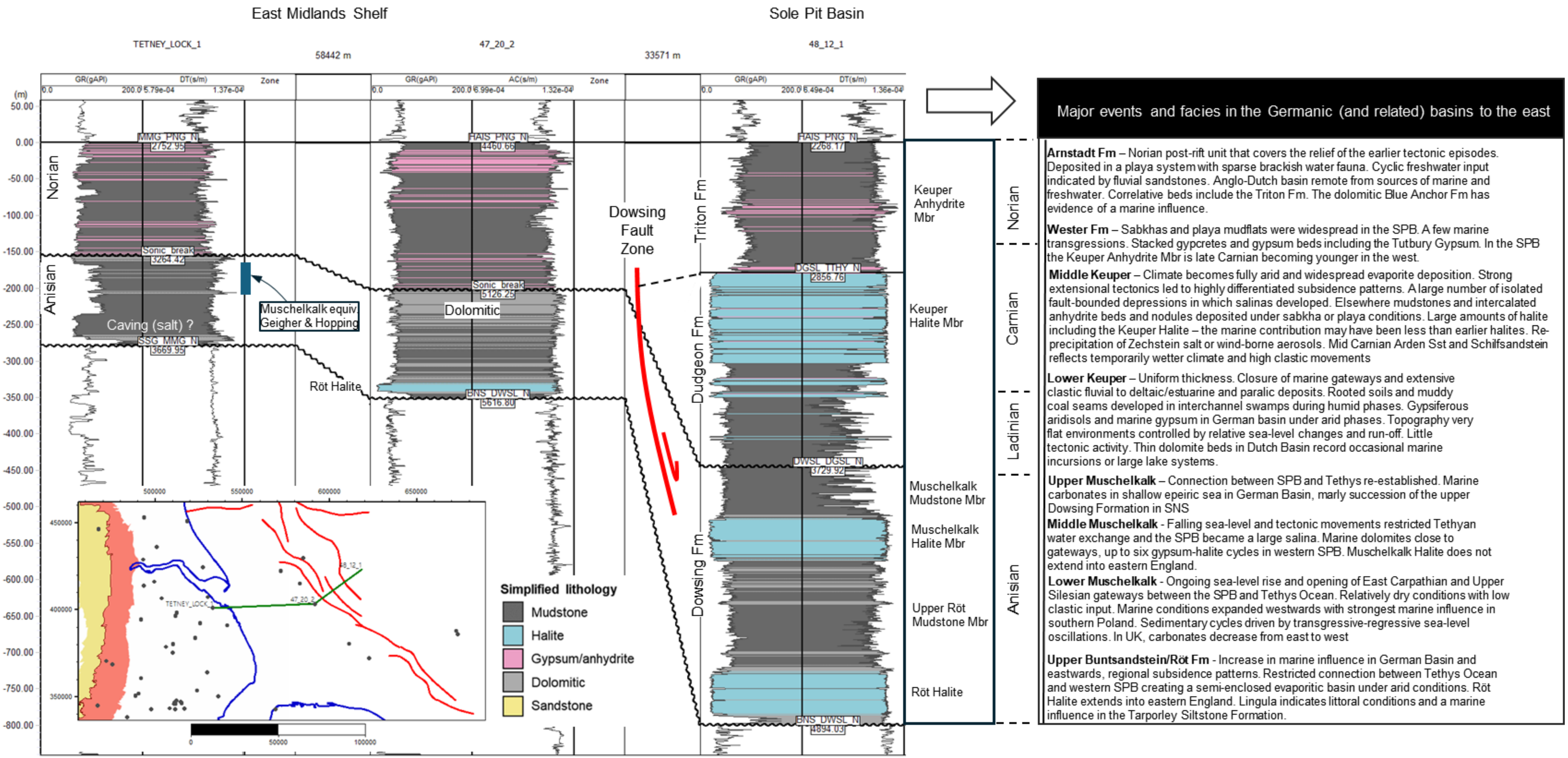


Figure 13 Summary of major events in the Germanic Middle and Late Triassic (Bachmann et al., 2010b) as a context for understanding controls on the UK MMG/Haisborough Group. UK sequences illustrated using boreholes from the East Midlands Shelf and Sole Pit Basin. Periodically marine conditions of the 'Muschelkalk' were replaced by deltaic, hypersaline and nonmarine environments of the Ladinian-Norian 'Keuper'.

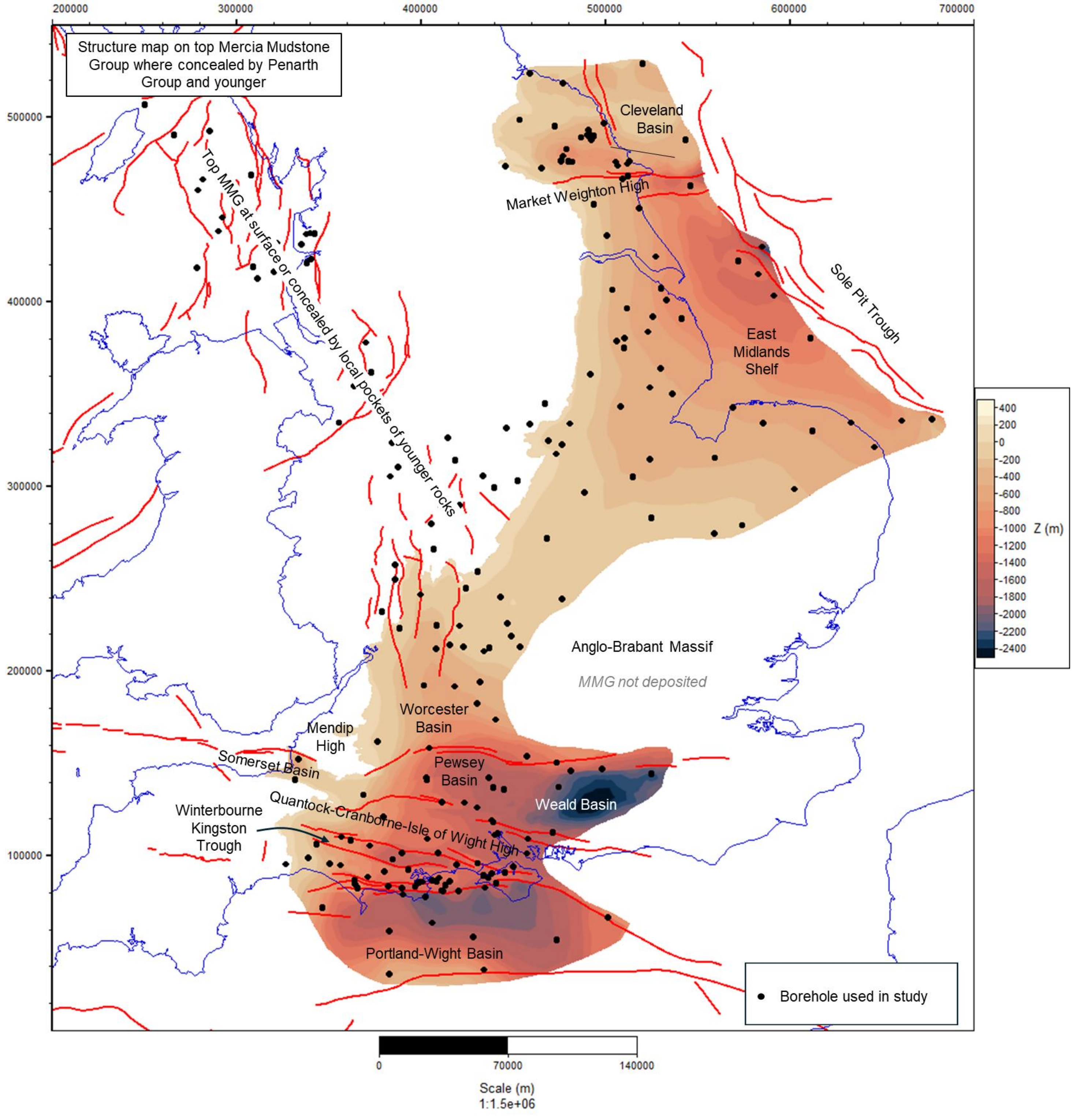


Figure 14 Structure map on the top of the MMG interpolated from borehole data whose locations are shown by a black circle. Only areas with a cover of Penarth Group and younger Jurassic rocks have been gridded. MMG within deep basins straddle the structural high created by the Anglo-Brabant Massif. Map uses OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024.

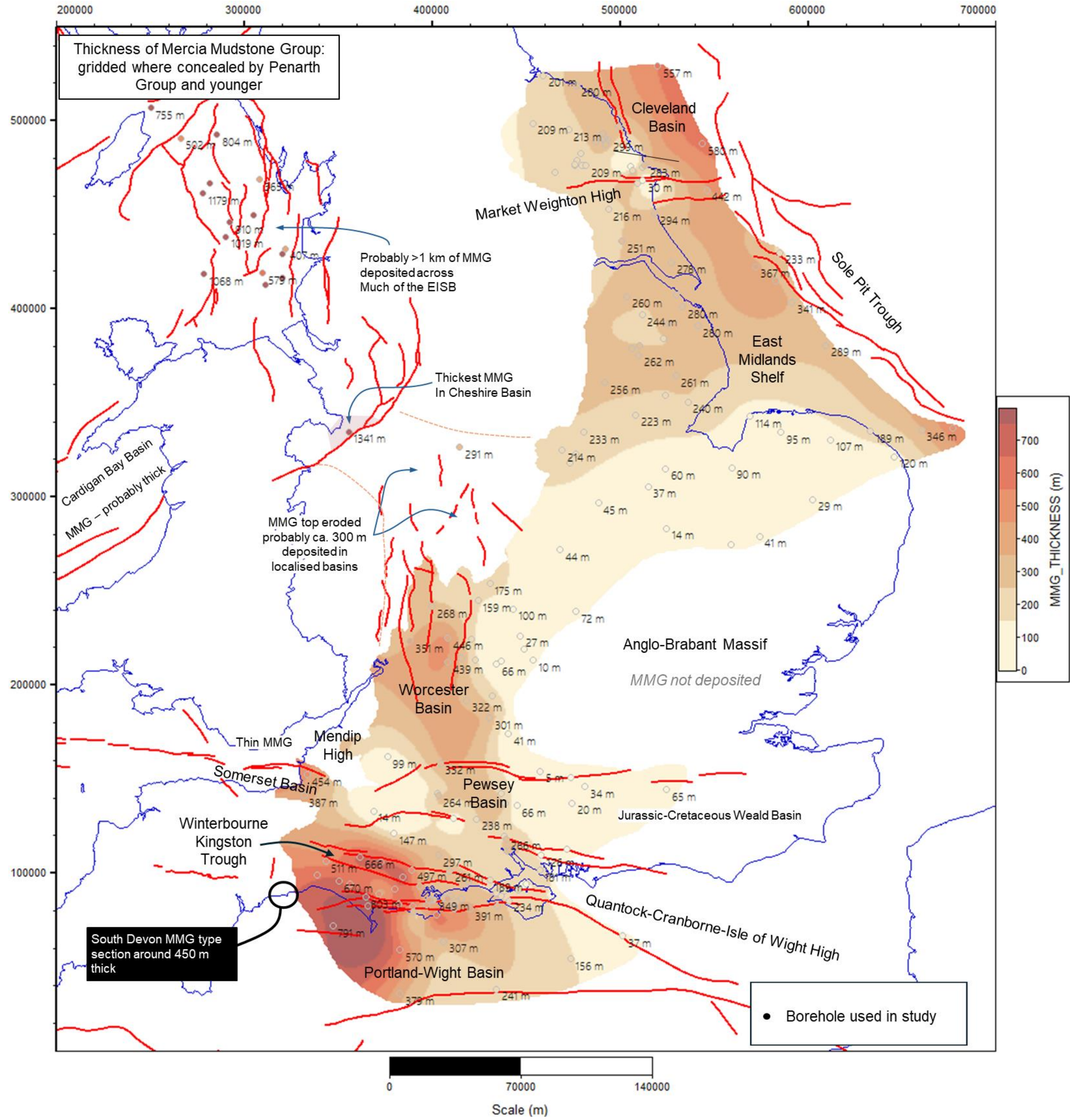


Figure 15 Map of total MMG thickness in metres. Borehole values are interpolated only where full sequences are preserved beneath Penarth Group. Thickness values are posted against borehole locations – in the East Irish Sea Basin most of these values represent erosionally-truncated MMG which accounts for the variability. The thickest MMG occurs in the north-west, with around 1300 m in the Cheshire Basin and probably a comparable (or greater) maximum thickness deposited in the East Irish Sea Basin. Thick successions (ca. 900 m) were also deposited in the Portland-Wight Basin. Note the thin to absent MMG of the Weald Basin which did not subside significantly until the Jurassic and Early Cretaceous. Map uses OSGB36/British National Grid with grid coordinates in metres. Contains Ordnance Survey data © Crown copyright and database rights 2024.

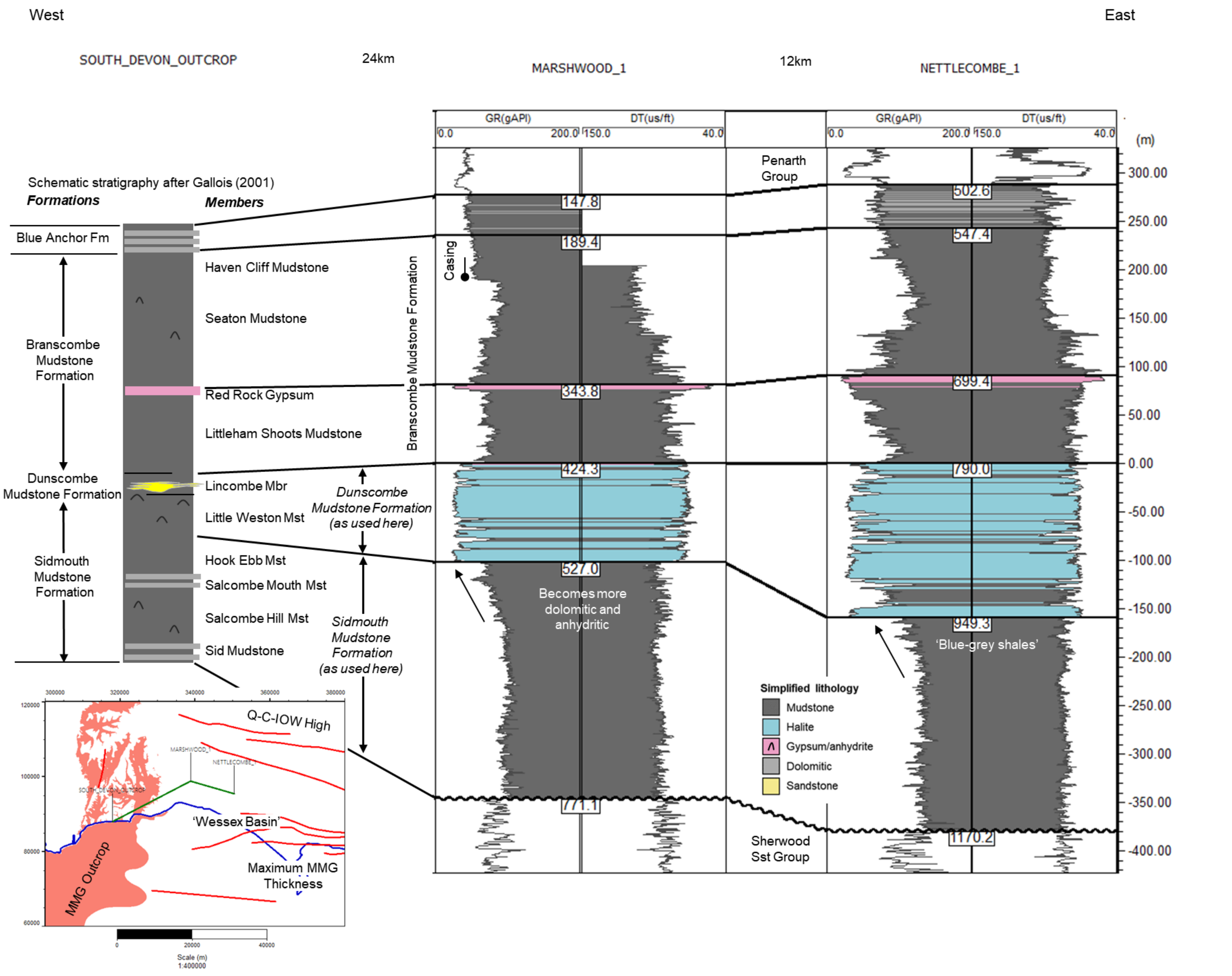


Figure 16 Correlation between MMG type-section outcrops in south Devon (Gallois, 2001) and boreholes in the Dorset Basin, where the Dunscombe Mudstone Formation includes thick halite. The definition of the Dunscombe Mudstone Formation is extended in this report to include the Little Weston Mudstone Member of Gallois (2001).

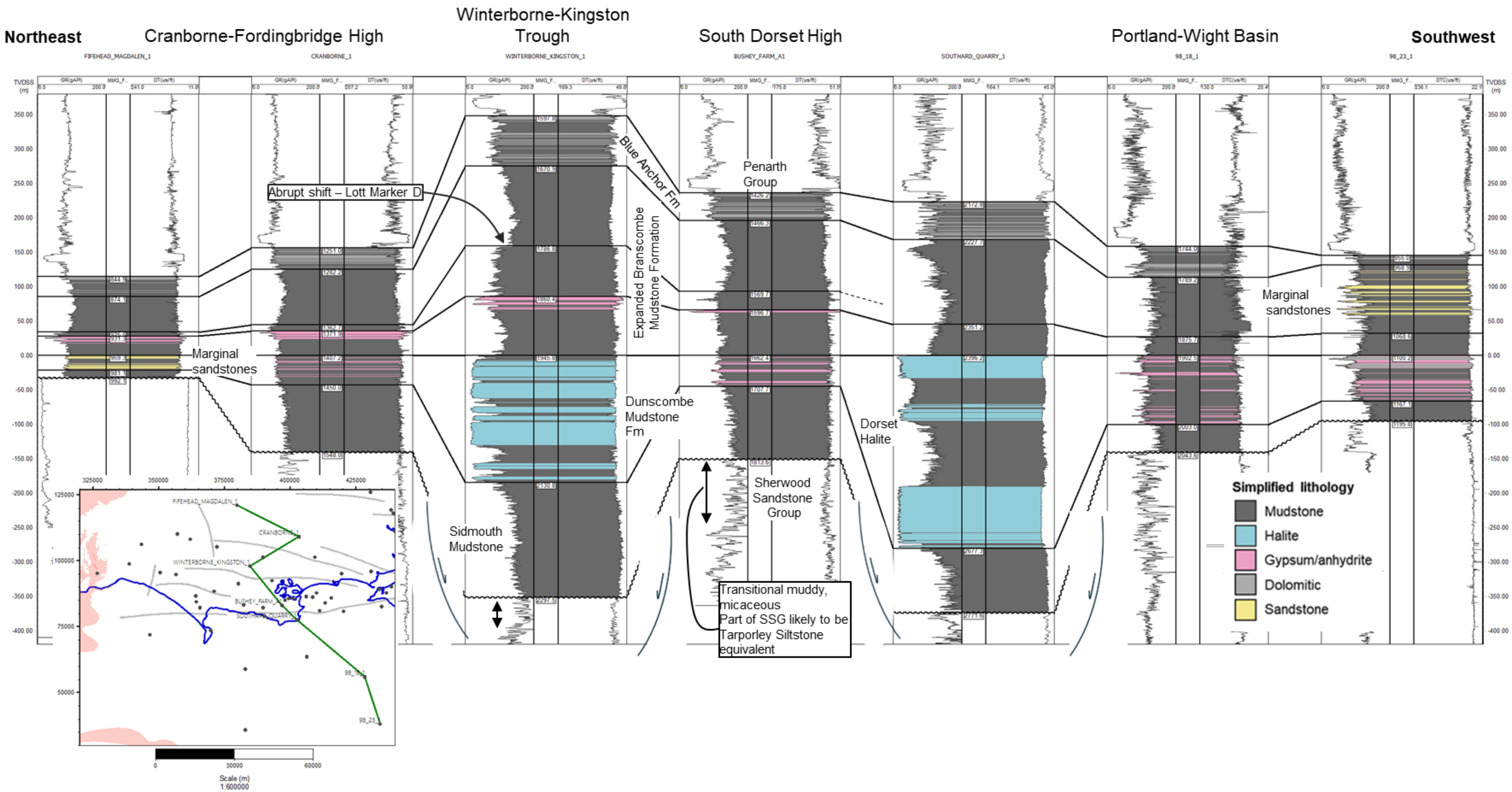


Figure 17 NE to SW correlation panel across the Wessex Basin from the Cranborne-Fordingbridge High to the southern limits of the Portland-Wight Basin. Note fault control on halite distribution. The Branscombe Mudstone Formation is greatly expanded in the Winterborne-Kingston Trough.

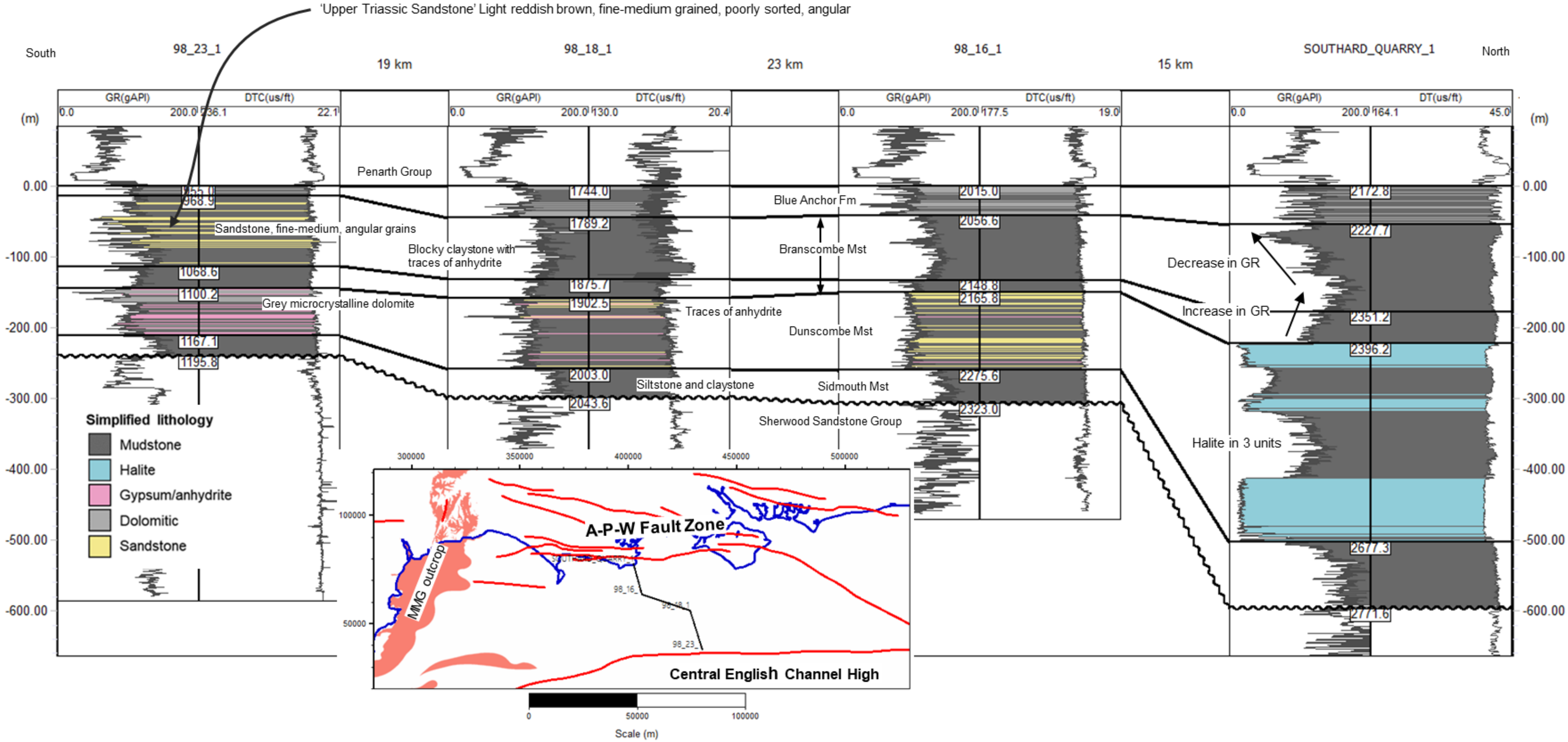


Figure 18 South to north panel from southern margin of the Portland-Wight basin into the main depocentre adjacent to the Abbotsbury-Purbeck-Wight (A-P-W) Fault Zone. Thick developments of halite adjacent to the fault pass southwards into dolomitic-anhydritic muds, sands and siltstones. Note the abrupt decrease in gamma ray values at the top of the Sidmouth Mudstone Formation as this interval is entered. Note the presence of sandstones in the Branscombe Mudstone Formation in borehole 98/23 -1 probably related to the proximity of the Central English Channel High. Lithological annotations are taken from cuttings descriptions on composite logs.

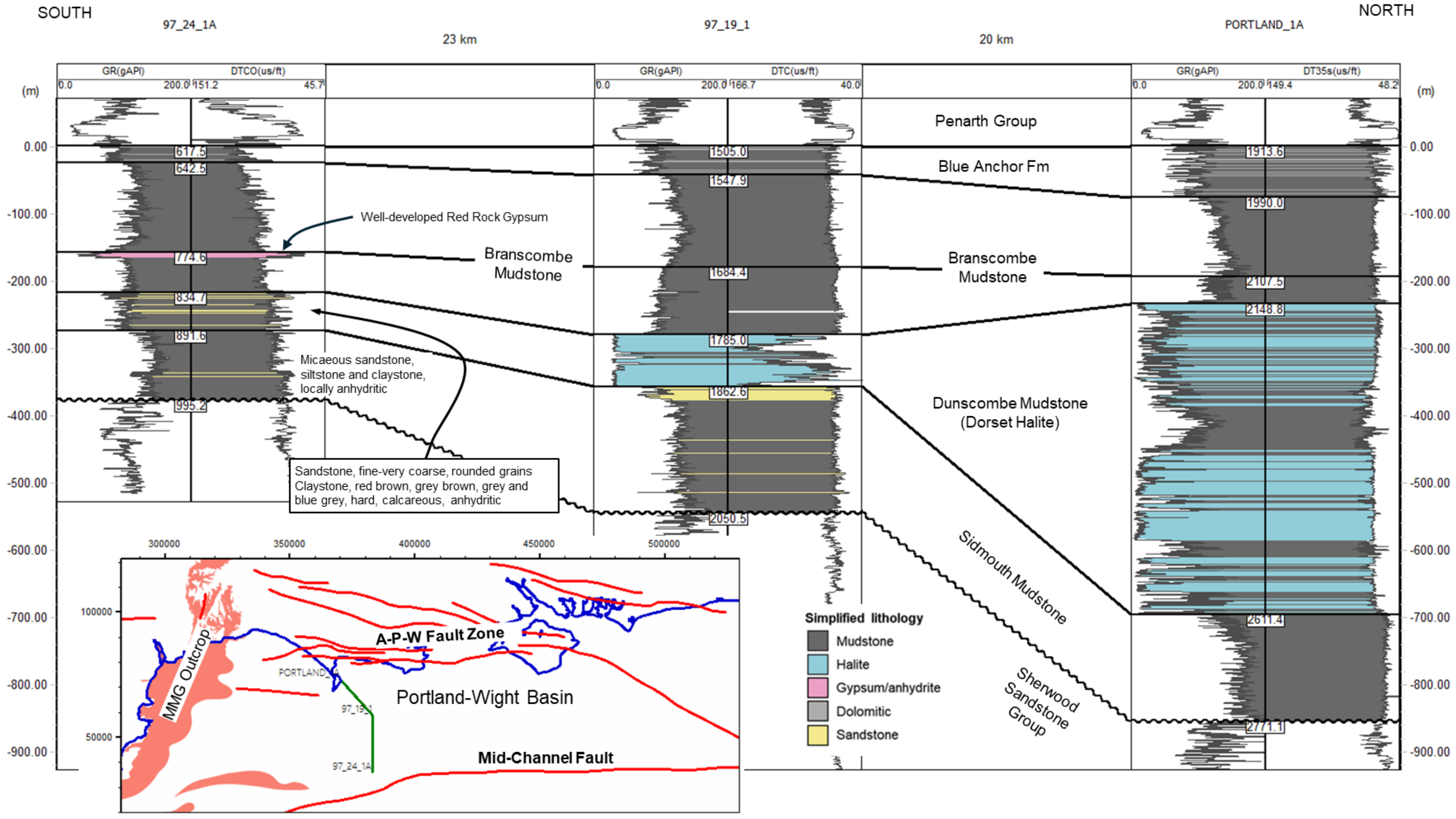


Figure 19 South to north panel from southern margin of the Portland-Wight basin into the main depocentre adjacent to the Abbotsbury-Purbeck-Wight (A-P-W) Fault Zone. Thick developments of halite adjacent to the fault at Portland show rapid thinning (across a fault) to the south in 97/19 -1. Further south in 97/24 -1A the lateral equivalent of the Dorset Halite includes sandstones and anhydritic or calcareous mudstones. Note the presence of micaeous sandstones in the Sidmouth Mudstone Formation of 97/24 -1A and a well-developed anhydrite marker in the Branscombe Mudstone Formation, a correlative of the Red Rock Gypsum Member at outcrop (see Figure 10).

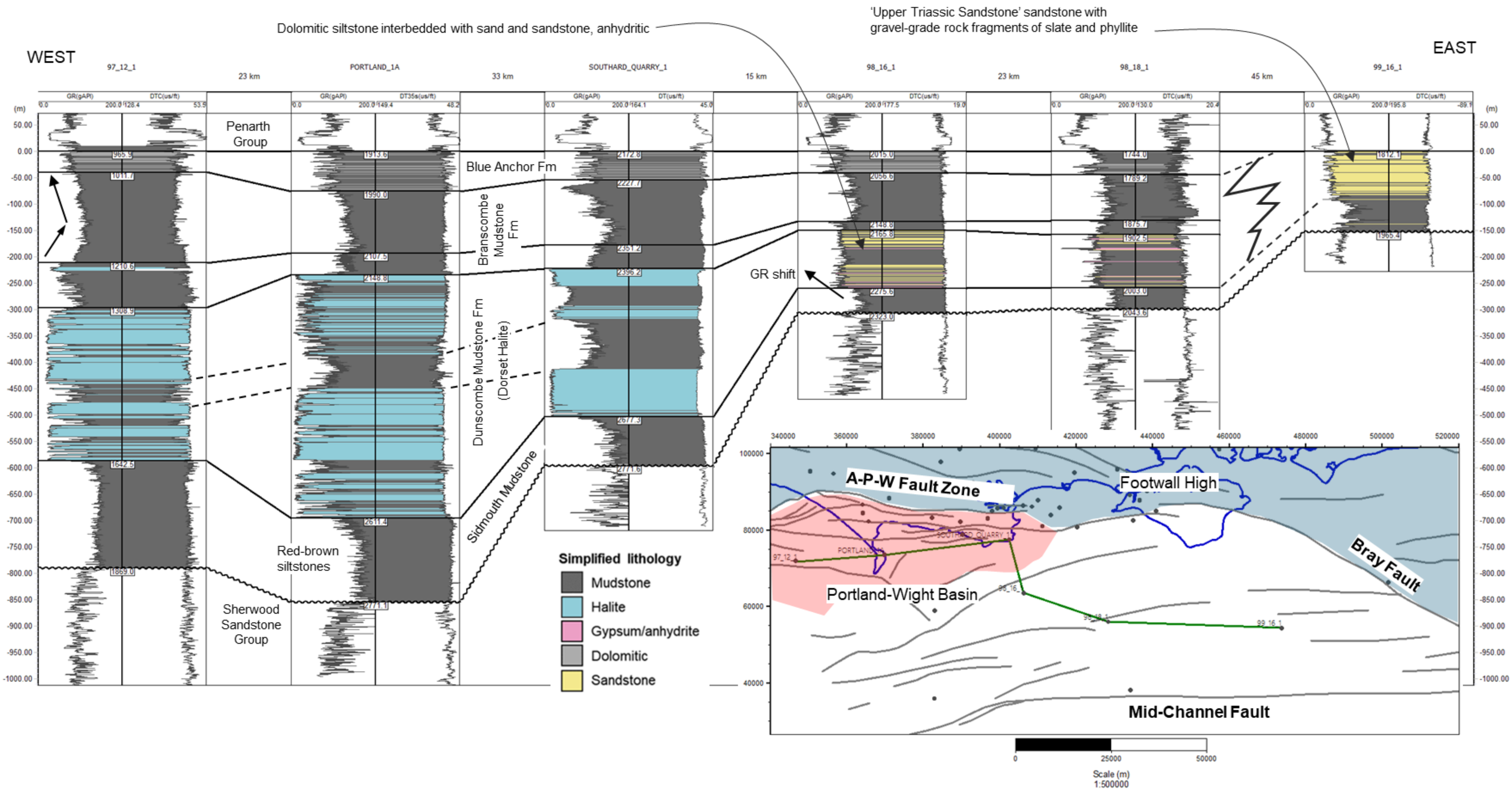


Figure 20 West to east correlation panel in the Portland-Wight Basin. Thick halites (of variable thickness) occur with the depocentre of the Portland-Wight Basin adjacent to the Abbotsbury-Purbeck-Wight (A-P-W) Fault Zone. Eastward the Dorset Halite correlates with dolomitic siltstones interbedded with sandstones and anhydritic mudstone in 98/16-1 and 98/18-1. Closer to the basin margin in 99/16-1 the MMG becomes dominated by sandstones and breccias.

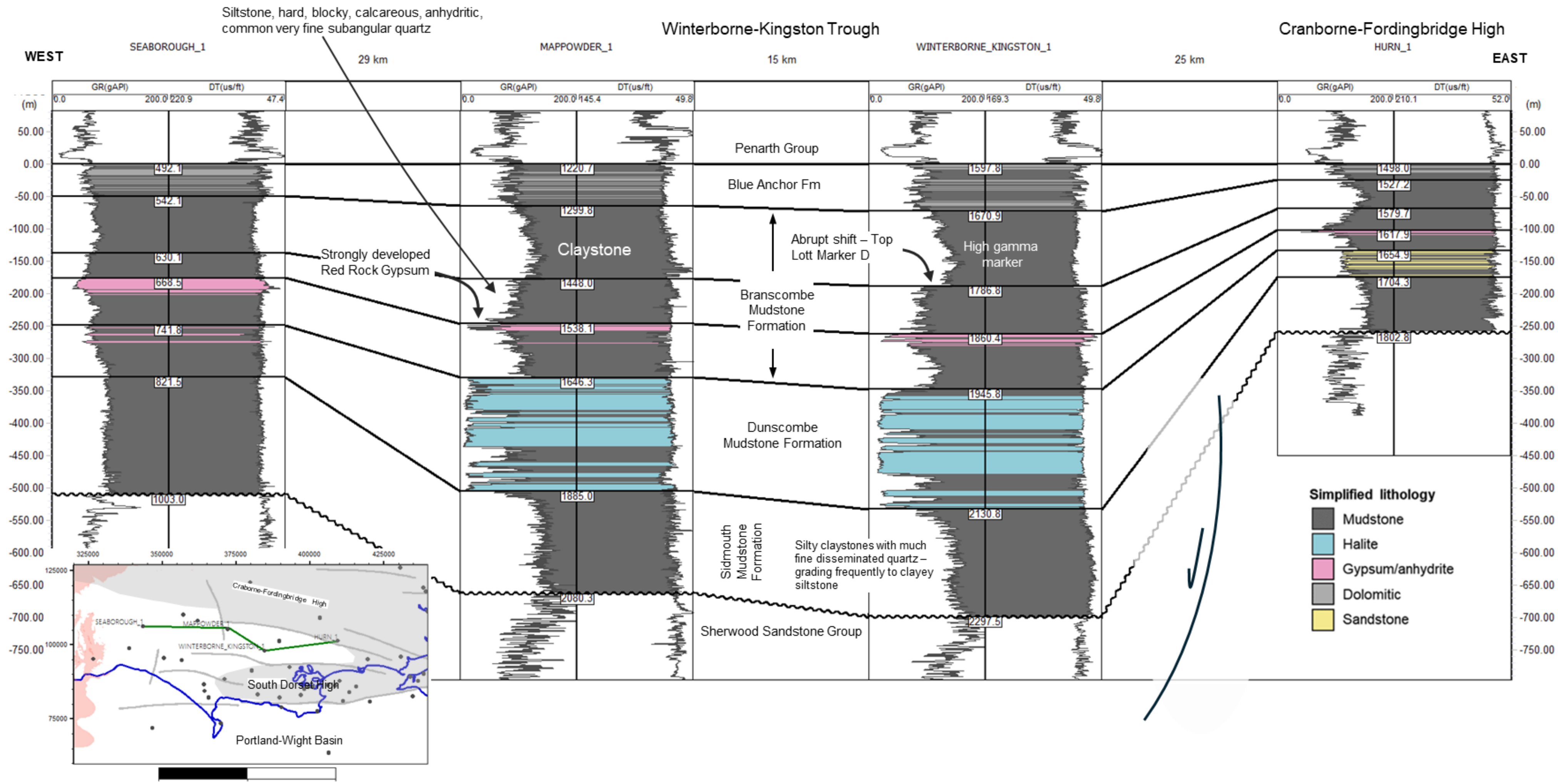


Figure 21 West-East panel along the axis of the Winterborne-Kingston Trough and stepping onto the Cranborne-Fordingbridge High. Halites are present within the graben structure at Mappowder and Winterborne Kingston. These pass laterally into sandstones on the Cranborne-Fordingbridge High at Hurn. The Red Rock Gypsum Member is a strongly developed log marker consisting of anhydrite (at depth) in a mudstone matrix with dolomite and gypsum. In Mappowder and Winterborne Kingston, this anhydrite marker is overlain by a 70 m thick unit of hard blocky siltstones with much fine angular quartz (possible loess deposits). This unit forms a prominent 'bench' on the gamma-ray log with an apparently sharp change into overlying claystones (corresponding to the top of Lott Unit D (Lott et al., 1982)).

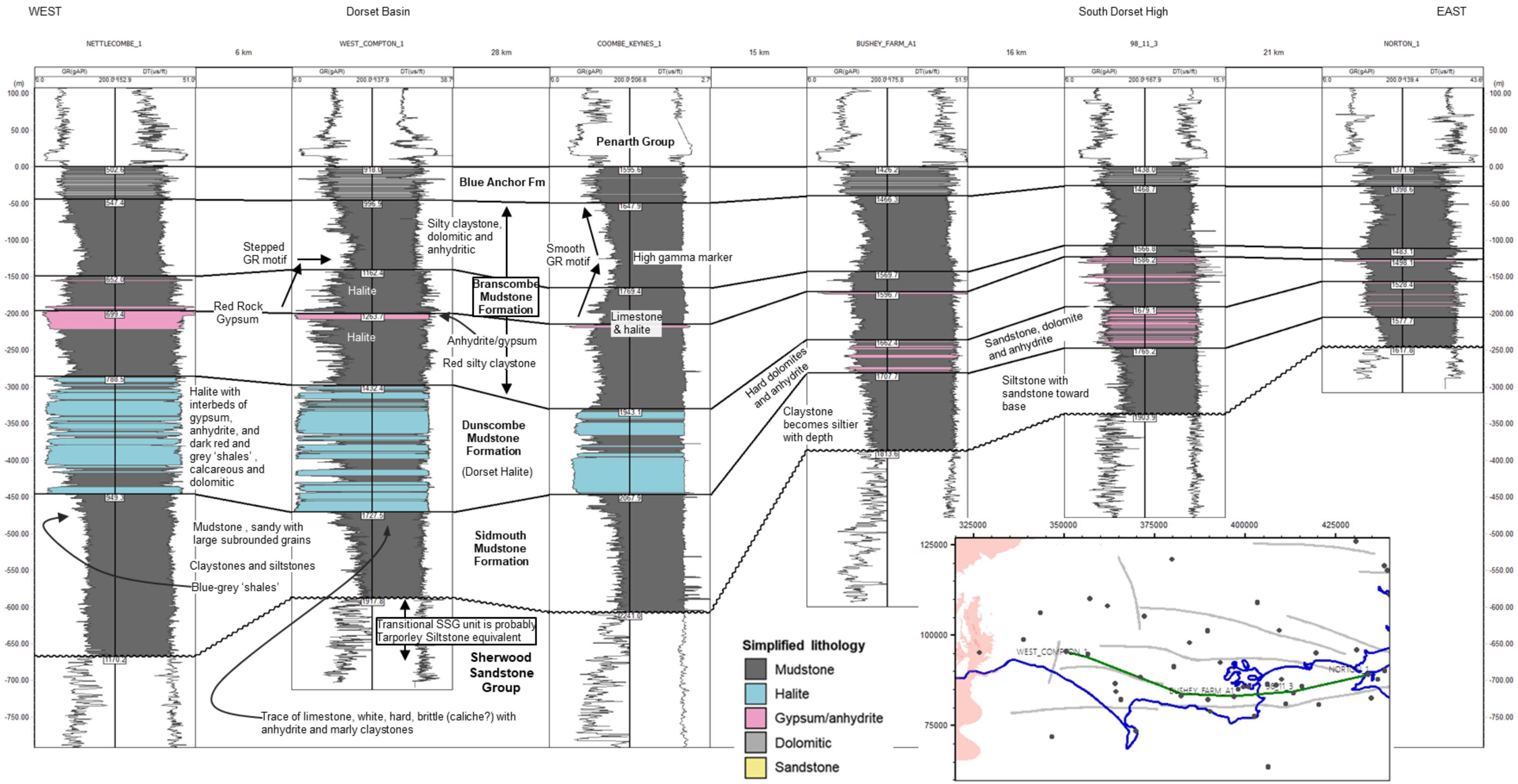


Figure 22 West to east correlation panel from the Dorset Basin onto the South Dorset High showing progressive thinning of the MMG. The Sidmouth Mudstone is a remarkably uniform silty mudstone despite thinning. Low gamma-ray spikes at the top are associated with white, hard limestones (interpreted as calcrete) in West Compton 1; coarse, subrounded sand grains in Nettlecombe 1; and halite in Coombe Keynes 1 The Dunscombe Mudstone Formation thins eastward and passes from halite into mudstones with anhydrite, dolomite and sandstone. In the Branscombe Mudstone, anhydritic silty mudstones occur above and below a well-developed anhydrite marker bed. In West Compton there is evidence of halite above and below the anhydrite marker.

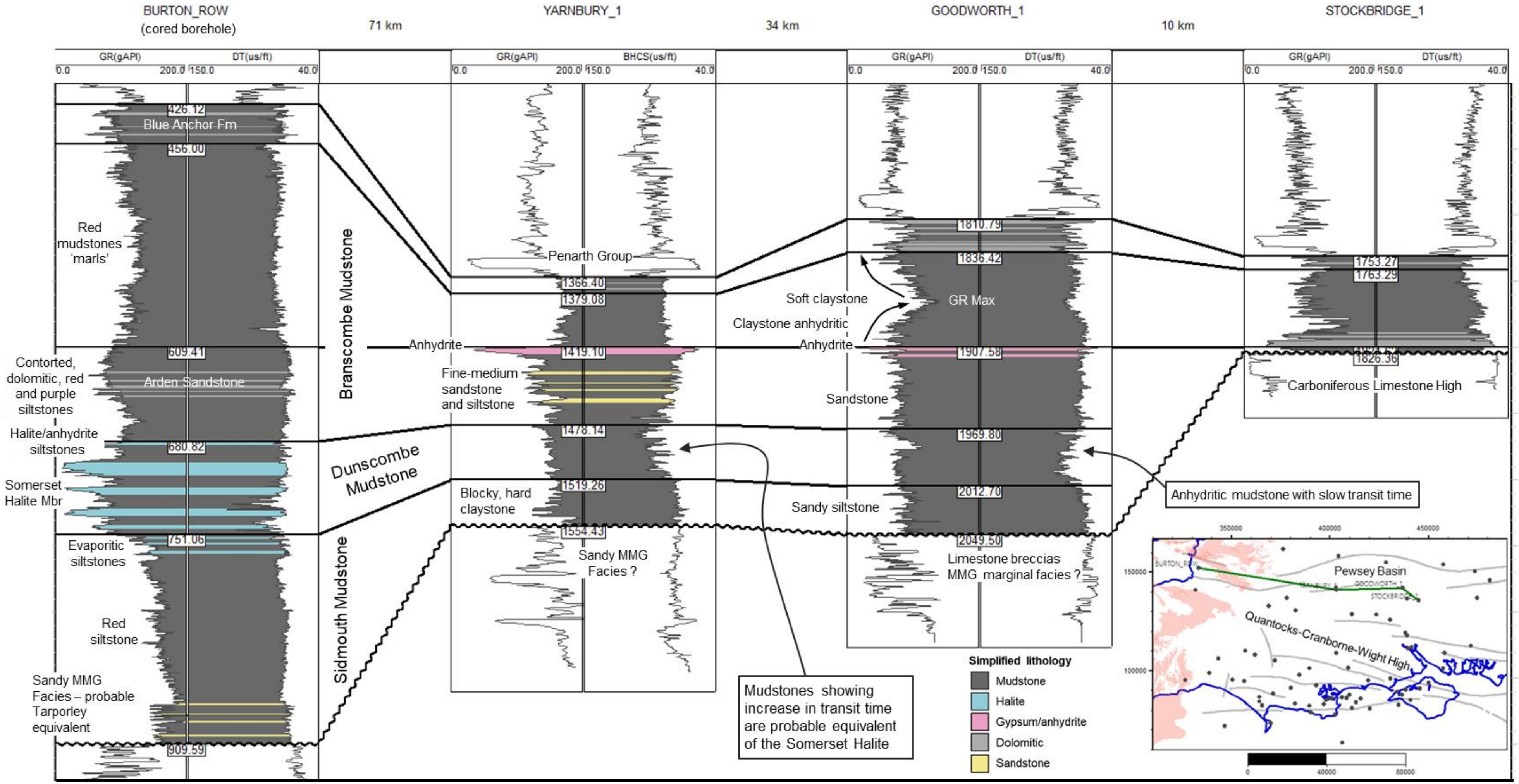


Figure 23 Correlation panel from Burton Row in the Somerset Basin toward Stockbridge 1, south of the Pewsey Basin. In the Somerset Basin, the Sidmouth Mudstone is a thick red silty claystone/siltstone which shows a progressive upward decrease in gamma-ray value into evaporitic siltstones at the top (Whitaker and Green, 1983). The Dunscombe Mudstone (Somerset Halite) is composed of four main halite intervals which are thin relative to those in the Portland-Wight Basin. Eastwards, correlative Dunscombe Mudstone comprises anhydritic mudstone whose main distinguishing feature is a high sonic transit time. The Branscombe Mudstone is a succession of red mudstones, siltstones and sandstones split into two parts by the Red Rock Gypsum. This is strongly developed in the Yarnbury 1 borehole, less so in Burton Row. In the lower part of the Branscombe Mudstone, dolomitic contorted siltstones in the Burton Row and sandstones in Yarnbury 1 are likely correlatives of the Carnian North Curry (Arden) Sandstone seen at outcrop (Dawson et al., 2022). In the upper part of the Branscome Mudstone, the 'gamma-ray-maximum' marker seen to the south is clearly seen in Goodworth 1.

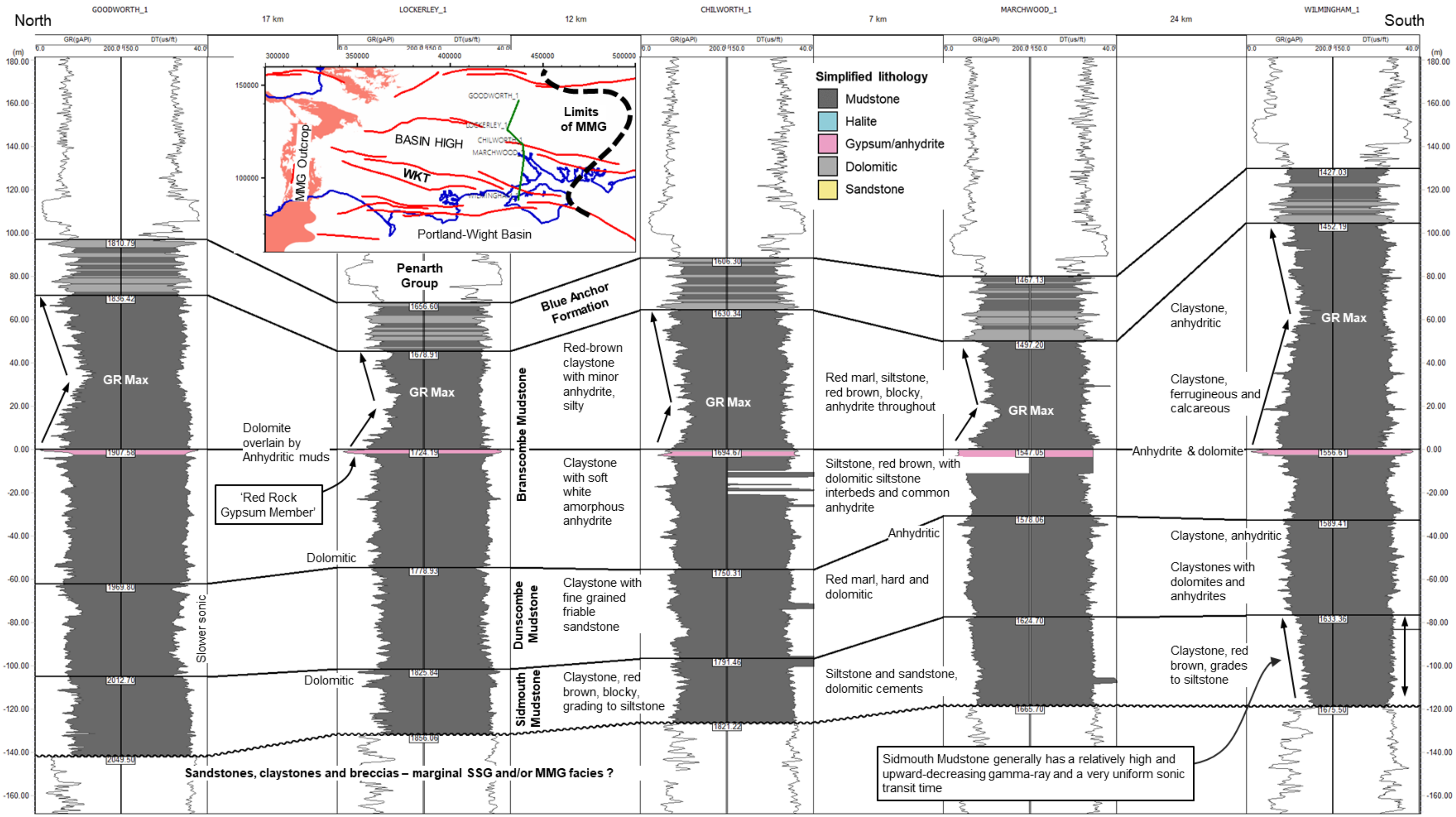


Figure 24 North-south correlation panel toward the eastern limits of the MMG subcrop from Goodworth 1 to Wilmingham 1 on the Isle of Wight. Here individual MMG formations start to loose clear identity. The Sidmouth Mudstone is thin relative to basinal settings but can still be recognised as a blocky mudstone or siltstone with a uniform sonic travel time and a relatively high, upward decreasing gamma-ray response (e.g. see Wilmingham 1). The Dunscombe Mudstone is subtlety marked by the appearance of dolomites, anhydrite and sandstones. Gamma ray and sonic logs may show slightly greater serration because of the heterogeneity. The slow sonic zone that distinguishes the Dunscombe Mudstone in Goodworth 1 becomes more difficult to recognise southwards. The main marker within the Branscombe Mudstone (and the MMG as a whole) is formed by the 'Red Rock Gypsum' (an anhydrite at depth). Above this anhydrite marker the Branscombe Mudstone shows the widely-developed pattern of upward increasing gamma-ray to a maxima (GR Max), followed by an upward decrease toward the base of the Blue Anchor Formation. Note the considerable expansion of the Branscombe Mudstone interval (particularly below GR Max) in the Wilmingham 1 borehole on the Isle of Wight, possibly reflecting eastward propagation of the Winterborne-Kingston Trough (WKT).

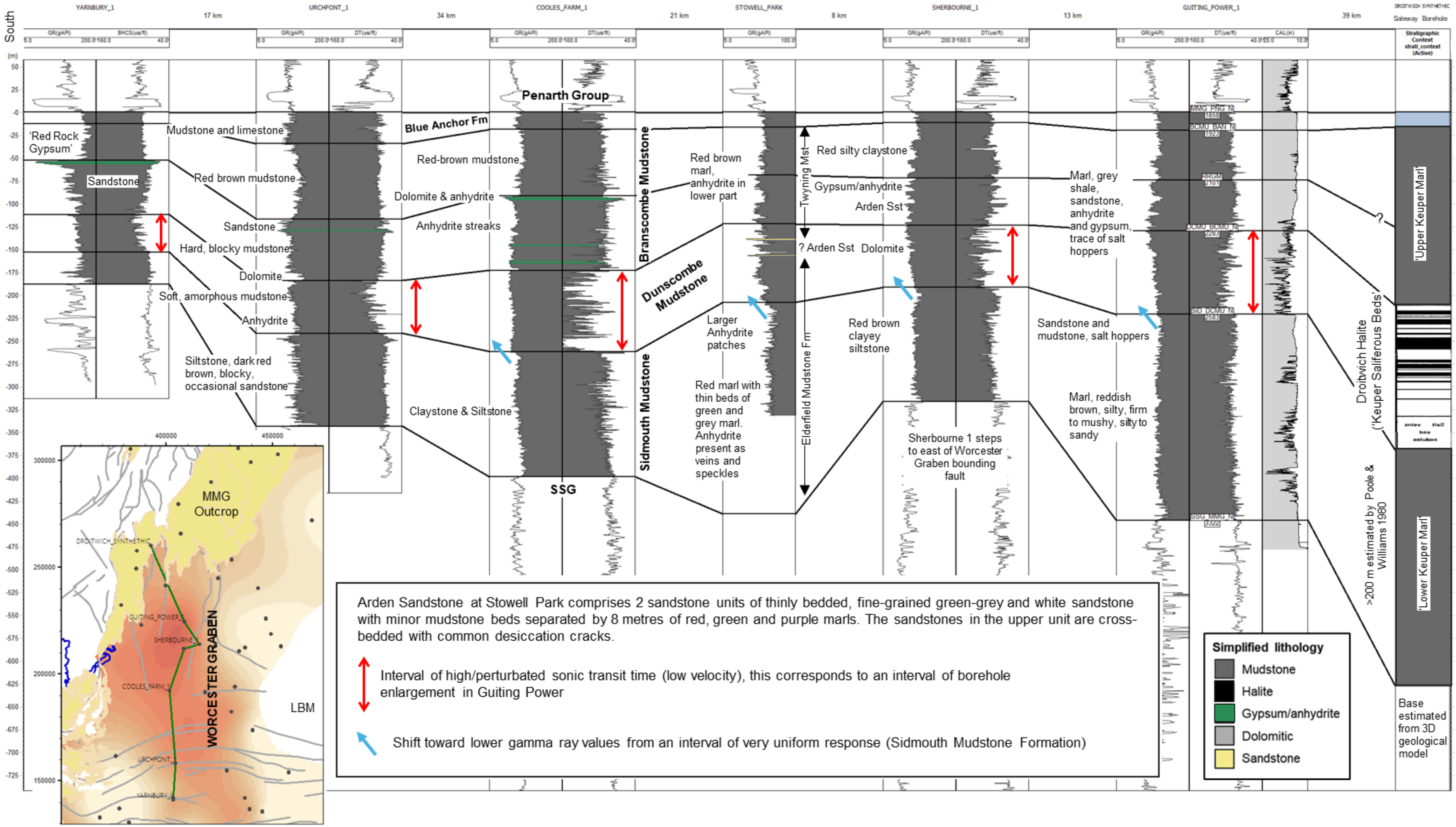


Figure 25 South to north section along the axis of the Worcester Graben (Sherbourne 1 steps east of the eastern bounding fault with thinning of MMG). Note the overall thickening from south to north. In the Worcester Graben the MMG below the Blue Anchor Formation was conventionally divided into 3 main parts: the Lower Keuper Marl, Keuper Saliferous Beds and the Upper Keuper Marl (Poole and Williams, 1981). This was later revised into two main parts (Eldersfield and Twyning Mudstone) separated by the Arden Sandstone (Barclay et al., 1997). A three-part subdivision is suggested by the sonic log. As seen elsewhere, the Sidmouth Mudstone has a typically short transit time and a relatively high gamma-ray response. Fine serrations in the gamma-ray log probably represent an alternation of blocky red brown mudstones and fine-grained sandstones (Milroy et al., 2019). The Dunscombe Mudstone is represented an interval of high sonic transit time (from soft mudstones and evaporites) which can be correlated between boreholes. These facies are lateral correlatives of the Droitwich Halite proven in the Saleway Borehole (Poole and Williams, 1981). Caliper logs may show irregular borehole enlargement (e.g. see Guiting Power 1). The Branscombe Mudstone marks a return to low and relatively uniform sonic transit times. The anhydrite marker bed seen in Yarnbury 1 can be tracked northward to Cooles Farm 1 but becomes indistinct thereafter. The Arden Sandstone occurs in the lower part of the Branscombe Mudstone, but a sandstone identified (in the borehole record) as the Arden Sandstone appears in the Dunscombe Mudstone in the Stowell Park borehole.

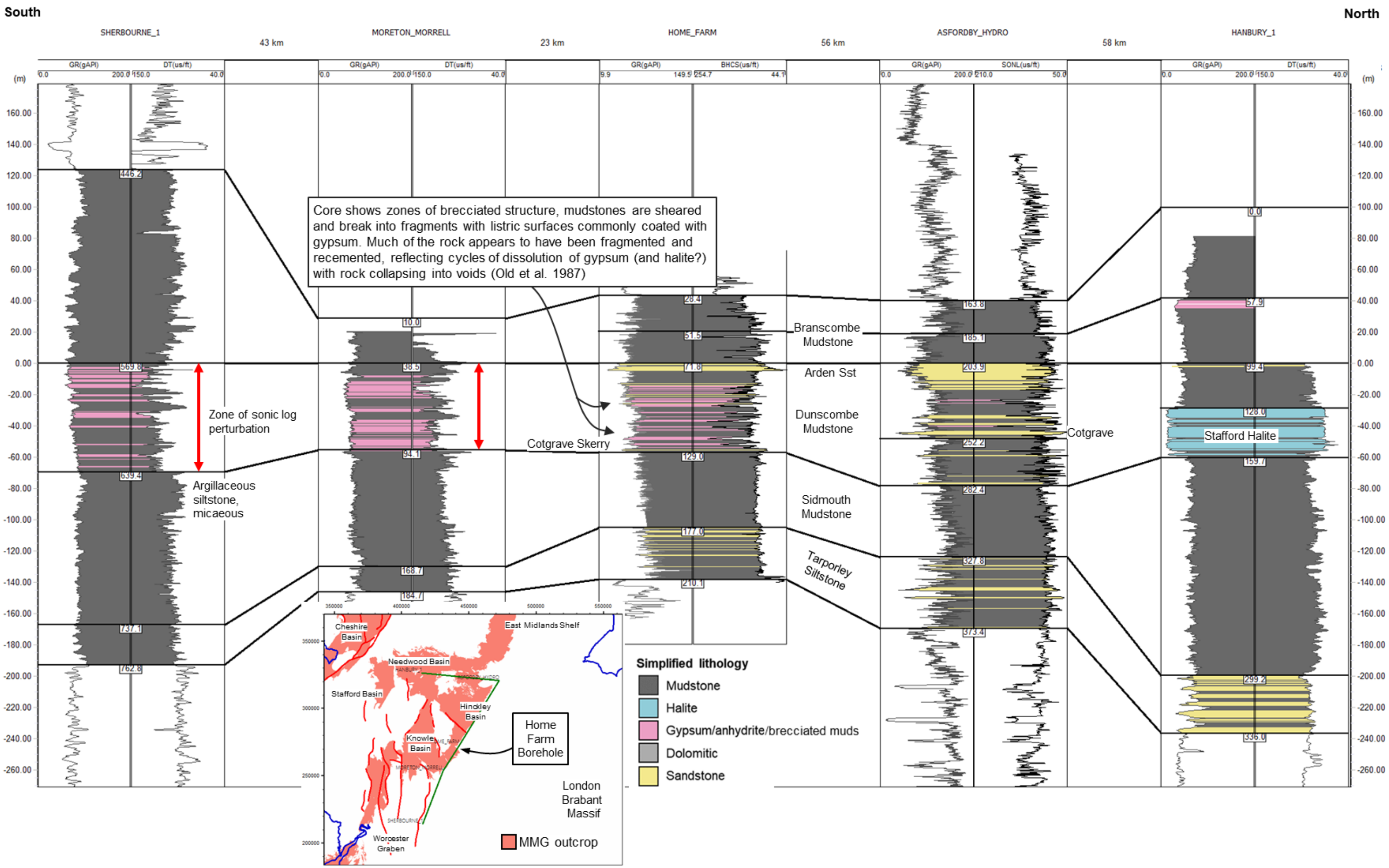


Figure 26 Correlation from the eastern footwall of the Worcester Graben into the Triassic basin complex of the English Midlands. The Tarporley Siltstone becomes a readily identifiable unit of thin sandstones and mudstones (around 40 m thick) from the Home Farm borehole northwards. The Sidmouth Mudstone is predominantly red brown mudstone with relatively high (but finely serrated) gamma-ray response (micaeous) and uniform high sonic velocity. It thickens markedly (to 140 m) into Hanbury 1 in the Needwood Basin. The Dunscombe Mudstone is marked by a zone (around 60 m thick) of highly perturbed sonic transit time with many high (slow) values. In the cored Home Farm borehole this interval is marked by many intervals of brecciated mudstones with evaporites and thin sandstone units (Old et al., 1987). The Dunscombe Mudstone correlates with the Stafford Halite (and overlying evaporitic mudstones) in the Hanbury 1 borehole. The Arden Sandstone forms the top of the Dunscombe Mudstone Formation. The Branscombe Mudstone is thin (around 40 m) across the Moreton Morell, Home Farm and Asfordby Hydro boreholes of the English Midlands and comprises mudstones and gypsum/anhydrite generally concentrated into (often named, e.g. Tutbury Gypsum) beds toward the middle.

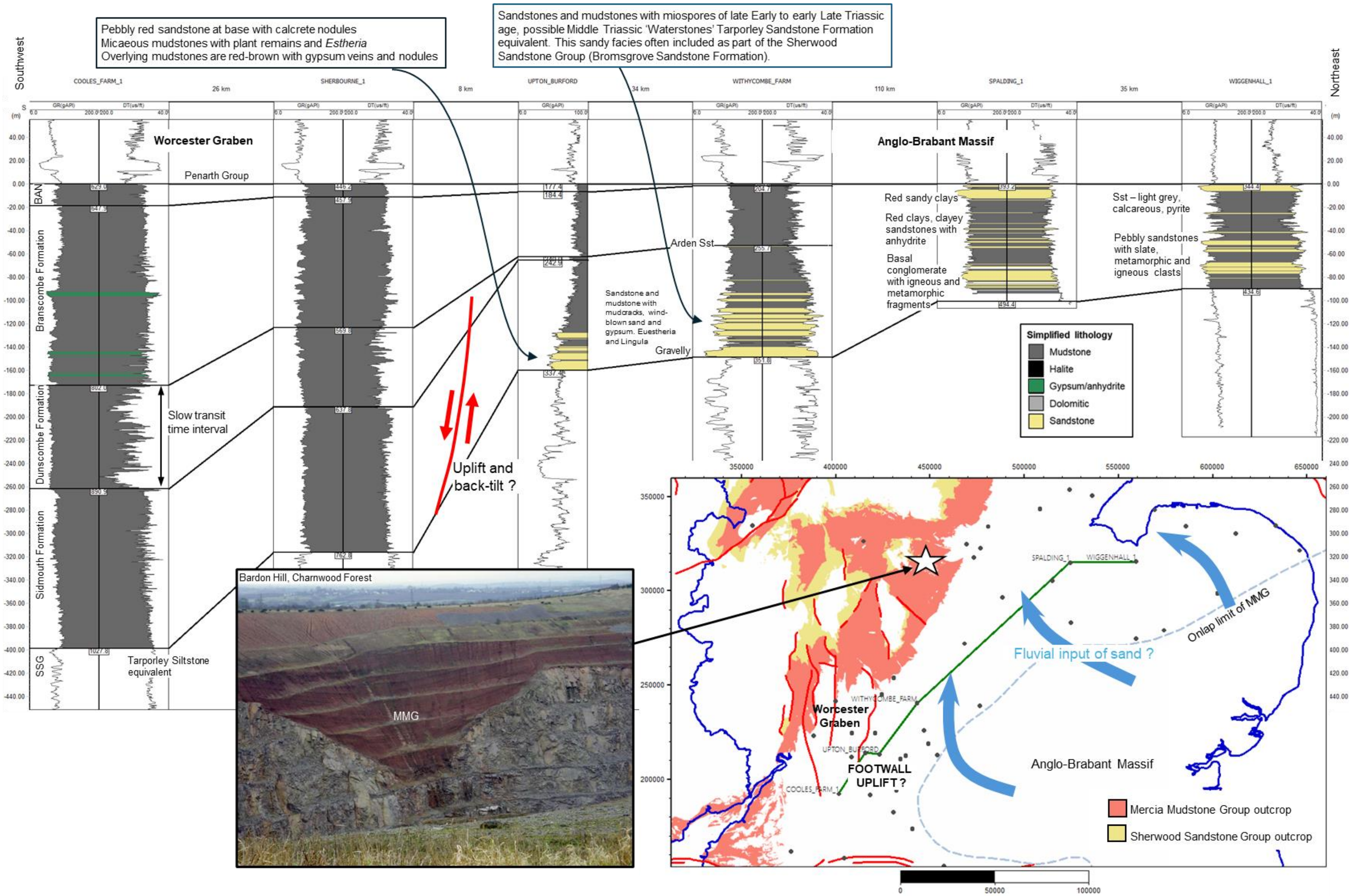


Figure 27 Correlation panel from the Worcester Graben across the northern flank of the Anglo-Brabant Massif. The MMG thins abruptly across the eastern bounding fault of the Worcester Graben between Sherbourne 1 and Upton Burford. Boreholes such as Withycombe Lane show a notably sandy development of Tarporley Siltstone equivalent strata that (lithostratigraphically) are usually included within Sherwood Sandstone Group. These include marine bivalves, ostracods and the brachiopod Lingula. Toward the east in Spalding and Wiggenhall the MMG thins and becomes conglomeratic toward the base. Inset photograph shows MMG infilling high relief topography developed on Precambrian volcanics in the area of Bardon Hill, Charnwood Forest [SK453128]. It is speculated that footwall uplift and back-tilting along the eastern flanks of the Worcester Graben may have diverted coarse clastics from the Anglo-Brabant Massif northwards rather than into the Worcester Graben.

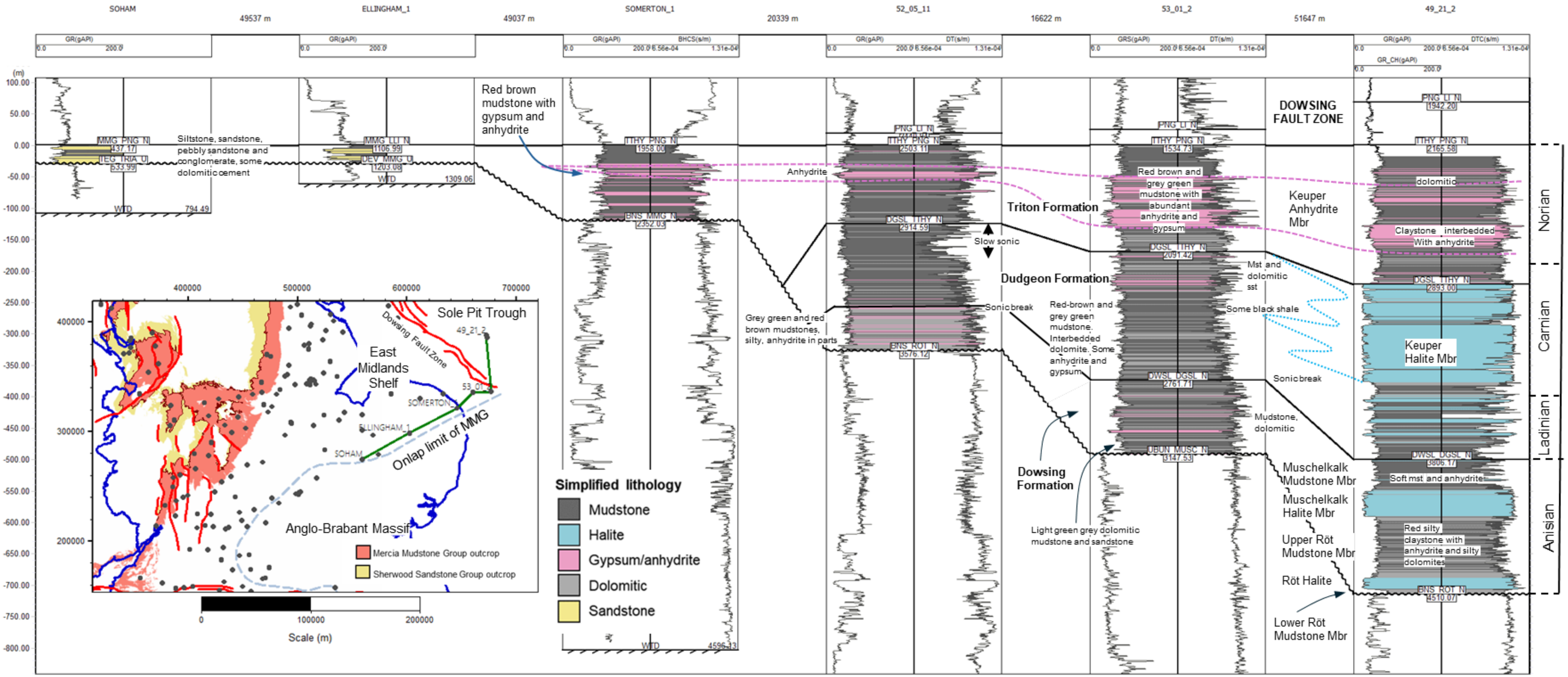


Figure 28 Correlation panel from the Anglo-Brabant Massif (ABM) into the Sole Pit Trough. Lithological notes from composite logs (cuttings). High on the ABM, near the limits of MMG onlap, it consists mainly of thin pebbly sandstones and conglomerates with some dolomitic cement. The attribution of these to the MMG is on assumed conformity to overlying Jurassic strata but there is no independent dating evidence (Lee et al., 2015). From Somerton 1, the MMG forms an eastward thickening (onlapping) wedge of mudstones and evaporites. Three thick halite bodies are developed in the Sole Pit Trough (49/21-2): the Röt Halite, Muschelkalk Halite and Keuper Halite. The lowermost two are contained with the Dowsing Formation. The halites do not extend into 53/01-2 west of the Dowsing Fault where the Dowsing Formation consists of grey-green and red-brown mudstone and sandstone with common dolomite. The sonic velocity is serrated but high. In the Sole Pit Basin (49/21-2), the Dudgeon Formation transitions upwards from mudstone and thin halites into thick halites. On the shelf (53/01-2), mudstones with dolomite and anhydrite at the base of the Dudgeon Formation pass upwards in mudstones and dolomitic sandstones. An interval of slow sonic occurs toward the top of the Dudgeon Formation in 52/05-11. In the Sole Pit Trough, halites are sharply overlain by mudstones and anhydrites of the Triton Formation. The Keuper Anhydrite Member within the Triton Formation can be readily correlated, thinning westwards onto the shelf.

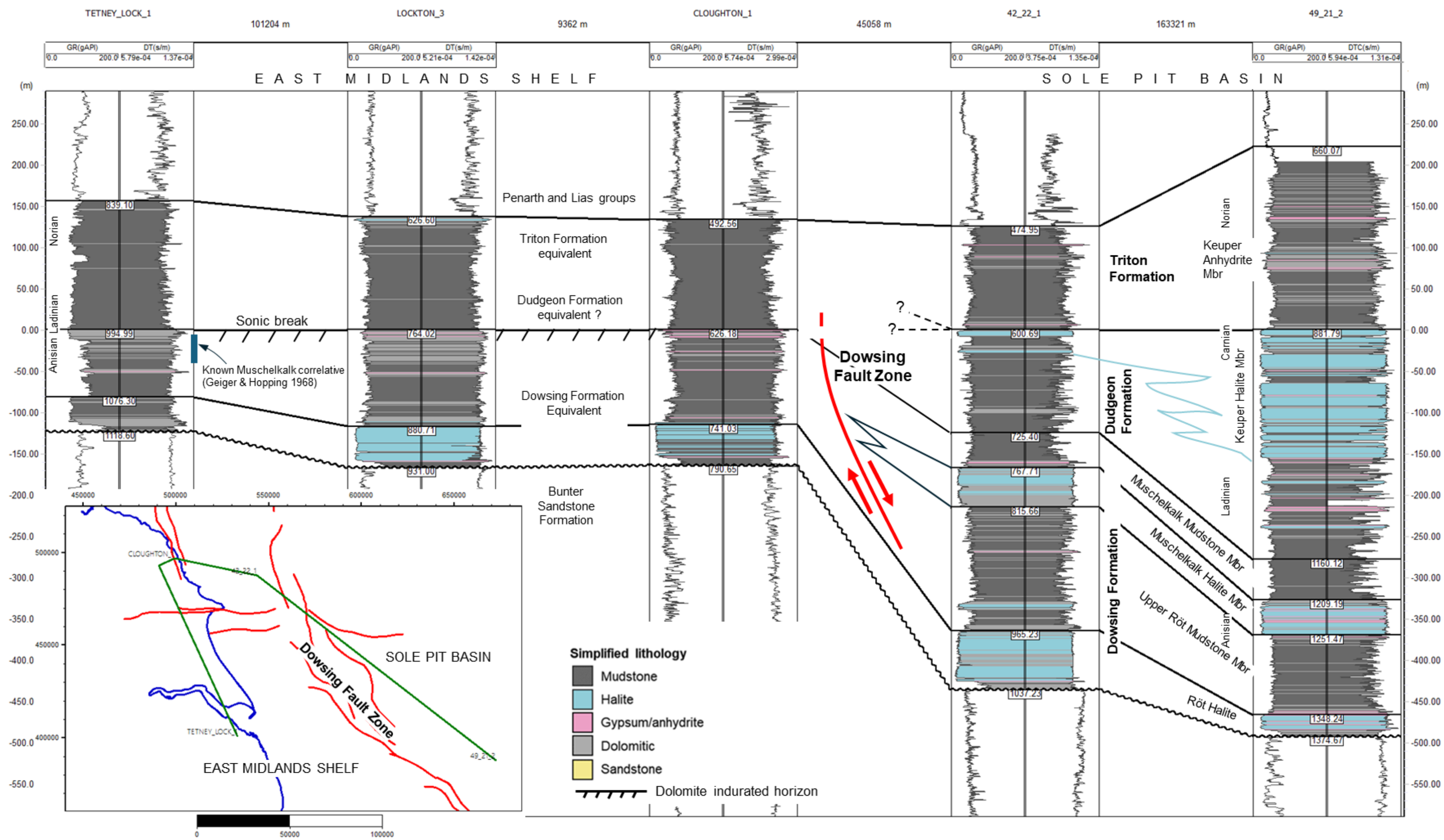
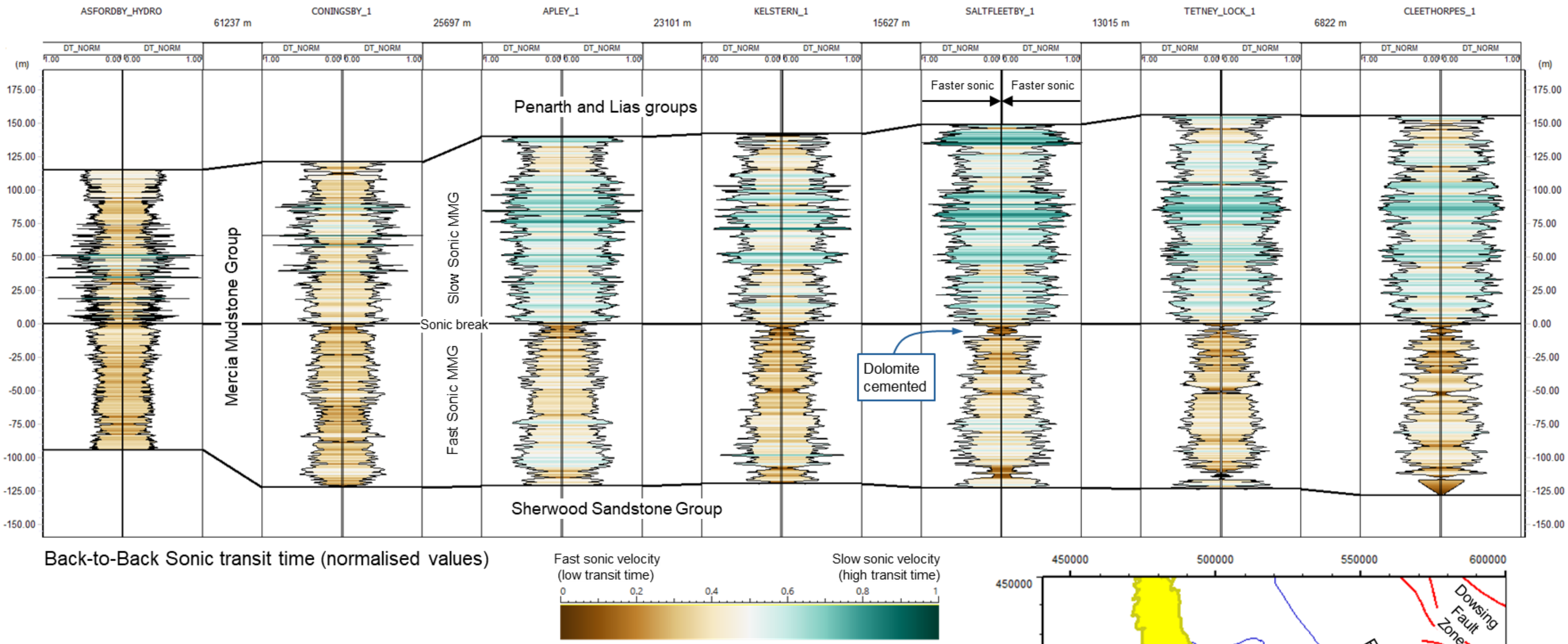


Figure 29 Correlation panel from the East Midlands Shelf (EMS) into the Sole Pit Basin. Note the abrupt thickening of the MMG across the Dowsing Fault Zone. The three main halites show a trend of increasingly basin-centric deposition (Cameron et al., 1992). The Röt Halite can be readily correlated from basin onto shelf. The Muschelkalk (and particularly Keuper) halites have a more restricted distribution within the Sole Pit Trough. Muschelkalk (late Anisian) equivalent strata on the EMS have been identified using biostratigraphy in Tetney Lock 1 (Geiger and Hopping, 1968). These strata occur just below an abrupt increase in sonic transit time ('sonic break') which can be correlated across the East Midlands Shelf (see Figure 29). In the absence of reliable biostratigraphy, is difficult to know how much of the MMG mudstone overlying the sonic break is representative of the Ladinian-Carnian Dudgeon Formation versus the overlying Carnian-Norian Triton Formation. The sonic break (and associated hard dolomitic limestones) could represent an interval of missing MMG when deposition shifted into the Sole Pit Basin.



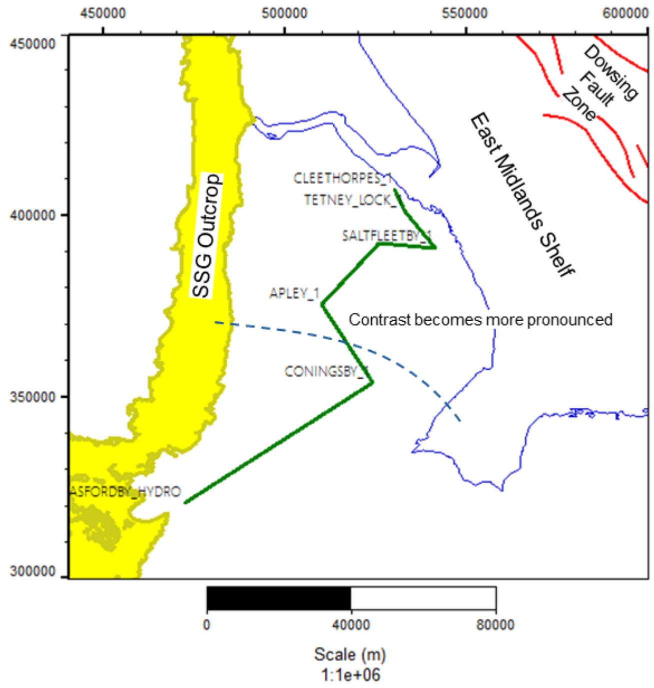


Figure 30 Correlation panel from the Asfordby Hydo borehole to Cleethorpes 1, providing a southwest to northeast transect across the East Midlands Shelf. The log tracks show sonic transit time logs which have been clipped to the stratigraphical range of the MMG and normalised in the range [0,1]. Logs are plotted back-to-back to visually accentuate trends. The MMG shows a clear 2 part subdivision that is particularly marked in boreholes northeast from Coningsby. The ‘sonic break’ boundary between the two parts is marked by a thin high velocity zone of dolomite cemented sandstones and mudstones. Logs are coloured with sonic transit time with brown fast (small travel time) and green slow (large travel time). The panel is flattened on the ‘sonic break’.

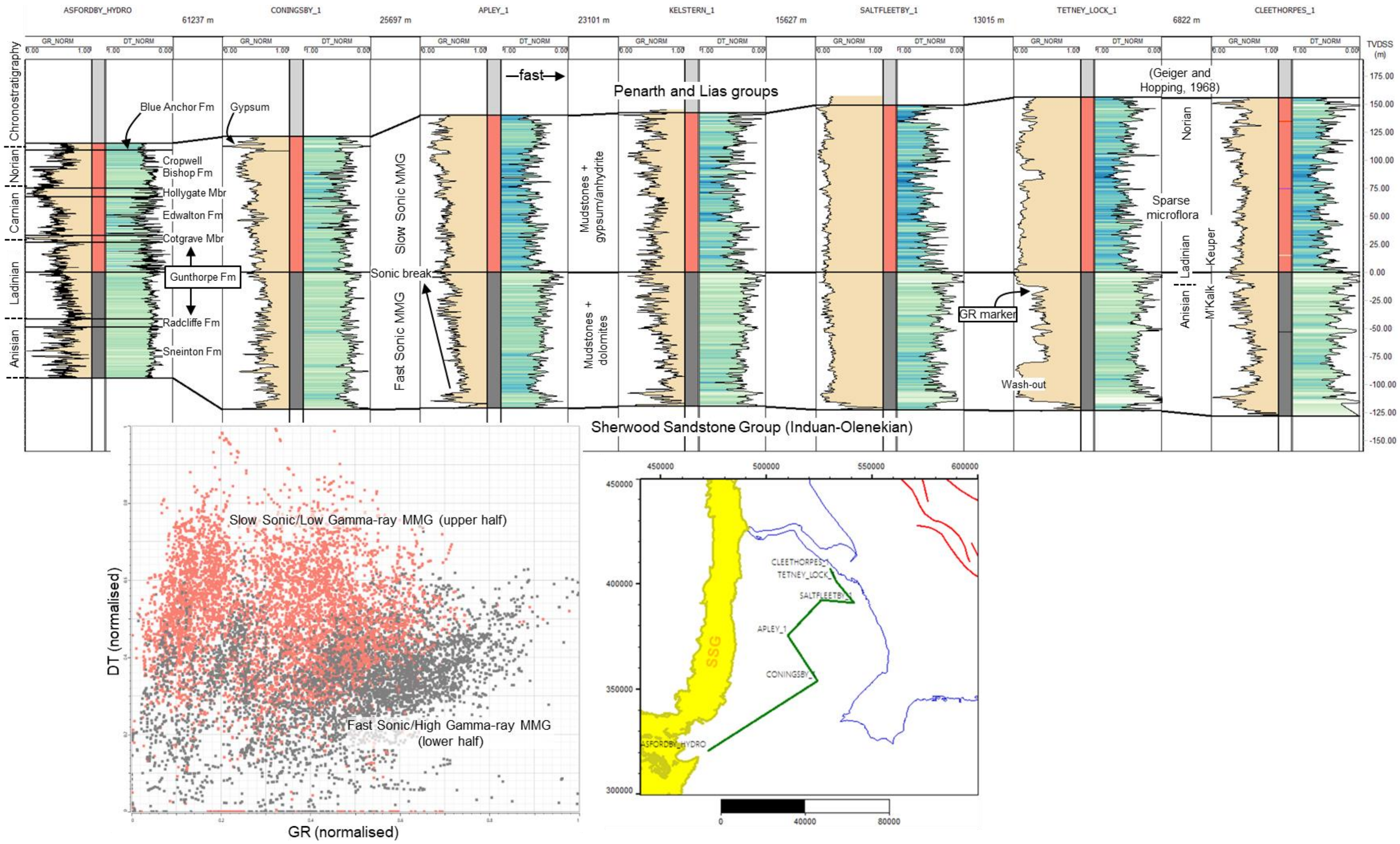


Figure 31 Correlation panel showing normalised gamma ray and sonic transit time logs across the MMG interval of the East Midlands Shelf. Inset is a cross-plot of gamma ray against sonic transit time which highlights two (overlapping) two subdivisions. The lower subdivision (grey dots) has a generally high gamma ray and low sonic transit time (fast). The upper subdivision (red dots) has a generally lower gamma ray and longer sonic transit time (slow). The ‘sonic break’ marker identified here occurs just above gamma-ray marker of Balchin & Ridd (1970) which is shown in Tetney Lock 1 and can be identified in most boreholes. This occurs around the Anisian-Ladinian according to dating in the Tetney Lock borehole (Geiger & Hopping, 1968) or within the Ladinian (mid Gunthorpe Formation) in the Asfordby Hydo borehole (Carney et al. 2004).

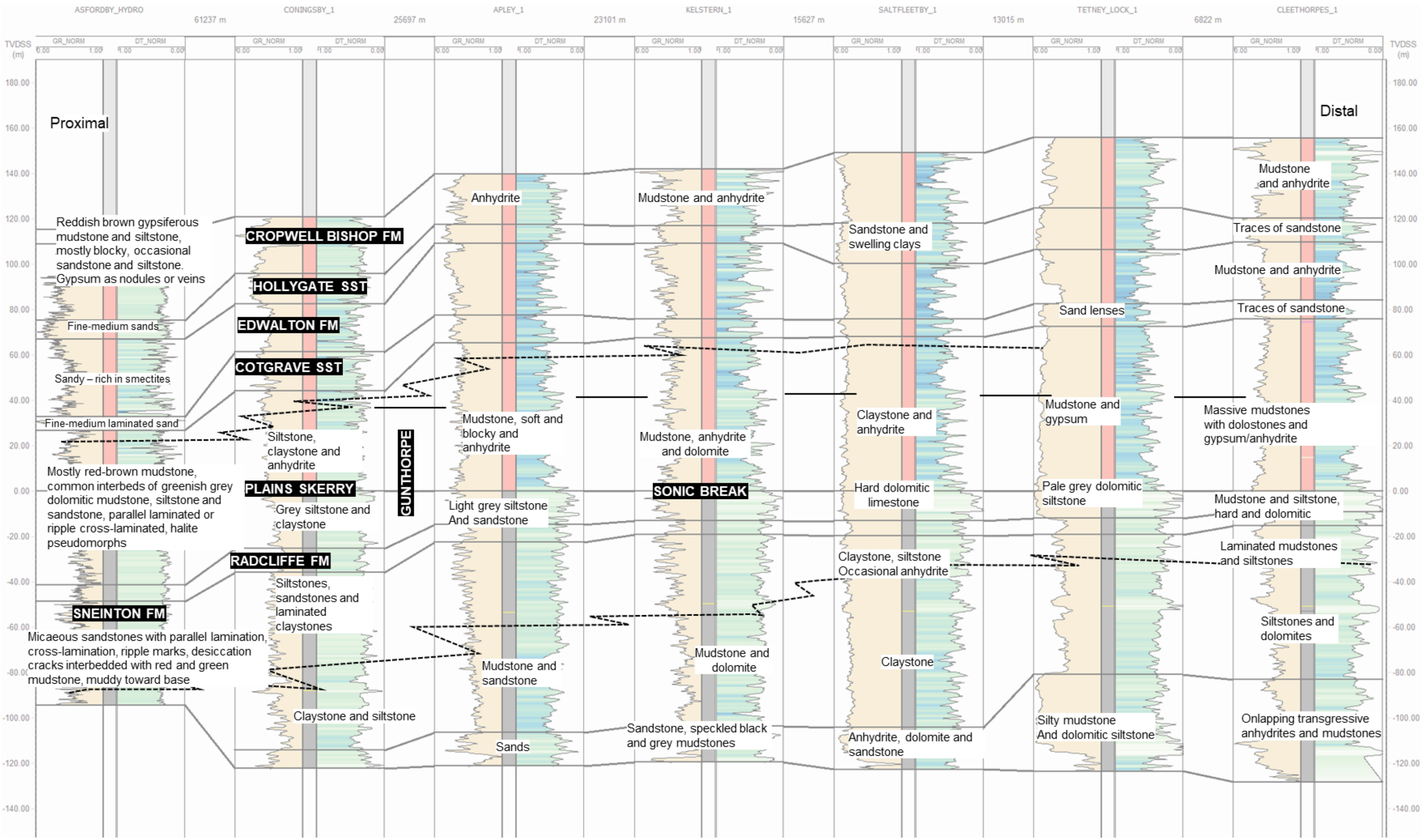


Figure 32 Borehole lithology information extracted from composite logs and plotted on the panel. These are a summary of cuttings descriptions with the exception of Asfordby Hydro (core). In the interval below the sonic break, micaeous sandstones in proximal (southwest) locations (the Sneinton/Tarporley Siltstone Formation) pass northeast into mudstones and dolomite. The sands appear to be diachronous/progradational and capped by hard dolomite cemented lithologies which probably corresponds with the Plains Skerry of Elliott (1961). Above the sonic break mudstones become soft, blocky and contain gypsum and/or anhydrite. The Cotgrave and Hollygate sandstones of the Edwalton Formation may represent a second progradational phase. The mudstones and anhydrite/gypsum of the Cropwell Bishop Formation caps the MMG succession.

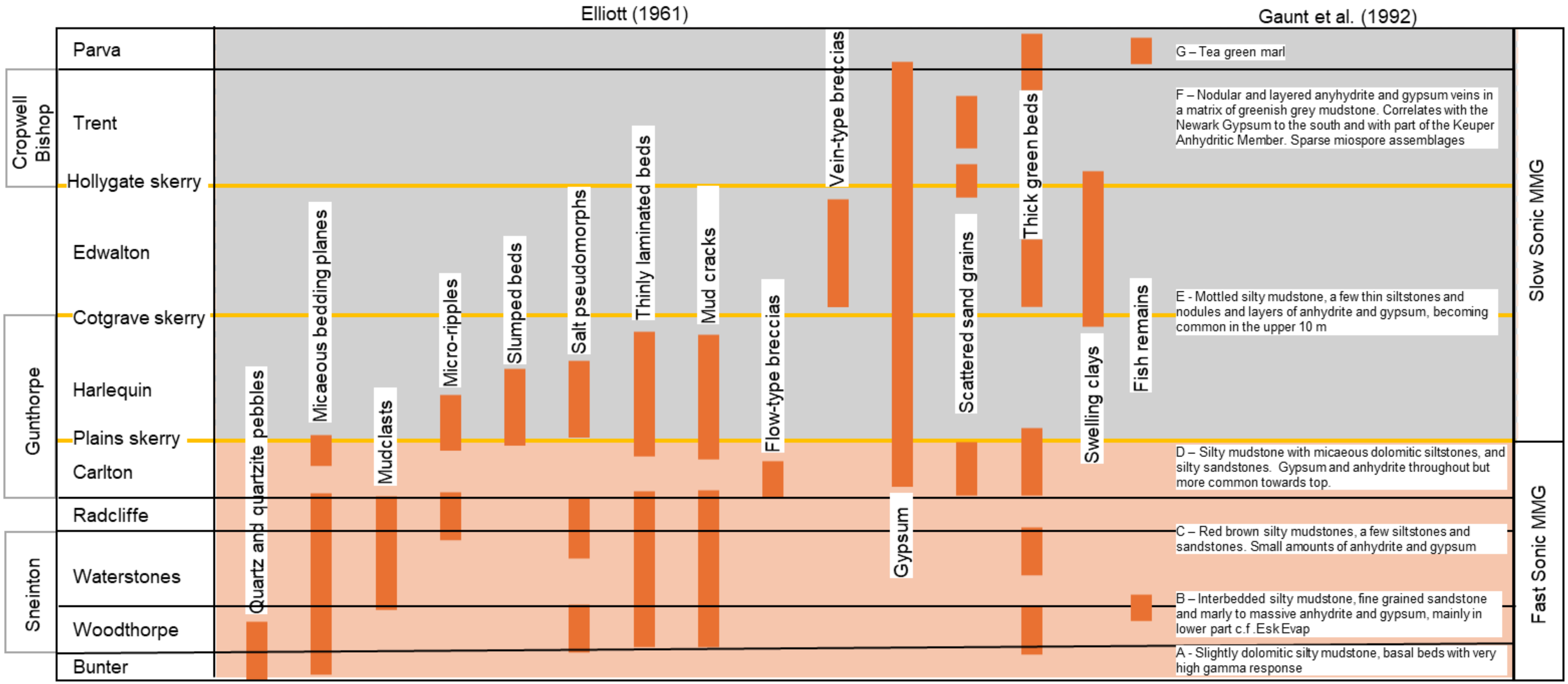
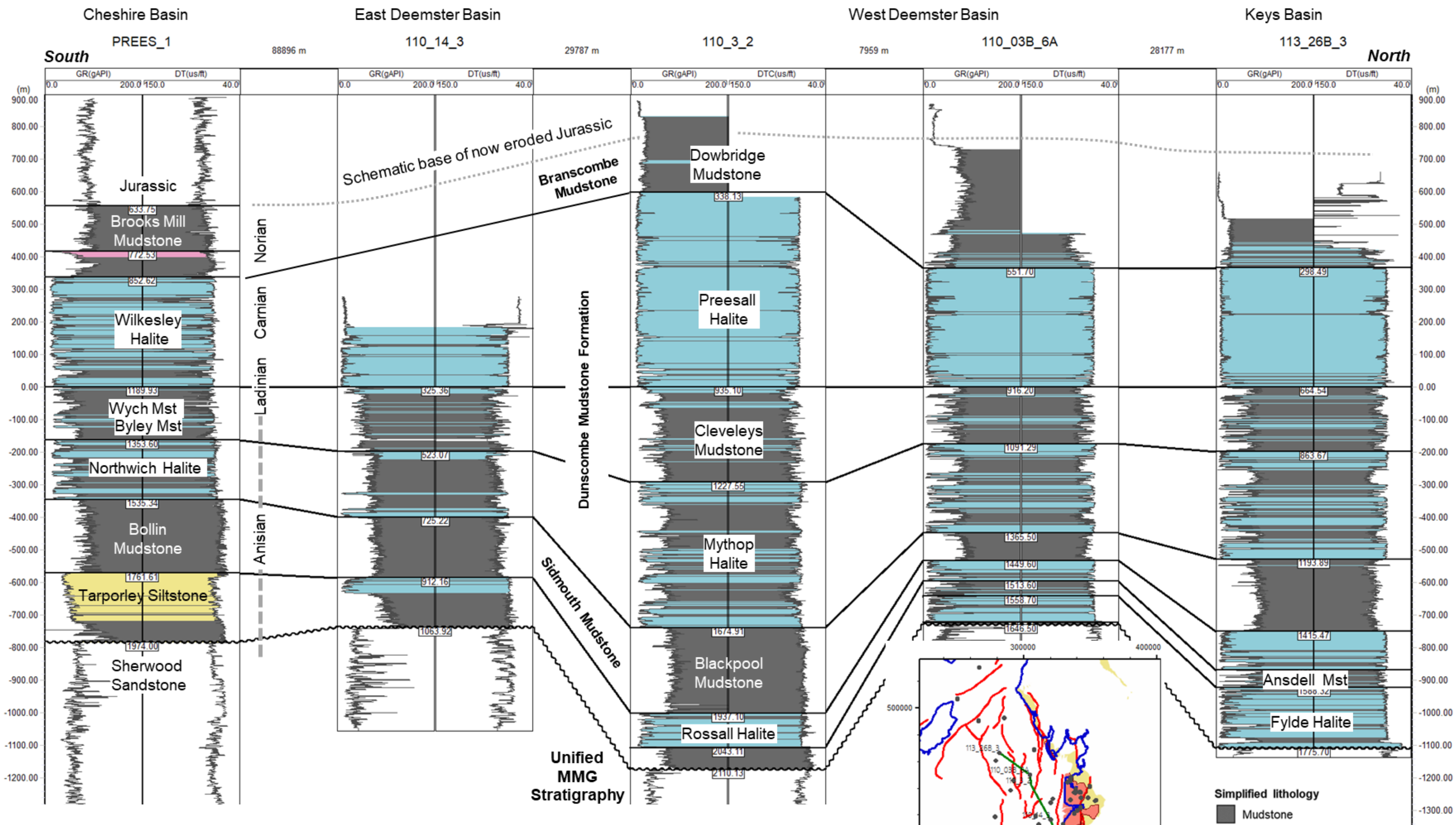


Figure 33 Distribution of sedimentary features across the stratigraphy of the MMG on the East Midlands Shelf (mostly based on borehole and outcrop observations in Nottinghamshire by Elliot, 1961). Thinly laminated micaeous sandstones with ripples, mudstone clasts and salt pseudomorphs are common in the lower half. Gypsum-rich mudstone is more common in the upper half. The succession of lettered subdivisions (A-G) of the MMG recognised in boreholes by Gaunt et al. (1992) are shown on the right. These reflect the MMG in a more basinward setting around the Humber Estuary.



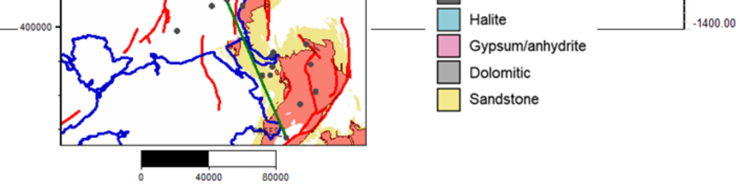
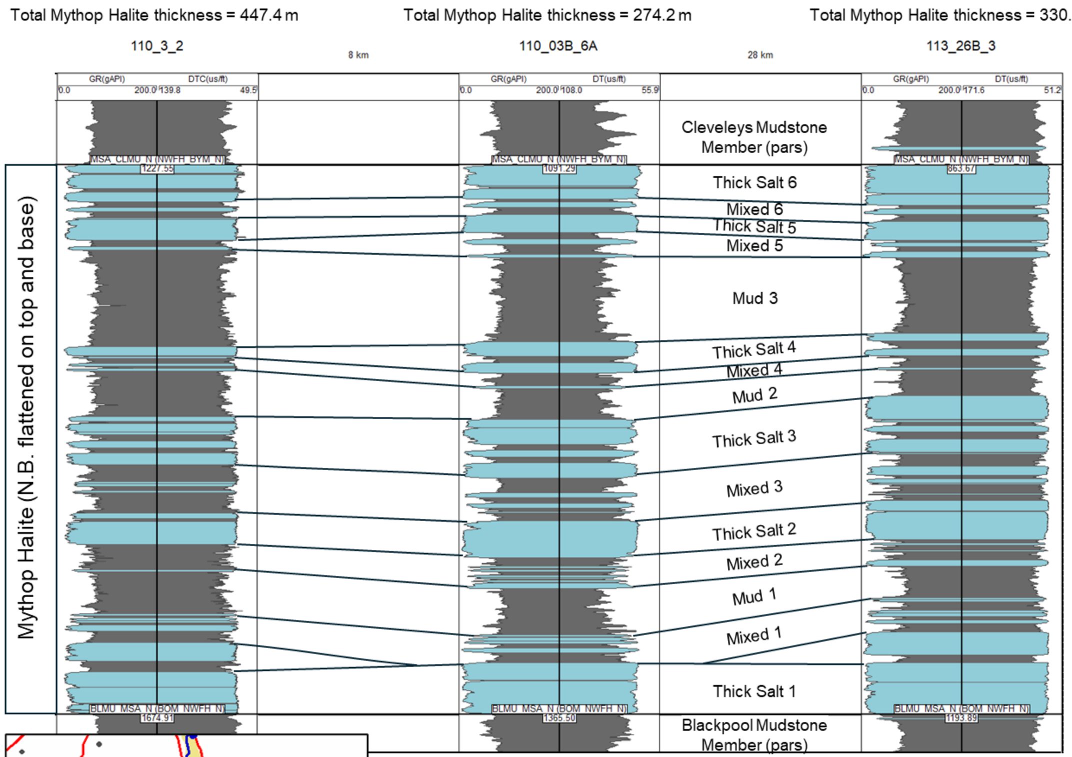
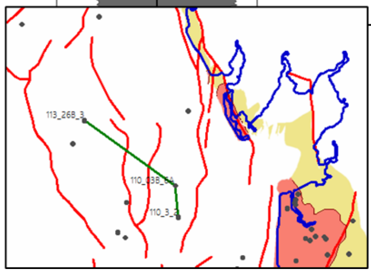


Figure 34 Correlation panel from the Cheshire Basin into the East Irish Sea Basin (EISB). In the Cheshire Basin a thick package of halite (and interbedded mudstone) occurs between the Bollin Mudstone and the Brooks Mill Mudstone. The Tarporley Siltstone forms an exceptionally thick arenaceous unit at the base. Northwards into the EISB the Tarporley Siltstone is replaced by mudstones and halites (Fylde Halite and Rossall Halite). The Blackpool Mudstone (=Bollin Mudstone) forms a remarkably consistent unit across the EISB. Together with the overlying Dowbridge Mudstone, the Blackpool Mudstone encloses a thick interval of halites and mudstones. As in the Cheshire Basin, the evaporites divide into two halite-rich intervals (Mythrop/Northwich and Preesall/Wilkesley) separated by a more mudstone-rich part. Note that this stratigraphy/correlation differs from that offered by Wilson (1990) and Jackson et al. (1997).



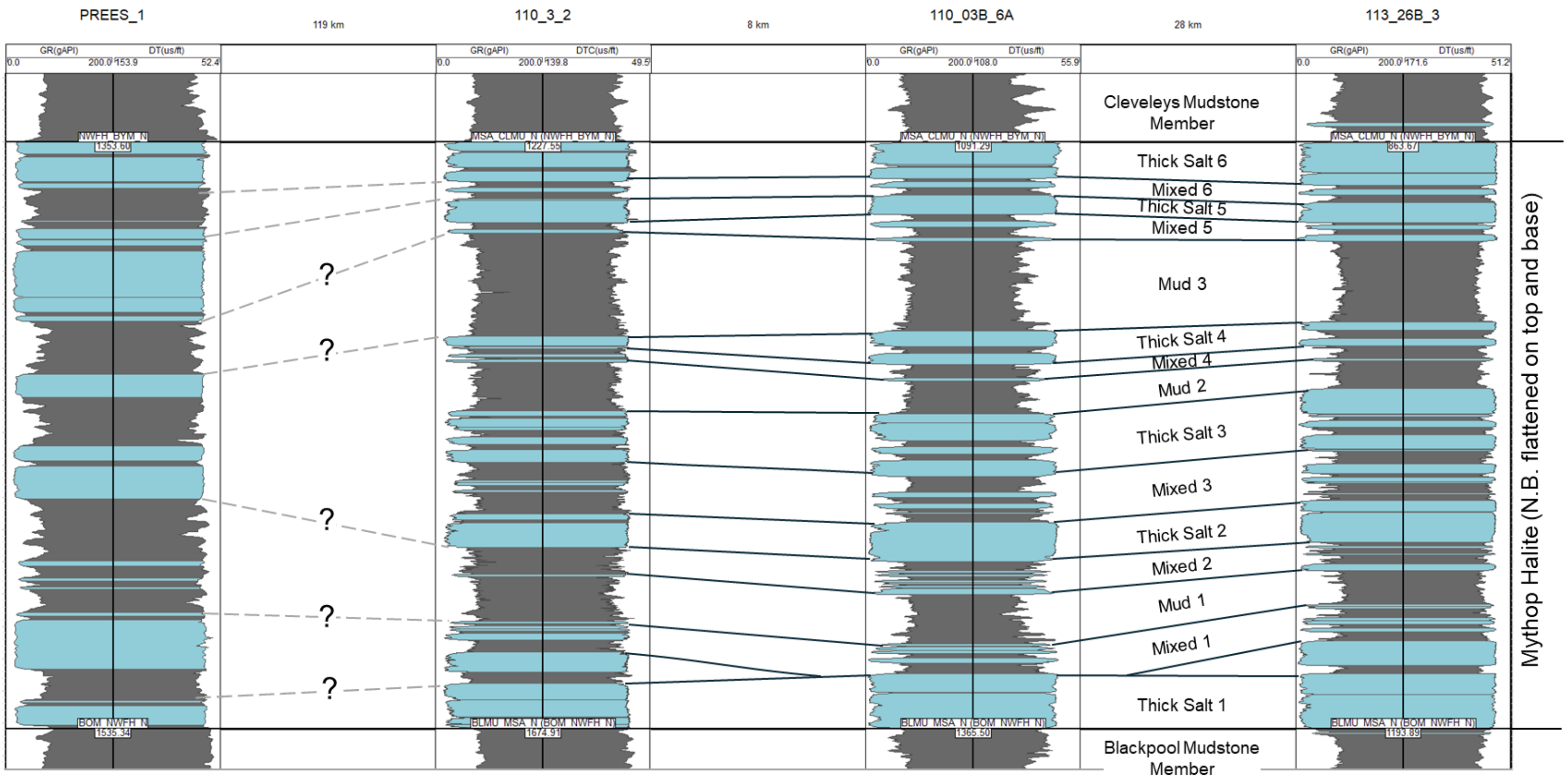


Descriptive statistics for the Mythop Halite in Borehole 110/03B-6A

Descriptive Statistics	Mudstone
Mean	4.57
Standard Error	1.43
Median	2.14
Standard Deviation	8.23
Range	42.07
Minimum	0.15
Maximum	42.22
Sum	150.77
Count	33.00

Descriptive Statistics	Halite
Mean	3.86
Standard Error	0.73
Median	2.36
Standard Deviation	4.14
Range	15.85
Minimum	0.15
Maximum	16.00
Sum	123.44
Count	32.00

Figure 35 High resolution correlation of the Mythrop Halite across 3 boreholes in the EISB. Note that the panel is flattened (expanded/contacted to an equal thickness) on both lower and upper contacts to remove thickness variations due to structure and aid correlation. Depths on top and base markers are given in metres (different scales apply to each borehole depending on thickness). Halite-mudstone units are classified into three types (Mud=mostly mudstone; Thick Salt=mostly halite; Mixed = multiple thin interbeds of mudstone and halite). Regardless of thickness, many of the units can be correlated across large horizontal distances (distance between boreholes given in km). Descriptive statistics for bed thickness of mudstone and halite in 110/03B-6A are given in the inset table (unit is metres except count).



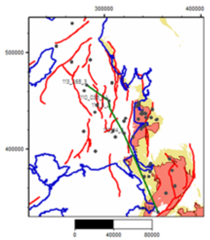


Figure 36 Extended correlation of previous figure toward Prees 1 in the Cheshire Basin where the relationship and correlation of individual halite units becomes less clear.

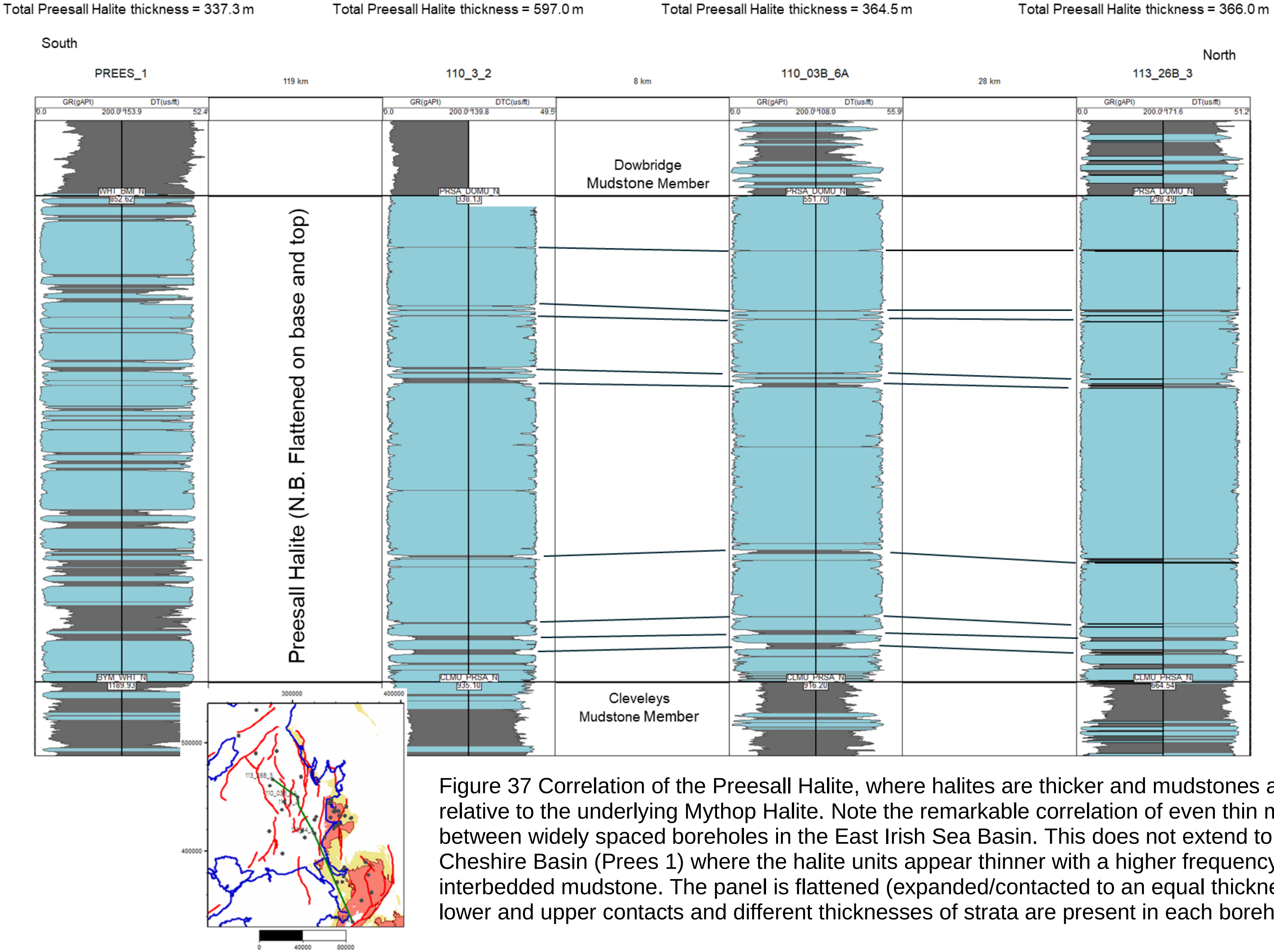


Figure 37 Correlation of the Preesall Halite, where halites are thicker and mudstones are thinner relative to the underlying Mythop Halite. Note the remarkable correlation of even thin mudstones between widely spaced boreholes in the East Irish Sea Basin. This does not extend to the Cheshire Basin (Prees 1) where the halite units appear thinner with a higher frequency of interbedded mudstone. The panel is flattened (expanded/contacted to an equal thickness) on both lower and upper contacts and different thicknesses of strata are present in each borehole.

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