The Sherwood Sandstone and Bacton groups of the East Midlands Shelf – an onshore to offshore correlation using outcrop evidence and geophysical logs

Decarbonisation and Resource Management Programme

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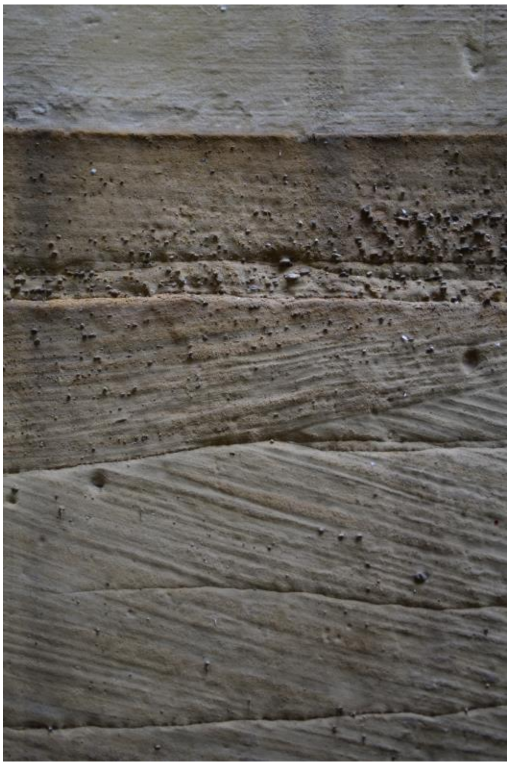

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The Nottingham Castle Sandstone Formation at Nottingham Castle.

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The Sherwood Sandstone and Bacton groups of the East Midlands Shelf – an onshore to offshore correlation using outcrop evidence and geophysical logs

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Keyworth, Nottingham British Geological Survey 2023

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) carried out as part of the CO_2 Storage Research Facility (CSRF) project. One focus of this project is the distribution of rock properties as relevant to CO_2 storage in the Bunter Sandstone Formation of the UK Southern North Sea.

This report is based on a study of 20 days duration and extends work on the Bunter Sandstone inshore from the Dowsing Fault Zone to correlative strata (Sherwood Sandstone Group) onto the onshore portion of the East Midlands Shelf.

Stratigraphic interpretations and descriptions are based on BGS understanding at the time of writing, and may be subject to change as further studies are developed and understanding evolves.

All 2D and 3D geographic information systems were compiled in OSGB36 / British National Grid (EPSG:27700).

Acknowledgements

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1 Introduction

This report presents new stratigraphical correlations of the Triassic Sherwood Sandstone Group and correlative Bacton Group of the East Midlands Shelf, which extends offshore into the Southern North Sea (SNS) to the western boundary of the Sole Pit Basin. In the SNS, the Bacton Group (and in particular the Bunter Sandstone Formation) is under consideration for large-scale CO_2 storage in saline aquifers and depleted hydrocarbon reservoirs because of its high storage capacity and favourable injectivity (Alshakri et al., 2023; Williams et al., 2023).

The main aim of the study is to create a robust stratigraphic framework for Triassic strata of the East Midlands Shelf, that bridges the divide between onshore and offshore lithostratigraphical schemes (Johnson et al., 1994; Ambrose et al., 2014). The report combines information from onshore outcrop, onshore boreholes and offshore boreholes in an attempt to increase our understanding of Triassic depositional systems and the controls on rock properties across all surface and subsurface domains. All tables and figures can be found at the rear of the report.

1.1 AREA OF INTEREST

Figure 1 shows the area of interest which is centred on the East Midlands Shelf. The area is bounded to the west by the erosional edge of the Permo-Triassic outcrop, which strikes parallel to the N-S trending Pennine High and curves around the Cleveland Basin in the north to intersect the coast at Middlesborough. The southern boundary is formed by the concealed onlap limit of the Sherwood Sandstone onto the W-E trending London Brabant Massif (Pharaoh, 2018). The eastern boundary is formed by the Dowsing Fault Zone which forms the western margin of the Sole Pit Trough in the Southern North Sea (Cameron et al., 1992).

1.2 STRATIGRAPHIC INTERVAL OF INTEREST

Simplified charts showing the lithostratigraphy covered by the report are shown in Figure 2. The existing scheme of Johnson et al. (1994) (shown in Figure 2A) is modified slightly to reflect the terminology and correlations that are applied in this report (Figure 2B). Broadly, the report covers all Late Permian and Early Triassic strata that occur between the evaporite and carbonate dominated component of the Zechstein Group and the Mercia Mudstone Group (Haisborough Group in the SNS). In the SNS this interval directly equates with the Bacton Group. Across much of the onshore East Midlands Shelf it equates the Sherwood Sandstone Group (Nottingham Castle Sandstone and Lenton Sandstone) and the Roxby Formation, which is included at the top of the Zechstein Group (Smith et al., 1986).

It should be noted that the lithostratigraphy is in a state of flux and some terms are applied in different ways by different workers, for example, Ambrose et al. (2014) omit the Lenton Sandstone from the Sherwood Sandstone Group. Units such as the Nottingham Castle Sandstone represent part of a chain of linked Early and Middle Triassic arenaceous formations deposited across the post-Variscan rift basins of southern Britain (Figure 3). Ambrose et al. (2014) have proposed a rationalisation of the local basinal nomenclature into unified formations and, while not applied here, this is shown in Figure 3 for reference. Thus the Nottingham Castle Sandstone falls under the Chester Formation of this unified scheme.

1.3 GEOLOGICAL STRUCTURE

The present geological structure of the area is relatively simple with north-south striking Permo-Triassic strata at outcrop generally dipping eastwards beneath a cover of younger rocks toward the western boundary of the Sole Pit Trough (Figure 4). The Sole Pit Trough is a strongly inverted halokinetic basin and includes outliers of Permo-Triassic deposits at seafloor (Cameron et al., 1992). Along the southern boundary the strike becomes west-east along the London-Brabant Massif. In north Yorkshire the structure contours curve around the inverted Cleveland

Basin, which is an onshore extension of the Sole Pit Trough (Powell, 2010). In all areas, the dip is relatively constant at around 1-2 degrees.

2 Data sources

2.1 BOREHOLES

Boreholes provide geophysical logs, lithology information from cuttings returns and occasionally core. No core or cuttings were examined as part of this study with most information sourced from company composite logs and reports. These were downloaded from UKOGL (onshore wells) and from the UK National Data Repository (offshore) as required. The distribution of boreholes is shown in Figure 1 and the boreholes used are listed in Table 1. The study included 11 offshore boreholes and 70 onshore boreholes. Many more boreholes are available (particularly onshore) but this subset was selected to provide an even distribution across the area of interest. All of the boreholes have geophysical logs which vary widely in age, quantity and quality. Where the Sherwood Sandstone is found at shallow depths the boreholes may be cased across some or all of the interval of interest. Gamma ray logs are most widely available and were most utilised in the study to discriminate quartz-sand rich intervals from clay-rich intervals. The main potential issues with applying gamma-ray logs in the Sherwood Sandstone and Bacton Group are the influence of feldspar-rich or micaeous sands (increasing gamma-ray response), the inability to distinguish between bedded mudstone and mudstone that has been eroded and reworked into mudclast conglomerates, and lack of resolution in thinly interbedded sandstone and mudstone intervals (Serra, 1984). Sonic interval transit time logs were used where available to gain a general understanding of cementation and porosity patterns. Caliper logs were used to check borehole quality.

2.2 OUTCROP INFORMATION

Limited field visits were undertaken in Nottingham and areas immediately to the north, but most outcrop information was derived from BGS memoirs and other publications (Ruffell and Hounslow, 2006; Wakefield et al., 2015). The distribution of published memoirs across the area of interest is shown in Figure 5. Table 2 summarises the key findings from the memoir data-mining exercise.

With the exception of those around Nottingham Castle (Ambrose and Wakefield, 2014), large natural outcrops of the Sherwood Sandstone are relatively sparse across the low-lying, superficial-covered terrain of eastern England. The Sherwood Sandstone Group was formerly widely quarried for moulding sand, building stone and aggregate across eastern England but with a few exceptions (Wakefield et al., 2015) most of these quarries are long abandoned and infilled. To derive information from these lost exposures a search was conducted using the BGS GeoScenic database which produced many useful geological photographs, some dating to the early part of the last century. Figure 6 shows the distribution of GeoScenic images that occur on the outcrop of the Sherwood Sandstone Group.

3 Methods

Borehole data were loaded into SKUA-GOCAD 22 3D visualisation software. Borehole paths were set to vertical or deviated where required (see Table 1) using well path deviation files sourced from UKOGL and UK NDR. Logs were loaded from LAS files sourced from BGS archives or UKOGL/NDR. No additional processing of geophysical log data was undertaken.

3.1 PICKING OF STRATIGRAPHICAL HORIZONS

Stratigraphical markers were created interactively within the SKUA-GOCAD 22 3D software. Boreholes were grouped into panels, rather than interpreted individually, with multiple panel intersections and orientations to ensure consistency and test existing marker interpretations. Panels were flattened on one (or multiple) stratigraphical horizons to improve the correlation process.

Markers were primarily picked on geophysical log criteria, but cross-checked against existing interpretations and additional information (e.g. core, borehole cutting returns descriptions) from borehole composite logs and BGS Memoirs.

Stratigraphical horizon markers were named using the convention:

'Stratigraphical Unit Below'_'Stratigraphical Unit Above'_'Type of Contact'

Stratigraphical units were designated using their BGS Lexicon codes and the type of contact (N=Normal conformable, U=Unconformable, F=Faulted). The full list of marker codes is given in Table 3. Markers were further grouped within SKUA-GOCAD under horizon features which may encompass a number of different markers (e.g. correlative units or unconformities).

3.2 FACIES CLASSIFICATION OF GAMMA-RAY LOGS

Gamma ray logs across the stratigraphical interval of interest were classified into intervals of high gamma ray and low gamma ray response. In the largely (but not exclusively) siliciclastic sequence, this will generally indicate quartz sand-rich and clay-rich intervals. Prior to the classification, gamma ray logs were clipped to the stratigraphical interval of interest and normalised using:

$$Curve_{norm} = \left(\frac{CurveValue - CurveValue_{min}}{CurveValue_{max} - CurveValue_{min}}\right)$$

The output values are dimensionless values between zero and one and any reference to the original absolute magnitude of the log response is lost. A cross-check of gamma-ray value against cutting return descriptions on composite logs suggested that a sandstone-mudstone cut-off of 0.3 was appropriate for many boreholes. This cut-off value was universally applied to all wells and then manually adjusted where required to produce a plausible distribution of sandstone and mudstone rich lithologies. Table 1 provides the cut-off value applied to the normalised gamma-ray curve for each borehole. Cut-off values should be regarded as a very approximate measure of sandstone and claystone content. The gamma-ray tool operates over a relatively wide borehole interval and thinly interbedded sandstones and mudstones will produce values mid-range between sandstones and mudstones. Nonetheless the classified logs provide a simple method to assist visualisation of the stratigraphy and correlations.

3.3 GENERATION OF STRUCTURE MAPS

Structure maps were generated using borehole markers and outcrop elevation data using SKUA-GOCAD 22 implicit modelling workflows (Newell, 2018a). Faults were only included where these assisted the modelling i.e. large vertical offsets between adjacent boreholes. This was only around the Flamborough Fault Zone where the seismic-derived fault maps of Kirby and Swallow (1987) were used. The structure map (Figure 4) was generated primarily to check for obvious anomalies in borehole stratigraphic picks and to provide a simple visualisation of the present structure based on boreholes. No additional seismic data were included.

3.4 GENERATION OF THICKNESS MAPS

Thickness maps were constructed by interpolating thickness data from borehole stratigraphical markers. Marker thickness values were corrected for borehole inclination where required (True Vertical Thicknesses) but not structural dip which was sufficiently low (generally two degrees or less) in all borehole locations to be a minor component of the total variation. Thickness values were interpolated using the Inverse Distance method where the weighting of each data point is inversely proportional to the distance or some exponential function of the distance between the data point and the interpretation point. The further away the data point is, the less influence it has on the estimation. For all maps an inverse distance exponent of 3 was used to provide a balance between sufficient granularity and smoothing of thickness variation. No fault barriers were used during the interpolation. The visualisation of regional trends was further enhanced by applying a colour ramp where values were binned, for example, at 20 metre intervals.

3.5 GENERATION OF 3D SIMULATED MODEL

An irregular (geological) 3D grid was created which covered the Bacton Group (and equivalent onshore strata) interval. The base of the model was top Zechstein Group carbonates/evaporites. The top of the model was top Bunter Sandstone/Sherwood Sandstone. Cell dimensions were set at 2000 m horizontal and 5 m vertical. Sandstone and mudstone properties created by the gamma-log cut-off exercise were blocked to the grid and used as hard data for a simple sequential indicator simulation of the stratigraphy. The simulation was set to replicate the bulk observed proportion of sandstone (70%) and mudstone (30%) and used a nominal omnidirectional variogram range of 5000 m horizontal and 10 m vertical. The purpose of the simple rock property attributed grid (see Figure 19) was to provide a secondary means of visualising stratigraphical trends in the data.

4 Stratigraphy

4.1 ONSHORE STRATIGRAPHY

4.1.1 Outcrop

In south Nottinghamshire, the Sherwood Sandstone Group is traditionally subdivided into the Lenton Sandstone Formation and the Nottingham Castle Sandstone Formation. Note that Ambrose et al. (2014) propose that the Lenton Sandstone should not be included in the Sherwood Sandstone Group (Figure 2).

4.1.1.1 Lenton Sandstone

The Lenton Sandstone Formation is a heterogeneous unit of grey and red mottled silty sandstones, clean cross-bedded sandstones and occasional thin mudstones (Ambrose and Wakefield, 2014). At outcrop, the unit is mainly present within Nottinghamshire but it has a wider subcrop (Table 2).

In south Nottinghamshire, it typically grades upwards from a thin heterogeneous assemblage of mudstones, sandstones, breccias and limestones representing proximal Zechstein Group facies. Further north it grades upwards from the more homogeneous red gypsiferous mudstones of the Roxby Formation.

The signature characteristics of the Lenton Sandstone are the fine-grain size and the high clay content (the unit was formerly quarried as moulding sand for use in iron foundries). The presence of wavy, parallel and cross-lamination suggests mixed aeolian and fluvial environments (Ambrose and Wakefield, 2014).

4.1.1.2 Nottingham Castle Sandstone

The Nottingham Castle Sandstone is a medium-coarse grained pebbly sandstone with large-scale trough and tabular cross-bedding (Figure 6) indicating deposition within large perennial river channels (Wakefield et al., 2015). The primary distinguishing feature with the Lenton Sandstone is the presence of numerous well-rounded quartzite pebbles. The abundance of pebbles decreases to the north, down the palaeotransport direction. North of Worksop (Figure 5), mapping shows that pebbles become sparse or absent over much of the Sherwood

Sandstone stratigraphy and the Lenton Sandstone becomes more difficult to distinguish as a unit separate from the Nottingham Castle Sandstone.

Where observed, the basal contact of the Nottingham Castle Sandstone with the Lenton Sandstone is sharp. A photograph of a former quarry at Mansfield held in the BGS GeoScenic archive shows the contact between Lenton Sandstone and the Nottingham Castle Sandstone to be an erosion surface, described by the workers at the time as an ‘unconformity’ (Figure 7).

The upper contact is also an unconformity with the Mercia Mudstone Group. The uppermost beds of the Sherwood Sandstone are often recognised in boreholes as being of anomalous character with common aeolian grains, white bleaching, green micaeous marls, and the presence of wind-facetted pebbles (ventifacts) formed during a prolonged phase of wind-deflation and non-deposition. This break has been correlated with the Hardegsen Unconformity, a tectonically-induced erosion event at the top of the Early Triassic (intra-Spathian) which is widely developed in north European basins (Bourquin et al., 2011). For example, in the Germanic Basin, the base of the Solling Formation corresponds to the Hardegsen Unconformity when approximately 100 m of Middle Buntsandstein were eroded in response to one of the most pronounced extensional tectonic events in the German Triassic (Röhling, 1991).

4.1.2 Subsurface discrimination of the Lenton and Nottingham Castle Sandstone

In borehole core and cuttings the Lenton Sandstone can be distinguished as silty, fine-grained, micaeous sandstones with some beds rich in well-rounded (probably aeolian) quartz grains. The grains are cemented by calcite and gypsum and can contain some carbonaceous debris. The Nottingham Castle Sandstone is less clayey, generally coarser grained and locally pebbly.

In some gamma-ray logs the clayey (and micaeous) character of the Lenton Sandstone produces a clear response with overall values that are higher than the overlying Nottingham Castle Sandstone. The Keddington 1 borehole provides a good example where the Lenton Sandstone can be clearly distinguished from the Roxby Formation below and the Nottingham Castle Formation above (Figure 8). While variable, the sandstone baseline of the Lenton Sandstone is much higher than the baseline of the Nottingham Castle Sandstone. Differences in the sonic log are less pronounced. The Nottingham Castle Sandstone may show greater variability suggesting greater contrasts in the degree of cementation.

In other gamma-ray logs (particularly those to the north within the Cleveland Basin) the Sherwood Sandstone shows no evidence of a two-part subdivision and the sandstone baseline remains constant throughout the entire interval between the Roxby Formation and the Mercia Mudstone Group. Harsley 1 provides a good example (Figure 8).

4.1.3 Palaeocurrent directions and provenance

Palaeocurrent data have been digitised from maps contained within BGS Memoirs for sheets 79, 88 and 101 (Figure 9). All the measurements occur on terrain that is mapped as Sherwood Sandstone Group (Nottingham Castle Sandstone) and their wide spatial distribution suggests a reasonable representation of most parts of the stratigraphy. In the memoirs the results are presented as a vector mean with no indication of the standard deviation or the number of observations at each station. In sheets 79 and 101, the measurements show an overall trend to the northeast. However, easterly directions become more prevalent toward the north of sheet 101. This trend continues into sheet (88) where all vector means indicate easterly flow.

In the Nottingham Castle Sandstone, the predominance of northeast flow directions, and the northeast reduction in gravel-content and grain-size, fit the long-established ‘Budleighensis river’ model for the conglomeratic and pebbly sandstones of the Nottingham Castle Sandstone and their Early Triassic equivalents which fall under the unified ‘Chester Formation’ (Figure 3). This envisages a major fluvial system flowing northward from the Armorican Massif of the English Channel region, into the Worcester Graben and then bifurcating northwest into the East Irish Sea Basin via the Cheshire Basin and northeast onto the East Midlands Shelf (Warrington, 1970; Medici et al., 2015) (Figure 10B)

The pre-dominance of well-rounded, pale brown quartzite clasts is the most conspicuous compositional link between the various units deposited by this major axial drainage system, although it has been problematic to trace these quartzites (and many of the other metamorphic and igneous rock types found in the unified Chester Formation) to specific source areas (Campbell-Smith, 1963). Tyrrell et al. (2012) consolidated the concept of an Armorican Massif source using Pb isotopic analysis of K-feldspar and importantly showed the commonality of source across the entire 400 km western fluvial transport chain from the Wessex basin to the East Irish Sea Basin. Unfortunately this work did not extend to the Nottingham Castle Sandstone of the East Midlands Shelf.

The Pennine-Charnwood High which extends as a col between the Pennine Massif and the London-Brabant Massif has long presented a connectivity problem for the East Midlands Shelf (Figure 10). This high is largely devoid of Sherwood Sandstone Group and is directly onlapped by Mercia Mudstone Group. It may have represented an area of sediment-bypass across which rivers could flow but where deposition was negligible. Alternatively, Warrington (1970) proposed a phase of uplift following the deposition of the Nottingham Castle Sandstone, which effectively 'shut-the-door' to future rivers flowing northeast from the Needwood Basin. Thus the post-Hardegsen Unconformity Bromsgrove Sandstone (and related units) are only found to the west of the Pennine-Charnwood High (Figure 10). During this time, the top of the Nottingham Castle Sandstone of the East Midlands Shelf may have become an aeolian deflation surface under the influence of easterly tradewinds undersaturated in sediment load from crossing the Muschelkalk basin (Figure 10B). Evidence for this comes in the discovery of ventifacts on the Hardegsen Unconformity (Table 2).

In the Wessex Basin, heavy mineral, mineral–chemical, and zircon dating analyses of Triassic fluvial deposits indicate that the sediment supply patterns were complex and involved multiple subcatchments (Morton et al., 2016). Comparable work has not been undertaken on the East Midlands Shelf and the relative contribution of long-travelled sediment from the Armorican Massif versus local sources from the London-Brabant Platform, the Pennine High and the Charnwood High are unknown. Petrographic analysis of the Lenton Formation shows the importance of local source areas such as the Proterozoic rocks at Charnwood Forest (Frost and Smart, 1979). Common easterly palaeocurrents in the Sherwood Sandstone of the East Midlands Shelf (Figure 9) suggest that the Pennine High may also have formed a local source. The rarity of pebbles in the Pennine-derived Sherwood Sandstone Group north of Doncaster may indicate relatively small catchments of low relief (Ruffell and Hounslow, 2006)

4.2 OFFSHORE STRATIGRAPHY

The stratigraphy of the Bacton Group to the west of the Dowsing Fault Zone divides into three well-defined parts (Figure 11). These are present regardless of variability within the Bacton Group total thickness. Each part represents a sharp, step-wise increase in the sandstone content of the Bacton Group. For clarity of description, each of these parts is here given formation status: thus the Bunter Shale Formation, the Amethyst Formation and the Bunter Sandstone Formation (Figure 11). Note that Johnson et al. (1994) use the term Amethyst Member within the Bunter Shale Formation. This creates a descriptive problem of an unnamed member below the Amethyst Member – here this unit is referred to as Bunter Shale Formation. The thick and well-defined Amethyst Formation is thus removed from the Bunter Shale which here refers only to the basal mudstone-rich interval.

4.2.1 Bunter Shale Formation

This unit overlies the carbonates and evaporites of the Zechstein Group and is predominantly mudstone with minor thin siltstones and a few beds of dolomite and traces of anhydrite (Cameron et al., 1992). It includes the Bröckelschiefer Member at its base which has a distinctive upward decreasing gamma-ray profile and a high sonic velocity. The unit locally includes sandstones (including the Hewett Sandstone reservoir) and appears to represent initial fluvial influx across the former Permian evaporite basin prior to establishment of the Bunter Shale lacustrine environment (Cameron et al., 1992).

4.2.2 Amethyst Formation

The base of the Amethyst Formation is marked by the onset of numerous, closely spaced sandstone beds which produce a highly serrated gamma ray and sonic log (Figure 11). Sandstone beds are thin and separated by mudstones. The gamma ray log tends to indicate closer spacing of thicker sandstone beds toward the middle of the unit, with muddier units below and above. The Amethyst Formation (or member sensu Johnson et al. (1994)) extends offshore for up to 70 km from the coastline and represents an interdigitation of coarse-grained fluvial facies with distal floodbasin and lacustrine deposits (Cameron et al. 1992). It is considered a lateral equivalent of the Sherwood Sandstone Group (Warrington et al. 1980).

4.2.3 Bunter Sandstone Formation

The Bunter Sandstone Formation represents a greater amalgamation of sandstones into a sheet-like unit of overall low gamma-ray response. The gamma-ray log shows some evidence of an upward decreasing trend with a marked unit of low-gamma ray response at the very top beneath the Haisborough Group (Figure 11). The Bunter Sandstone is a fluvial sheet sand complex of red, orange and occasionally white sandstones which are mostly fine-grained but occasionally medium or coarse grained (Cameron et al., 1992). Log correlation has been used to infer that the influx of fluvial sands was more or less simultaneous across the southern North Sea area (Brennand, 1975). The sands were derived principally from the London-Brabant Massif and the Pennine High and have been interpreted as the product of a number of coalescing fans (Bifani, 1986).

4.3 ONSHORE-OFFSHORE CORRELATION

The general time equivalence between the Bacton and Sherwood Sandstone groups is well established (Warrington et al., 1980), although the rarity of palynomorphs and other fossils within these oxidised terrestrial deposits greatly limits the application of biostratigraphical methods to refine the correlation. Viewed on a southwest to northeast transect (perpendicular to the thickness contours) across the East Midlands Shelf the Bacton Group (and correlative onshore strata) form a striking wedge-shaped unit progressively thickening toward the northeast (Figure 12).

Figure 12 shows the formation-level correlation proposed by this work for this post Zechstein evaporite terrestrial wedge.

The Bunter Shale Formation (as used here) immediately overlying the carbonates and evaporites of the Zechstein Group is correlated with the Roxby Formation. Thin sandstones which are frequently seen at the base of the onshore Roxby Formation are likely to be correlatives of the Bröckelschiefer Member.

The Amethyst Formation (as used here) is correlated with the Lenton Sandstone Formation. Onshore to offshore correlations show a progressive ‘downstream’ decrease in the proportion of sandstone (Figure 13). This trend continues across the Dowsing Fault Zone where the Amethyst transitions into the less sandy Rogenstein Member (Cameron et al., 1992).

The Bunter Sandstone Formation is correlated with the Nottingham Castle Sandstone. Both units represent an abrupt fluvial progradation of relatively coarse-grained sediment. An erosive sequence boundary may underlie both units.

4.3.1 Significance of new Staithes sulphur isotope stratigraphy

Recent work on the sulphur isotope stratigraphy of the Staithes S20 borehole (N. Yorkshire) has suggested that the Bacton Group here is entirely Permian in age (Salisbury et al., 2022; Salisbury et al., 2023). Given that Middle Triassic (Anisian) palynomorphs have been recovered from the basal Mercia Mudstone Group, the Permo-Triassic boundary is thus contained within the substantial time-gap at the Hardegsen Unconformity (Figure 14). If correct, this would have major implications for the chronostratigraphy of the Bacton Group and Sherwood Sandstone Group of the East Midlands Shelf and adjacent areas.

Figure 14 shows that this age determination could maybe be accommodated if the Nottingham Castle Sandstone/Bunter Sandstone Formation is not present at Staithes, but has been removed by erosion beneath the Hardegsen Unconformity. This is supported by log correlation. The very distinctive gamma-ray step-out of this unit appears to be absent in the Staithes 1 and Seal Sands 1 boreholes. All of the strata above the Bunter Shale Formation and below the Hardegsen Unconformity may be a correlative of the Lenton Sandstone/Amethyst Formation. It is notable that the Bunter Shale maintains its thickness across the five boreholes in the correlation panel, suggesting that the Amethyst Member might not be expected to thin significantly. A similar pattern can be seen in other correlation panels (Figure 15, Figure 16). This would collaborate correlation of the Amethyst Member with the Lenton Sandstone which may be partly Permian in age.

This would, however, shift the likely position of the Permo-Triassic boundary toward the top of the Lenton Sandstone/Amethyst Member rather than toward the base. The boundary could coincide with the erosive base of the Nottingham Castle Sandstone/Bunter Sandstone Formation but this would be counter to present understanding (Bachmann et al., 2010; Szurlies et al., 2012) which places the Permo-Triassic boundary in the lower part of the Lower Bundsandstein Subgroup based on the conchostracan biostratigraphy, carbon isotopes and magnetostratigraphy. The Lower Bundstandstein consists of fine-grained clastics and oolitic carbonate beds in the Netherlands and NW Germany and is considered a lateral correlative of the Bunter Shale (Bachmann et al., 2010). The boundary lies close to uppermost Zechstein evaporitic deposits which have very few fossils, presenting additional difficulties in precisely positioning the Permo-Triassic boundary.

4.4 THICKNESS TRENDS

Figure 17 shows a thickness plot for the entire Bacton Group (and onshore equivalent). The group shows progressive thickening from the south toward the thickest deposits in the northeast. Note that the thickness contours strike broadly WNW-SSW and the thickening trend does not occur down the present structural dip. It is also notable that the thickest Bacton Group occurs across the future position of the Market Weighton High, which developed in the onshore-offshore area south of the Flamborough Fault Zone (FFZ). This Caledonian granite-cored footwall block periodically became an important structural high during the Jurassic and Cretaceous across which there was stratal thinning, omission and erosion (Wright, 2022). Conversely the Cleveland Basin on the hanging wall of the FFZ is an area of relatively thin Bacton Group.

Figure 18 breaks down the thickness in three units which show changes in the locus of deposition (and/or) intra-Triassic erosion. The Roxby Formation/Bunter Shale is thickest along the north Yorkshire coast. The Sherwood Sandstone is thickest around the eastern end of the Flamborough Fault Zone and notably thin across the present Cleveland Basin. This may be partly related to erosion of the Bunter Sandstone. The Mercia Mudstone Group is thickest along the edge of the Sole Pit Basin and is relatively thin and uniform across much of the East Midlands Shelf and the Cleveland Basin. The MMG presents the first evidence for thinning across the Market Weighton High.

5 Depositional systems

The Bacton Group and correlative onshore strata probably represent three distinct depositional systems. The Bunter Shale/Roxby Formation represent a fine-grained siliciclastic lacustrine system. The Lenton Sandstone/Amethyst Formation represents an aeolian-fluvial-lacustrine system with a well-developed basinward decrease in the proportion of sand (Figure 19). This may represent a terminal fan system, with sandy channels dispersing and bifurcating into a muddy floodbasin. The Sherwood Sandstone/Bunter Sandstone represents a significant and abrupt basinward progradation of relatively coarse-grained perennial fluvial systems which formed a sheet-sandstone complex. This may have occurred at around the Permo-Triassic boundary, when numerous other fluvial systems around the world are known to have enlarged and prograded in response to extreme climatic events at the Permo-Triassic mass extinction event (Benton and Newell, 2014). Evidence from onshore (ventifacts, aeolian grains) and offshore (distinctly low-gamma ray response sandstones) suggests that there may have been significant aeolian activity in the uppermost part of the Bunter Sandstone. If preserved beneath the Hardegsen Unconformity, these aeolian sandstones could have high depositional porosities and permeabilities.

5.1 CONCLUSIONS

1/ The correlation of the different components of the Bacton Group on the offshore portion of the East Midlands Shelf to the onshore equivalents appears relatively clear based on borehole data. The work presented here provides a framework which could be tested using chemostratigraphy, magnetostratigraphy and carbon isotope analysis. The latter utilises the high magnitude carbon-isotope excursions that are known globally around the Permo-Triassic boundary climate crisis and mass extinction event (Dal Corso et al., 2022).

2/ The Bunter Sandstone/Nottingham Castle Sandstone may be absent from much of the Cleveland Basin due to erosion beneath the Hardegsen Unconformity. This may account for a recent interpretation of a Permian age from sulphur isotope stratigraphy (Salisbury et al., 2022).

3/ The abrupt progradation of the Nottingham Castle Sandstone/Bunter Sandstone may have been in response to the climatic extremes around the Permo-Triassic boundary when many other fluvial systems around the world exhibited similar behaviour. Photographic evidence from former quarries indicates an erosional unconformity between the Lenton Sandstone and the Nottingham Castle Sandstone. Further work is required to characterise this fluvial system in more detail. In proximal areas (e.g. Nottingham) gravelly sandstone facies often show deep scouring and nested concave-based sandstone bodies. Such geometries often typify the proximal zones of distributary fluvial systems (Nichols and Fisher, 2007). Further from source (in northern onshore outcrops) sandstone bodies are finer grained with laterally extensive tabular geometries. These often characterise the medial parts of distributary fluvial systems, and are likely to extend into offshore areas of the East Midlands Shelf and Southern North Sea Basin.

4/ Work on the sediment provenance of the East Midlands shelf using isotopic techniques on zircon (Morton et al., 2016) and feldspar grains (Tyrrell et al., 2012) that have been successfully applied in other basins could help elucidate the relative contribution of material from different sources areas.

5/ A detailed understanding of vertical and lateral changes in grain-size distribution (which can be rapidly conducted on disaggregated core or cuttings samples using laser diffraction analysers) across the East Midlands Shelf and adjacent offshore areas may also assist in understanding sediment pathways.

Table 1 List of boreholes used in study.

NAME	BGS_SOBI/OFFSHORE WELL ID	BNG_X_M	BNG_Y_M	DATUM_MAOD	LENGTH_M	BGS_ID	PATH	NORMALISED GAMMA CUT-OFF
42_22_1	42/22- 1	543882	487598	37.49	2639.57	NA	VERTICAL	0.62
42_27A_1	42/27a- 1	546276	462947	33.53	3201.01	NA	VERTICAL	0.30
47_09A_7	47/09a- 7	572228	422131	35.05	2921.51	NA	VERTICAL	0.35
47_14B_G1	47/14b-G1	582541	409801	43.89	3560.06	NA	DEVIATED	0.25
47_18_1	47/18- 1	569812	394385	35.97	2420.11	NA	DEVIATED	0.50
47_20_2	47/20- 2	591673	403190	38.1	3400	NA	DEVIATED	0.48
47_25_1	47/25- 1	597821	383186	26.52	2442.36	NA	DEVIATED	0.30
47_25_2	47/25- 2	591342	370337	30.78	1952.85	NA	DEVIATED	0.40
47_29A_1	47/29a- 1	574596	364613	28.65	1762.05	NA	DEVIATED	0.30
48_21_2	48/21- 2	604389	381211	27.43	2459.74	NA	VERTICAL	0.40
48_22_2	48/22- 2	625220	378820	28.35	2383.54	NA	VERTICAL	0.48
ALKBOROUGH_1	SE82SE3	488345	422644	7.27	1999	132197	VERTICAL	0.30
APLEY_1	TF17NW2	510147	375105	13.39	1715	472577	VERTICAL	0.35
BARDNEY_1	TF16NW26	511906	368619	5.76	1897.99	472347	VERTICAL	0.52
BASSINGHAM_1	SK96SW16	492080	360598	16.62	1402	250736	VERTICAL	0.53
BECKERING_1	TF18SW13	510396	380252	27.84	1699.26	472732	DEVIATED	0.30
BELVOIR_1	SK83SW107	480924	333979	63.81	960	242335	VERTICAL	0.30
BISCATHORPE_1	TF28SW11	523050	383714	80.21	2075	503750	VERTICAL	0.38
BRIGG_1	TA00NW122	503777	406391	13.7	1936.9	456311	VERTICAL	0.40
BROACH_ROAD	SK95SW7	492920	354550	10.5	907.62	250109	VERTICAL	0.45
BROOMFLEET_1	SE82NE10	489324	427706	4.3	2024	132161	VERTICAL	0.30
BROUGHTON_B1	SE91SW456	494624	410766	68.19	1920	134540	VERTICAL	0.30
BURTON_AGNES_1	TA16SW36	512274	461985	18.5	2290	18275481	VERTICAL	0.30
BURTON_UPON_STATHER_1	SE81NE2	487865	418829	64.01	1857.76	131735	VERTICAL	0.30
CAYTHORPE_1	TA16NW10	512222	467920	26.5	2066.54	463900	VERTICAL	0.30
CLAXBY_1	TF26SE16	529813	364283	54.25	1542.28	503472	VERTICAL	0.30
CLEETHORPES_1	TA30NW51	530237	407090	4.5	2100.07	466355	VERTICAL	0.30
CLOUGHTON_1	SE99NE5	499391	496802	174.65	3078.48	135474	VERTICAL	0.35
CONINGSBY_1	TF25SW18	524141	353553	2.44	1537.71	503382	VERTICAL	0.30
COXS_WALK	SK83NW10	484115	338077	52.67	800.65	241609	VERTICAL	0.30
CRAWBERRY_HILL_1	SE93NE12	497670	437721	93.3	2750	19378885	DEVIATED	0.30
CROPWELL_BRIDGE	SK63NE28	467730	335473	46.12	699.82	232896	VERTICAL	0.30
CROSBY_WARREN_2Z	SE91SW566	491186	412908	4.2	1774	19358265	DEVIATED	0.30
DUKES_WOOD_1	SK65NE141	467664	359583	69	793	19198755	DEVIATED	0.10
FORDON_2	TA07SE19	506897	473599	67.69	2444.5	460181	VERTICAL	0.30
GLANFORD_1	TA00NW124	501744	407277	11.15	2012	456313	VERTICAL	0.30
GUNTHORPE_GRANGE_FARM	SK64SE23	467243	344823	17.12	687.93	234154	VERTICAL	0.35
HALTON_HOLEGATE_2	TF46NW91	541300	365640	80.57	1822.7	18715564	VERTICAL	0.30
HARLSEY_1	SE49NW6	442230	498070	112.34	1081.73	114972	VERTICAL	0.40
HATTON_LODGE	SK62SE3	469328	324597	80.57	548.03	232805	VERTICAL	0.30
HELPRINGHAM_1	TF13NE9	517530	338840	7.01	762.3	471775	VERTICAL	0.30
HIGH_HUTTON_1	SE76NW14	474423	469412	52.1	2744.72	125667	VERTICAL	0.30
HORNSEA_1	TA15SE8	518460	450620	11.17	2059.84	463701	VERTICAL	0.20
HUNMANBY_1	TA17NW10	513010	475880	76.6	2252.47	463974	VERTICAL	0.38
HUNSTANTON_1	TF64SE12	569230	342700	10.7	862.3	509713	VERTICAL	0.30
KEDDINGTON_1	TF38NE39	536651	388170	25.9	1999.5	504771	VERTICAL	0.30
KELSTERN_1	TF29SE12	525865	392034	132.87	2518.56	503828	VERTICAL	0.30
KILN_LANE_1	TA11SE308	518656	412921	10.4	2291	19786421	VERTICAL	0.40
KIRBY_LANE_1	SK71NW1	473239	317589	74.65	413.94	237685	VERTICAL	0.30
KIRBY_MISPERTON_1	SE77NE17	477105	478933	35.97	3421	125949	VERTICAL	0.30
LOCKTON_4	SE88NE2	486948	488913	203.66	2025.7	132749	VERTICAL	0.30
LOCKTON_EAST_1	SE98NW6	493705	489822	87.17	1898.93	135425	VERTICAL	0.30
LONG_EATON_1	SK43SE161	446400	331660	44.55	2752.34	220556	VERTICAL	0.30
MALTON_3	SE77NE15	479990	475992	21.5	1721.82	125947	VERTICAL	0.20
MAREHAM_GRANGE	TF04SE23	508446	343288	8.1	958.3	468879	VERTICAL	0.15
MARSH_LANE_1	SK78NE32	479657	388562	6.18	1280.27	239817	VERTICAL	0.26
MELTON_SPINNEY	SK72SE9	476754	322556	123.58	619	238175	VERTICAL	0.30
NETTLETON_1	TF19NW53	511843	396404	162.6	1555.7	472819	VERTICAL	0.40
NEWPORT_1	SE82NE17	485703	429309	7.07	1207.25	18407553	VERTICAL	0.30
NOCTON_7	TF06SW7	500492	363228	50.3	975.06	469415	VERTICAL	0.30
NORTH_DALTON_1	SE95SW6	493815	452771	61	1699.26	135318	VERTICAL	0.30
PICKERING_1	SE78SE14	479658	482158	26.21	2046.43	126173	VERTICAL	0.30
RISBY_1	TA03NW83	501051	435774	51.21	1502.36	458615	VERTICAL	0.40
ROSEDALE_1	SE79SW1	472657	494952	158.9	1642.87	126224	VERTICAL	0.20
RUDDINGTON_HALL	SK53SE12	459146	333812	35.66	596.49	226011	VERTICAL	0.30
RUDSTON_1	TA06NE15	509340	466320	48.2	2514	459977	VERTICAL	0.30
SALTFLEETBY_7	TF49SW133	542557	391333	6.5	2671	13222175	VERTICAL	0.19
SAXTHORPE_1	TG13SW1	612260	330130	48.8	986.9	515065	VERTICAL	0.30
SEAL_SANDS_1	NZ52SW308	453796	523805	11.28	4194.05	917593	VERTICAL	0.15
SESSAY_1	SE47SE2	447808	474042	29	30.48	114704	VERTICAL	0.30
SIBSEY_1	TF35SE2	536206	350211	7.62	1219.2	504490	VERTICAL	0.20
SOMERTON_1	TG42SE1	646070	321201	4.3	1400.86	519476	VERTICAL	0.30
SOUTH_CREAKE_1	TF83SE8	585730	334019	41.8	772.36	511364	VERTICAL	0.30
SPALDING_1	TF21SW2	524340	314780	1.97	500	473512	VERTICAL	0.30
SPALDINGTON_1	SE73SE6	479275	432455	9.9	1850	125310	VERTICAL	0.30
STAINTON_A1_1	TF07NE21	506276	378509	15.2	1620	469493	VERTICAL	0.35
STAITHES_1	NZ71NE9	476950	518513	61.4	1146.35	620314	VERTICAL	0.40
TETNEY_LOCK_1	TA30SW83	533187	400939	5.6	2851.4	466577	VERTICAL	0.30
WHENBY_1	SE67SE7	465408	472464	110.64	1831.85	124355	VERTICAL	0.20
WILLOWS_1	TA17SW24	512027	474868	115.55	2407	18126679	VERTICAL	0.30
WINESTEAD_1	TA22SE7	527410	424334	8.96	2004.06	466012	VERTICAL	0.40

Table 2 Summary of information sourced from BGS memoirs.

SORT	NUMBER_REF	TITLE	DATE	SHERWOOD SANDSTONE SUMMARY
1	27	Durham & West Hartlepool	1967	Soft fine-grained thick bedded dull red sandstones with subsidiary grey sandstones and red mudstones and siltstones. Current bedding, ripple marks, desiccation breccias Foresets show a south-westerly provenance Westerly increase in the proportion of sand with a diachronous base falling westwards Extensive yellow and grey colouration which may be due to a former cover of peat
2	42	Northallerton	1998	SSG largely obscured by drift Outcrop at River Leven shows fine-grained, red-brown, massive, cross-bedded sandstone contains numerous red mudstone clasts
3	52	Thirsk	1992	Upward-fining cycles 1-2m thick which are erosively based with a mudflake conglomerate and pass upwards into cross-bedded sandstone Tops of cycles show mudcracks and pseudomorphs after gypsum
4	62	Harrogate	1993	Junction between Upper Marl and SSG is interbedded gradation over a few metres Mudstone flake breccias are common No evidence for the presence of coarse pebbly facies Poorly cemented fine-medium grained sandstone Brick red but also grey, yellow and mottled Medium to thick bedded Cross-bedding and cross-lamination Clasts consist mainly of quartz but include feldspars and rock fragments Ilmenite and zircon are the dominant heavy minerals
5	70	Leeds	2002	Bunter Sandstone cannot be subdivided Bunter is not characterised by abundant pebbles Soft red sandstone with occasional beds of red marl
6	71, 72	York and Hull	1886	Soft brick-red thick bedded sandstone Thin marly partings Occasionally veins of opaque white quartz
7	79 & 88	Goole, Doncaster and the Isle of Axholme	1994	Thin layers and lenses of red brown and green grey siltstone. Common reworked mudstone clasts and flakes. Rounded quartzite pebbles common in the middle and upper parts of the sandstone in southern areas becoming smaller and rarer to the north. Cross-bedding, ripple cross-lamination and parallel lamination. Micaeous partings. Local occurences of rounded grains and ventifacts indicate aeolian activity Paleocurrents to east in south, becoming more variable to the north
8	80 & 89	Kingston upon Hull and Brigg	1992	Lowest sandstones are variably coloured, micaeous and clayey, silty well sorted and fine-grained. Some layers rich in rounded grains. Cemented by calcite and gypsum. Green reduction haloes and some carbonaceous debris with a fragment of lignite in the Brigg borehole. Main part of SSG is red, less clayey, generally coarser grained and locally pebbly. Fine-coarse grained, uncemented, unconsolidated, friable, porous and permeable. Some thin red or green mottled mudstone. At top are white grey and buff sandstones largely free from pebbles. In some boreholes a coarse grained wind winnowed remanie layer, possibly marking the Hardegsen Disconformity
9	87	Barnsley	1947	Red marl and fine-grained red sandstone comprise the Permian Marl No information on SSG
10	101	East Retford, Worksop & Gainsborough	1973	Pebbly formations are traceable into East Retford but further north pebbles become less abundant
11	113	Ollerton	1967	The junction of the Permian and Bunter rocks is not precisely defined Approximate boundary between sandstones above and mudstones below The boundary is convergent on the Lower Magnesian Limestones southwards toward Mansfield Rocks of Bunter type rest on Upper and in places of Lower Magnesian Limestone (Cadeby Formation) to the east. But generally mudstones of Permian facies are present The Lower Mottled Sandstone (Lenton Sandstone Fm) is around 100 feet thick and is red brown sand and sandrock with thin lenses of red and green grey mudstone and siltstone. Can contain a few small pebbles of Bunter type. Lower Mottled Sandstone (Lenton Sandstone Fm) differs from Bunter Sandstone (SSG) in being generally finer grained, more marly, more compact, deeper red colour, lacks abundant pebbles The Pebble Beds (SSG) are a mass of cross-bedded sandstone, mostly medium to coarse grained with numerous pebbles Pebble Beds have thin layers and lenses of red and grey-green mudstone and siltstone In colour they are red-brown, yellow or pink In the Egmanton Oilfeld much of the Pebble Beds are reported as calcareous and especially in the topmost beds - pyritic. A trace of gypsum is logged in a few wells The pebbles are less than 5 inches (1270mm) across and are well-worn and smooth with flattened oval shapes. Most are dull red or liver-coloured quartzites, also vein quartz, siliceous breccia, jasper, chert and igneous rocks A face in a sand-pit at Mansfield showed 62 feet of sandrock. Red-brown, pink and yellow. Coarse grained and cross-bedded with pebbles up to 2 inches. Pebbles scattered or concentrated in bands. Mudstone as fragments and lenses of red sandy micaeous mudstone. The junction with the Lower Mottled Sandstone (Lenton Sandstone) is well defined and sharp suggesting erosion. Pebbles are more abundant at some levels than others but their distribution appears to be random Subangular pebbles are occasionally noted and many wind-rounded quartz grains are recorded at No. 20 well at Caunton 80 feet above the base White conglomerate with broken pebbles and green micaeous marls at top of Bunter (Green Beds) in Caunton No. 20 well
12	126	Nottingham	2002	Divisible into pebble-free Lenton Sandstone and pebble-bearing Nottingham Castle Formation Swinnerton (1914) described from near Nottingham a dreikanter bed at the top of the Bunter and stated that their uppermost 2-3 feet were much cemented with calcite and partially covered by loose gravel up to 3 feet thick with wind-worn stones Lenton Sandstone passes northeast to Lenton Sandstone over Roxby Formation Lenton Sandstone is generally bright red-brown with yellow mottling and is soft and friable. Fine grain size and clay content made it suitable as a moulding sand.
13	127	Grantham	1999	Around 5-100 m of Permian pebbly sandstones and conglomerates overlain by Sherwood Sandstone Borehole chippings and gamma-ray logs indicate an overall coarsening-upward sequence within the lower half of the Sherwood Sandstone
14	145 & parts of 129	King's Lynn and The Wash	1994	Triassic rocks thin and variable in thickness - infilling irregular topography. In Hunstanton 1 yellowish grey medium grained sandstone with quartzite and vein quartz pebbles. Conglomerate at base.

Table 3 List of horizon picks and codes used in study.

Marker_Code	Number	Unit_Below	Unit_Above	Type	Unit_Below_Full	Unit_Above_Full
CARB_LNS_U	1	CARB	LNS	U	Carboniferous Rocks (Undifferentiated)	Lenton Sandstone Formation
CARB_PUND_U	55	CARB	PUND	U	Carboniferous Rocks (Undifferentiated)	Permian Rocks (Undifferentiated)
CL_SSG_U	1	CL	SSG	U	Carboniferous Limestone Supergroup	Sherwood Sandstone Group
HAI_PNG_N	6	HAI	PNG	N	Haisborough Group	Penarth Group
LCM_PUND_U	4	LCM	PUND	U	Lower Coal Measures Formation	Permian Rocks (Undifferentiated)
LNS_NTC_U	51	LNS	NTC	N	Lenton Sandstone Formation	Nottingham Castle Sandstone Formation
MCM_PUND_U	2	MCM	PUND	U	Middle Coal Measures Formation	Permian Rocks (Undifferentiated)
MMG_LI_F	2	MMG	LI	F	Mercia Mudstone Group	Lias Group
MMG_PNG_N	63	MMG	PNG	N	Mercia Mudstone Group	Penarth Group
ORD_PUND_U	1	ORD	PUND	U	Ordovician Rocks (Undifferentiated)	Permian Rocks (Undifferentiated)
PNG_LLI_N	5	PNG	LLI	N	Penarth Group	Lower Lias (Undifferentiated)
PNG_SMD_N	58	PNG	SMD	N	Penarth Group	Scunthorpe Mudstone Formation
ROX_SSG_N	53	ROX	SSG	N	Roxby Formation	Sherwood Sandstone Group
SSG_MMG_N	68	SSG	MMG	N	Sherwood Sandstone Group	Mercia Mudstone Group
UCM_LNS_U	3	UCM	LNS	U	Upper Coal Measures Formation	Lenton Sandstone Formation
UCM_PUND_U	5	UCM	PUND	U	Upper Coal Measures Formation	Permian Rocks (Undifferentiated)
ZG_LNS_N	1	ZG	LNS	N	Zechstein Group	Lenton Sandstone Formation
ZG_ROX_N	9	ZG	ROX	N	Zechstein Group	Roxby Formation
BNS_HAI_N	15	BNS	HAI	N	Bunter Sandstone	Haisborough Group
LIA_ROX_N	45	LIA	ROX	N	Littlebeck Anhydrite	Roxby Formation
VS_PUND_U	1	VS	PUND	U	Precambrian (Undifferentiated)	Permian Rocks (Undifferentiated)
VS_ROX_U	2	VS	ROX	U	Precambrian (Undifferentiated)	Roxby Formation
VS_SSG_U	1	VS	SSG	U	Precambrian (Undifferentiated)	Sherwood Sandstone Group
ROX_AMTH_N	9	ROX	AMTH	N	Roxby Formation	Amethyst Formation
ZG_BTSH_N	12	ZG	BTSH	N	Zechstein Group	Bunter Shale
AMTH_BNS_N	5	AMTH	BNS	N	Amethyst Formation	Bunter Sandstone
BTSH_BNS_N	7	BTSH	BNS	N	Bunter Shale	Bunter Sandstone

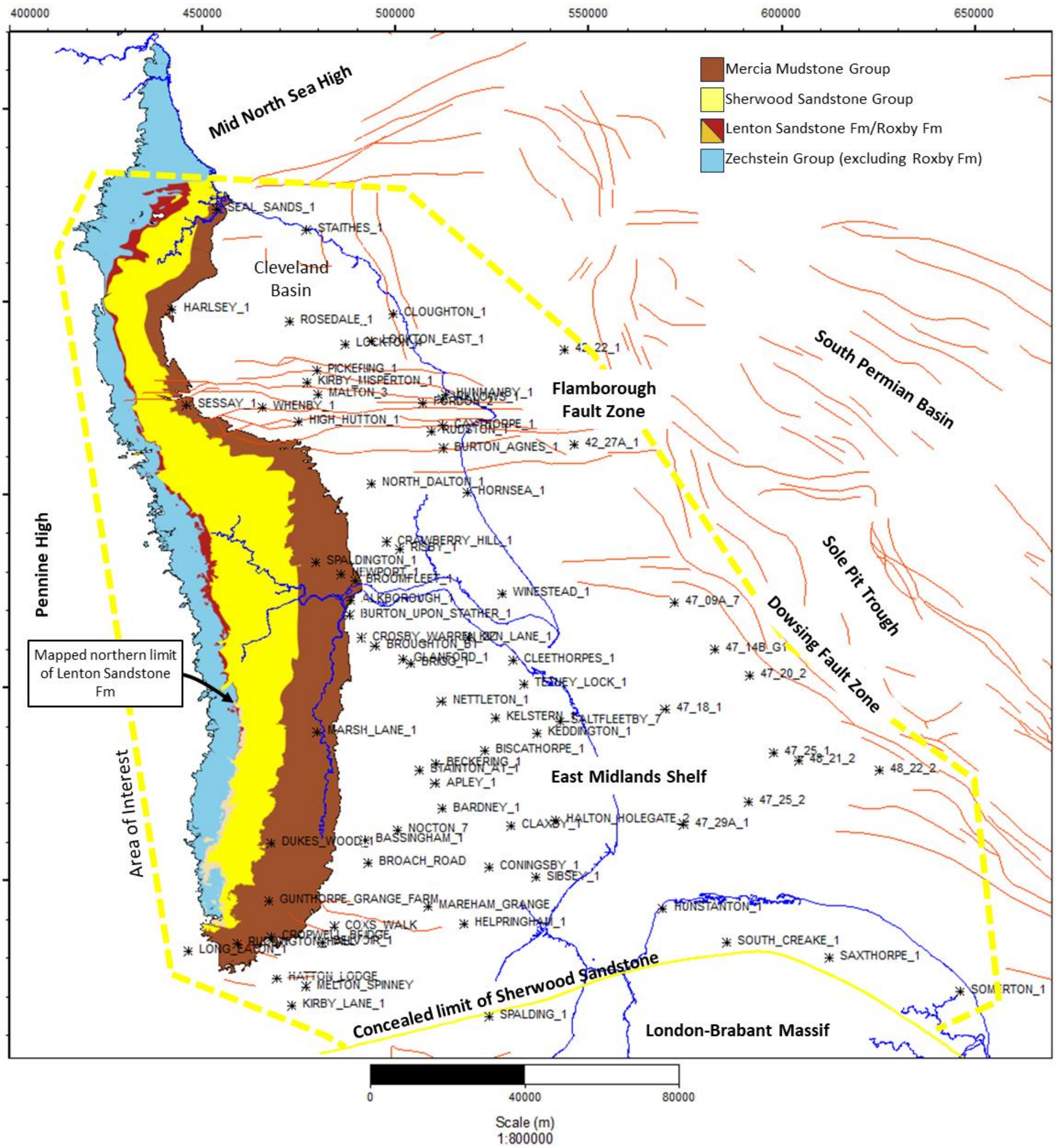


Figure 1 Map showing the area of interest (dashed yellow polygon) which is bounded by the Mid North Sea High, the onlap limit of the Sherwood Sandstone onto the London-Brabant Massif, the eastern margin of the East Midlands Shelf at the Dowsing Fault Zone, and the erosional limit of Permo-Triassic strata parallel to the Pennine High. The map shows Permo-Triassic outcrop processed from BGS Geology 50K, the distribution of boreholes used in the study, and major Mesozoic faults (red polylines) from BGS Tectonic map of Britain, Ireland and adjacent areas. Contains Ordnance Survey data © Crown copyright and database rights [2024].

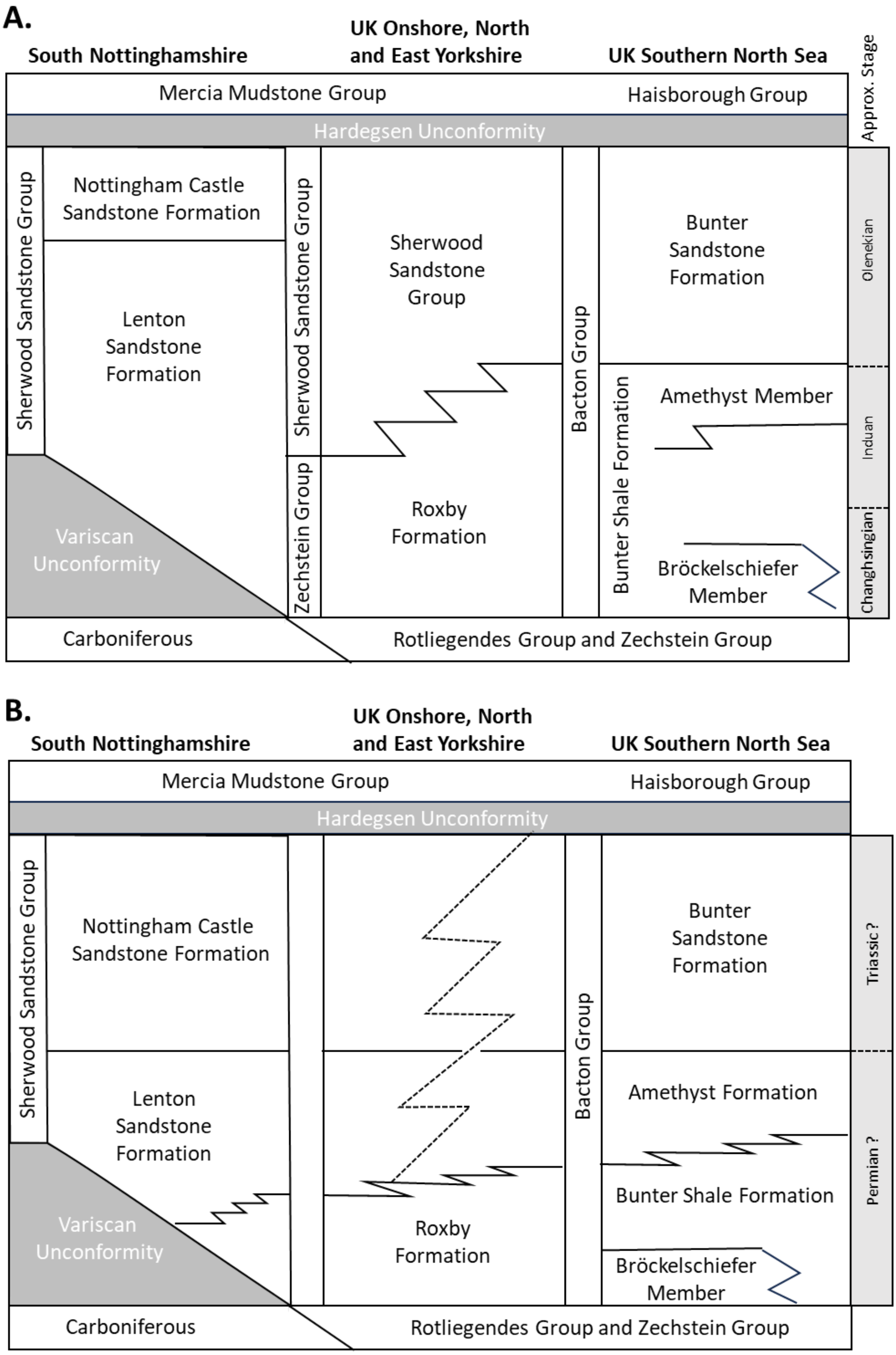
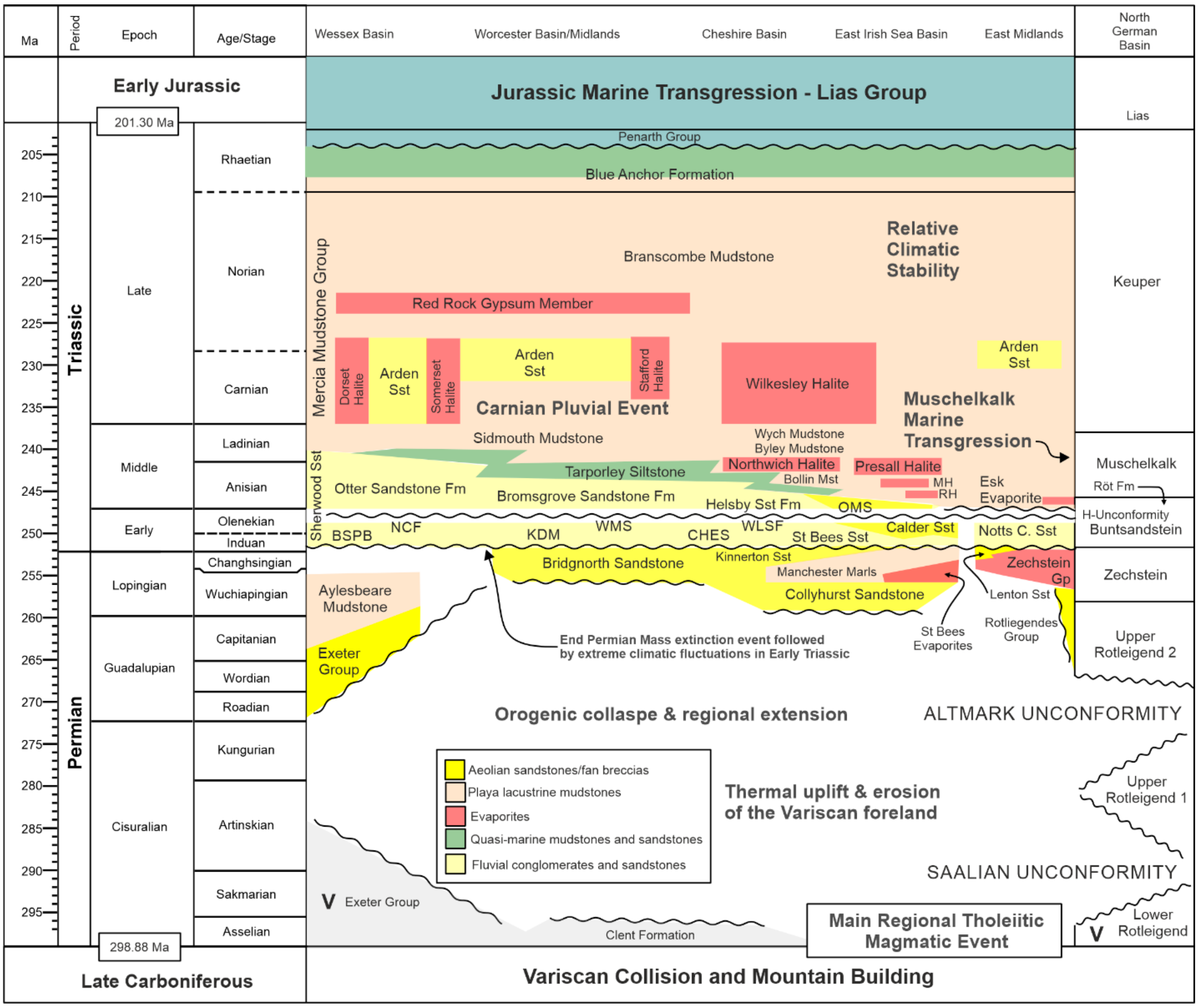


Figure 2 Simplified charts showing the lithostratigraphy covered by the report. Chart A is slightly modified from Johnson et al. (1994) and shows the current nomenclature and correlations. Chart B shows the modified nomenclature and the correlations used and proposed by this work. Speculative Permo-Triassic boundary shown in B is based on findings from the Staithes borehole (Salisbury et al., 2022) See text for details.



Proposed unifying nomenclature	Existing nomenclature (with key to abbreviations above)
Helsby Sandstone Formation	Otter Sandstone Formation Bromsgrove Sandstone Formation Ormskirk Sandstone Formation (OMS)
Wilmslow Sandstone Formation	Wildmoor Sandstone Formation (WLSF) Calder Sandstone Formation
Chester Formation	Budleigh Salterton Pebble Beds (BSPB) Kidderminster Formation (KDM) Cannock Chase Formation Polesworth Formation Hawksmoor Formation Chester Pebble Beds Formation (CHES) Nottingham Castle Sandstone Formation (Notts. C. Sst)

Figure 3 The wider stratigraphic context of the Nottingham Castle Sandstone, as part of a linked system of Early Triassic sandstone-dominated (and often gravelly) formations (modified from Newell (2018b)). The table provides a key to abbreviated formations and the proposal by Ambrose et al. (2014) for a rationalization of local basin-specific nomenclature. Note that a representative of the unified Helsby Sandstone Formation above the Hardegsen Unconformity (H-Unconformity) is absent from the East Midlands where Anisian-age Mercia Mudstone Group is present.

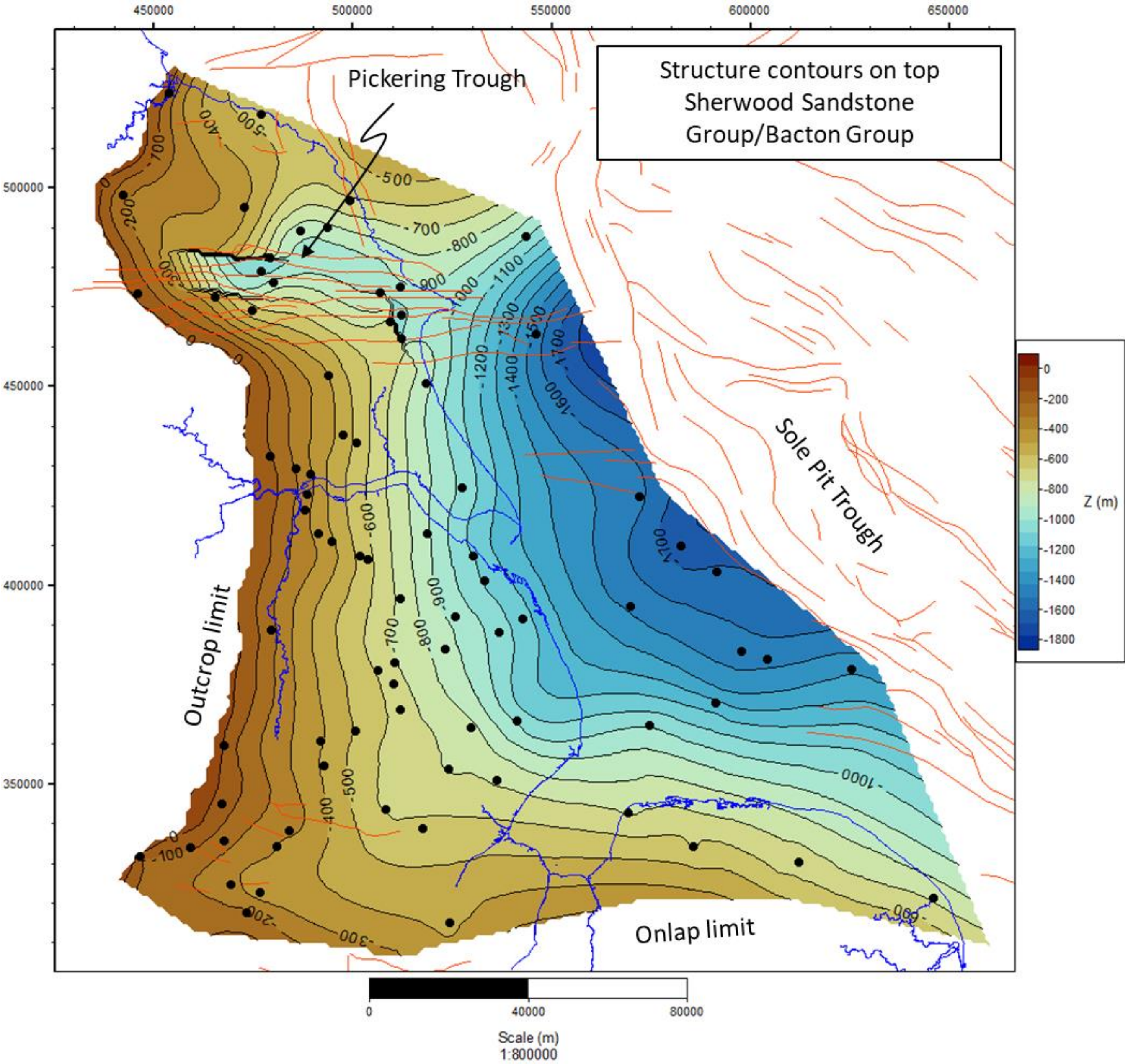


Figure 4 Map showing the present geological structure on the top of the Sherwood Sandstone Group/Bacton Group. The map is contoured from outcrop elevation and borehole picks (shown as black dots). Faults shown as red polylines are sourced from the BGS Tectonic map of Great Britain and Ireland for reference. Contains Ordnance Survey data © Crown copyright and database rights [2024].

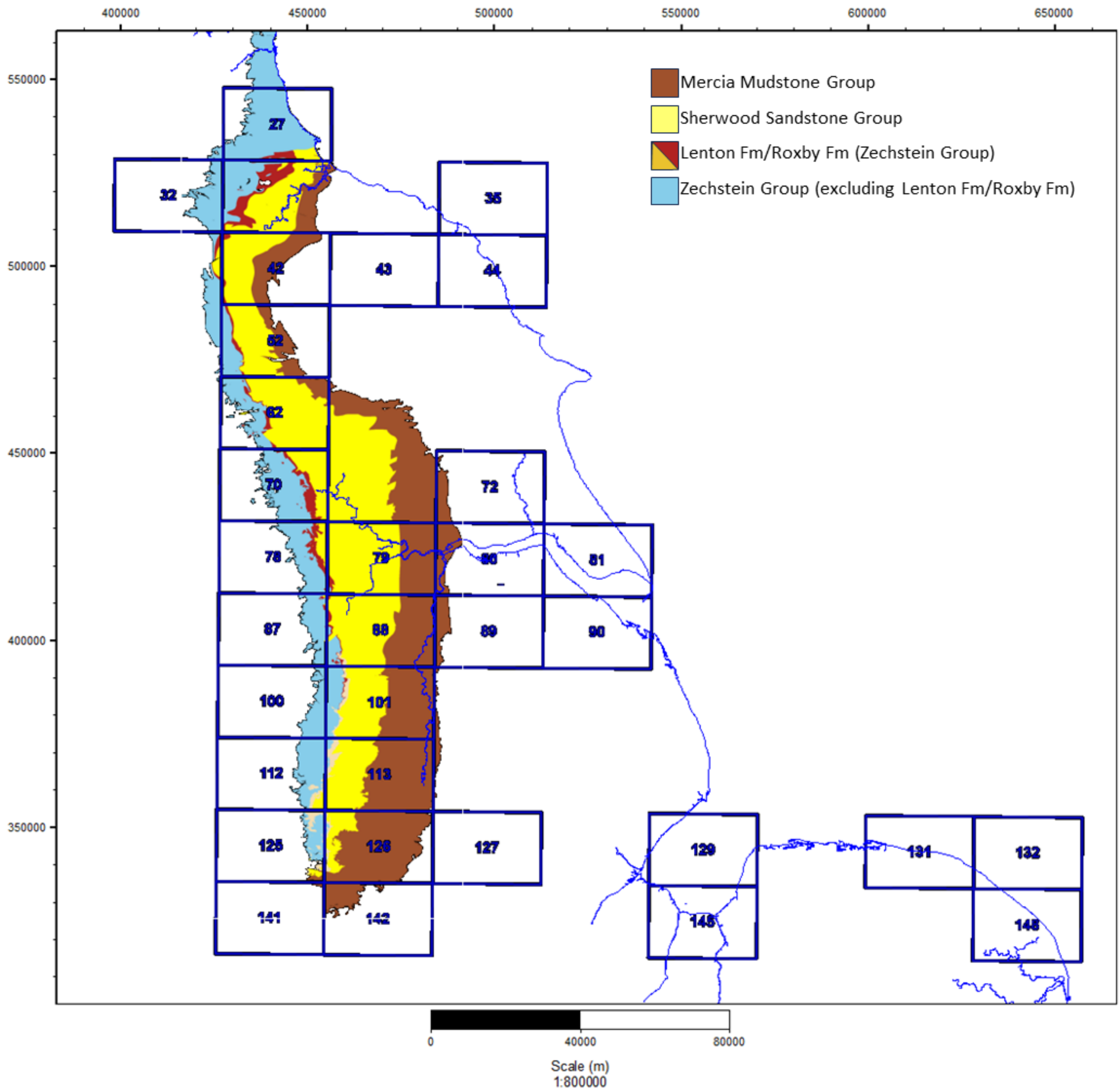


Figure 5 Map showing availability of BGS memoirs that include information on the SSG at outcrop or in the subsurface. Information from the memoir areas is summarised in Table 2. Contains Ordnance Survey data © Crown copyright and database rights [2024].

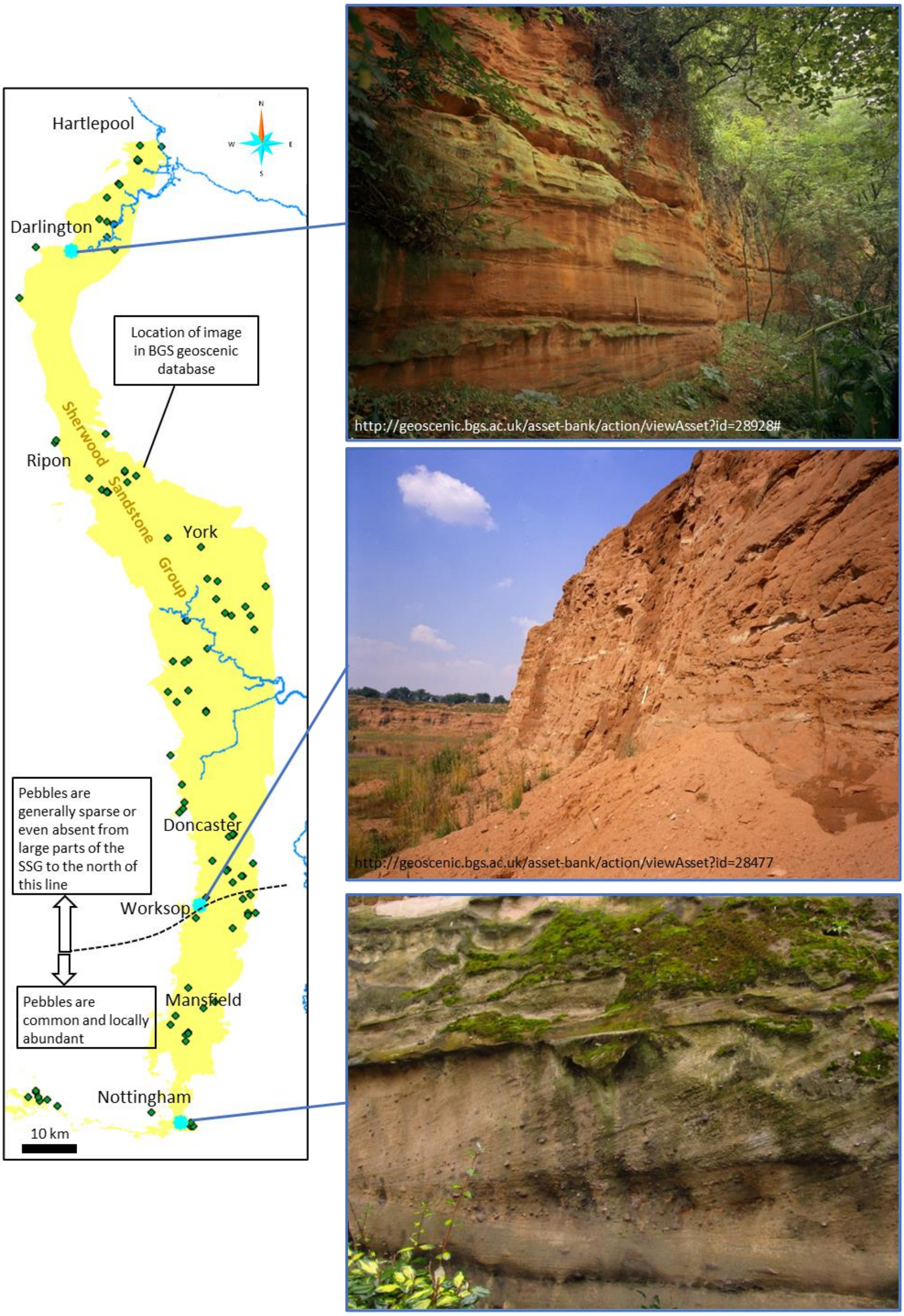
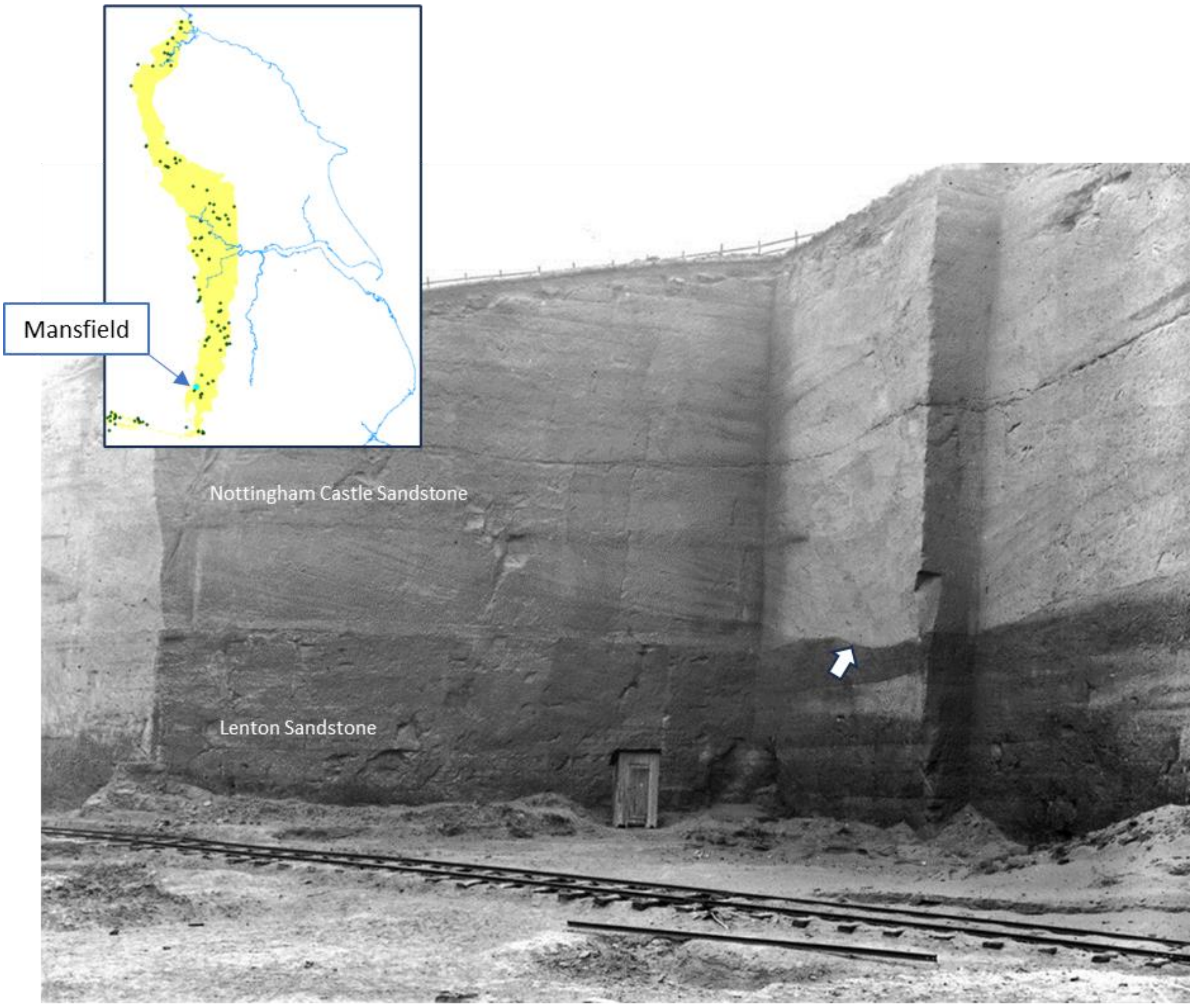


Figure 6 Outcrop photographs of the Sherwood Sandstone Group from the BGS geoscenic database. South of Worksop the SSG is developed in a pebbly sandstone facies with large-scale cross-bedding and often high relief erosion surfaces. Northwards pebbles disappear and the sandstone beds become more tabular. Contains Ordnance Survey data © Crown copyright and database rights [2024].



http://geoscenic.bgs.ac.uk/asset-bank/action/viewAsset?id=15668&index=1&total=2&view=viewSearchItem#

Figure 7 Erosive contact (white arrow) between the Lenton Sandstone and Nottingham Castle Sandstone. Photograph taken in 1911 at the Standard Sand Co. Quarry, Rock Hill, Mansfield.

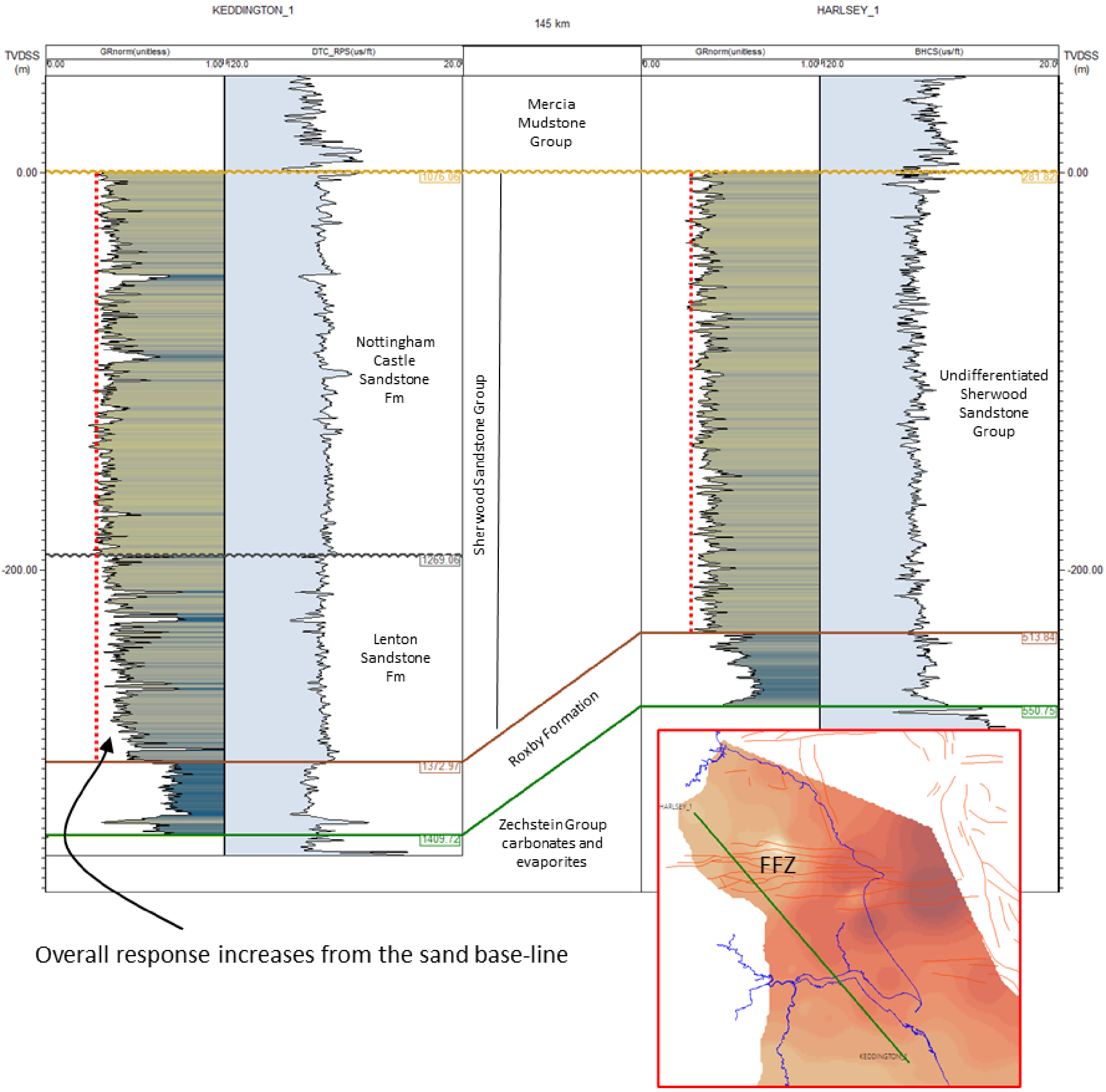


Figure 8 Typical gamma-ray log character of the Sherwood Sandstone in locations south and north of the Flamborough Fault Zone. To the south (e.g. Keddington 1), gamma ray logs often suggest the presence of two units. A lower unit characterised by higher gamma ray responses and numerous thin mudstones. The upper unit has a generally lower gamma-ray response with some intervals of very low response. Thick mudstones (or possibly mudstone intraclast breccias) are locally present. To the north (e.g. Harlsey 1) the overall gamma ray response is relatively uniform throughout the entire Sherwood Sandstone Group. High frequency serrations probably indicate many thin interbedded mudstones. Inset map shows line of panel and total Bacton Group thickness (dark colours=thicker). See Figure 17 for the full version of this map and the thickness scale. Contains Ordnance Survey data © Crown copyright and database rights [2024].

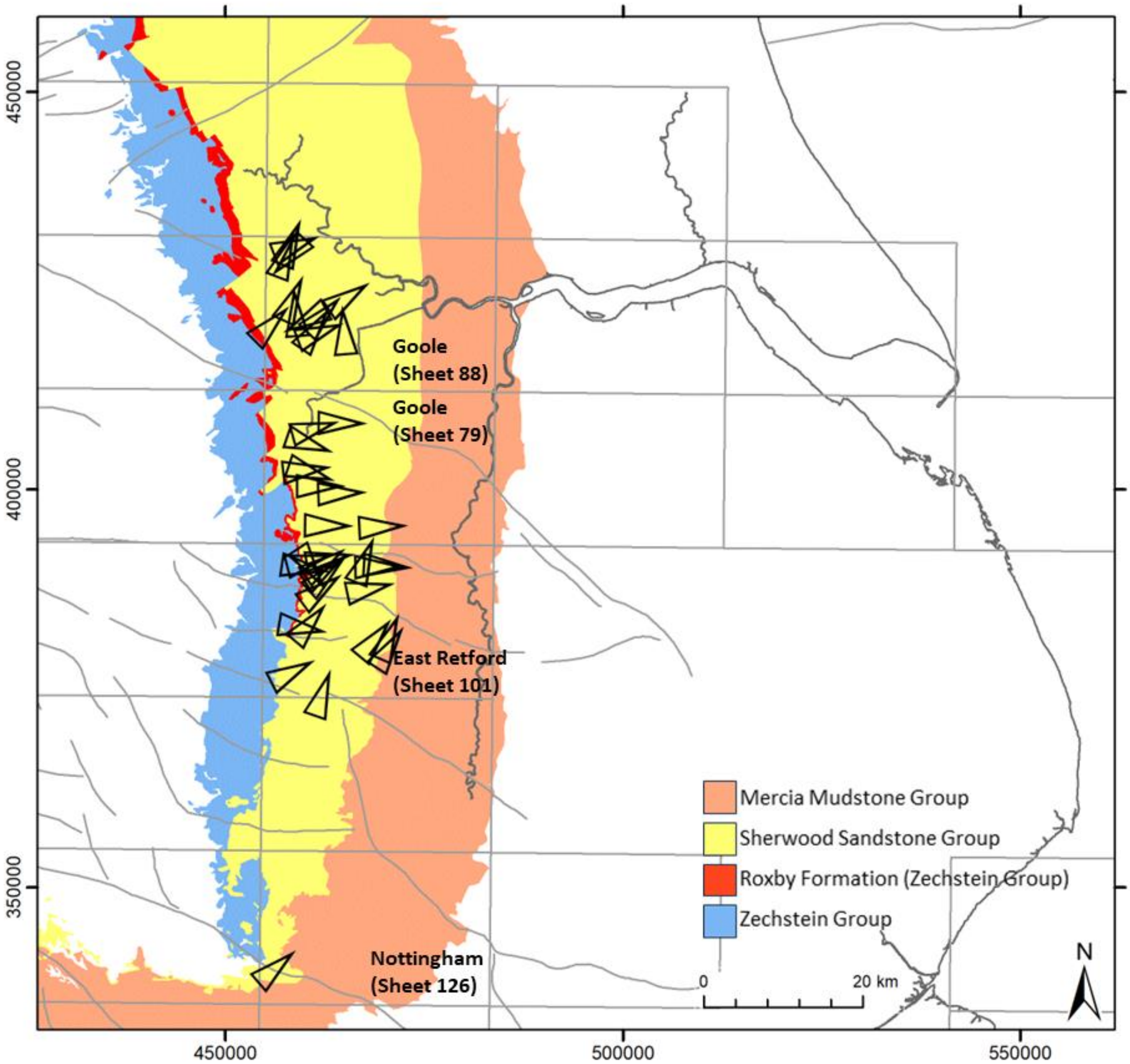


Figure 9 Palaeocurrent data extracted from BGS Memoirs showing predominance of northeast directed flows, but also a strong component of easterly flow. Changes in the predominant trend correlate with sheet boundaries but there is no evidence that collector or other sampling bias of adversely impact the dataset. Contains Ordnance Survey data © Crown copyright and database rights [2024].

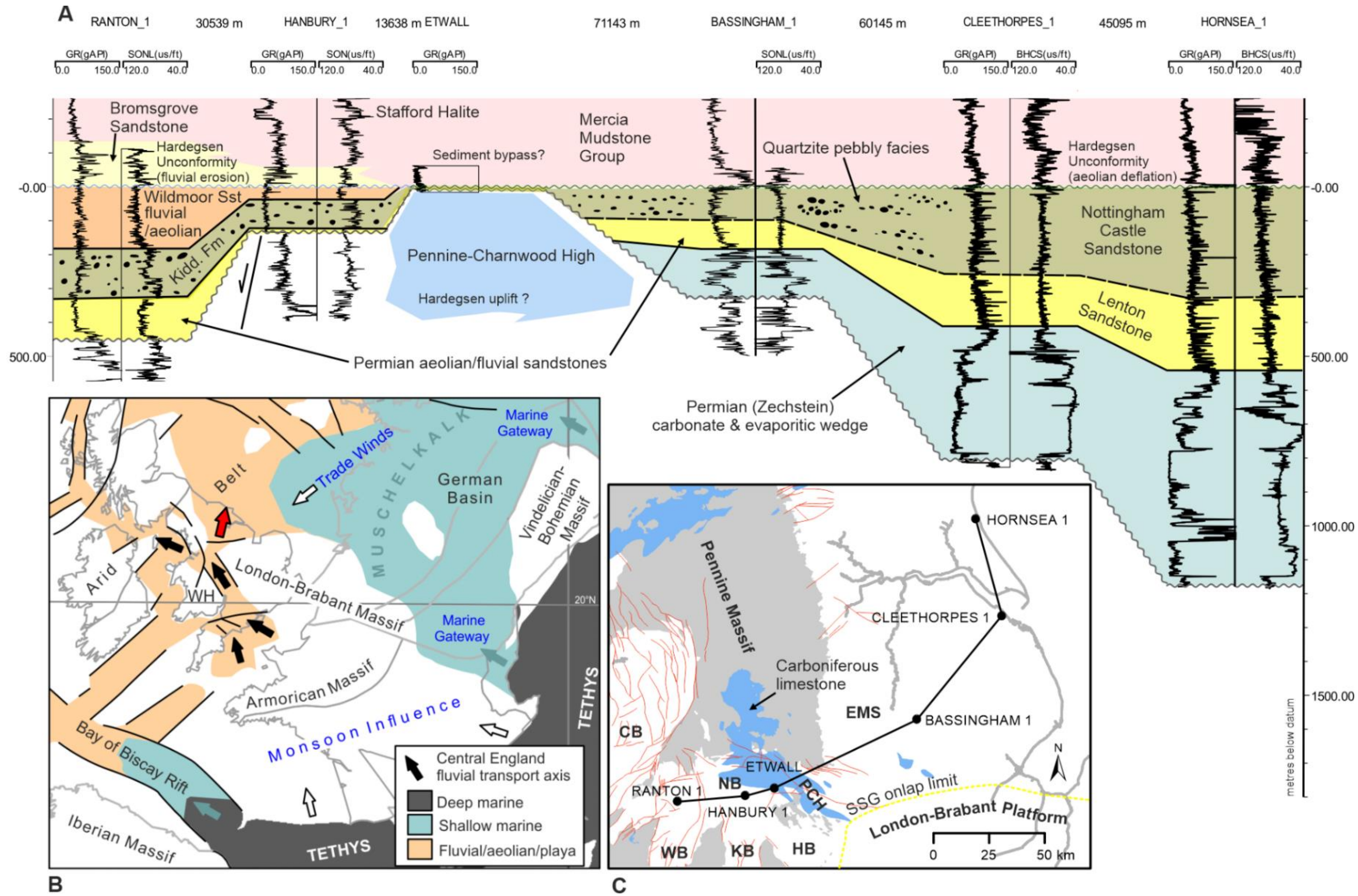


Figure 10 A) Stratigraphic relations across the Pennine-Charnwood High (PCH) which separates the Needwood Basin (NB) and Hinckley Basin (HB) from the East Midlands Shelf (EMS) (modified from (Newell, 2018b). The continuity of quartzite conglomerates across the PCH suggests it did not present a barrier to major axial drainage systems flowing from the Armorican Massif (B) during the deposition of the Nottingham Castle Sandstone. The absence of deposits may indicate the Pennine-Charnwood High was a zone of sediment bypass or it may have been uplifted and eroded at the Hardegsen Unconformity (Warrington, 1970). Post-Hardegsen fluvial sandstones are only present on the west side of the PCH, while the East Midlands Shelf became a zone of aeolian deflation under sediment-undersaturated trade winds. Borehole locations showing in (C).

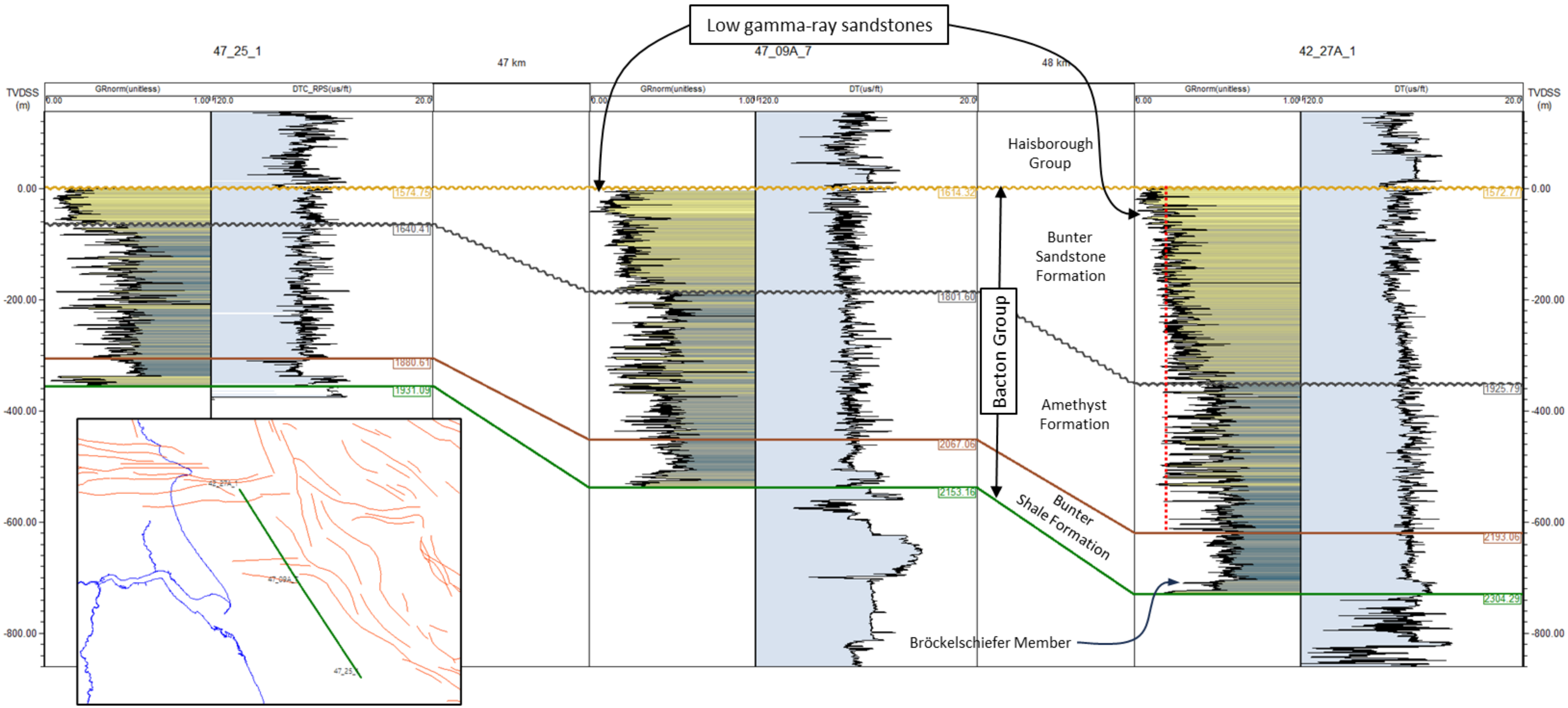


Figure 11 Stratigraphical subdivision of the Bacton Group in offshore boreholes showing the nomenclature used in this report.

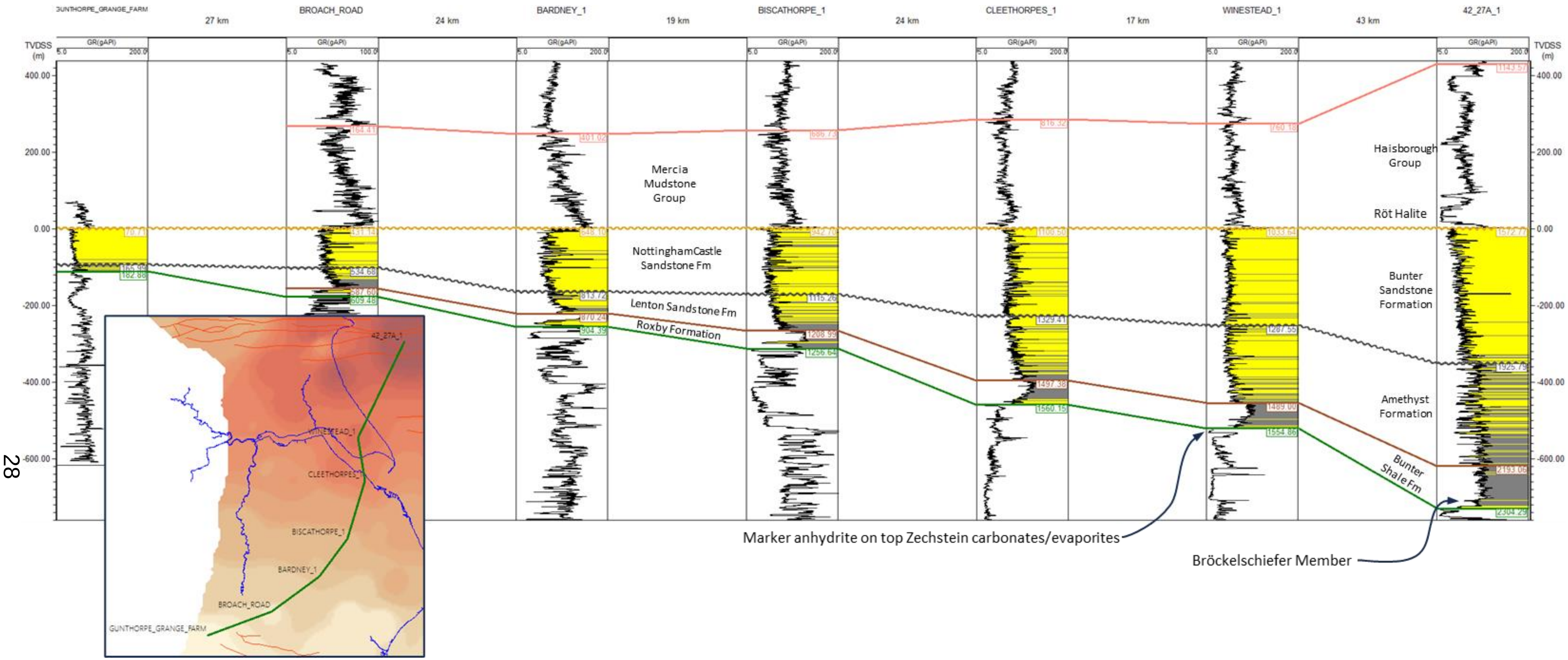


Figure 12 SE to NE trending correlation panel showing wedge-like thickening of the Bacton Group and probable onshore-offshore correlation. Inset map shows line of panel and total Bacton Group thickness (dark colours=thicker). See Figure 17 for the full version of this map and the thickness scale.

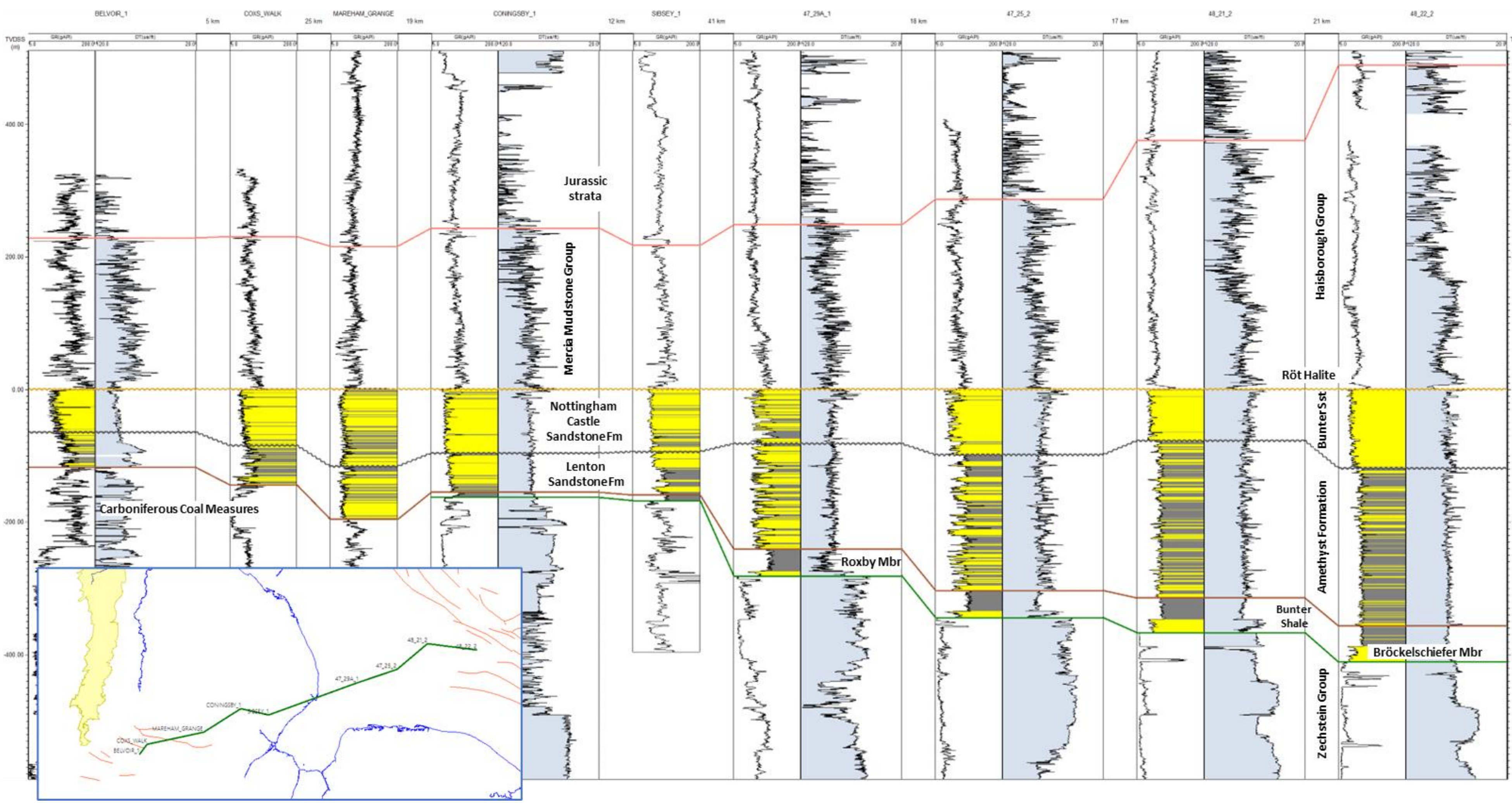


Figure 13 West to east correlation showing marked decrease in sand in the Amethyst Member

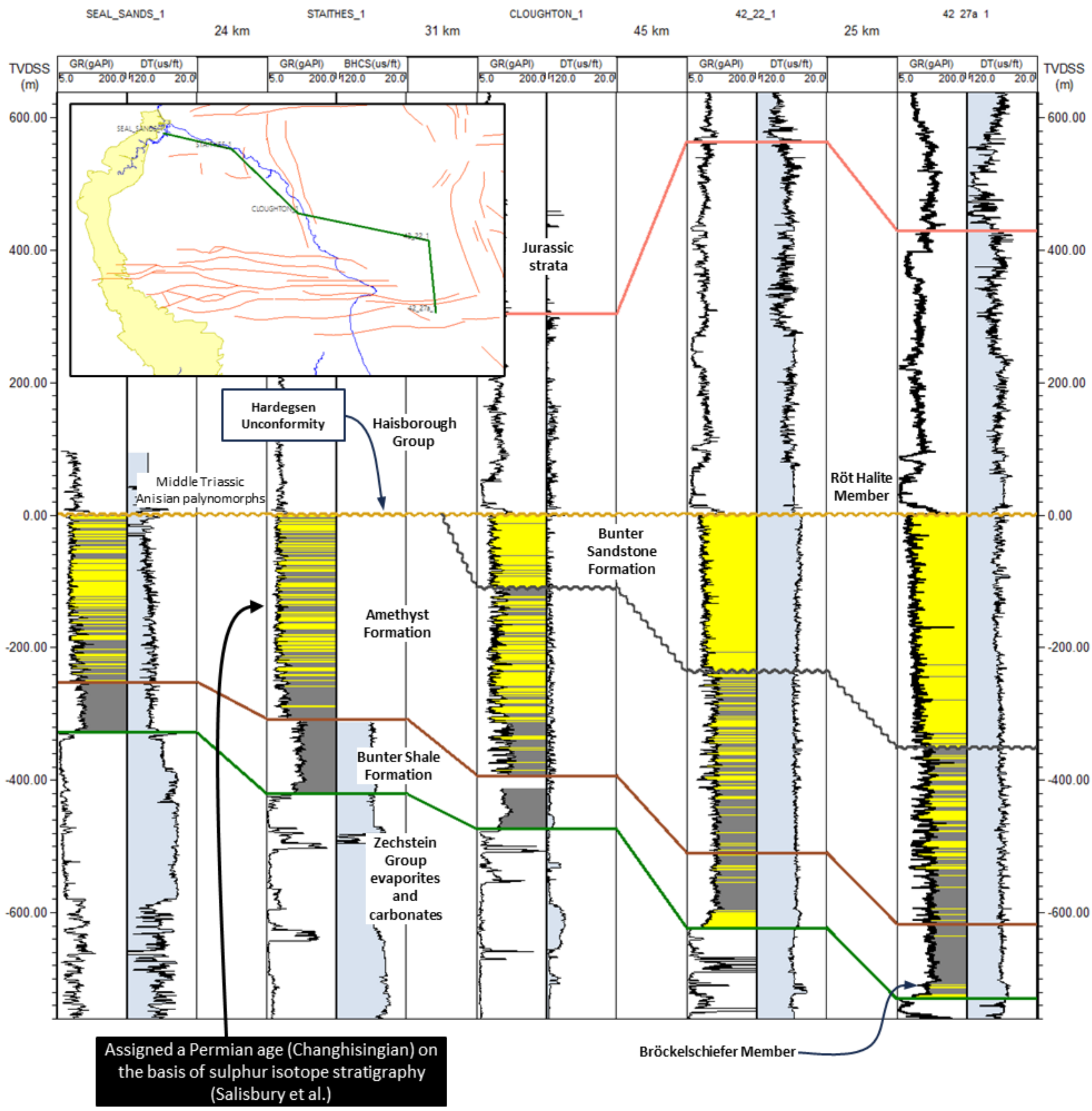


Figure 14 Correlation from Seal Sands to offshore Flamborough Head. The relatively thin Bacton Group in Seal Sands and Staithes may result from complete erosion/non-deposition of the Bunter Sandstone Formation. Sulphur isotope stratigraphy in a borehole at Staithes suggests that the entire Bacton Group is Late Permian in age with a substantial unconformity below Anisian-age Mercia Mudstone Group (Salisbury et al., 2022).

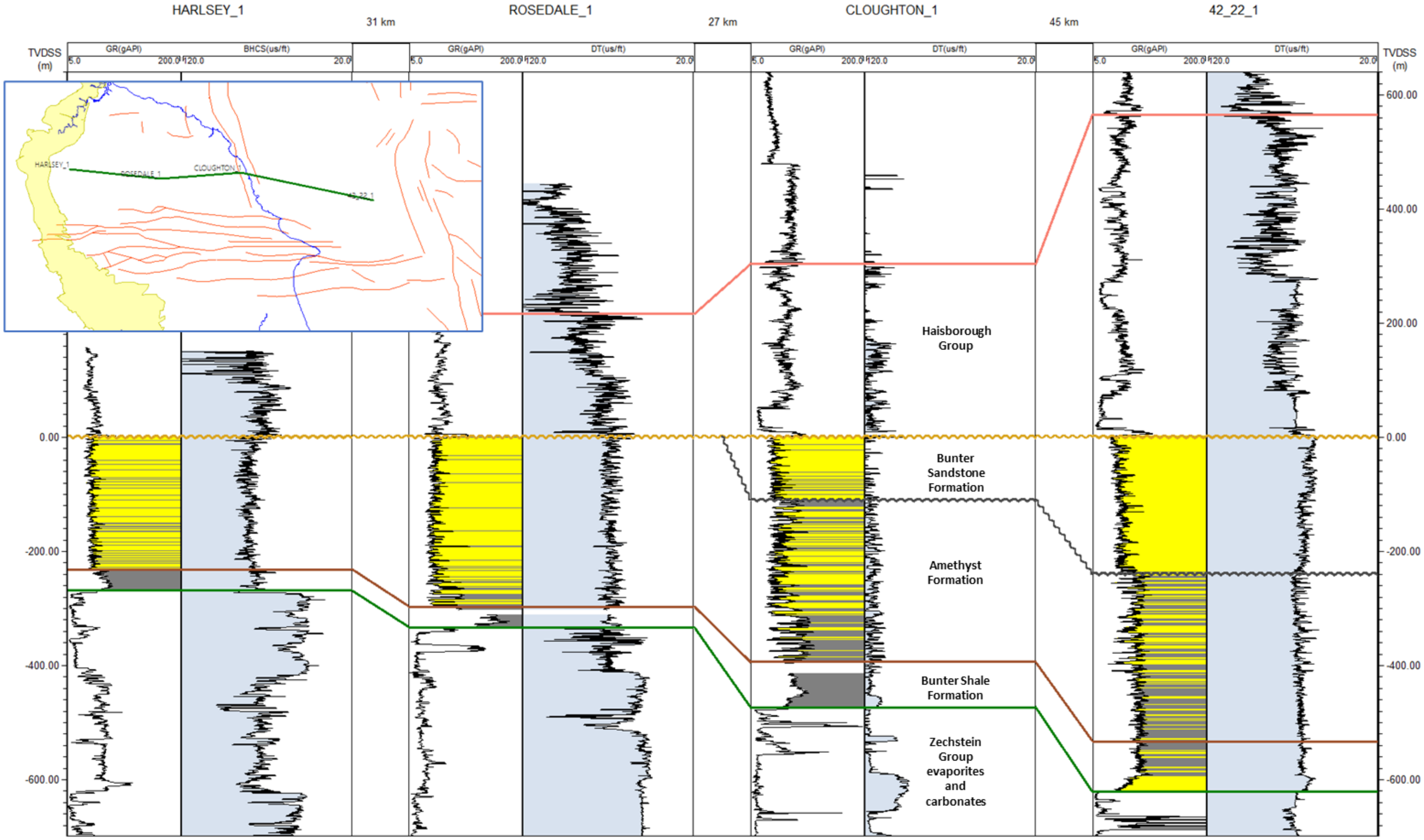


Figure 15 Correlation from Harsley 1 to 42/22-1 showing similar stratigraphic relationships.

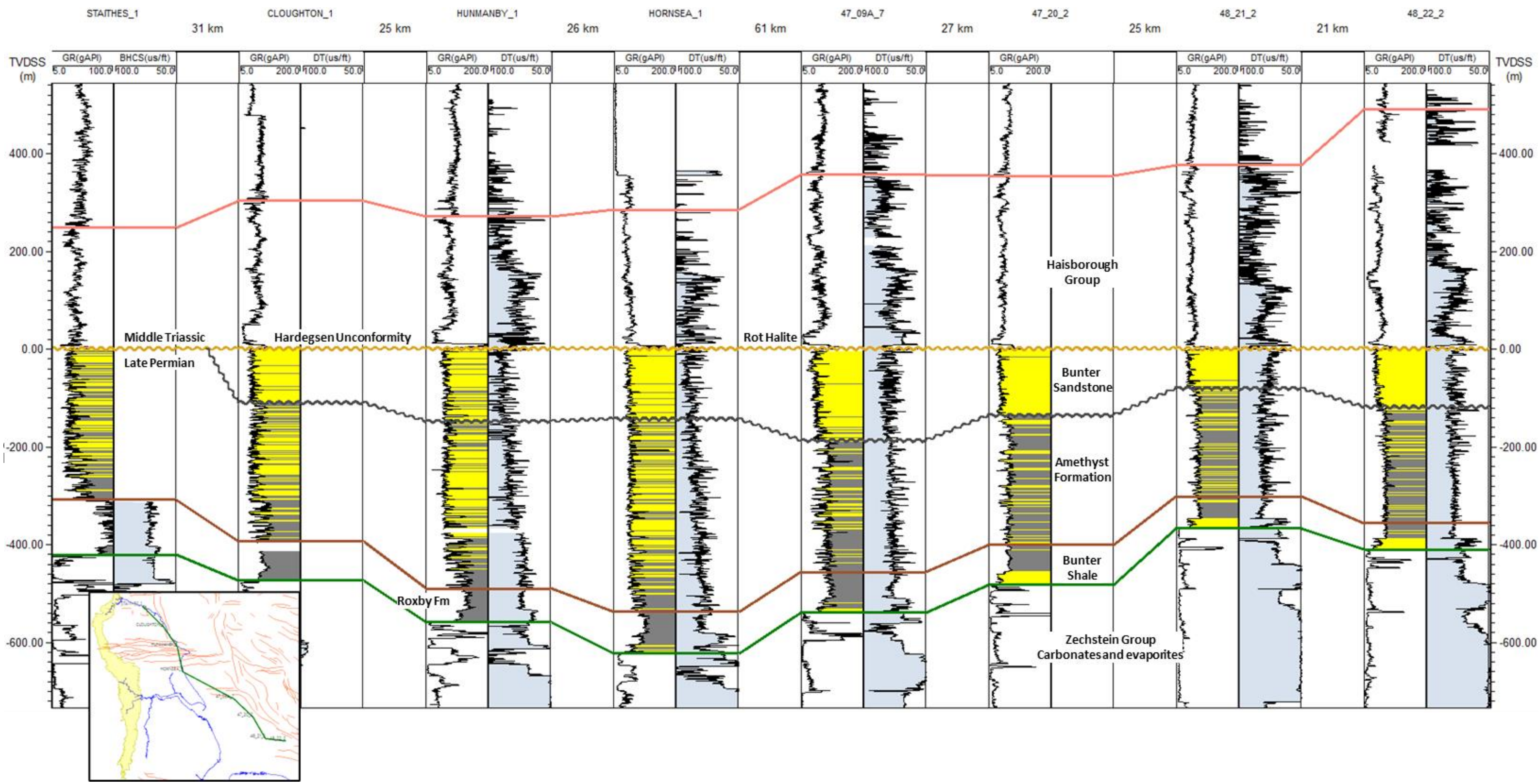


Figure 16 Extended correlation from Staithes along the eastern margin of the East Midland Shelf

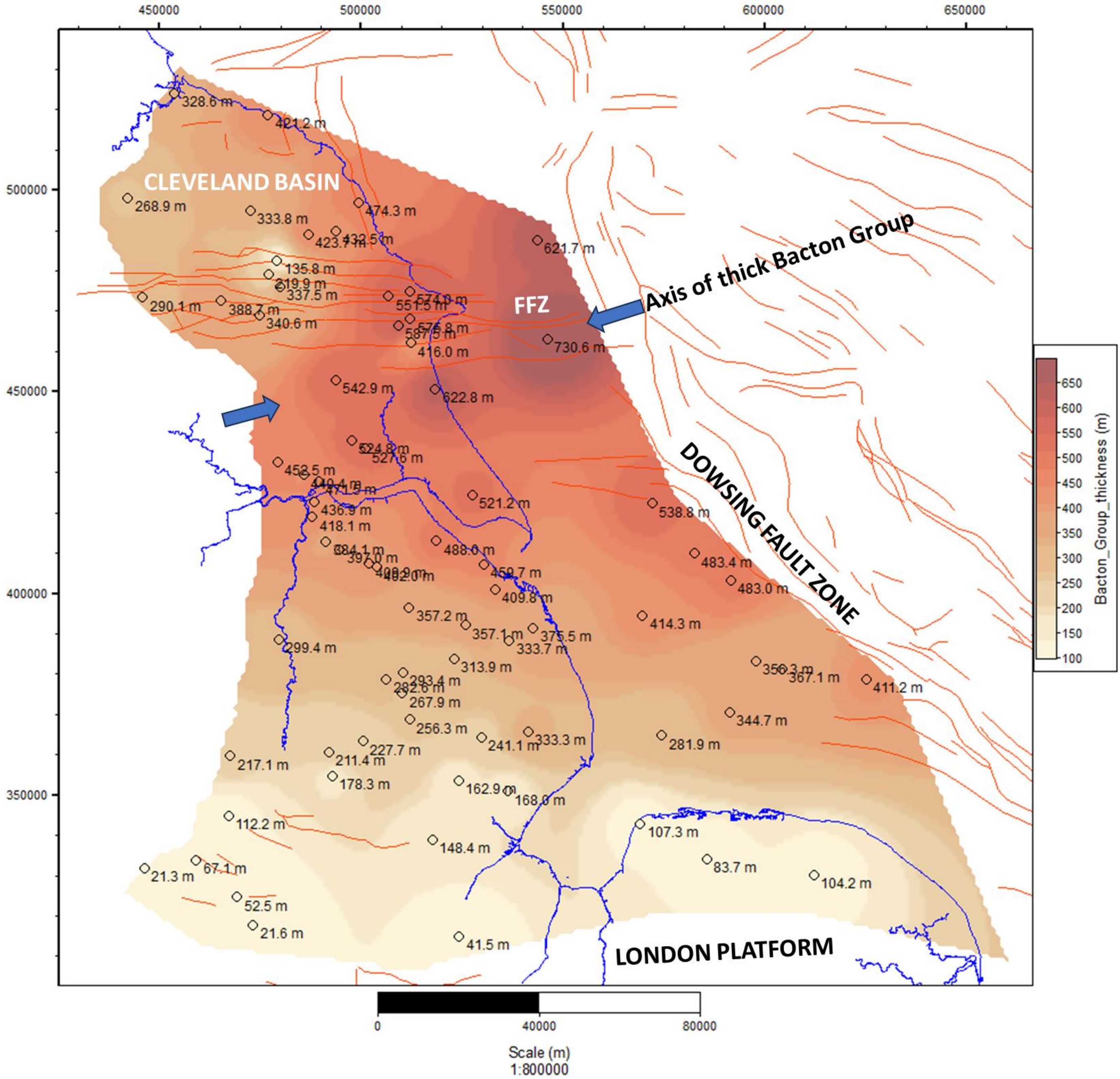


Figure 17 Map showing thickness distribution of the entire Bacton Group (Bunter Shale and Bunter Sandstone) and onshore equivalent (Roxby Formation, Lenton Sandstone and Nottingham Castle Sandstone). There is a general thickening trend from the London Platform toward the intersection of the Flamborough Fault Zone and the Dowsing Fault Zone. This thicker zone extends as a broadly W-E trending axis across the Market Weighton High. Note that the trend of the thickness contours is rotated relative to the present structural dip. The Cleveland Basin is an area of relatively thin Bacton Group. Contains Ordnance Survey data © Crown copyright and database rights [2024].

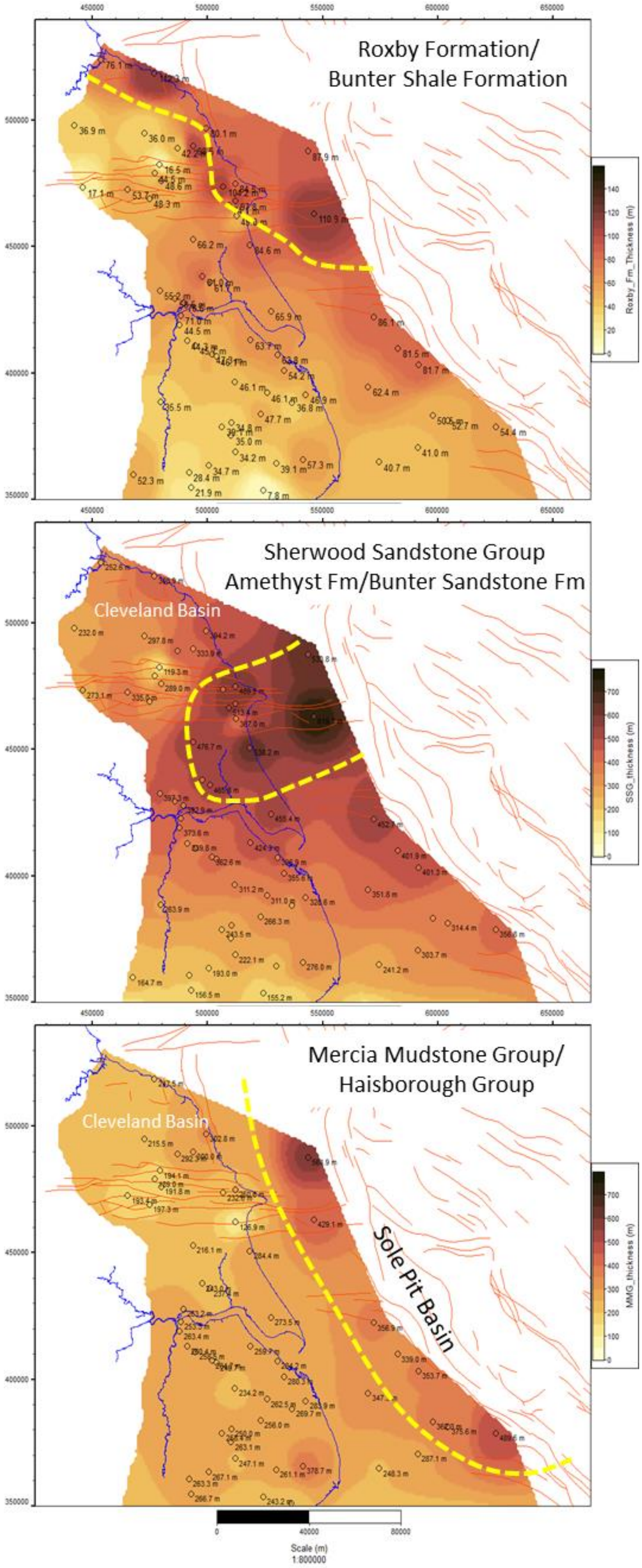


Figure 18 Maps for three intervals. The Roxby Mudstone is thickest offshore from Flamborough Head with a relatively thick succession extending toward Staithes. The Sherwood Sandstone (Lenton Sandstone and Nottingham Castle Sandstone) is thickest offshore Flamborough Head, extending inland across the Market Weighton High. The Cleveland Basin is a notably thin area, possibly as a result of basin inversion and erosion. The Mercia Mudstone Group is relatively thin across much of the East Midlands Shelf and Cleveland Basin with the thickest development moving to the periphery of the Sole Pit Basin. Contains Ordnance Survey data © Crown copyright and database rights [2024].

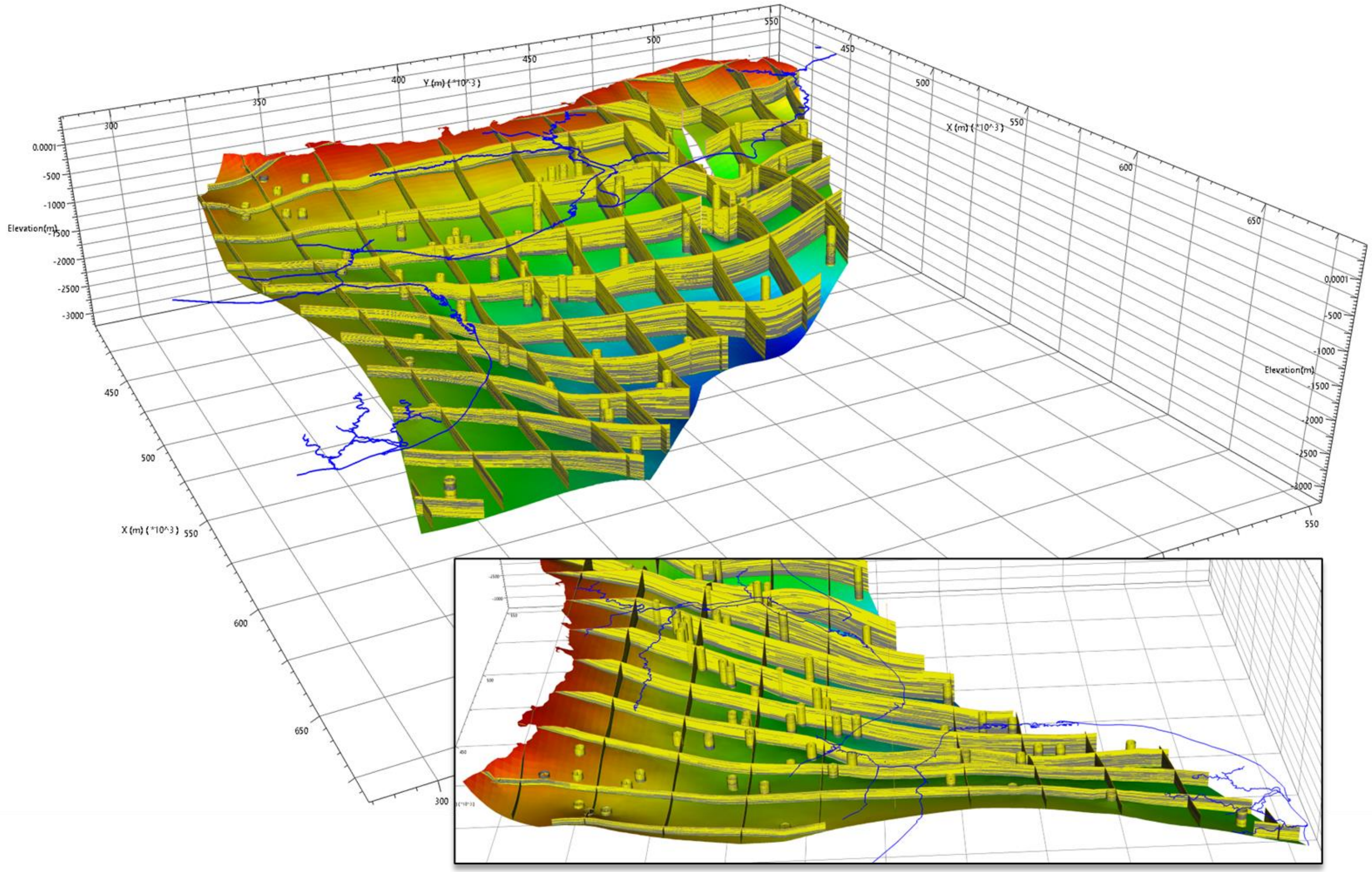


Figure 19 Sections through the 3D geological grid attributed with sandstone (yellow) and mudstone (grey) property. Contains Ordnance Survey data © Crown copyright and database rights [2024].

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

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