Elsevier Editorial System(tm) for Proceedings of the Geologists' Association
Manuscript Draft

Manuscript Number:

Title: Rifts, rivers and climate recovery: a new model for the Triassic of England

Article Type: SI: The Geology of England

Keywords: Permian; Triassic; England

Corresponding Author: Dr. Andrew J Newell,

Corresponding Author's Institution: British Geological Survey

First Author: Andrew J Newell

Order of Authors: Andrew J Newell

Abstract: Triassic basins of England developed under a regime of largely W-E extension and progressed from non-marine fluvial and aeolian sedimentation (Sherwood Sandstone Group), through semi-marine playa lacustrine deposits (Mercia Mudstone Group) to fully marine environments (Blue Anchor Formation and Penarth Group). A new tectono-stratigraphic model for the Sherwood Sandstone Group is proposed in which two major long-distance river systems developed under conditions of relative fault inactivity in the Early Triassic (Budleigh Salterton Pebble Beds and equivalent) and Middle Triassic (Otter Sandstone and equivalent). These are separated by a late Early Triassic syn-rift succession of fluvio-aeolian sandstones (Wildmoor and Wilmslow sandstone formations) and playa lacustrine muds (Nettlecombe Formation) which show major thickness variation and localisation with hanging wall basins. The partitioning of syn-rift deposits into mudstones in upstream basins (close to the source of water and sediment) and clean aeolian or fluvio-aeolian sandstones in downstream basins is similar to the pattern observed in the underlying Late Permian. Under conditions of rapid tectonic subsidence chains of extensional basins may become disconnected with upstream basins (Wessex Basin) acting as traps for fines and water permitting more aeolian activity in temporarily unlinked downstream basins (Worcester and Cheshire basins). In addition to tectonic controls, fluctuating climate, relief related to limestone resilience in arid settings, the smoothing effect of fill and spill sedimentation and Tethyan sea-level change all contributed toward the observed Triassic stratigraphy in England.

Suggested Reviewers: Alaistair Ruffell
a.ruffell@qub.ac.uk
Triassic expert

***Cover Letter**

Dear Editors

Please find a new manuscript attached.

There is a lot of new data in the paper and a lot of large colour figures which I hope can all be included.

Kind regards
Andrew Newell

Rifts, rivers and climate recovery: a new model for the Triassic of England

Andrew J Newell*

British Geological Survey, Maclean Building, Wallingford, OX10 8BB Oxfordshire

*ajn@bgs.ac.uk

Abstract

Triassic basins of England developed under a regime of largely W-E extension and progressed from non-marine fluvial and aeolian sedimentation (Sherwood Sandstone Group), through semi-marine playa lacustrine deposits (Mercia Mudstone Group) to fully marine environments (Blue Anchor Formation and Penarth Group). A new tectono-stratigraphic model for the Sherwood Sandstone Group is proposed in which two major long-distance river systems developed under conditions of relative fault inactivity in the Early Triassic (Budleigh Salterton Pebble Beds and equivalent) and Middle Triassic (Otter Sandstone and equivalent). These are separated by a late Early Triassic syn-rift succession of fluvio-aeolian sandstones (Wildmoor and Wilmslow sandstone formations) and playa lacustrine muds (Nettlecombe Formation) which show major thickness variation and localisation with hanging wall basins. The partitioning of syn-rift deposits into mudstones in upstream basins (close to the source of water and sediment) and clean aeolian or fluvio-aeolian sandstones in downstream basins is similar to the pattern observed in the underlying Late Permian. Under conditions of rapid tectonic subsidence chains of extensional basins may become disconnected with upstream basins (Wessex Basin) acting as traps for fines and water permitting more aeolian activity in temporarily unlinked downstream basins (Worcester and Cheshire basins). In addition to tectonic controls, fluctuating climate, relief related to limestone resilience in arid settings, the smoothing effect of fill and spill sedimentation and Tethyan sea-level change all contributed toward the observed Triassic stratigraphy in England.

Keywords

Permian, Triassic, England, Sherwood Sandstone, Mercia Mudstone

1 Introduction

The Triassic represents a pivotal time in the geological record, both globally and within the stratigraphy of England. Throughout much of the preceding Palaeozoic the continents of the world had been progressively amalgamating into the supercontinent Pangaea ('all Earth'), a single landmass that extended virtually from pole to pole (Stampfli et al., 2013) (Figure 1). The Triassic represents an important turnaround point. Pangaea showed signs of instability almost as soon as it had coalesced in the Permian and began to break apart in a process which would eventually lead to the formation of the North Atlantic Ocean. In England and adjoining areas the initial rifting of Pangaea was marked by the development of fault-bounded basins which acted as conduits for rivers which mostly flowed away from eroding Carboniferous (Variscan) mountain belts around the periphery of the Tethys Ocean (Bourquin et al., 2007; Hounslow and Ruffell, 2006; McKie and Williams, 2009). As North Atlantic rifting progressed, these terrestrial basins would eventually become marine at the end of the Triassic and into the Early Jurassic (Hesselbo et al., 2004). However, the initial continental clastic Triassic basin fills would later assume huge economic importance as subsurface stores for water and hydrocarbons. Triassic sandstones host western Europe's largest onshore oilfield at Wytch Farm (Bowman et al., 1993) and together with underlying Permian deposits represents England's second most important aquifer (Tellam, 1994).

The Triassic also marks the start of the Mesozoic which began in the wake of the end Permian mass extinction and ended with the Cretaceous-Tertiary mass extinction (Benton, 2016). The end Permian mass extinction at around 252.3 Ma was the largest of all time and had a devastating effect on marine life and terrestrial plants and animals, wiping out approximately ninety percent of all living organisms (Benton and Newell, 2014; Chen and Benton, 2012). The Triassic lasting from 252 to 201 million years was a time of gradual recovery during which time modern ecosystems and all of the key modern vertebrate groups originated (Benton, 2016).

The Triassic stratigraphy of England thus needs to be considered against a very dynamic background of tectonic and climatic instability. Events in the Triassic are fundamental to understanding the evolution of England throughout the Mesozoic and how it arrived at its current position on the eastern seaboard of the North Atlantic Ocean.

2 Aim and methods

A great deal has been published on the structure, stratigraphy, dating and depositional systems of the Triassic of England (Benton et al., 2002; Bourquin et al., 2007; Chadwick and Evans, 1995; Hounslow and Ruffell, 2006; McKie and Williams, 2009; Warrington et al., 1980; Wills, 1970). The aim of this paper is not only to summarize some of this work but to introduce as much new data as possible in a very graphical form. The paper makes particular use of deep boreholes and geophysical logs which have been obtained over many decades of oil, coal and hydrogeological exploration and production in onshore England. Boreholes have an advantage over outcrops in that they provide a continuous stratigraphic record through the often extremely thick (up to 3 km) Permo-Triassic successions of England's onshore basins. Geophysical logging is a form of remote sensing where the properties of rocks are determined indirectly by measuring attributes such as resistivity, radioactivity and sonic velocity (Asquith and Gibson, 1982). Geophysical logs have long been used as tools for high resolution stratigraphic subdivision and correlation (Whittaker et al., 1985). This study is based largely on a database of 56 geophysically-logged boreholes distributed across the onshore Triassic basins of England and adjacent offshore areas.

The paper will cover all of the Triassic, but the primary focus is on the Early and Middle Triassic Sherwood Sandstone Group: a fining upward succession of fluvial conglomerates and fluvio-aeolian sandstones which ranges up to around 1.2 km thick (Figure 2). The Sherwood Sandstone Group represents a relatively short time span (around 10 million years) relative to the overall duration of the Triassic (50.9 million years) but has long attracted the most attention because of its economic importance, well-exposed sedimentary structures and tetrapod faunas (Benton et al., 2002). However, it is of course impossible to understand the Sherwood Sandstone Group without considering underlying Permian deposits and the overlying Middle to Late Triassic Mercia Mudstone Group (Figure 2). Late Permian deposits are very much part of the Triassic story because they represent the initial fill of sedimentary basins formed during orogenic collapse and regional extension of the Variscan mountain belt and its foreland (McCann et al., 2006). In England and adjacent parts of western Europe, major unconformities related to thermal uplift and erosion of the Variscan foreland separate late Permian syn-rift deposits from early Permian molasse formed during the closing stages of Variscan mountain building (Edwards et al., 1997; Glennie, 1997; Glover and Powell, 1996). The Mercia Mudstone Group must be included in the discussion because of the great thickness (up to around 1.3 km) of this succession of playa lacustrine mudstones and evaporites, the large amount of Triassic time it occupies, and its diachronous relationship with the Sherwood Sandstone Group (Warrington et al., 1980). An understanding of thickness changes within the Mercia Mudstone Group has an important role to play in understanding the extent to which tectonics controlled the deposition of the Sherwood Sandstone (Ruffell and Shelton, 1999).

3 Triassic palaeogeographic and palaeoclimatic context

During the Triassic, England was located on the eastern part of the Pangaean Supercontinent at a palaeolatitude of around 20°N (Figure 1). While it was relatively close to the oceanic areas of Palaeotethys and Neotethys it was largely isolated from marine influence by a chain of upland areas which included the Iberian, Armorican, Vindelician and Bohemian massifs (Figure 3). In the Triassic marine influence in northwest Europe was limited to incursions through narrow gateways which mostly did not extend far beyond the Middle Triassic Muschelkalk Sea of the Central European Basin (Franz et al., 2015; Ziegler, 1991) and the western extension of Tethys between Iberia and Africa (Ziegler, 1991). The narrow fault-bounded Triassic basins of England were separated from the German Basin by the London-Brabant Massif and remained an area of largely terrestrial fluvial, aeolian and playa lacustrine sedimentation throughout most of the Triassic until marine transgression in the Rhaetian (Blue Anchor Formation), which marked the start of long-term sea-level rise into the Early Jurassic (Hesselbo et al., 2004). This is not to say that the Triassic of England was totally immune from marine influence. Organic-walled microplankton provide evidence of marine influence in the Mid Triassic Tarporley Siltstone, coincident with the Muschelkalk transgression (2008; Warrington, 1970; Williams and Whittaker, 1974). Marginal marine influence continued throughout the Late Triassic with stable isotopic signatures of sulphates and dolomites (Taylor, 1983) and magnesian-rich clays (Leslie et al., 1993) showing that marine and continental derived waters mixed during the deposition of the Mercia Mudstone Group.

The bulk of the Lower to Middle Sherwood Sandstone Group is fluvial in origin and the general configuration of the drainage system in the onshore Triassic basins of England has long been established through the use of various sediment provenance indicators and palaeocurrent analysis (Audley-Charles, 1970; Wills, 1951). The Early Triassic Budleigh Salterton Pebble Beds contains quartzite clasts with Ordovician and Devonian body and trace fossils that were derived from sources in Brittany and Normandy (Cocks, 1993; Radley and Coram, 2015) and the presence of comparable quartzite clasts in the English Midlands lead to the concept of the Budleighensis River: a major drainage system which flowed for some 400 km northward from the Armorican Massif through the Worcester Basin into Cheshire and NE England (Audley-Charles, 1970; Wills, 1951) (Figure 3). Isotopic age determinations on detrital micas (Fitch et al., 1966), heavy minerals (Morton et al., 2013), zircon-age constraints (Morton et al., 2013) and the Pb isotopic composition of feldspars (Tyrrell et al., 2012) largely confirm the Armorican source and concept of long-distance fluvial transport paths for younger sandstone-dominated parts of the Sherwood Sandstone, although Morton et al. (2013) highlight the potential for the development of multiple distinct sub-catchments with local sources.

The presence of aeolian dune deposits and calcretes within the Sherwood Sandstone Group and extensive evaporite bodies within the Mercia Mudstone Group indicate a generally warm and dry climate during the Triassic, consistent with the low palaeolatitude and relatively interior position of England within Pangaea, where the clustering of continents is thought to have increased temperatures relative to the more dispersed pattern of today (Roscher et al., 2011). Most of the large rivers draining northward from the Armorican Massif are believed to have been endorheic: terminating within flood basins in the southern North Sea and East Irish Sea basins as discharge decreased through infiltration, evaporation and channel bifurcation (McKie and Williams, 2009; McKie, 2014). There must have been considerable rainfall in source areas to sustain rivers flowing for large distances through arid terrain and this probably resulted from intense monsoonal precipitation falling on Armorican source areas which lay within a humid maritime climatic zone close to the Tethys Ocean (Roscher et al., 2011). Further north, cross-bed orientations within Permian and Triassic aeolian dune sandstones show that England lay within a north-easterly trade-wind belt (Glennie, 1997).

The potential for abnormal climatic conditions during the first five million years of the Triassic needs to be carefully considered when interpreting the stratigraphic record in England (Radley and Coram, 2016). Carbon isotope curves show that high amplitude fluctuations that are synchronous with the End Permian mass extinction continued into the Early Triassic before ending abruptly early in the Middle Triassic (Payne and Kump, 2007) (Figure 4). The disruption of the carbon cycle in the Early Triassic may have been driven by the sustained eruption of the Siberian Traps and coincides with other indicators of abnormal terrestrial and marine conditions including a gap in coal deposition, an absence of coral reefs and generally low biological diversity (Benton and Newell, 2014; Chen and Benton, 2012).

4 Tectonic framework of Triassic basins

During the Triassic, England was located at the centre of a highly complex stress and strain system (Chadwick and Evans, 1995; Chadwick et al., 2005; Peacock, 2004). To the north of Britain was a zone of major rifting which extended southwards from the Barents Sea via the Norwegian–Greenland Rift into the North Sea. Rift systems were also propagating northwards from the Central Atlantic and westwards across the Bay of Biscay and NW Africa (Figure 1) (Coward, 1995). A large number of smaller rift basins developed across England in response to the regional tensional stress field and these basins became sites for the deposition of continental clastic sediments and evaporites during the late Permian and Triassic. In most cases Permo-Triassic extensional faults formed through the reactivation of pre-existing Precambrian, Caledonian and Variscan faults, which cross-cut the extremely anisotropic crust of the British Isles (Chadwick and Evans, 1995). Because faults are reactivated rather than newly formed, it is challenging to determine the direction of the overall regional tensional stress field. Using plate-tectonic reconstructions and studies of basin geometry and fault kinematics Chadwick et al. (1989) proposed that Permo-Triassic extension was orientated approximately E-W. This is supported by regionally extensive Pb-Zn-F mineralised fracture systems in SW England, which have a predominantly N-S orientation and have been dated at 236±3 Ma at around the Ladinian-Carnian boundary (Scrivener et al., 1994).

Figure 5 shows the major Permo-Triassic basins and faults of England and adjacent offshore regions (Pharaoh et al., 1996), the distribution of Permo-Triassic outcrop and the approximate area of subcrop where Permo-Triassic deposits are concealed beneath younger strata around the flanks of the London-Brabant Massif (Sumbler, 1996). The Cheshire Basin contains the thickest Permo-Triassic fill in England (at around 4 km) and in general terms is a south-east dipping half graben controlled by the Wem-Red Rock Fault System, a reactivation of the easterly part of the extremely long-lived Pontesfont Lineament (Woodcock, 1984). The Cheshire Basin links to the south to the relatively shallow Stafford Basin and Needwood Basin, which are located to the west and east of the structural high which includes the exposed Carboniferous block of the South Staffordshire Coalfield. To the south is the Worcester Basin (or Worcester Graben) which, together with the smaller Knowle Basin, comprises a graben system whose overall structural trend is N-S, parallel to the Malvernoid structural trend of the underlying basement rocks (Chadwick and Evans, 1995). The Worcester Basin is controlled by Clopton-Clapton-Northleach Fault system along its eastern margin and the East Malvern Fault on the west. The Worcester Basin represents a particularly spectacular example of negative basin inversion, with the area having been thrust-faulted into a structural high and area of erosion during the late Carboniferous and Early Permian but switching to a subsiding extensional basin in the Late Permian and Triassic, accumulating some 3 km of Permo-Triassic deposits which rest unconformably on Precambrian basement rocks (Barclay et al., 1997). The development of the Worcester Graben was fundamental to the development of long-distance 'Budleighensis-type' river systems in the Triassic because it created a conduit through the formerly continuous Welsh-London-Brabant Massif (Glover and Powell, 1996) allowing the transit of water and sediments from sources in the Armorican Massif of northern France toward sinks in the East Irish Sea Basin and the Southern North Sea (Figure 3).

The deepest part of the Worcester Graben lies within the Severn Valley around Worcester (Barclay et al., 1997) and to the south of this area Permo-Triassic rocks thin (Figure 7) and occur at shallower elevations across the Mendip High (Figure 6). To the south of the Mendip High, is the Wessex Basin which has a long history of Permian to Cretaceous extension and subsidence, followed by basin inversion related to Cenozoic Alpine compression (Newell and Evans, 2011; Underhill and Stoneley, 1998). In its present configuration, the Wessex Basin comprises a number of typically W-E trending sub-basins which include the Pewsey Basin, Mere Basin, Winterborne-Kingston Trough (or Dorset Basin) and Portland Wight Basin. The Wessex Basin links eastward into the Weald Basin which lies to the south of the London Platform (Figure 6). Most of the basins and sub-basins to the south of the Variscan Front are related to down-to-the-south movement on predominantly W-E trending extensionally-reactivated Variscan thrusts (Chadwick, 1986). However, many of these faults and basins had not come into play at the relatively early Permo-Triassic stage in the extensional history of southern England. As will be discussed in greater detail below, Permo-Triassic sedimentation appears to have been controlled by a small sub-set of NW and N-S trending structures such as the Quantocks-Coker-Cranborne fault system (Miliorizos and Ruffell, 1998). Most major west-east faults and associated basins such as the Weald were inactive until the Jurassic and Cretaceous, probably reflecting a change in the orientation of the regional stress field, from W-E extension in the Triassic (Scrivener et al., 1994) related to North Atlantic rifting, toward N-S extension in the Jurassic and Cretaceous related to the rotation of Iberia and the opening of the Bay of Biscay (Chadwick et al., 1989).

Maps such as Figure 5 show that Permo-Triassic faulting was concentrated along the western part of England, in a broadly north-south belt extending from SW England to the East Irish Sea; however, to the east of the Pennines and to the north of the London-Brabant Massif, the East England Shelf also formed an important Permo-Triassic depocentre (Figure 5). The structure of this area differs in that it has the form of a relatively undeformed NE-dipping ramp that flanked the North Sea Basin (Figure 6). On this ramp Permo-Triassic strata show gradual thickening from Nottingham toward NE Yorkshire (Figure 7 and see also Figure 15). In comparison to the fault-bounded basins of the west, the Sherwood Sandstone of the East England Shelf is a relatively thin, uniform fluvial sandstone (Wakefield et al., 2015), which contains large stratigraphic gaps and evidence for slow rates of vertical accretion (Medici et al., 2015). There is a marked thinning in Permo-Triassic strata between the Needwood-Hinckley basin and the East England Shelf, across what Wills (1970) termed the Pennine-Charnwood Sill (Figure 7).

Since the earliest structural and palaeogeographic reconstructions (Wills, 1951), areas that are presently without a cover of Permo-Triassic deposits such as the Pennines, Wales, SW England and the London-Brabant massif have been regarded as areas of non-deposition or erosion during the Triassic. In reality, we can only be certain that the London-Brabant Massif was a structural high and area of non-deposition. The London-Brabant Massif had formed a positive structural element since the Acadian orogenic phase in the mid Devonian (Pharaoh et al., 1993) and during the Triassic was progressively onlapped, but not entirely covered (Sumbler, 1996). It remains possible that SW England, Wales and the Pennines formerly had some Permo-Triassic cover that could have been eroded during phases of uplift and inversion during the Early Cretaceous (McMahon and Turner, 1998) and Cenozoic (Brodie and White, 1994).

The key point from the above summary, and one that is graphically illustrated by the 3D reconstruction of the Variscan unconformity in Figure 6, is that, with the exception of the East England Shelf, the Triassic landscape is likely to have had considerable tectonically-induced topography, comprising a series of deep pocket-like basins and intervening highs. At first glance this tectonic configuration would not appear to be conducive for the development of long-distance fluvial transport networks moving material from northern France to sediment sinks in the East Irish Sea Basin and Southern North Sea (Figure 6). How such river systems, for which the Triassic is renowned, could have developed on a landscape of such potentially high topographic roughness will be explored in following sections.

5 Permo-Triassic Stratigraphy

5.1 The application of geophysical logs

Figure 8 shows five boreholes which are representative of the late Permian to mid Triassic stratigraphy within the major fault-bounded basins of western England. Each borehole provides a continuous record of the stratigraphy from close to the base of the Mercia Mudstone Group into rocks of variable age beneath the Variscan Unconformity. The boreholes are shown with two vertical geophysical log tracks, the left track contains a gamma-ray log and the right track contains a log of sonic interval travel time. Gamma-ray logs are a measurement of the natural radioactivity of a rock that is mostly derived from the elements uranium, thorium and potassium and the minerals that contain them (Asquith and Gibson, 1982). In the Triassic terrestrial deposits of England (and elsewhere) gamma-ray logs are a useful indicator of lithology because clean quartz-rich conglomerates and sandstones have low gamma-ray values (typically in American Petroleum Institute or API units) while mudstones rich in clay minerals have higher values. Evaporites such as halite and anhydrite will also have low gamma-ray values. Careful cross-checking against borehole cuttings returns needs to be undertaken because sandstones that are micaceous, such as the Triassic Tarporley Siltstone Formation, or those that contain a high proportion of potassium feldspar will have elevated values. The sonic log measures the interval transit time (the reciprocal of velocity) of a compressional sound wave travelling through one foot of formation. The interval travel time, generally shown in units of microseconds per foot (μs/ft.), is dependent on both lithology and porosity. In the Triassic of England the sonic log is particularly useful for subdividing thick sequences of Permo-Triassic sandstone into those that have low porosity (short interval travel time) and those that have high porosity (long interval travel time). High porosity sandstone in the Triassic of England is commonly of aeolian origin while well-cemented, low porosity sandstone is generally fluvial (Meadows, 2006).

5.2 Illustrating the tectono-stratigraphic framework

In the following discussion two figures are used to illustrate the tectono-stratigraphic framework of Permo-Triassic deposits in England (Figure 9 and Figure 10). The diagrams incorporate data from geophysically logged boreholes and a semi-schematic structural model (restored to a level at around the top of the Sherwood Sandstone) along the tract of extensional basins from SW England to the E Irish Sea (Figure 5). The East English Shelf which, as discussed above, represents a different structural province is excluded for now. Figure 8, Figure 9 and Figure 10 are related but illustrate different aspects of the stratigraphy. Figure 8 provides greater detail on the lithology and geophysical log character of the Permian and Sherwood Sandstone Group; Figure 9 shows the structural context of the lithostratigraphy and includes additional boreholes and information on the stratigraphy of the Mercia Mudstone Group; Figure 10 is a semi-schematic view of lithofacies distribution in the Permian and Sherwood Sandstone of the major basins.

5.3 Late Permian stratigraphy

Late Permian deposits overlie the Variscan Unconformity and may rest on rocks of highly variable age from Precambrian to Early Permian (Smith, 1985). The well-exposed Permian stratigraphy in SW England is complex but shows a broadly fining upward trend from basal fan breccias and aeolian sandstones (Newell, 2001) into thick playa lacustrine mudstones (with local aeolian sandstones) of the Aylesbeare Group, which are latest Permian (Capitanian to Wuchiapingian) in age (Hounslow et al., 2017). A comparable stratigraphy, marked by a progressive upwards increase in gamma-ray values as thick mudstone deposits are entered (Figure 8), is seen in concealed parts of the Wessex Basin (Hamblin et al., 1992). In basins to the north of the Wessex Basin, the Late Permian stratigraphy is markedly different. In the Worcester Basin almost 1 km of clean aeolian sandstone characterised by uniformly low gamma-ray value and a high sonic interval travel time (Figure 8) was proved by the Kempsey borehole (Barclay et al., 1997). These aeolian sandstones are correlated with the Bridgnorth Sandstone Formation at outcrop which were deposited by a combination of transverse and barchanoid draas under the influence of winds which predominantly blew from the east (Karpeta, 1990). Aeolian sandstones with similar gamma and sonic log characteristics are present in the Stafford Basin but here are much thinner (Figure 8). In the Cheshire Basin and East Irish Sea Basin thick correlative sequences of aeolian sandstone are termed the Collyhurst Sandstone (Jackson and Mulholland, 1993). In the East Irish Sea Basin the Permian stratigraphy is distinguished by the presence of the Manchester Marls which overlie the Collyhurst Sandstone. The Manchester Marls is mostly a fine-grained unit of mudstones, carbonates and evaporites and is a general correlative of the St Bees Evaporites, which are coeval with Zechstein Cycles EZ1 and EZ2 on the Eastern England Shelf (Smith, 1995). The Manchester Marls can be traced for a short distance into north Cheshire toward the Knutsford and Prees boreholes but are much thinner and less conspicuous in geophysical logs (Figure 9).

In summary, the stratigraphic pattern for the Permian is relatively simple. In the Wessex Basin there is a predominance of muddy playa lacustrine deposits, while basins to the north are filled almost entirely by thick intervals of aeolian sandstone. The aeolian sandstones show marked changes in thickness and toward the margins of the East Irish Sea Basin start to show evidence of the Zechstein/Bakevellia margin transgression through the inclusion of mudstones of the Manchester Marls (Smith, 1995).

5.4 Triassic Stratigraphy

There has always been considerable uncertainty over the position of the Permo-Triassic boundary in the English Triassic because it generally lies within a thick succession of terrestrial mudstones, sandstones and conglomerates with extremely sparse biostratigraphical control (Warrington et al., 1980). New palaeomagnetic data from SW England, however, provides evidence that the base of the Sherwood Sandstone Group is broadly coincident with the Permo-Triassic boundary (Hounslow and McIntosh, 2003; Hounslow et al., 2017), and the lowermost, conglomeratic, part of the Sherwood Sandstone Group (Budleigh Salterton Pebble Beds in SW England) is likely to be Olenekian in age. Hounslow et al. (2017) indicate a 7 Ma hiatus between the Budleigh Salterton Pebble Bed and the underlying Late Permian Aylesbeare Mudstone Group in SW England. In most places this boundary is a sharp erosion surface and may show evidence of considerable topography (Steel and Thompson, 1983).

The magnetostratigraphy and correlation of conglomerate units at the base of the Sherwood Sandstone (Budleigh Salterton Pebble Beds, Kidderminster Formation, Cannock Chase Formation, Chester Pebble Beds) is far from complete (Hounslow et al., 2017) but these units are united by a strong similarity in quartzite-dominated clast composition and sedimentology when traced from the Wessex Basin in the south, through the Worcester Graben and into the Midlands: observations which lead to the concept that they were deposited in a large, connected 'Budleighensis' river system flowing northward from the Armorican Massif (Wills, 1951). In the Wessex Basin and in the Midlands, the planar, trough and horizontally bedded conglomerates are interpreted as the product of gravel bars within substantial but poorly confined braided channels (Smith and Edwards, 1991; Steel and Thompson, 1983). The conglomerates are typically only a few tens of metres thick and are readily identified on geophysical logs by their low gamma-ray values and low sonic travel times suggesting extensive cementation (Figure 8). Further to the NW in the Cheshire Basin the Chester Pebble Beds become finer grained and pass laterally into correlative fluvial sandstones of the St Bees Sandstones of the East Irish Sea Basin (Jones and Ambrose, 1994; Medici et al., 2015). Interestingly there is evidence that the Early Triassic gravelly braided rivers of the Midland also flowed to the NE, correlating with the pebbly Nottingham Castle Sandstone which fines and thickens toward NE England (see Figure 15) (Wakefield et al., 2015).

While the base of the Sherwood Sandstone conglomerates is a sharp erosion surface, the top is generally a gradual transition into fluvial pebbly sandstones, sandstones and thin mudstones (Ambrose et al., 2014). This unit of overlying fluvial sandstones tends to be highly variable in thickness relative to the underlying fluvial conglomerates. The top of the fluvial sandstones is typically marked by an abrupt shift on sonic logs toward longer interval travel times, generally accompanied by a shift toward lower and less variable gamma-ray values. This geophysical log character is most clearly illustrated in Figure 8 by boreholes at Ranton, Knutsford and 110/10-1 in the East Irish Sea Basin. The geophysical log shift marks an important change in lithofacies toward an interval of mixed aeolian and fluvial deposits, which in the Cheshire Basin is termed the Wilmslow Sandstone Formation, a lateral correlative of the Wildmoor Sandstone in the Worcester Basin and Calder Sandstone of the East Irish Sea Basin. In marked contrast to the underlying fluvial deposits, these sandstones are typically silty, micaeous and very poorly cemented, leading to their former use as naturally-bonded moulding sands in the foundries of the Midlands (Highley and Cameron, 1995). Intra-formational sandstone and mudstone clasts predominate in the fluvio-aeolian deposits over extra-formation clasts such as quartzite (Bouch et al., 2006). The Wildmoor and Wilmslow sandstone formations typically show a range of cross-bedding, cross-lamination, low-angle lamination and wavy lamination and appear to have been deposited in both fluvial and relatively wet aeolian environments (Bloomfield et al., 2006; Bouch et al., 2006). Thicker aeolian dune deposits with high-angle cross-bedding (Thurstaston Sandstone) are locally developed at the top of the Wilmslow Sandstone in the Cheshire Basin (Howard et al., 2007; Thompson, 1970). The Wilmslow and Wildmoor sandstone formations shows very large thickness variation and in the Cheshire Basin seismic data shows an angular discordance and major unconformity with the overlying Helsby Formation (Evans et al., 1993).

In the Wessex Basin, strata equivalent to the Wildmoor and Wilmslow Sandstone are often assumed to be absent (Ambrose et al., 2014). This interpretation is based on observations from outcrop in S Devon where the Otter Sandstone Formation appears to rest directly on a ventifact layer developed on the upper surface of the Budleigh Salterton Pebble Beds (Wright et al., 1991). However, in concealed parts of the Sherwood Sandstone Group to the east, the Nettlecombe borehole shows an approximately 65 m thick layer of mudstone and anhydrite between the Budleigh Salterton Pebble Beds and the Otter Sandstone Formation (Figure 8). On the Nettlecombe borehole completion log this unit was called the ‘Bunter Anhydrite and Shales’ while Holloway et al. (1989) termed this interval SS2 in their Sherwood Sandstone stratigraphic scheme. In this paper it is called the Nettlecombe Formation and, despite the major difference in lithology, is considered a lateral correlative of the Wildmoor-Wilmslow-Calder formations (Figure 8). The reasons for this are explored in greater detail in a following section.

The uppermost part of the Sherwood Sandstone Group includes the Otter Sandstone Formation in the Wessex Basin, the Bromsgove Sandstone Formation in the Midlands, the Helsby Sandstone Formation in the Cheshire Basin and the Ormskirk Sandstone Formation of the East Irish Sea Basin. In comparison to other parts of the Permo-Triassic of England, this slice of the stratigraphy is relatively well constrained by biostratigraphy and magnetostratigraphy (Benton et al., 1994; Hounslow and McIntosh, 2003; Seyfullah et al., 2013; Warrington et al., 1980). The Otter Sandstone Formation contains a varied tetrapod fauna dominated by rhynchosaurs and has generally been considered Anisian in age (Benton et al., 1994), a conclusion now supported by magnetostratigraphy (Hounslow and McIntosh, 2003). Plants, palynomorphs and tetrapods also indicate an Anisian age for the Bromsgrove Sandstone and Helsby Sandstone (Benton et al., 1994; Seyfullah et al., 2013). In the Cheshire Basin, palynomorphs indicate that part of the Mercia Mudstone Group up to the level of the Byley Mudstone is also of Anisian age; showing that the boundary between the Sherwood Sandstone Group and Mercia Mudstone Group is diachronous, becoming younger southwards as the limit of sand deposition was pushed closer to source areas, coincident with (part) of the Muschelkalk transgression in the German Basin (Franz et al., 2015).

The basal part of the Otter-Bromsgrove-Helsby sandstone formations represents a resurgence in the input of extra-formational quartzite clasts, which occur within cross-bedded fluvial sandstones (Ambrose et al., 2014; Old et al., 1991). In most places the base of these Mid Triassic sandstones is an erosion surface which cuts across different parts of the underlying Sherwood Sandstone stratigraphy. In the Cheshire Basin, an angular unconformity between the Wilmslow Sandstone and the Helsby Sandstone is discernible in seismic reflection data (Evans et al., 1993). This major intra-Triassic unconformity has long been correlated with, and indeed named after, the Hardesgen Unconformity of the German Basin (Audley-Charles, 1970; Warrington, 1970; Wills, 1970). However, while there is no dispute regarding the existence of an unconformity at this level in the stratigraphy, Hounslow and McIntosh (2003) suggest that it may not be the exact correlative of the Hardesgen Unconformity of the German Basin. For this reason a more generalised term such as mid-Triassic unconformity may be preferable.

In the Wessex Basin (Otter Sandstone Formation), Worcester Graben (Bromsgrove Sandstone Formation) and Cheshire Basin (Delamere Member of the Helsby Sandstone) the sandstones overlying the mid-Triassic unconformity are predominantly fluvial (Newell, 2006; Old et al., 1991), with broadly northward-directed palaeocurrents and provenance indicators which suggest the re-emergence of a Budleighensis-type river system with long-distance transport of sediment from sources in the Armorican massif northward into the East Irish Sea Basin (Tyrrell et al., 2012) (Figure 10). In contrast to the first (Early Triassic) development of this long-distance river system it appears that no sediment was delivered across the Pennine-Charnwood Sill onto the East England Shelf: here an unconformity exists between the Nottingham Castle Sandstone Formation and the Mercia Mudstone Group. Instead all of the sediment was diverted into the Cheshire Basin and onward into the East Irish Sea Basin. Here the Helsby Sandstone (Mountney and Thompson, 2002; Thompson, 1970) and Ormskirk Sandstone (Meadows, 2006) show complex interbedding of aeolian and fluvial deposits in an area which must have been close to the terminus of these major endorheic rivers.

The Mid Triassic sandy river systems of England were relatively short-lived as coincident with the Muschelkalk transgression into the German Basin they began a process of back-stepping toward their sources in the Armorican Massif of northern France. By the Anisian playa lacustrine mudstones and evaporites of the Mercia Mudstone Group were already accumulating in the Cheshire Basin and had advanced into the Wessex Basin by the Ladinian. Base-level rise and back-stepping was marked by the development of transitional tidally-influenced facies such as those seen in the Tarporley Siltstone of the Midlands (McKie and Williams, 2009; Williams and Whittaker, 1974). In the Wessex Basin the Otter Sandstone Formation shows an upward change from amalgamated fluvial sheet sandstones into heterolithic point-bar deposits and overbank or frontal splays (Newell and Shariatipour, 2016). By the Ladinian major sandy fluvial sedimentation was largely extinguished across England and the Triassic basins became sites of fine-grained playa lacustrine and marginal marine deposition, marked by the localised development of evaporitic lake deposits within the Mercia Mudstone Group (Simms and Ruffell, 1989). With continued subsidence and sea-level rise the terrestrial and quasi-marine environments of the Mercia Mudstone Group would shift to fully marine at the end of the Triassic and into the Early Jurassic (Hesselbo et al., 2004).

In summary, while facies patterns are locally complex, the Triassic Sherwood Sandstone Group can be broadly considered in terms of the development of two major through-going fluvial systems (labelled 1 and 2 on Figure 10). These are separated by sequence of mixed fluvio-aeolian sandstones in the Worcester and Cheshire basins (Wildmoor and Wilmslow sandstone formations) and mudstones and evaporites (Nettlecombe Formation) in the Wessex Basin. At this stratigraphic level the partitioning of mud and sand either side of the Mendip High is comparable to that seen in the late Permian. Deposits of the through-going river systems (Budleigh Salterton Pebble Beds and Otter Sandstone and their lateral equivalents) are typically pebbly toward the base, overlie a major erosive unconformity and tend to form thin, laterally extensive units which cross basin-bounding faults. By contrast intervening deposits (Nettlecombe-Wildmoor-Wilmslow formations) tend to be localised and are rotated within fault-bounded basins. This suggests variable extension-related subsidence during the Triassic, a concept that is explored in greater detail below using the Wessex Basin as an example.

6 Variable rift activity: an example from the Wessex Basin

In many rift-basins, subsidence related to extension and normal faulting is not a continuous process but consists of discrete episodes of fault activity separated by periods of tectonic quiescence (Leeder and Gawthorpe, 1987; Newell, 2000). Evidence for variable fault activity can be found in the stratigraphic record, using for example relative changes in thickness across a fault, and has already been demonstrated from the Triassic of England and adjacent areas (Miliorizos and Ruffell, 1998; Ruffell and Shelton, 1999). Here we consider an example from the Wessex Basin, expanding on some of the discussion in previous parts of the paper. The Wessex Basin contains a number of major fault structures which appear to have had an important control on Triassic depositional patterns. These include the Quantocks Fault (Miliorizos and Ruffell, 1998), the Wynford-Hooke Fault, the Beer-Musbury fault zone and, to a lesser extent, the Cranborne Fault (Figure 11). The area to the west of the Wynford-Hooke Fault around Nettlecombe appears to have formed a particularly important Triassic depocentre (Butler, 1998; Holloway et al., 1989) and is here termed the south Dorset sub-basin. The area to the west of the Beer-Musbury fault zones was a subsidiary Triassic basin and is here termed the south Devon sub-basin. The evidence for these basins and their variable subsidence rates throughout the Triassic is provided by thickness and facies patterns in deep boreholes.

Figure 12 shows a correlation panel of six deep boreholes which extends from immediately behind the coastal outcrop of the Sherwood Sandstone Group near Sidmouth in south Devon eastwards toward Cranborne. The correlation panel crosses the Beer-Musbury fault zone, the Wynford-Hooke Fault and the Cranborne Fault and is restored (flattened) to a stratigraphic level at the top of the Sherwood Sandstone Group. The main lithostratigraphic units are correlated for the Triassic interval. In the Wessex Basin, the lowermost of these, the Budleigh Salterton Pebble Beds, is readily identified in geophysical logs (and cuttings returns) by a low blocky gamma ray response and low sonic interval travel time (Figure 12). Traced from coastal outcrop, across the Musbury high and toward Nettlecombe the Budleigh Salterton Pebble shows some, but relatively minor, thickening into the south Dorset sub-basin. The conglomerates are not present to the east of the Wynford-Hooke Fault. Above the conglomerates are an interval of mudstones and evaporites which are here called the Nettlecombe Formation. Holloway et al. (1989) included these within their SS2 unit of the Sherwood Sandstone Group. These show very marked thickening and localisation within the south Dorset sub-basin suggesting strong movement on the Wynford-Hooke Fault. A comparable unit of mudstone and evaporite is not present at the much-visited outcrops at Budleigh Salterton in south Devon. The presence of a ventifact layer and palaeosol at the top of the Budleigh Salterton Pebble Beds may indicate a lengthy hiatus at this level (Wright et al., 1991). Based on our general understanding of sedimentation within active extensional half-graben (Leeder and Gawthorpe, 1987) it is possible that deposition had moved eastwards toward an active depocentre in the hanging wall of the Beer-Musbury fault zone. Alternatively, the Nettlecombe Formation may correlate with the thin (15 m) package of aeolian sandstones (see Figure 16) which overlie the Budleigh Salterton Pebble Beds and are eroded by the overlying fluvial Otter Sandstone Formation (Newell, 2006). Evidence from the Monk's Wall borehole to the east of Budleigh Salterton indicates that the aeolian sandstones pass laterally into reddish brown mudstones with a high gamma-ray response (Figure 12), a possible thin lateral equivalent of the Nettlecombe Formation. The overlying Otter Sandstone Formation forms a sheet of relatively consistent thickness between outcrop in south Devon and Nettlecombe. It also marks a considerable expansion in the area of deposition as it crosses the Wynford-Hooke Fault and thins and onlaps the Mid-Dorset Platform and parts of the Cranborne-Fordingbridge High (Figure 11).

During the deposition of the overlying Mercia Mudstone Group the major Quantock-Coker-Cranborne Fault appears to have a major control on the deposition of Late Triassic playa lacustrine mudstones and evaporites (Miliorizos and Ruffell, 1998). There is marked thinning of the Mercia Mudstone Group across the Cranborne Fault, particularly at the level of the Dorset Halite (and correlative Arden Sandstone) of Carnian age (Warrington et al., 1980) (Figure 12). It is notable that this phase of extension-driven subsidence correlates with the development of numerous N-S orientated mineralised veins in SW England (Scrivener et al., 1994) and indeed what appears to have been a major phase of extension across western Europe during the Carnian (Arche and López-Gómez, 2014).

In summary then, it would appear that in the Wessex Basin the coarse-grained deposits of the Budleigh Salterton Pebble Beds and Otter Sandstone Formation formed during episodes of relatively low fault activity, supporting the conclusions of Ruffell and Shelton (1999). It might indeed be expected that major long-range fluvial drainage systems flowing across the structural grain of extensional basins required relative tectonic quiescence to develop (Smith and Edwards, 1991). In the Wessex Basin there is evidence for two particularly marked phases of active extension and subsidence in the Triassic, during the later parts of the Olenekian (Nettlecombe Formation) and in the Carnian (Dorset Halite). These were marked by the development of saline lakes captured within the rapidly subsiding footwalls of active extensional faults.

7 The importance of inherited topography

Tectonics is not the only mechanism of creating topography. The late Permo-Triassic extensional basins of England are flanked and underlain by a wide range of bedrock types, ranging from early Permian sedimentary deposits to Precambrian metamorphic rocks, brought together during several orogenic cycles (Pharaoh et al., 1993; Smith, 1985). Different bedrock types weather and erode at different rates and it is likely that during the lengthy phase of post-Variscan uplift and erosion in the mid Permian associated with the Saalian and Altmark unconformities (see Figure 2), that considerable surface topography was generated by differential denudation. In particular, Simms (2004) highlights the marked difference in the denudation rates of limestone relative to silicate rocks and how this can vary under different climates. Silicates are removed largely by mechanical erosion processes but limestone is removed primarily by chemical dissolution at a rate that is directly proportional to runoff and the prolonged availability of water (Simms, 2004). Under the generally hot and arid climate that existed during the Permian and Triassic in England it is likely that low rainfall and a sparse vegetation cover would have enhanced the mechanical degradation of silicates while inhibiting the denudation of limestone (Simms, 2004). Limestones would therefore have tended to form topographic highs, a point that is graphically illustrated by Variscan fold structures in the Mendip Hills of southwest England (Figure 13) where Triassic breccia and mudstone drapes a recently exhumed Permo-Triassic landscape that preserves large Carboniferous limestone ridges adjacent to troughs underlain by Devonian sandstone (Simms, 2004).

Carboniferous limestone is not restricted to the Mendip Hills, but occurs at subcrop in a broad belt which extends across the northern parts of the Wessex Basin and into the Weald Basin: the former Dinantion carbonate shelf on the southern flanks of the Wales-Brabant High (Waters and Davies, 2006) (Figure 13). This belt of limestone lay across the path of Triassic rivers attempting to flow northward from the Wessex Basin into the Worcester Graben. A north-south transect of boreholes from Cranborne to Cooles Farm show that it probably had a strong influence on Permo-Triassic depositional patterns (Figure 14). The Sherwood Sandstone shows severe attenuation over the Carboniferous limestone in the Farley South borehole and thickens to the south and north into the adjacent basins which are underlain by shales and sandstone. The Carboniferous limestone is associated with localised limestone-clast breccias which overlie the Carboniferous limestone in the Farley South borehole and form a relatively thick succession at the base of the Lockerley borehole around 7 km to the east (Figure 14). The breccias occur in association with red-brown mudstone and while the age of these facies is unknown they appear broadly analogous to those developed around limestone ridges in the Mendip Hills (Simms, 2004). Limestone-related topography could of course not be due entirely to the particularly slow denudation rate of this lithology under arid conditions. In some cases limestones could have formed, what would be under arid conditions, extremely robust footwall blocks to active extensional faults (Goldsworthy and Jackson, 2000).

A second ridge of Lower Carboniferous limestone extends SE from the Derbyshire Dome and along the NE flanks of the Leicestershire Coalfield (Figure 15). This limestone ridge is also associated with anomalously thin Permo-Triassic successions, with only a few metres of sandstone found beneath the Mercia Mudstone Group in the Etwall borehole before entering Carboniferous limestone (Figure 15). It is possible that the Pennine-Charnwood Sill of Wills (1970) had at least a partial origin as an exposed block of limestone that was resistant to denudation under Permo-Triassic climates.

8 Climate change and vegetation cover

Tectonics is rarely the only control on the stratigraphic record and the importance of climate change on Triassic continental sedimentation in England and adjacent basins has already been shown (McKie, 2014; Simms and Ruffell, 1990). Climate change could have driven shifts in episodes of aeolian and fluvial sedimentation within the Sherwood Sandstone and the water balance of playa lakes during the deposition of the Mercia Mudstone Group.

The Early Triassic is particularly notable for marked instability in the carbon cycle which appears to have been associated with the massive flood volcanism of the Siberian Traps (Figure 4). Volatility in levels of greenhouse gases may have caused severe instability in the earth's atmospheric and marine systems, accounting for the anomalous absence of coals, coral reefs and other biological products in the Early Triassic stratigraphical record (Chen and Benton, 2012; Corsetti et al., 2005). The Early Triassic of England (and elsewhere) is well known for its paucity of body and trace fossils (Bourquin et al., 2007; Seyfullah et al., 2013).

In western Europe, plant fossils show an initial Early Triassic survival period dominated by the lycopsids, and it was not until the Early Anisian that there was a resurgence of conifers (e.g. within the 'Grès á Voltzia' Formation in NE France) followed by pteridosperms and cycadophytes in the Late Anisian, typical of the Dont Formation of NE Italy (Seyfullah et al., 2013). The likelihood of relatively sparse plant cover within Early Triassic drainage basins could have had a major influence on the size and behaviour of rivers: possibly analogous to pre-Silurian environments where uncontrolled runoff and erosion and a lack of biological sediment binding favoured the development of large braided river systems (Eriksson et al., 2006; Radley and Coram, 2016). Moreover, analogous to what is projected under modern global warming (IPCC, 2014), rainfall may have been of low frequency but extremely high intensity: driving the development of large 'Budleighensis-type' river systems, which under semi-arid conditions would tend to scale to the largest flood event rather than average discharge (Newell et al., 1999).

Toward the end of the Lower Triassic (Olenekian) the mixed aeolian and fluvial sandstones of the Wildmoor and Wilmslow sandstone formations and the evaporitic lake deposits of the Nettlecombe Formation point toward a phase of increasing aridity in England. However, in the Anisian fluvial sandstones return which, relative to those of the Early Triassic, shows a marked increase in the abundance of plants, as shown by root traces (rhizocretions) in the Otter Sandstone Formation (Purvis and Wright, 1991) and plant fossils in the Bromsgrove Sandstone (Seyfullah et al., 2013). Invertebrate and vertebrate fossils are also found within most middle Triassic formations of England (Benton et al., 2002; Benton et al., 1994). Both the Otter Sandstone Formation and the Bromsgrove Sandstone Formation show evidence that humidity may have been increasing throughout the Middle Triassic (Figure 16). Calcrete or early diagenetic carbonate, which is typically (but not exclusively) associated with warm and seasonally to mostly dry climates (Tanner, 2010), predominates in the lower half of the formations and shows a marked decrease toward the top, while in the Bromsgrove Sandstone plant remains become common toward the top of the formation (Old et al., 1991). This was concurrent with the Muschelkalk transgression of the German basin and it is possible that the apparent increase in humidity may be related to the local ingress of marine waters bringing moisture-laden air into the formerly dry continental interior of Pangaea. This local effect may have enhanced climatic amelioration related to the abrupt stabilisation of the global carbon cycle in the Middle Triassic (Payne and Kump, 2007) (Figure 4).

In England the relatively biologically-diverse river systems of the 'Mid Triassic optimum' were severely disrupted by the transgression of the Mercia Mudstone Group, whose playa lacustrine environments and semi-marine saline pans had extended across all of the English basins by the Ladinian (Leslie et al., 1993). The climate was generally hot and arid throughout most of the Late Triassic (and into the Early Jurassic) with the exception of a widespread and well-constrained pluvial event in the Carnian, which may have been related to the rifting of Pangaea through disruption of atmospheric and marine circulation, sea-level change, or the effects of rift-related volcanism (Arche and López-Gómez, 2014; Simms and Ruffell, 1989).

9 A new tectono-stratigraphic model for the Sherwood Sandstone

While climate was clearly an important control on Triassic stratigraphy, it seems possible to rationalise the Sherwood Sandstone Group (and it is useful here to include related Late Permian deposits) into two general tectono-stratigraphic models which emphasise variable rates of fault activity and differential subsidence (Figure 17).

The first model (Figure 17A) illustrates a phase of active extensional faulting with strong differential subsidence between basins and highs. During this phase upstream basins (i.e. those close to sources of water and sediment) accumulate evaporitic playa lacustrine deposits while downstream basins (disconnected from sources across intra-basinal highs) because depocentres for aeolian or mixed fluvio-aeolian sand. This happened at two main time intervals. First during the Upper Permian when the upstream Wessex Basin was infilled by heterolithic breccias, sandstones and mudstones of the Aylesbeare Mudstone Group (and associated units), while to the north (downstream) thick piles of clean aeolian sand (Bridgnorth and Collyhurst formations) were trapped within the Worcester and Cheshire under the influence of NE trade winds. Second, toward the end of the Early Triassic when the upstream Wessex Basin again became a site for muddy and evaporitic playa lacustrine deposits (Nettlecombe Formation) trapped within rapidly subsiding hanging wall basins. Meanwhile to the north in the downstream Worcester and Cheshire Basin the basins were primarily filled with mixed fluvio-aeolian deposits of the Wildmoor and Wilmslow sandstone formations. The upper sandstone-dominated part of the fluvial Chester Formation (and correlative strata) should probably be included in this syn-rift stratigraphy because it tends to show substantial thickness variation. In both cases therefore the upstream Wessex Basin appears to have acted as a 'silt-trap' intercepting water and fine-grained sediments derived from Armorican sources to the south and allowing clean aeolian sandstones to accumulate in relatively dry, tectonically-disconnected downstream basins to the north.

The second model (Figure 17B) illustrates a phase of relative tectonic quiescent phases where there was little topography related to differential tectonic subsidence of fault blocks and topography related to previous episodes of tectonism had been smoothed by a sedimentary fill and spill process during waning fault activity. Under these conditions long-distance river systems were able to transport water and sediment across the chain of basins and highs. This happened at two separate times during the deposition of the Sherwood Sandstone Group. First during the Early Triassic when the main gravelly 'Budleighensis' river system developed and second during the Mid Triassic when the Otter Sandstone-Bromsgrove Sandstone-Helsby Sandstone formations formed a major linked northward-flowing drainage system. The deposits of these long-range fluvial systems share the characteristics of being relatively thin and uniform in thickness, having a major erosive unconformity at the base and overstepping basin-bounding faults. Intrabasinal highs still had a major control on thickness patterns. For example, across the Mendip High underlain by Carboniferous limestone the Otter Sandstone Formation shows considerable thinning while the Budleigh Salterton Pebble Beds appear to be entirely absent. Such intrabasinal highs may therefore have been areas of sediment bypass, which left no, or an extremely localised, sedimentary record. Alternatively sediments deposited on these highs could have been reworked and eroded during subsequent episodes of rifting.

Episodes of extensional fault activity continued throughout the Late Triassic and appear to have been particularly marked in the Carnian where they are associated with thick halites and sandstones in the Mercia Mudstone Group (Simms and Ruffell, 1989) and the development of numerous N-S trending mineralised veins in SW England (Scrivener et al., 1994).

10 Conclusions

Triassic basins of England developed under a regime of largely W-E extension and progressed from non-marine fluvial and aeolian sedimentation (Sherwood Sandstone Group), through semi-marine playa lacustrine deposits (Mercia Mudstone Group) to fully marine environments (Blue Anchor Formation and Penarth Group). A new tectono-stratigraphic model for the Sherwood Sandstone Group is proposed in which two major long-distance river systems developed under conditions of relative fault inactivity in the Early Triassic (Budleigh Salterton Pebble Beds and equivalent) and Middle Triassic (Otter Sandstone and equivalent). These are separated by a late Early Triassic syn-rift succession of fluvio-aeolian sandstones (Wildmoor and Wilmslow sandstone formations) and playa lacustrine muds (Nettlecombe Formation) which show major thickness variation and localisation with hanging wall basins. The partitioning of syn-rift deposits into mudstones in upstream basins (close to the source of water and sediment) and clean aeolian or fluvio-aeolian sandstones in downstream basins is similar to the pattern observed in the underlying Late Permian. Under conditions of rapid tectonic subsidence chains of extensional basins may become disconnected with upstream basins (Wessex Basin) acting as traps for fines and water permitting more aeolian activity in temporarily unlinked downstream basins (Worcester and Cheshire basins). Fluctuating climate, relief related to limestone resilience in arid settings, the smoothing effect of fill and spill sedimentation and Tethyan sea-level change all contributed toward the observed Triassic stratigraphy in England.

Acknowledgements

Andrew Newell publishes with the permission of the director of the British Geological Survey. Editors of the PGA are thanked for their invitation to prepare this paper.

List of Figures

Figure 1 Reconstruction of Pangea at around the Permo-Triassic boundary (250 ma). The position of England is shown and the lines of crustal separation in the future Atlantic are indicated. The plate tectonic reconstruction was produced using GPlates software using the datasets of Matthews et al. (2016).

Figure 2 Generalised chronostratigraphy of the English Permian and Triassic showing selected lithostratigraphical units and major tectonic and climatic events. At the scale of the diagram the relationship of the lithostratigraphical units to the time scale and stages is approximate and original sources should be consulted for details (Benton et al., 1994; Glennie, 1997; Hounslow and McIntosh, 2003; Hounslow et al., 2017; Hounslow and Ruffell, 2006; Warrington et al., 1980). (BSP=Budleigh Salterton Pebble Beds, NCF=Nettlecombe Formation; KDM=Kidderminster Conglomerate; WMS=Wildmoor Sandstone Formation; CF=Chester Pebble Beds Formation; WLS=Wilmslow Sandstone Formation; OMS=Ormskirk Sandstone Formation). Time scale generated using TimeScale Creator software.

Figure 3 Palaeogeographical sketch map showing England within the context of western Europe at around the Middle Triassic (WH=Welsh High). Reconstruction based on Matthews et al. (2016); (Ziegler, 1991)

Figure 4 Carbon isotope curve for the Early and Middle Triassic (Payne et al., 2004) showing large perturbations synchronous with the deposition of the lower part of the Sherwood Sandstone Group.

Figure 5 Map showing the distribution of Permian and Triassic outcrop, the approximate area of subcrop and the main faults and basins (DEB=Devon Basin, DoB=Dorset Basin, PB=Pewsey Basin, WG=Worcester Graben, KB=Knowle Basin, HB=Hinckley Basin; NB=Needwood Basin, SB=Stafford Basin, CB=Cheshire Basin, EISB=East Irish Sea Basin, EMS=Eastern Midlands Shelf, BF=Beer Fault, QCCF=Quantock-Coker-Cranborne Fault, PF=Pewsey Fault, CCNF=Clopton-Clapton-Northleach Fault IBF=Inkberrow Fault, EMF=East Malvern Fault, WRRF=Wem-Red Rock Fault). Red line linking white circles shows the boreholes and section shown in Figure 9.

Figure 6 Simplified 3D geological model showing the form and depth of the Variscan ('top Carboniferous') Unconformity in its present configuration. The model was generated in SKUA-GOCAD 15.5 and is based primarily on borehole data and a highly-simplified fault network.

Figure 7 Map showing the thickness of Permian strata (above the Variscan unconformity) plus the overlying Sherwood Sandstone Group. The thickness map is based on borehole data (black circles indicate borehole position) interpolated on a 5 km grid using Discrete Smooth Interpolation (Mallet, 1989). Faults and other barriers, such as the exposed Carboniferous coal-field blocks in the English Midlands, are omitted.

Figure 8 Correlation of geophysical logs across selected major Permo-Triassic depocentres in England (inset map shows borehole location). The logs focus on the stratigraphic interval between pre-Permian basement and the top of the Triassic Sherwood Sandstone Goup. An interval of broadly correlative Mercia Mudstone Group is included in the Cheshire and East Irish Sea basins. A gamma-ray log is shown in the left track and a sonic interval travel time log is shown in the right track. The logs are coloured for generalised lithofacies based on geophysical log response and borehole cuttings returns.

Figure 9 Semi-schematic lithostratigrapical-structural model for the Permo-Triassic from the Wessex Basin to the East Irish Sea Basin (see Figure 5 for location of boreholes and line of section). The correlation is flattened on the top of the Sherwood Sandstone and broadly correlative parts of the Mercia Mudstone Group in basins to the north of the Wem-Red Rock Fault. (From left to right and base to top the abbreviations are:, AYB=Aylesbeare Mudstone Group, NF=Nettlecome Formation, OS=Otter Sandstone Formation, PTU=Permo-Triassic undifferentiated, BNS=Bridgnorth Sandstone Formation, KDM=Kidderminster Conglomerate, WRS=Wildmoor Sandstone Formation, BMS=Bromsgrove Sandstone Formation, CS=Collyhurst Sandstone Formation, MM=Manchester Marls, KNSF=Kinnerton Sandstone, CHES=Chester Formation; WLSF= Wilmslow Sandstone Formation, HEY=Helsby Sandstone Formation, TS=Tarporley Siltstone Formation, SBS=St Bees Sandstone Formation, CSA=Calder Sandstone Formation, OMS=Ormskirk Sandstone Formation.

Figure 10 Semi-schematic facies model for the Permian and Sherwood Sandstone from the Wessex Basin to the East Irish Sea Basin (see Figure 5 for location of boreholes and line of section). The correlation is flattened on the top of the Sherwood Sandstone and broadly correlative parts of the Mercia Mudstone Group in basins to the north of the Wem-Red Rock Fault (PTU=Permo-Triassic undifferentiated, TSZ=Top Silicified Zone).

Figure 11 Map of the Wessex Basin showing the location of major Triassic faults, selected outcrop areas and the location of boreholes shown in Figure 12.

Figure 12 Correlation of boreholes which include the Sherwood Sandstone Group and Mercia Mudstone Group from west to east across the Wessex Basin. See Figure 11 for location of the boreholes.

Figure 13 Map showing the distribution of Lower Carboniferous (Dinantian) limestones at outcrop and at subcrop below the Variscan unconformity (Smith, 1985).

Figure 14 Log correlation across the Dinantian limestone belt between the Worcester Basin and Wessex Basin. See Figure 13 for the location of the boreholes.

Figure 15 Log correlation from the Stafford Basin, the Needwood Basin and onto the East Midlands shelf. Logs are flattened on the Mid-Triassic unconformity.

Figure 16 Comparison of the stratigraphy of the Otter Sandstone Formation at coastal outcrop in south Devon (Newell in prep.) and the Bromsgrove Sandstone Formation in the Sugarbrook borehole near Bromsgrove (Old et al., 1991).

Figure 17 Simplified models for the deposition of Late Permian to Middle Triassic coarse clastic deposits in the rift basins of England under conditions of (A) active extension and rifting and (B) slow thermal subsidence when major long-distance river systems could develop.

References

2008. The Geology of Central Europe Volume 2. Geological Society of London.

Ambrose, K., Hough, E., Smith, N., Warrington, G., 2014. Lithostratigraphy of the Sherwood Sandstone Group of England, Wales and south-west Scotland.

Arche, A., López-Gómez, J., 2014. The Carnian Pluvial Event in Western Europe: New data from Iberia and correlation with the Western Neotethys and Eastern North America–NW Africa regions. Earth-Science Reviews 128, 196-231.

Asquith, G.B., Gibson, C.R., 1982. Basic Well Log Analysis for Geologists. American Association of Petroleum Geologists, Tulsa, Oklahoma.

Audley-Charles, M.G., 1970. Triassic palaeogeography of the British Isles. Quarterly Journal of the Geological Society 126, 49-74.

Barclay, W.J., Ambrose, K., Chadwick, R.A., Pharaoh, T.C., 1997. Geology of the country around Worcester : memoir for 1:50 000 geological sheet 199 (England and Wales). Stationery Office, London.

Benton, M., Cook, E., Turner, P., 2002. Permian and Triassic Red Beds and the Penarth Group of Great Britain, Geological Conservation Review Series, No. 24. Joint Nature Conservation Committee, Peterborough.

Benton, M.J., 2016. The Triassic. Current Biology 26, R1214-R1218.

Benton, M.J., Newell, A.J., 2014. Impacts of global warming on Permo-Triassic terrestrial ecosystems. Gondwana Research 25, 1308-1337.

Benton, M.J., Warrington, G., Newell, A.J., Spencer, P.S., 1994. A review of the British Middle Triassic tetrapod assemblages. In the shadow of the dinosaurs, 131-160.

Bloomfield, J.P., Moreau, M.F., Newell, A.J., 2006. Characterization of permeability distributions in six lithofacies from the Helsby and Wilmslow sandstone formations of the Cheshire Basin, UK. Geological Society, London, Special Publications 263, 83-101.

Bouch, J.E., Hough, E., Kemp, S.J., McKervey, J.A., Williams, G.M., Greswell, R.B., 2006. Sedimentary and diagenetic environments of the Wildmoor Sandstone Formation (UK): implications for groundwater and contaminant transport, and sand production. Geological Society, London, Special Publications 263, 129-153.

Bourquin, S., Durand, M., Diez, J., Broutin, J., Fluteau, F., 2007. The Permian-Triassic boundary and Early Triassic sedimentation in Western European basins: an overview. Journal of Iberian Geology 33, 221-236.

Bowman, M.B.J., McClure, N.M., Wilkinson, D.W., 1993. Wytch Farm oilfield: deterministic reservoir description of the Triassic Sherwood Sandstone. Geological Society, London, Petroleum Geology Conference series 4, 1513-1517.

Brodie, J., White, N., 1994. Sedimentary basin inversion caused by igneous underplating: Northwest European continental shelf. Geology 22, 147-150.

Butler, M., 1998. The geological history of the southern Wessex Basin — a review of new information from oil exploration. Geological Society, London, Special Publications 133, 67-86.

Chadwick, R.A., 1986. Extension tectonics in the Wessex Basin, southern England. Journal of the Geological Society Journal of the Geological Society 143, 465-488.

Chadwick, R.A., Evans, D.J., 1995. The timing and direction of Permo-Triassic extension in southern Britain. Geological Society, London, Special Publications 91, 161-192.

Chadwick, R.A., Evans, D.J., British Geological, S., 2005. A seismic atlas of southern Britain : images of subsurface structure. British Geological Survey, Nottingham.

Chadwick, R.A., Livermore, R.A., Penn, I.E., 1989. Continental Extension in Southern Britain and Surrounding Areas and Its Relationship to the Opening of the North Atlantic Ocean, In: TANKARD, A.J., BALKWILL, H.R. (Eds.), Extensional Tectonics and Stratigraphy of the North Atlantic Margins. American Association of Petroleum Geologists, Memoir 46, pp. 411-424.

Chen, Z.-Q., Benton, M.J., 2012. The timing and pattern of biotic recovery following the end-Permian mass extinction. Nature Geosci 5, 375-383.

Cocks, l.R.M., 1993. Triassic pebbles, derived fossils and the Ordovician to Devonian palaeogeography of Europe. Journal of the Geological Society 150, 219-226.

Corsetti, F.A., Baud, A., Marenco, P.J., Richoz, S., 2005. Summary of Early Triassic carbon isotope records. Comptes Rendus Palevol 4, 473-486.

Coward, M.P., 1995. Structural and tectonic setting of the Permo-Triassic basins of northwest Europe. Geological Society, London, Special Publications 91, 7-39.

Edwards, R.A., Warrington, G., Scrivener, R.C., Jones, N.S., Haslam, H.W., Ault, L., 1997. The Exeter Group, south Devon, England: a contribution to the early post-Variscan stratigraphy of northwest Europe. Geological Magazine 134, 177-197.

Eriksson, P.G., Bumby, A.J., Brümer, J.J., van der Neut, M., 2006. Precambrian fluvial deposits: Enigmatic palaeohydrological data from the c. 2-1.9 Ga Waterberg Group, South Africa. Sedimentary Geology 190, 25-46.

Evans, D.J., Rees, J.G., Holloway, S., 1993. The Permian to Jurassic stratigraphy and structural evolution of the central Cheshire Basin. Journal of the Geological Society 150, 857-870.

Fitch, F.J., Miller, J.A., Thompson, D.B., 1966. The palaeogeographic significance of isotopic age determinations on detrital micas from the triassic of the Stockport-Macclesfield district, Cheshire, England. Palaeogeography, Palaeoclimatology, Palaeoecology 2, 281-312.

Franz, M., Kaiser, S.I., Fischer, J., Heunisch, C., Kustatscher, E., Luppold, F.W., Berner, U., Röhling, H.G., 2015. Eustatic and climatic control on the Upper Muschelkalk Sea (late Anisian/Ladinian) in the Central European Basin. Global and Planetary Change 135, 1-27.

Glennie, K.W., 1997. Recent advances in understanding the southern North Sea Basin: a summary. Geological Society, London, Special Publications 123, 17-29.

Glover, B.W., Powell, J.H., 1996. Interaction of climate and tectonics upon alluvial architecture: Late Carboniferous-Early Permian sequences at the southern margin of the Pennine Basin, UK. Palaeogeography, Palaeoclimatology, Palaeoecology 121, 13-34.

Goldsworthy, M., Jackson, J., 2000. Active normal fault evolution in Greece revealed by geomorphology and drainage patterns. Journal of the Geological Society 157, 967-981.

Hamblin, R.J.O., Crosby, A., Balson, P.S., Jones, S.M., Chadwick, R.A., Penn, I.E., Arthur, M.J., 1992. The geology of the English Channel. British Geological Survey United Kingdom Offshore Regional Report.

Hesselbo, S.P., Robinson, S.A., Surlyk, F., 2004. Sea-level change and facies development across potential Triassic–Jurassic boundary horizons, SW Britain. Journal of the Geological Society 161, 365-379.

Highley, D.E., Cameron, D.G., 1995. Mineral Resource Information for Development Plans Staffordshire: Resources and Constraints. British Geological Survey Technical Report WF/95/5.

Holloway, S., Milodowski, A.E., Strong, G.E., Warrington, G., 1989. The Sherwood Sandstone Group (Triassic) of the Wessex Basin, southern England. Proceedings of the Geologists' Association 100, 383-394.

Hounslow, M.W., McIntosh, G., 2003. Magnetostratigraphy of the Sherwood Sandstone Group (Lower and Middle Triassic), south Devon, UK: detailed correlation of the marine and non-marine Anisian. Palaeogeography, Palaeoclimatology, Palaeoecology 193, 325-348.

Hounslow, M.W., McIntosh, G., Edwards, R.A., Laming, D.J.C., Karloukovski, V., 2017. End of the Kiaman Superchron in the Permian of SW England: magnetostratigraphy of the Aylesbeare Mudstone and Exeter groups. Journal of the Geological Society 174, 56-74.

Hounslow, M.W., Ruffell, A.H., 2006. Triassic: seasonal rivers, dusty deserts and saline lakes, In: Brenchley, P.J., Rawson, P.F. (Eds.), The geology of England and Wales (2nd Edn). Geological Society, London, pp. 295-324.

Howard, A.S., Hough, E., Crofts, R.G., Reeves, H.J., Evans, D.J., 2007. Geology of the Liverpool district. Sheet Explanation of the British Geological Survey, Sheet 96 (England and Wales).

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jackson, D.I., Mulholland, P., 1993. Tectonic and stratigraphic aspects of the East Irish Sea Basin and adjacent areas: contrasts in their post-Carboniferous structural styles. Geological Society, London, Petroleum Geology Conference series 4, 791-808.

Jones, N.S., Ambrose, K., 1994. Triassic sandy braidplain and aeolian sedimentation in the Sherwood Sandstone Group of the Sellafield area, west Cumbria. Proceedings of the Yorkshire Geological and Polytechnic Society 50, 61-76.
Karpeta, W.P., 1990. The morphology of Permian palaeodunes—a reinterpretation of the Bridgnorth Sandstone around Bridgnorth, England, in the light of modern dune studies. Sedimentary Geology 69, 59-75.
Leeder, M.R., Gawthorpe, R.L., 1987. Sedimentary models for extensional tilt-block/half-graben basins. Geological Society, London, Special Publications 28, 139-152.
Leslie, A.B., Spiro, B., Tucker, M.E., 1993. Geochemical and mineralogical variations in the upper Mercia Mudstone Group (Late Triassic), southwest Britain: correlation of outcrop sequences with borehole geophysical logs. Journal of the Geological Society 150, 67-75.
Mallet, J.L., 1989. Discrete smooth interpolation. ACM Transactions on Graphics 8, 121-144.
Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., Müller, R.D., 2016. Global plate boundary evolution and kinematics since the late Paleozoic. Global and Planetary Change 146, 226-250.
McCann, T., Pascal, C., Timmerman, M.J., Krzywiec, P., López-Gómez, J., Wetzel, L., Krawczyk, C.M., Rieke, H., Lamarche, J., 2006. Post-Variscan (end Carboniferous-Early Permian) basin evolution in Western and Central Europe. Geological Society, London, Memoirs 32, 355-388.
McKie, T., Williams, B., 2009. Triassic palaeogeography and fluvial dispersal across the northwest European Basins. Geological Journal 44, 711-741.
McKie, T.O.M., 2014. Climatic and tectonic controls on Triassic dryland terminal fluvial system architecture, central North Sea, From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin. John Wiley & Sons, Ltd, pp. 19-57.
McMahon, N.A., Turner, J., 1998. The documentation of a latest Jurassic-earliest Cretaceous uplift throughout southern England and adjacent offshore areas. Geological Society, London, Special Publications 133, 215-240.
Meadows, N.S., 2006. The correlation and sequence architecture of the Ormskirk Sandstone Formation in the Triassic Sherwood Sandstone Group of the East Irish Sea Basin, NW England. Geological Journal 41, 93-122.
Medici, G., Boulesteix, K., Mountney, N.P., West, L.J., Odling, N.E., 2015. Palaeoenvironment of braided fluvial systems in different tectonic realms of the Triassic Sherwood Sandstone Group, UK. Sedimentary Geology 329, 188-210.
Miliorizos, M., Ruffell, A., 1998. Kinematics of the Watchet-Cothelstone-Hatch Fault System: implications for the fault history of the Wessex Basin and adjacent areas. Geological Society, London, Special Publications 133, 311-330.
Morton, A., Hounslow Mark, W., Frei, D., 2013. Heavy-mineral, mineral-chemical and zircon-age constraints on the provenance of Triassic sandstones from the Devon coast, southern Britain, Geologos, p. 67.
Mountney, N.P., Thompson, D.B., 2002. Stratigraphic evolution and preservation of aeolian dune and damp/wet interdune strata: an example from the Triassic Helsby Sandstone Formation, Cheshire Basin, UK. Sedimentology 49, 805-833.
Newell, A.J., 2000. Fault activity and sedimentation in a marine rift basin (Upper Jurassic, Wessex Basin, UK). Journal of the Geological Society 157, 83-92.
Newell, A.J., 2001. Bounding surfaces in a mixed aeolian–fluvial system (Rotliegend, Wessex Basin, SW UK). Marine and Petroleum Geology 18, 339-347.
Newell, A.J., 2006. Calcrete as a source of heterogeneity in Triassic fluvial sandstone aquifers (Otter Sandstone Formation, SW England). Geological Society, London, Special Publications 263, 119-127.
Newell, A.J., Evans, D.J., 2011. Timing of basin inversion on the Isle of Wight: New evidence from geophysical log correlation, seismic sections and lateral facies change in the Palaeogene Headon Hill Formation. Proceedings of the Geologists' Association 122, 868-882.
Newell, A.J., Shariatipour, S.M., 2016. Linking outcrop analogue with flow simulation to reduce uncertainty in sub-surface carbon capture and storage: an example from the Sherwood Sandstone Group of the Wessex Basin, UK. Geological Society, London, Special Publications 436.
Newell, A.J., Tverdokhlebov, V.P., Benton, M.J., 1999. Interplay of tectonics and climate on a transverse fluvial system, Upper Permian, Southern Uralian Foreland Basin, Russia. Sedimentary Geology 127, 11-29.
Old, R.A., Hamblin, R.J.O., Ambrose, K., Warrington, G., 1991. Geology of the country around Redditch. Memoir of the British Geological Survey Sheet 183 (England and Wales). .
Payne, J.L., Kump, L.R., 2007. Evidence for recurrent Early Triassic massive volcanism from quantitative interpretation of carbon isotope fluctuations. Earth and Planetary Science Letters 256, 264-277.
Payne, J.L., Lehrmann, D.J., Wei, J., Orchard, M.J., Schrag, D.P., Knoll, A.H., 2004. Large Perturbations of the Carbon Cycle During Recovery from the End-Permian Extinction. Science 305, 506.
Peacock, D.C.P., 2004. The post-Variscan development of the British Isles within a regional transfer zone influenced by orogenesis. Journal of Structural Geology 26, 2225-2231.
Pharaoh, T.C., Molyneux, S.G., Merriman, R.J., Lee, M.K., 1993. The Caledonides of the Anglo-Brabant Massif Reviewed. Geological Magazine 130, 561-562.
Pharaoh, T.C., Morris, J., Long, C.B., Ryan, P.D., 1996. The Tectonic Map of Britain, Ireland and adjacent areas. Sheet 1. 1:1 500 000 Scale. British Geological Survey and Geological Survey of Ireland.
Purvis, K., Wright, V.P., 1991. Calcretes related to phreatophytic vegetation from the Middle Triassic Otter Sandstone of South West England. Sedimentology 38, 539-551.
Radley, J.D., Coram, R.A., 2015. Derived Skolithos pipe rock in the Budleigh Salterton Pebble Beds (Early Triassic, East Devon, UK). Proceedings of the Geologists' Association 126, 220-225.

Radley, J.D., Coram, R.A., 2016. The Chester Formation (Early Triassic, southern Britain): sedimentary response to extreme greenhouse climate? Proceedings of the Geologists' Association 127, 552-557.
Roscher, M., Stordal, F., Svensen, H., 2011. The effect of global warming and global cooling on the distribution of the latest Permian climate zones. Palaeogeography, Palaeoclimatology, Palaeoecology 309, 186-200.
Ruffell, A., Shelton, R., 1999. The control of sedimentary facies by climate during phases of crustal extension: examples from the Triassic of onshore and offshore England and Northern Ireland. Journal of the Geological Society 156, 779-789.
Scrivener, R.C., Darbyshire, D.P.F., Shepherd, T.J., 1994. Timing and significance of crosscourse mineralization in SW England. Journal of the Geological Society 151, 587-590.
Seyfullah, L.J., Kustatscher, E., Taylor, W.A., 2013. The first discovery of in situ Verrucosisporites applanatus spores from the Middle Triassic flora from Bromsgrove (Worcestershire, UK). Review of Palaeobotany and Palynology 197, 15-25.
Simms, M.J., 2004. Tortoises and hares: dissolution, erosion and isostasy in landscape evolution. Earth Surface Processes and Landforms 29, 477-494.
Simms, M.J., Ruffell, A.H., 1989. Synchroneity of climatic change and extinctions in the Late Triassic. Geology 17, 265-268.
Simms, M.J., Ruffell, A.H., 1990. Climatic and biotic change in the late Triassic. Journal of the Geological Society 147, 321-327.
Smith, D.B., 1995. Marine Permian of England, Geological Conservation Review Series, No. 8, Chapman and Hall, London, 205 pp.
Smith, N.J.P., 1985. Pre-Permian geology of the United Kingdom (South). 1:1,000,000 Scale Map. British Geological Survey, Keyworth, UK.
Smith, S.A., Edwards, R.A., 1991. Regional sedimentological variations in lower triassic fluvial conglomerates (budleigh salterton pebble beds), southwest england: Some implications for palaeogeography and basin evolution. Geological Journal 26, 65-83.
Stampfli, G.M., Hochard, C., Vérard, C., Wilhem, C., vonRaumer, J., 2013. The formation of Pangea. Tectonophysics 593, 1-19.
Steel, R.J., Thompson, D.B., 1983. Structures and textures in Triassic braided stream conglomerates ('Bunter' Pebble Beds) in the Sherwood Sandstone Group, North Staffordshire, England. Sedimentology 30, 341-367.
Sumbler, M.G., 1996. British Regional Geology: London and the Thames Valley (4th ed.). HMSO, London.
Tanner, L.H., 2010. Chapter 4 Continental Carbonates as Indicators of Paleoclimate, In: Alonso-Zarza, A.M., Tanner, L.H. (Eds.), Developments in Sedimentology. Elsevier, pp. 179-214.
Taylor, S.R., 1983. A stable isotope study of the Mercia Mudstones (Keuper Marl) and associated sulphate horizons in the English Midlands. Sedimentology 30, 11-31.
Tellam, J.H., 1994. The groundwater chemistry of the Lower Mersey Basin Permo-Triassic Sandstone Aquifer system, UK: 1980 and pre-industrialisation-urbanisation. Journal of Hydrology 161, 287-325.
Thompson, D.B., 1970. The stratigraphy of the so-called Keuper Sandstone Formation (Scythian–? Anisian) in the Permo–Triassic Cheshire Basin. Quarterly Journal of the Geological Society 126, 151-181.
Tyrrell, S., Haughton, P.D.W., Souders, A.K., Daly, J.S., Shannon, P.M., 2012. Large-scale, linked drainage systems in the NW European Triassic: insights from the Pb isotopic composition of detrital K-feldspar. Journal of the Geological Society 169, 279-295.
Underhill, J.R., Stoneley, R., 1998. Introduction to the development, evolution and petroleum geology of the Wessex Basin. Geological Society, London, Special Publications 133, 1-18.
Wakefield, O.J.W., Hough, E., Peatfield, A.W., 2015. Architectural analysis of a Triassic fluvial system: The Sherwood Sandstone of the East Midlands Shelf, UK. Sedimentary Geology 327, 1-13.
Warrington, G., 1970. The stratigraphy and palaeontology of the 'Keuper' Series of the central Midlands of England. Quarterly Journal of the Geological Society 126, 183-223.
Warrington, G., Audley-Charles, M.G., Elliott, R.E., Evans, W.B., Ivimey-Cook, H.C., Kent, P.E., Robinson, P.L., Shotton, F.W., Taylor, F.M., 1980. A correlation of Triassic rocks in the British Isles. Special Report of the Geological Society of London, No.13.
Waters, C.N., Davies, S.J., 2006. Carboniferous : extensional basins, advancing deltas and coal swamps, In: Brenchley, P.J., Rawson, P.F. (Eds.), The geology of England and Wales. . Geological Society of London, London, England, pp. 173-223.
Whittaker, A., Holliday, D.W., Penn, I.E., Geological Society of, L., 1985. Geophysical logs in British stratigraphy. Published for the Geological Society by Blackwell Scientific, Oxford.
Williams, B.J., Whittaker, A., 1974. Geology of the country around Stratford-upon-Avon and Evesham. Memoir of the Geological Survey of Great Britain Sheet 200 (England and Wales).
Wills, L.J., 1951. A Palaeogeographical Atlas. Blackie, London-Glasgow
Wills, L.J., 1970. The Triassic succession in the central Midlands in its regional setting. Quarterly Journal of the Geological Society 126, 225-283.
Woodcock, N.H., 1984. The Pontesford Lineament, Welsh Borderland. Journal of the Geological Society 141, 1001-1014.
Wright, V.P., Marriott, S.B., Vanstone, S.D., 1991. A 'reg' palaeosol from the Lower Triassic of south Devon: stratigraphic and palaeoclimatic implications. Geological Magazine 128, 517-523.
Ziegler, P.A., 1991. Geological atlas of Western and Central Europe. Shell Internationale Petroleum Maatschappij B.V., The Hague.

Figure 1
Click here to download high resolution image

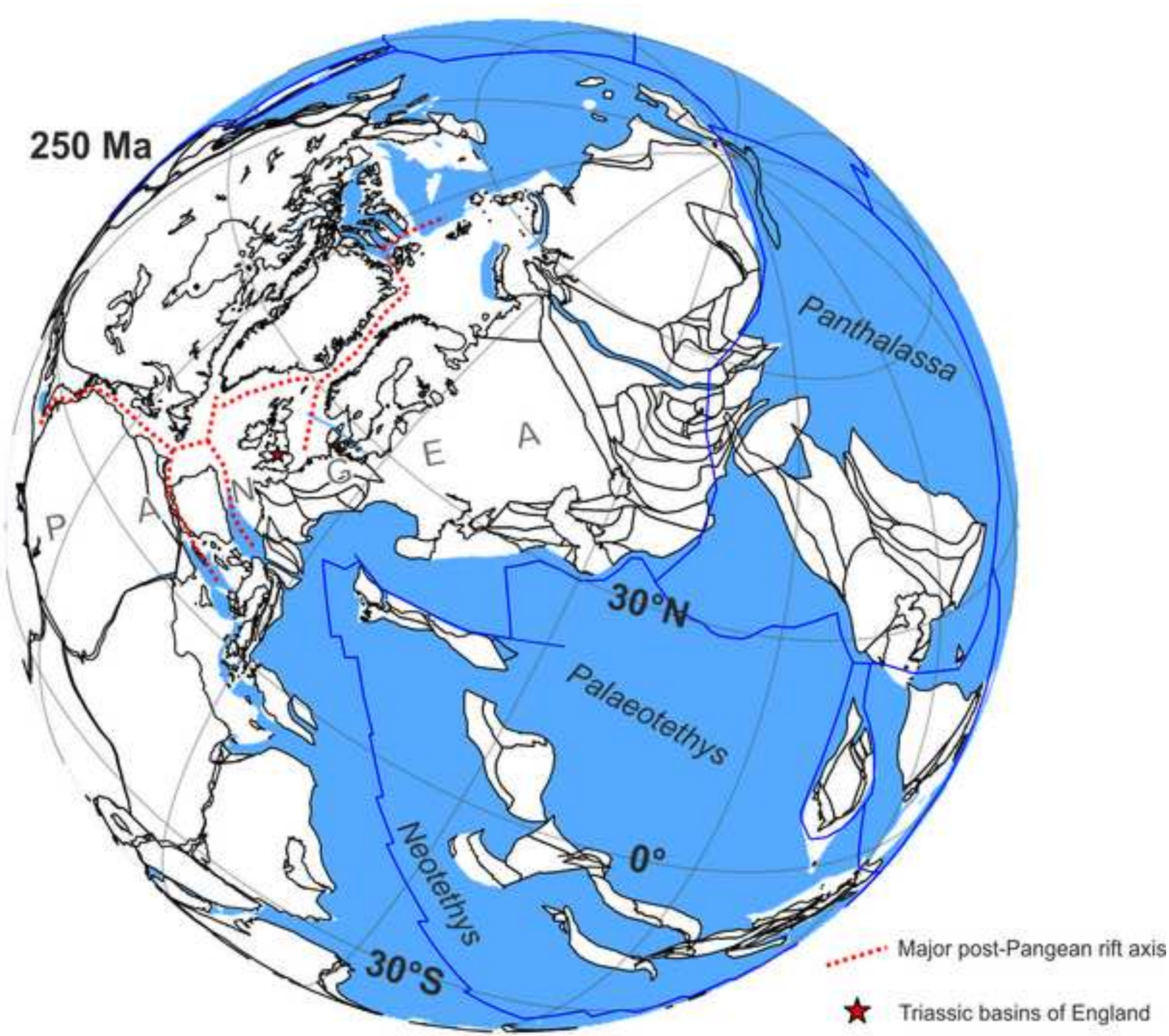

Figure 2

Click here to download high resolution image

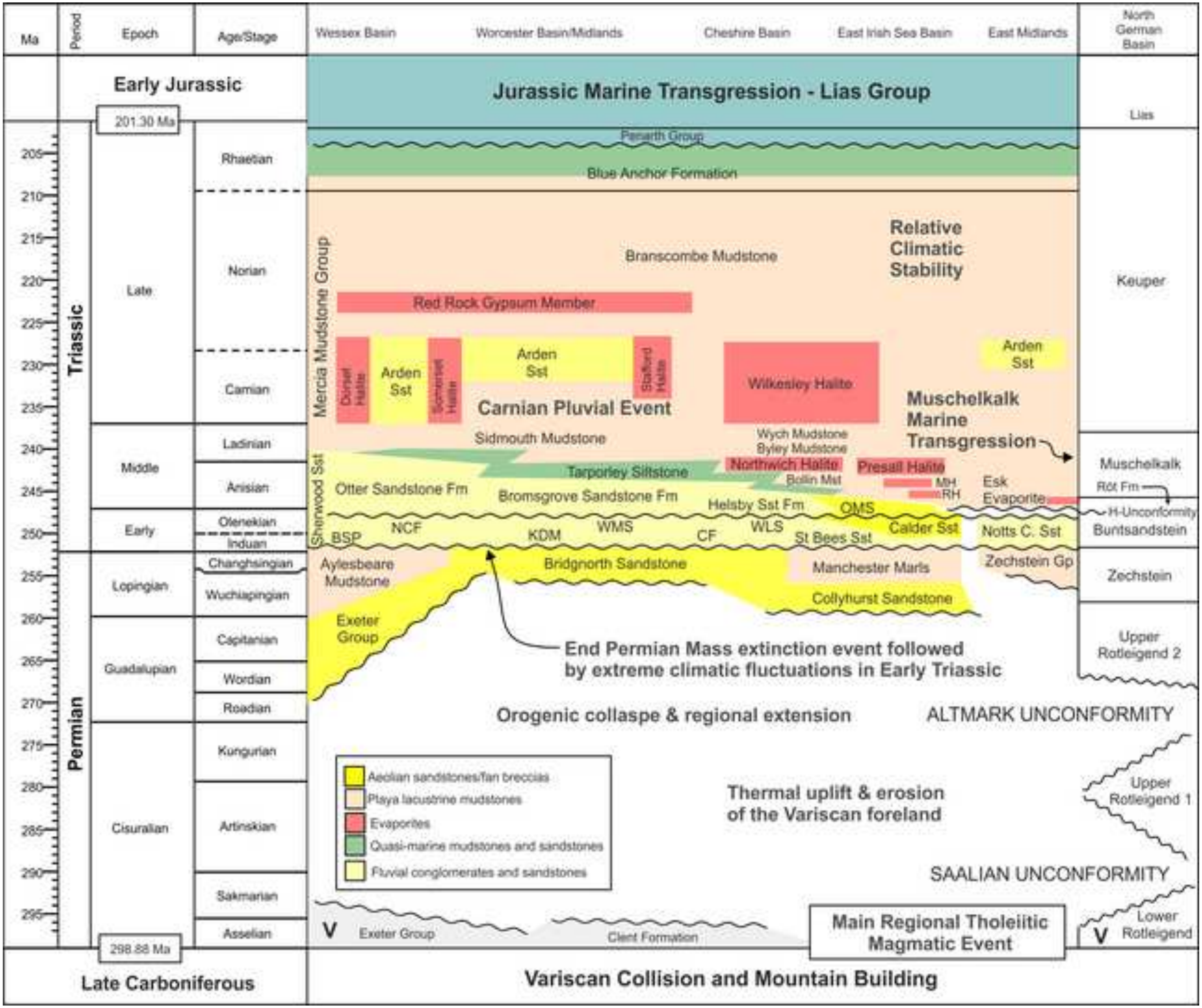

Figure 3

Click here to download high resolution image

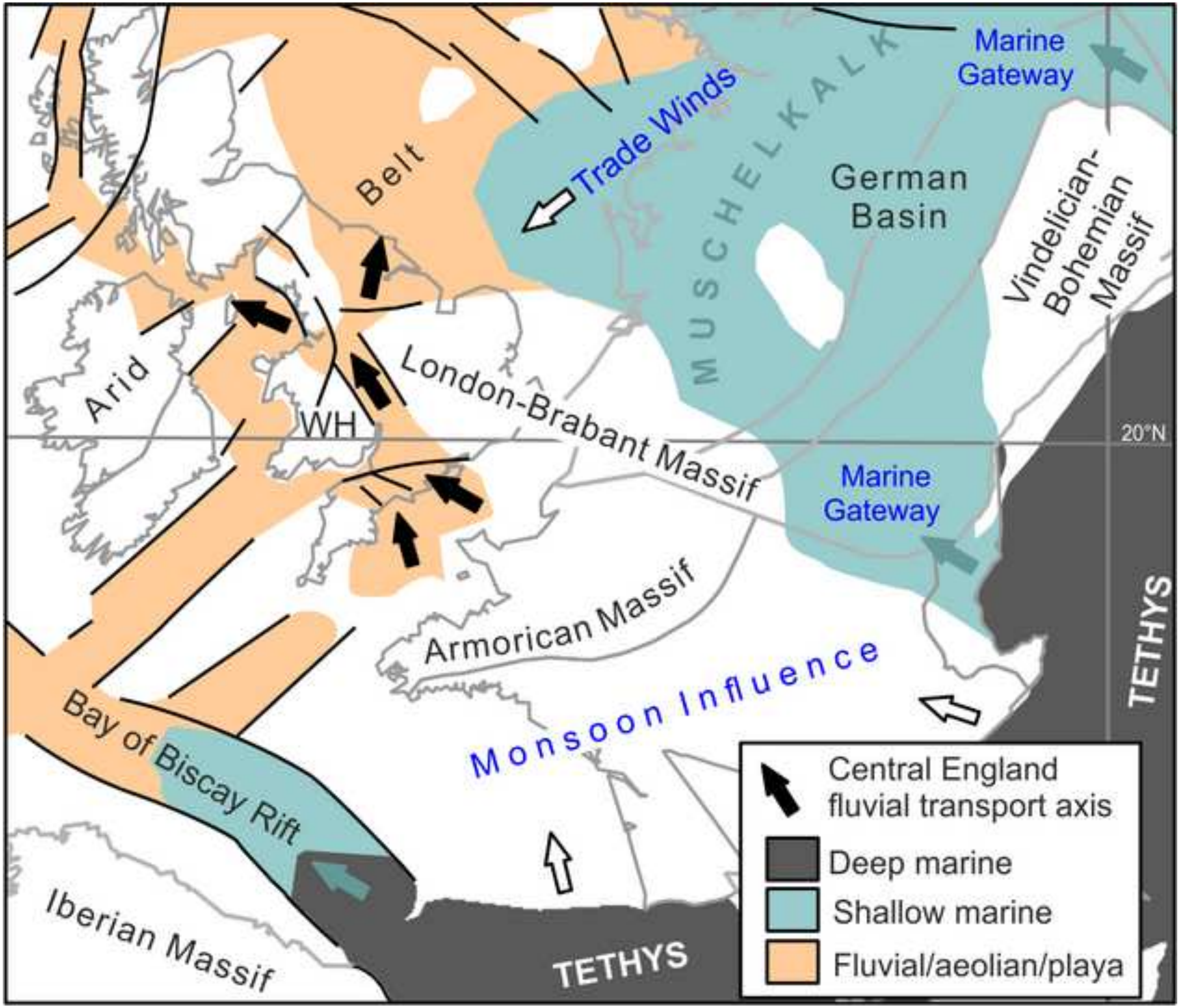

Figure 4
Click here to download high resolution image

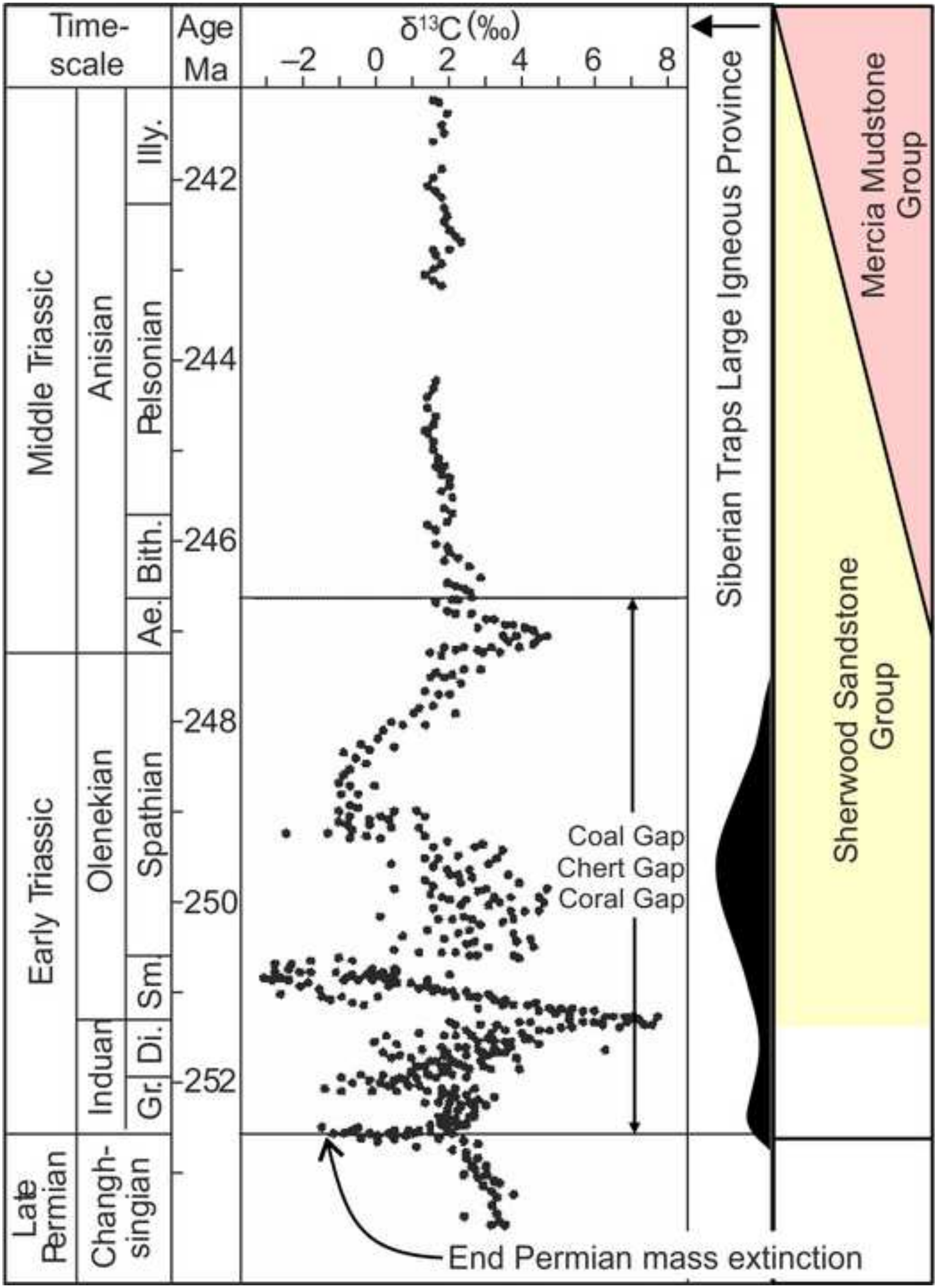

Figure 5

Click here to download high resolution image

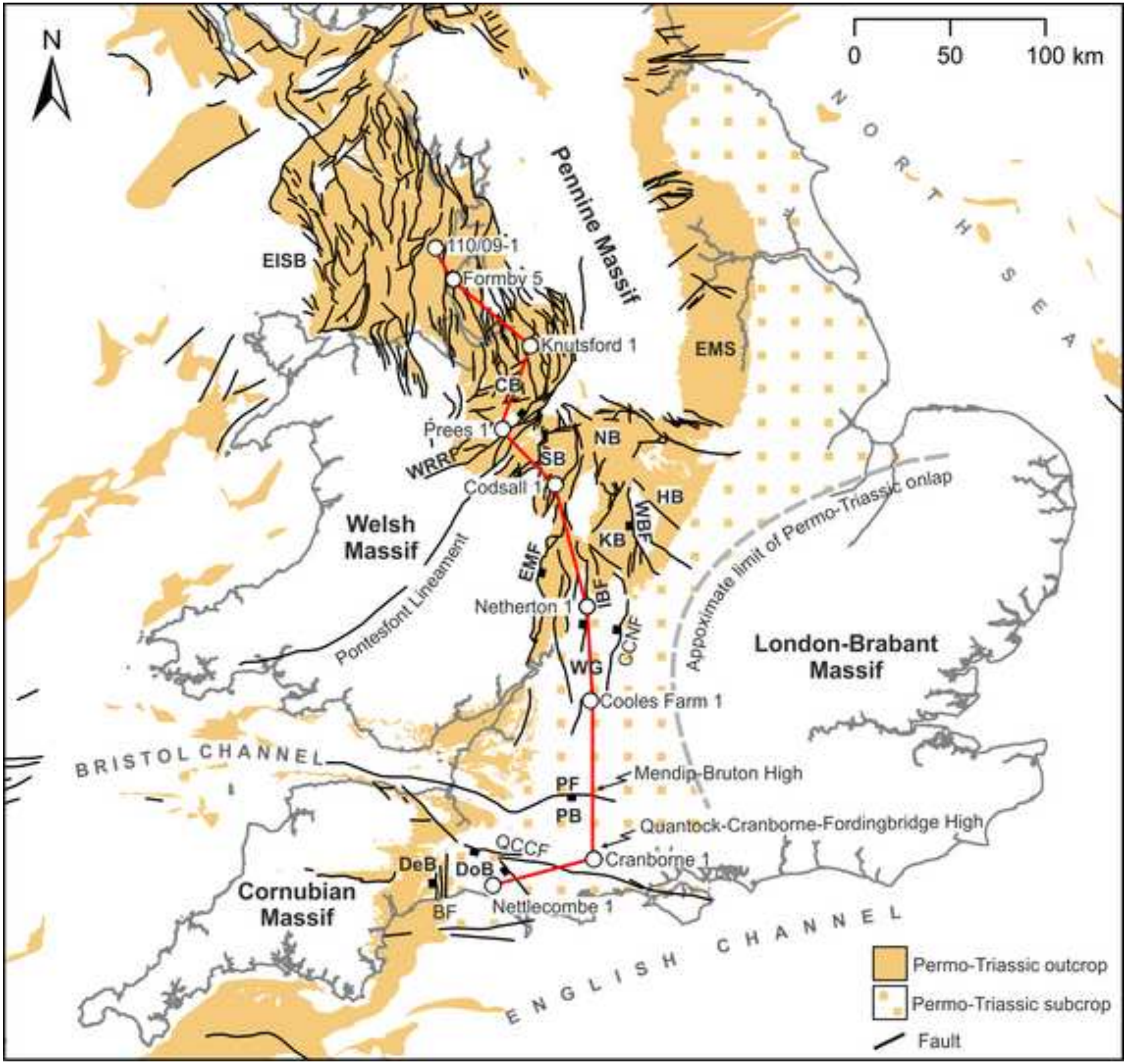

Figure 6

Click here to download high resolution image

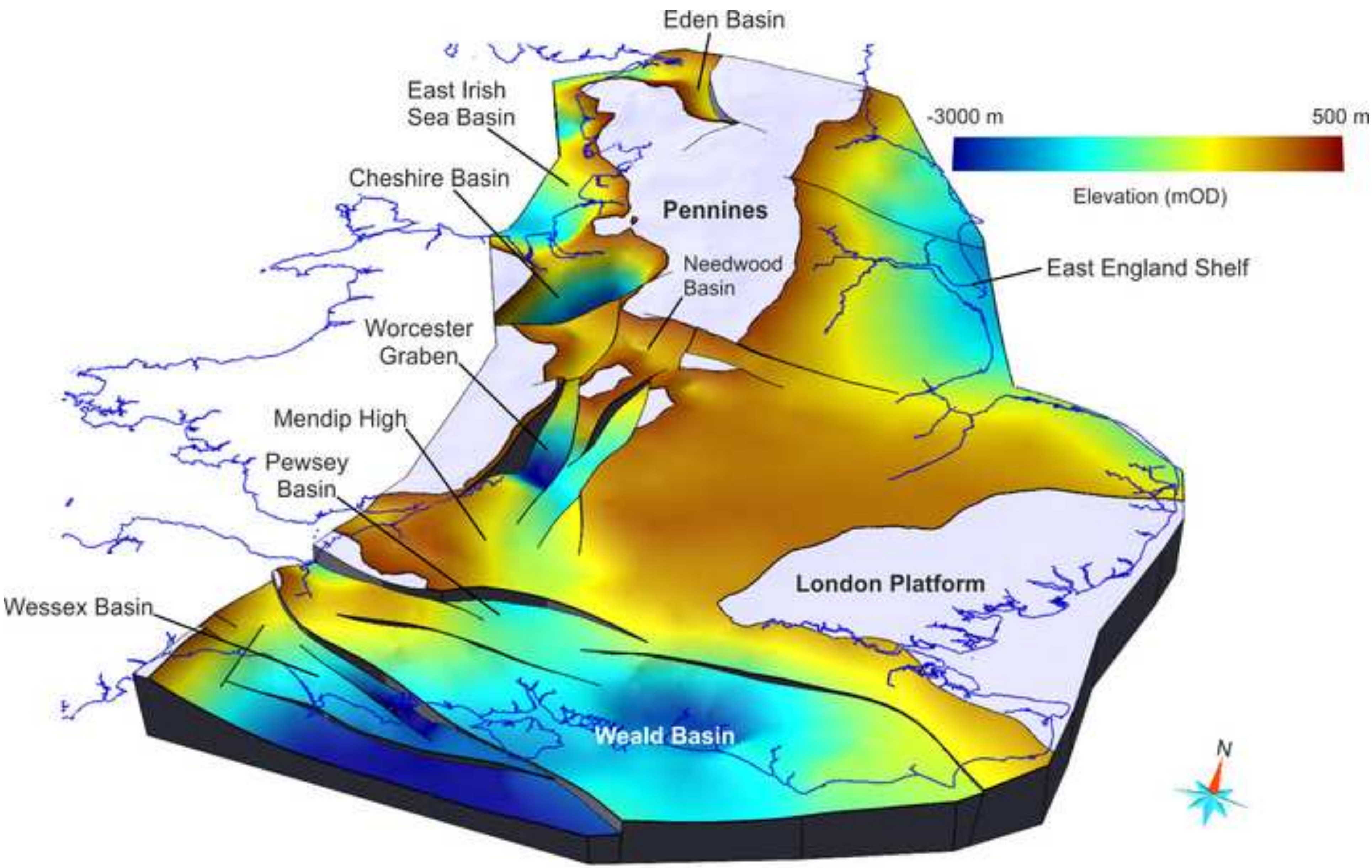

Figure 7
Click here to download high resolution image

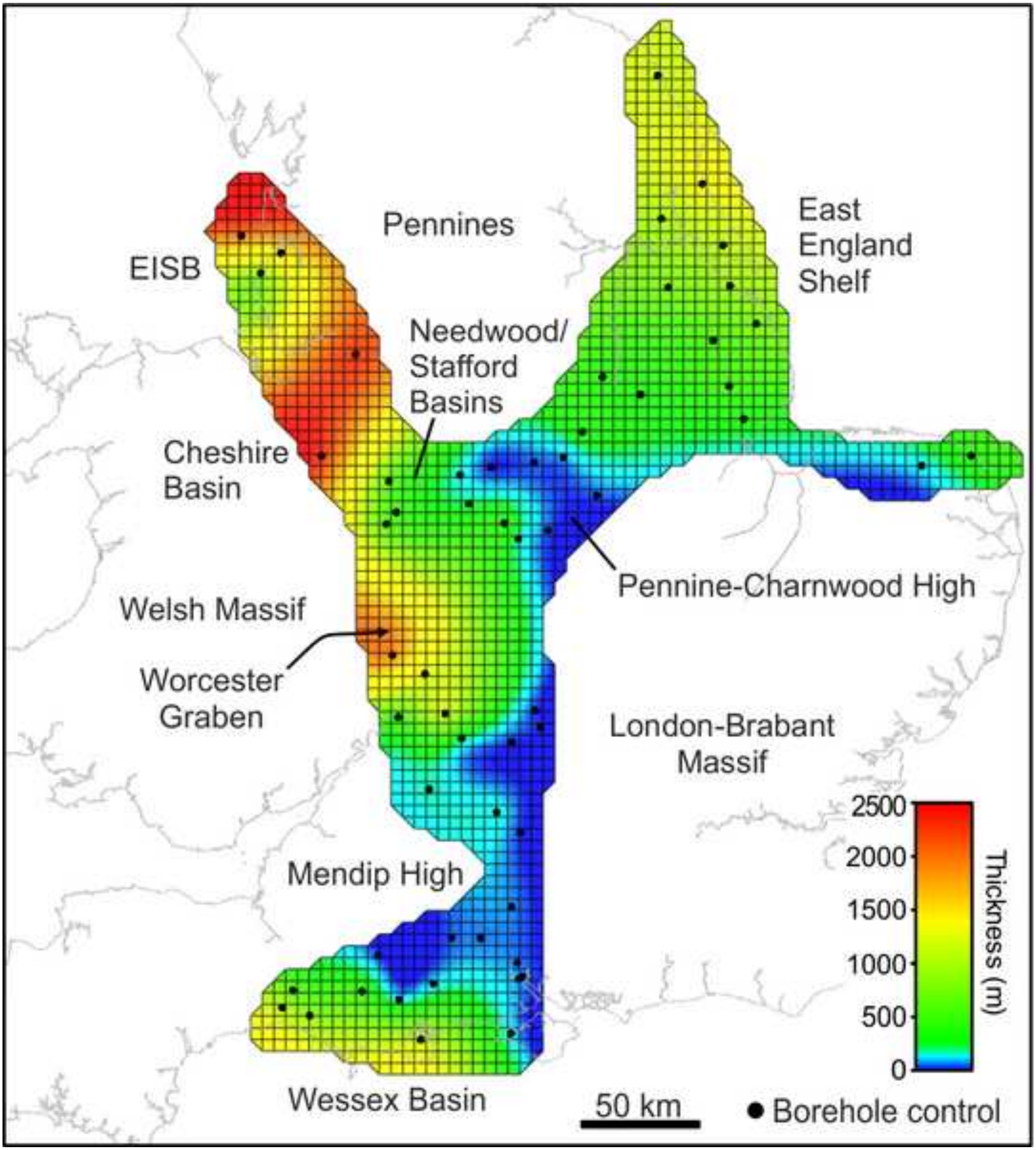

Figure 8
Click here to download high resolution image

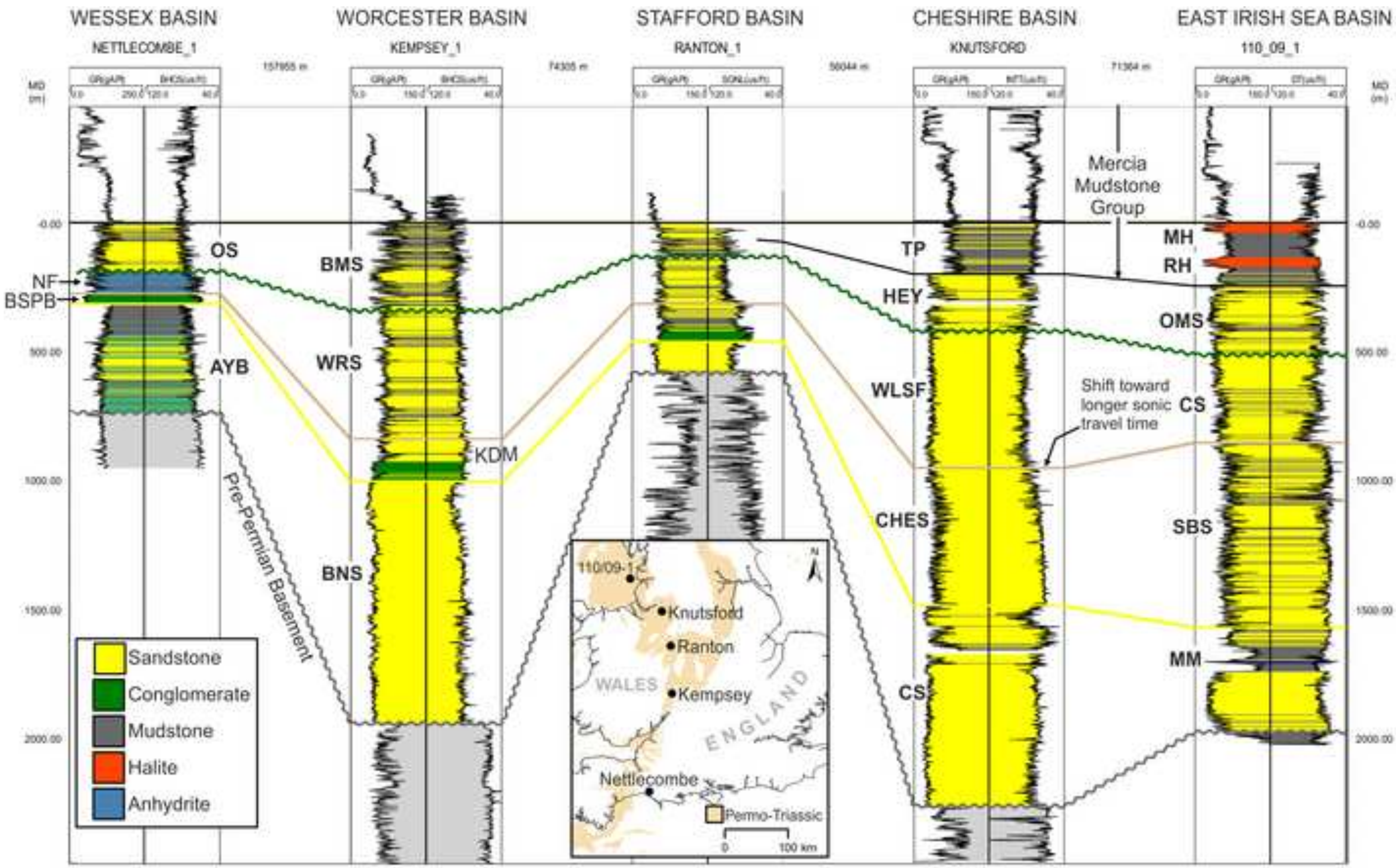

Figure 9
Click here to download high resolution image

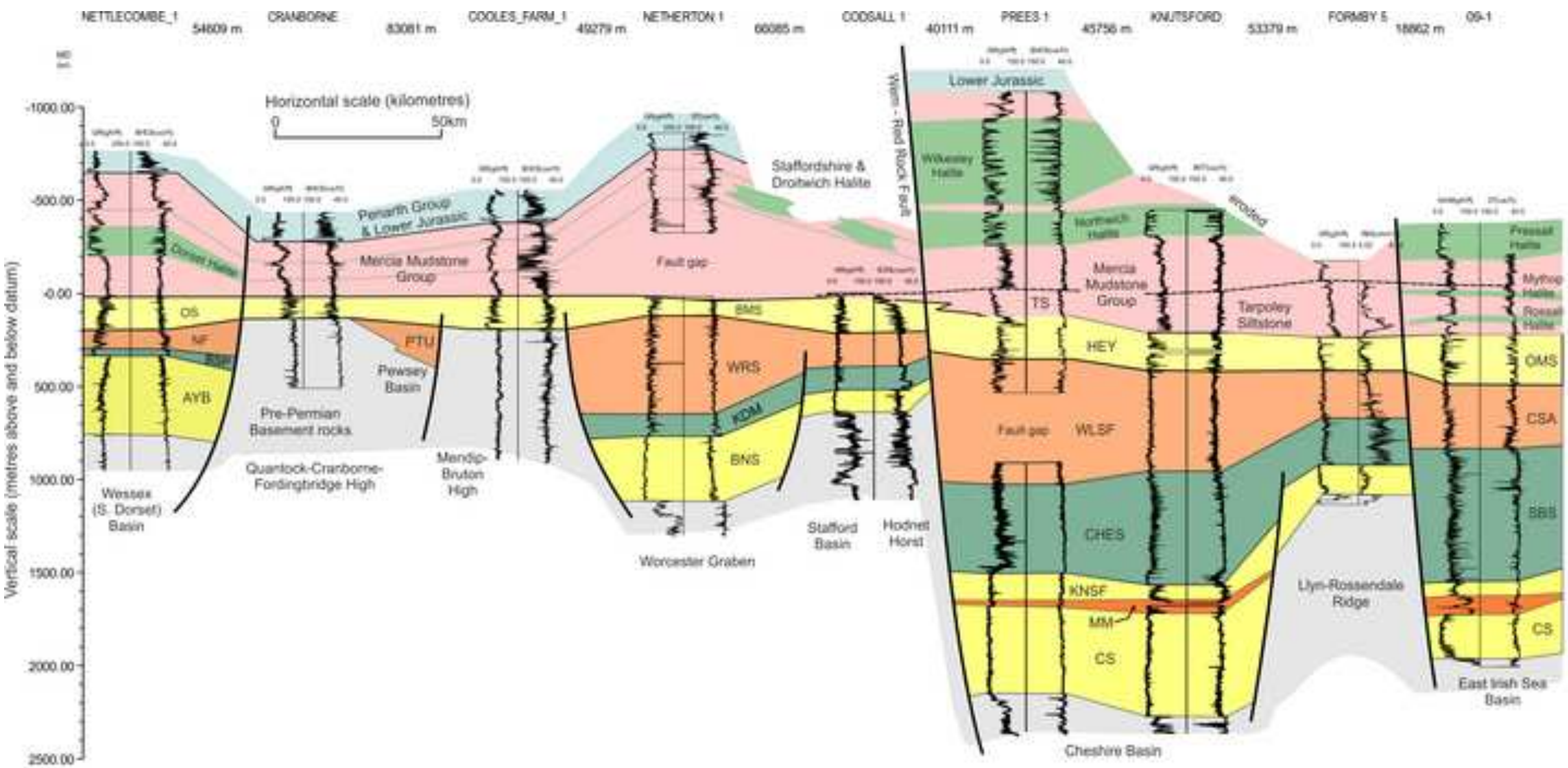

Figure 10

Click here to download high resolution image

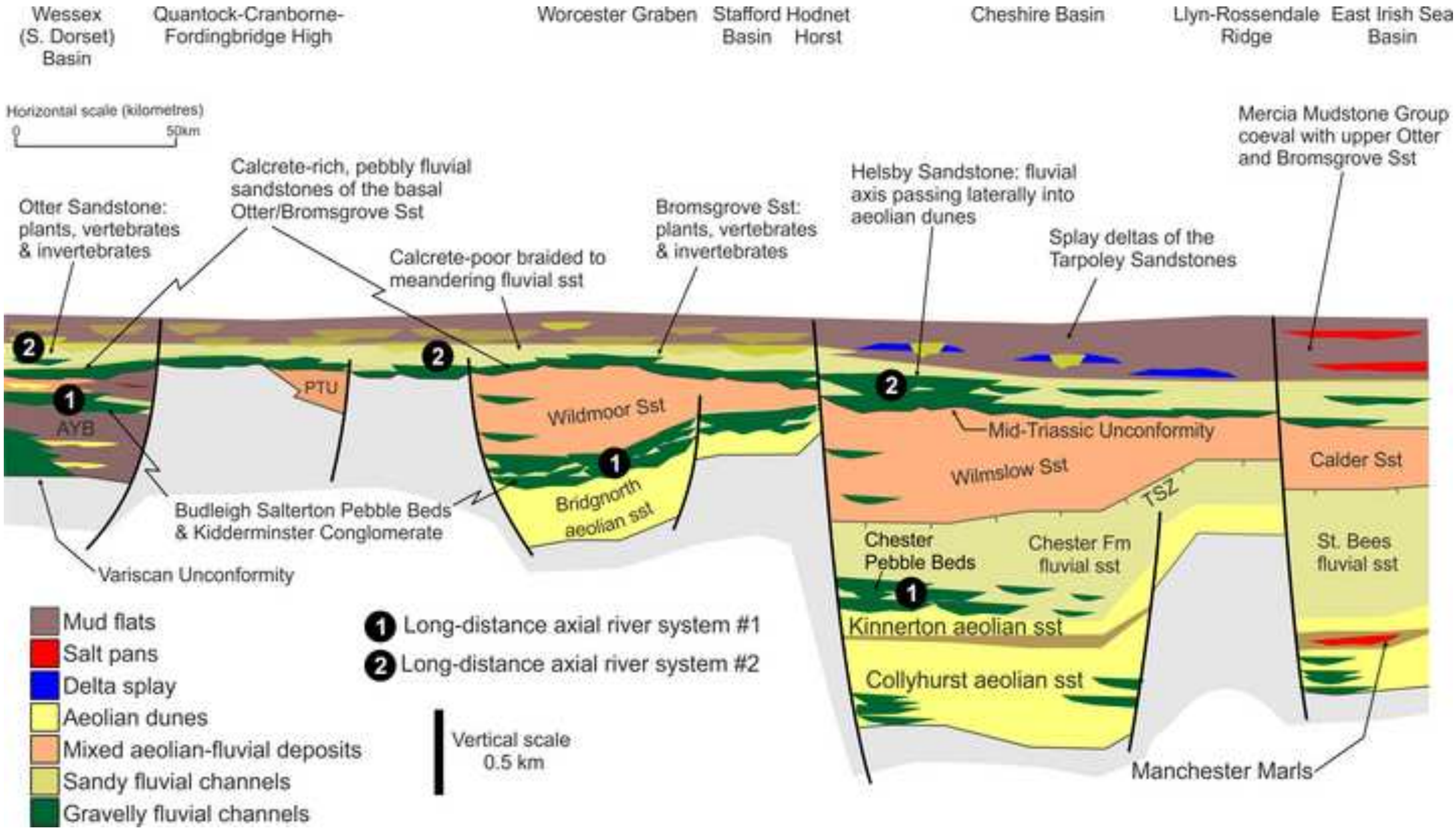

Figure 11

Click here to download high resolution image

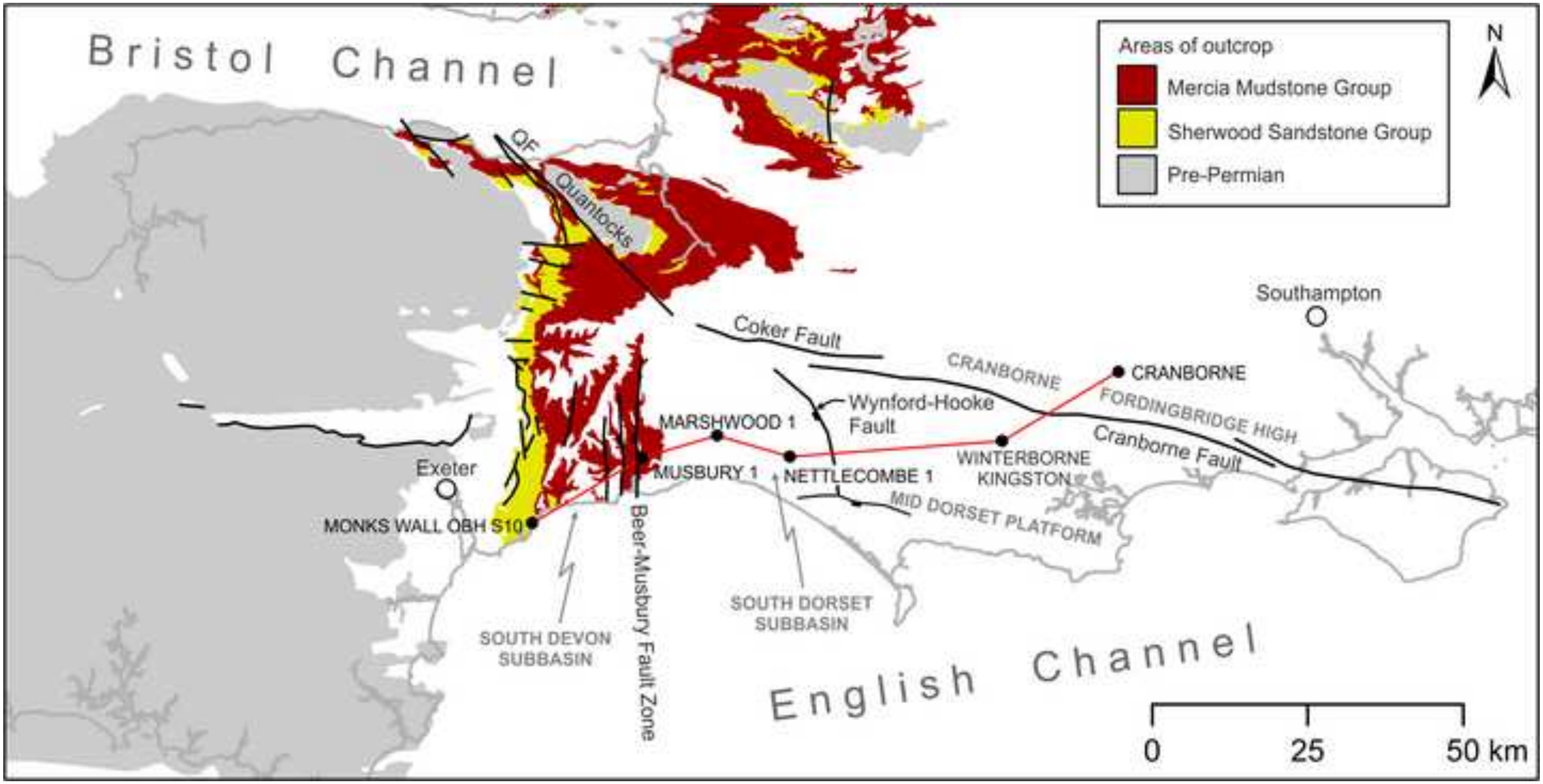

Figure 12
Click here to download high resolution image

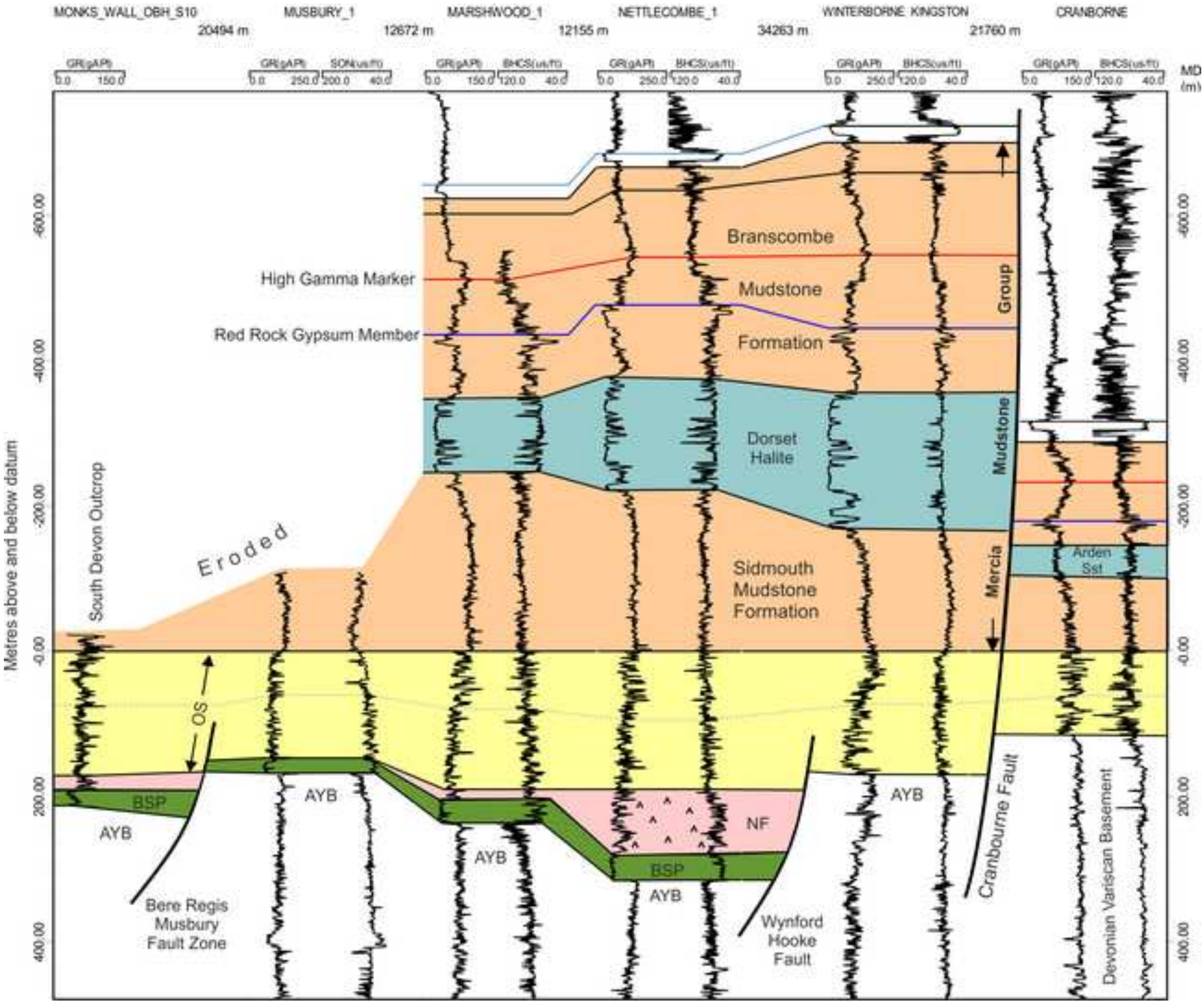

Figure 13
Click here to download high resolution image

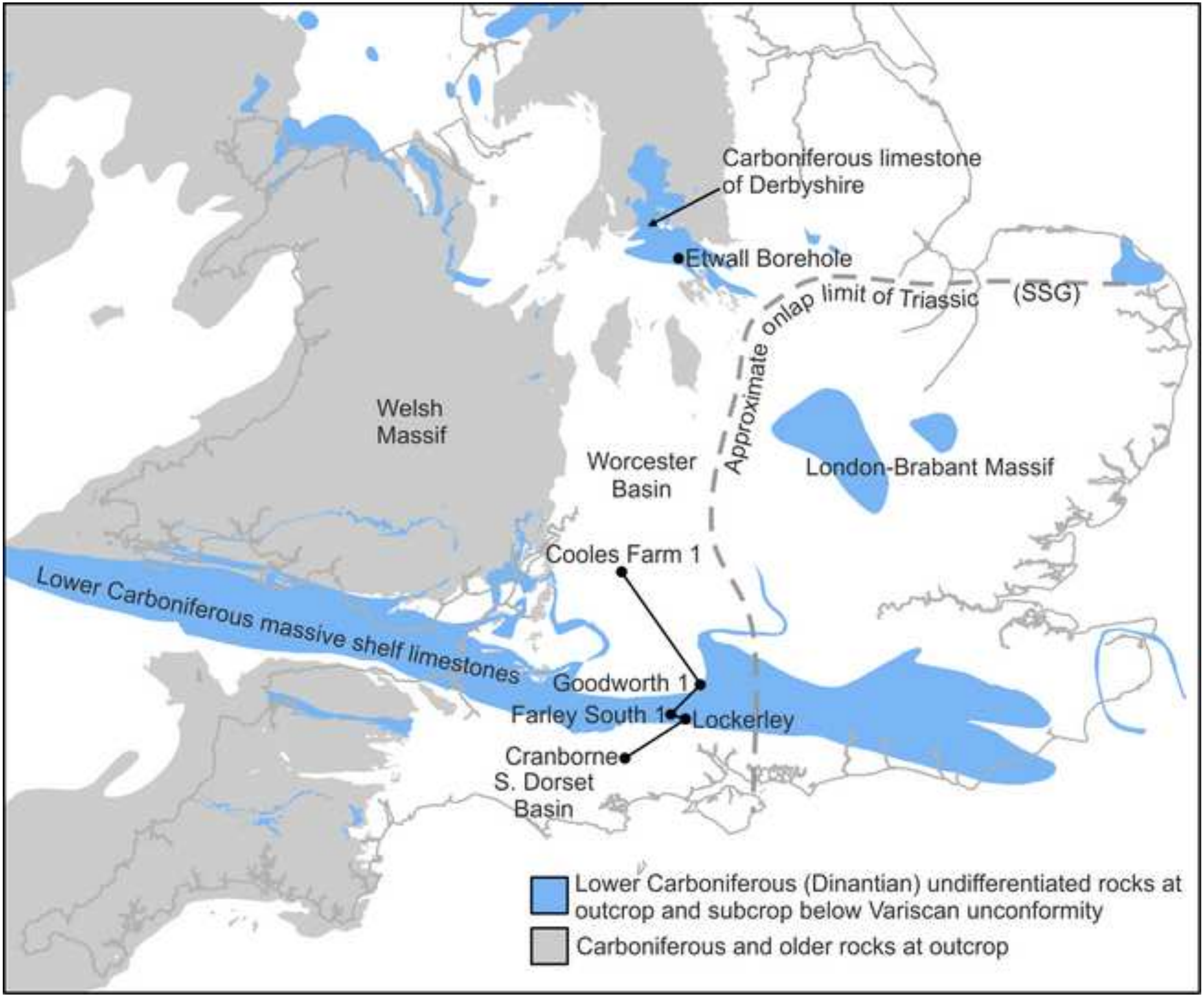

Figure 14

Click here to download high resolution image

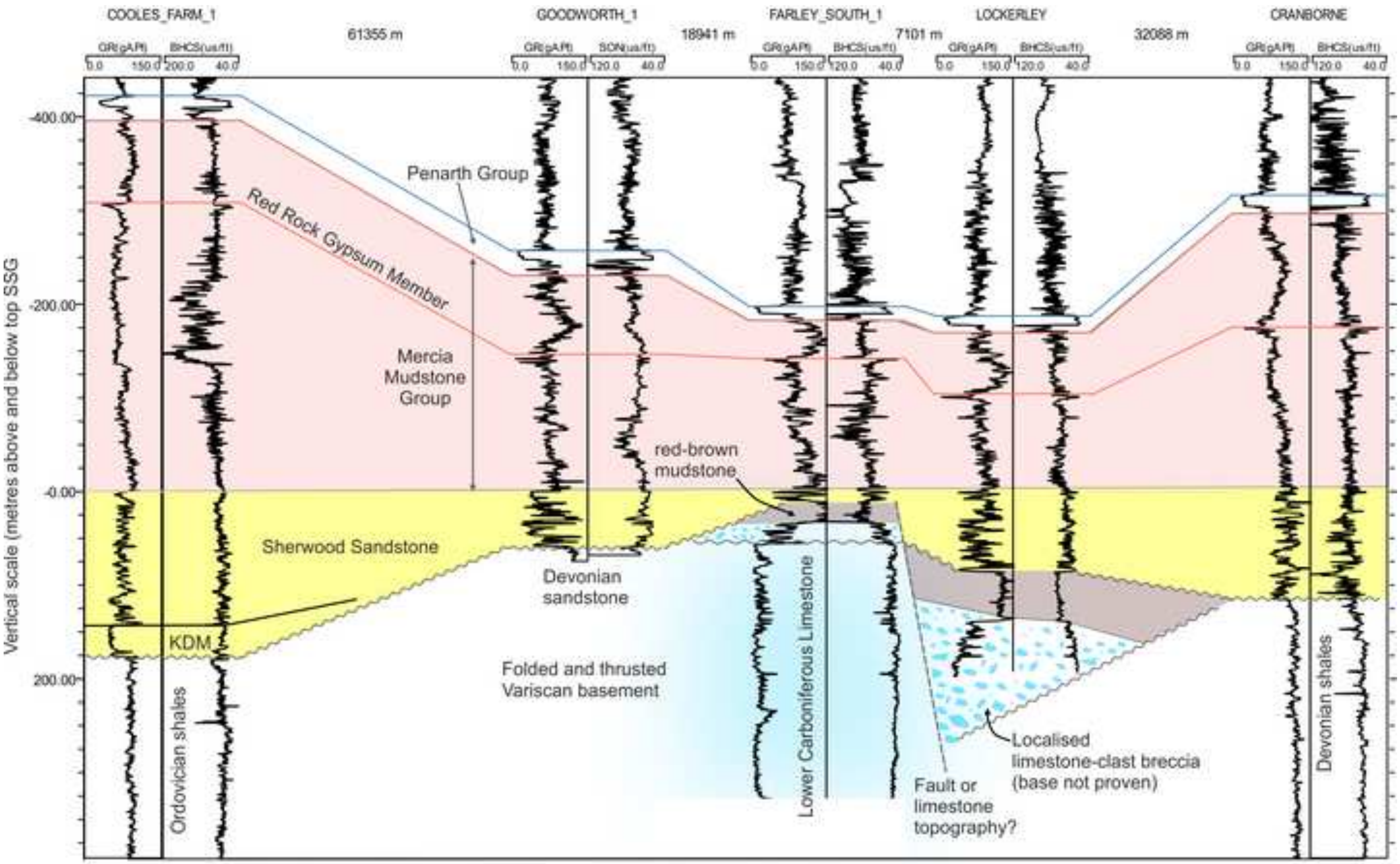

Figure 15

Click here to download high resolution image

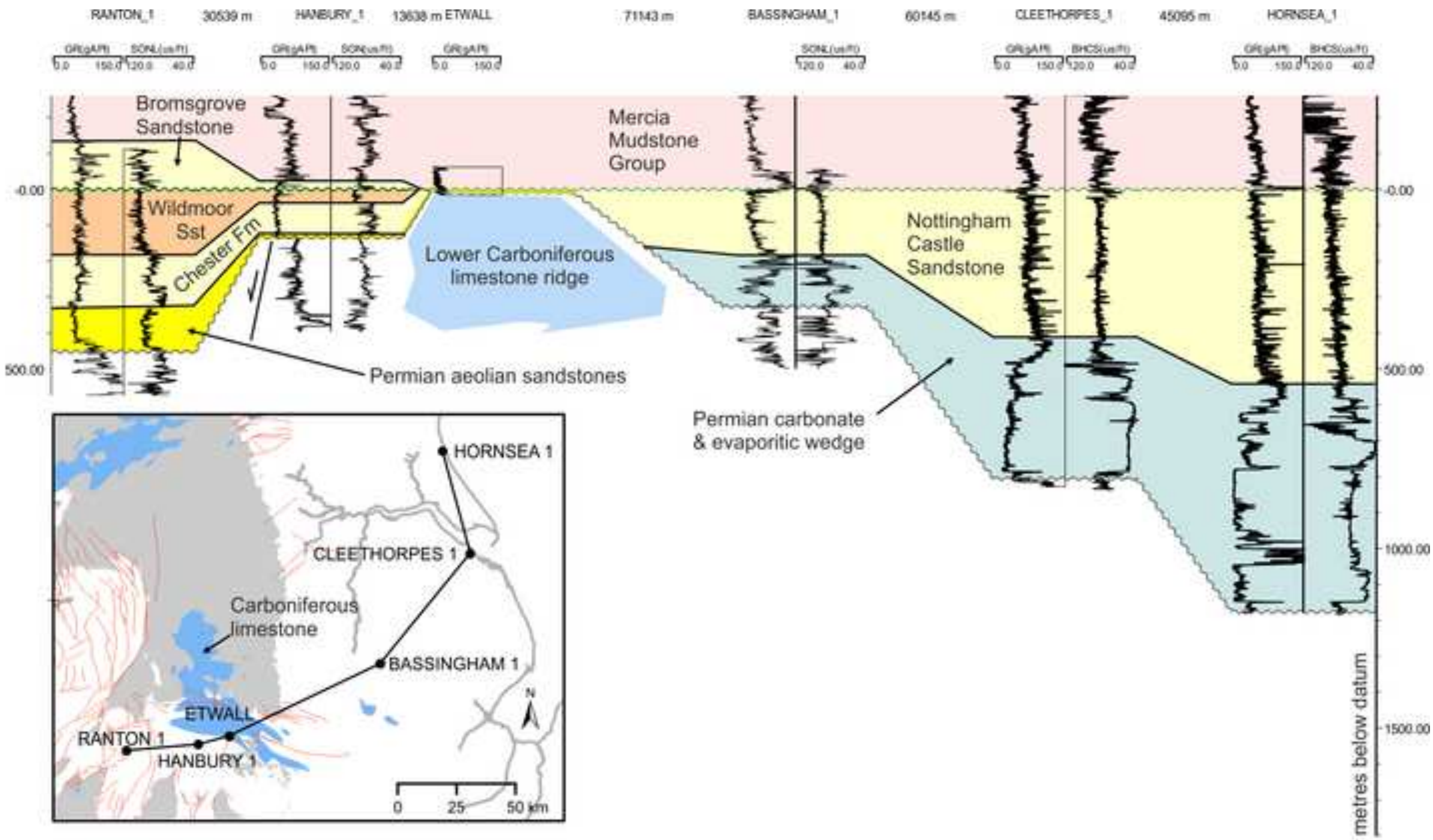

Figure 16

Click here to download high resolution image

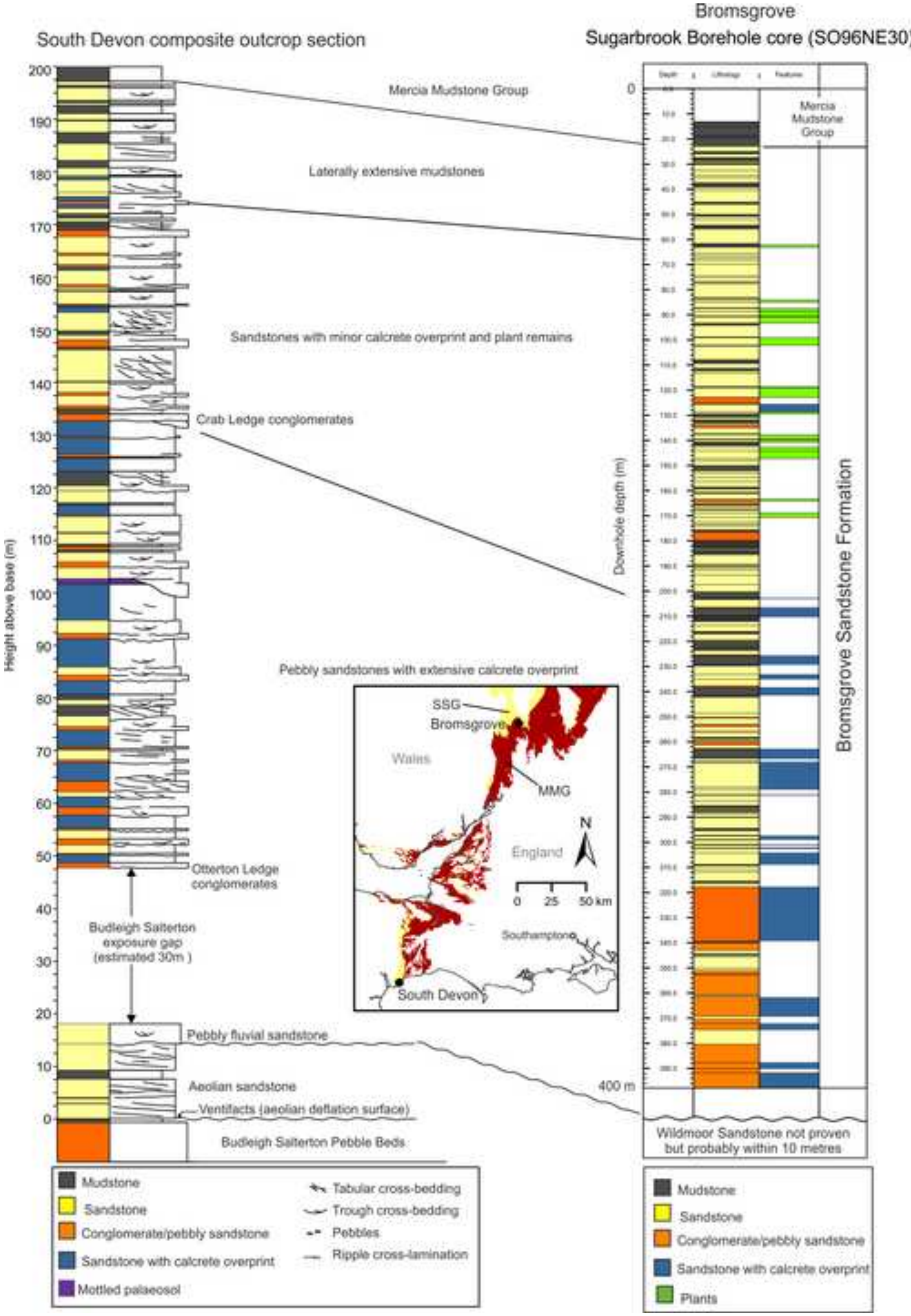

Figure 17

Click here to download high resolution image