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A formational framework for the Mercia Mudstone Group (Triassic) of England and Wales

National Geoscience Framework Programme

A S Howard, G Warrington, K Ambrose and J G Rees

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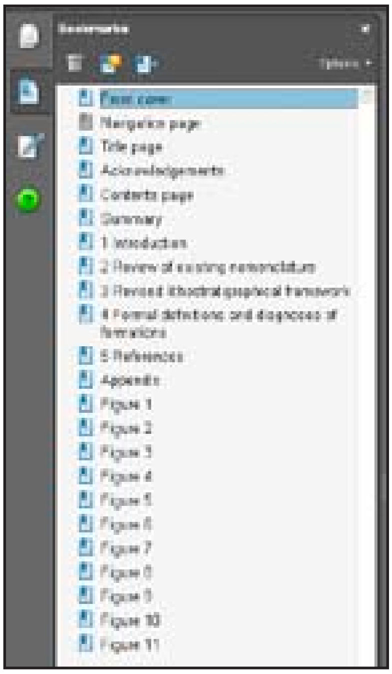

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Front cover

Red Mercia Mudstone Group is faulted against Blue Anchor Formation and Rhaetic strata, Blue Anchor, Somerset (P211340).

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The Geophysical log of the Wiscombe Park 2 borehole is published with the kind permission of British Gypsum plc. Cartography in this report is by I Longhurst.

Contents

Summary

This Research Report presents a reviewed and revised lithostratigraphical nomenclature for the Mercia Mudstone Group (Triassic) of England and Wales. Irrespective of existing nomenclature, five units that were in stratigraphical continuity *prior* to any subsequent tectonism or erosion are identified as constituting the group. These units are formations as defined by international and UK codes of stratigraphical practice (North American Commission on Stratigraphic Nomenclature, 1983: 2005; Whittaker et al., 1991; Rawson et al., 2002). Where present, the five units are consistently mappable at outcrop using conventional geological surveying techniques, and are recognisable in the subsurface in both borehole core and geophysical logs. The various local lithostratigraphical names formerly applied to these mappable subdivisions are replaced by a single formation name for each unit. These are, in upward succession, the Tarporley Siltstone Formation, Sidmouth Mudstone Formation, Arden Sandstone Formation, Branscombe Mudstone Formation and Blue Anchor Formation.

Local synonyms of these newly defined formations are abandoned in this revised scheme. In some regions, these newly defined units may encompass two or more subdivisions that were formerly defined as formations. In such cases, the former 'formations' are downgraded to member status, with the newly defined formation as their parent stratigraphical unit. Informal nomenclature is retained for some highly discontinuous, locally distrbuted units at basin margins, where correlation with adjacent formations is uncertain.

The report includes formal definitions of the Mercia Mudstone Group and its five component formations. Definitions of members, beds and informal subdivisions within these formations are given in the BGS Lexicon of Named Rock Units, which can be consulted on the BGS website http://www.bgs.ac.uk/lexicon/lexicon_intro.html.

1 Introduction

The Mercia Mudstone Group (Mercia Mudstone Group) of England and Wales is composed mainly of red and, less commonly, green and grey mudstone and siltstone. Substantial deposits of halite occur in the thicker, basinal successions of Dorset, Somerset, Worcestershire, Staffordshire, Cheshire, west Lancashire and south Cumbria, and east and north Yorkshire. Sulphate deposits (gypsum and anhydrite) and sandstone beds are common at some stratigraphical levels but are a minor constituent throughout most of the group. Fossils occur mostly in green and grey-coloured units; miospores are the most widespread stratigraphically. The Mercia Mudstone Group ranges in age from Mid Triassic (Anisian) to latest Triassic (Rhaetian). In most areas it overlies sandstones of the Sherwood Sandstone Group (Sherwood Sandstone Group), but locally overlaps these to rest on Permian, Carboniferous or older rocks. The Mercia Mudstone Group is overlain by the grey to black, fossiliferous mudstone of the Westbury Formation of the Penarth Group.

1.1 TECTONIC AND DEPOSITIONAL SETTING

During Permian and Triassic times, England and Wales lay in the interior of the supercontinent of Pangaea, to the north of the Variscan mountain chain. Both Pangaea and the Variscan mountains were the product of continental collision during the late Carboniferous but, by the early Permian, Pangaea was already showing the first signs of breaking apart. In what is now southern, central and north-west England, the resulting crustal tension led to the formation of a series of fault-bounded basins (Warrington and Ivimey-Cook, 1992; Chadwick and Evans, 1995). Eastern England lay on the margin of a much larger subsiding depocentre, the Southern North Sea Basin, which covered much of north-west Europe. The interplay of sea-level change, extension-driven basinal subsidence and climatic fluctuations profoundly influenced deposition throughout the Permian and Triassic (Ruffell and Shelton, 1999). In the early Triassic, monsoonal rains falling on the Variscan mountains fed a major river system that flowed northwards across southern Britain (the 'Budleighensis River' of Wills, 1956, 1970) and deposited thick sequences of pebbly sands, now preserved in the lower part of the Sherwood Sandstone Group. Deposition of the lower formations within the Sherwood Sandstone Group was largely restricted to the fault-bounded basins, although sediments were transported across the intervening highs. However, the upper formations of the Sherwood Sandstone Group, which include both aeolian and fluvial sandstones, overlapped progressively onto the adjacent highs. During Anisian times, fluvial environments of the upper Sherwood Sandstone Group retreated southwards and were replaced diachronously by the subaqueous hypersaline and evaporitic mudflat environments of the Mercia Mudstone Group (Warrington and Ivimey-Cook, 1992). Four main depositional processes prevailed on these mudflats (Arthurton, 1980; Warrington and Ivimey-Cook, 1992; Talbot et al., 1994):

- settling-out of mud and silt in brackish or hypersaline water bodies
- rapid deposition of sheets of silt and fine sand transported by flash floods
- accumulation of wind-blown dust on wet mudflat surfaces
- chemical precipitation of salts, principally halite and gypsum, from marine-sourced hypersaline water bodies and from contemporary groundwaters

The thickest Mercia Mudstone Group sequences accumulated within fault-bounded basins, but it overlapped the Sherwood Sandstone Group and Permian strata and overstepped onto Carboniferous and older rocks that formed adjacent highs, so that the basin infills coalesced. Deposition of the Mercia Mudstone Group ended in latest Triassic (Rhaetian) times when rising sea level flooded the mudflats and laid down the widespread, dark grey to black marine mud that formed the Westbury Formation at the base of the Penarth Group (Warrington and Ivimey-Cook, 1992).

1.2 STRATIGRAPHICAL OVERVIEW

The current lithostratigraphical nomenclature of Triassic rocks in England and Wales is based on an extensive review carried out by the Triassic Working Group of the Geological Society of London, published in 1980 (Warrington et al., 1980). Prior to this, the terms 'Bunter' and 'Keuper' were applied to these rocks, based on lithological similarity with units of those names in the German Triassic. The Triassic Working Group abandoned those terms because of their implied time connotation, and adopted a rigorous lithostratigraphical approach. The former 'Bunter' and 'Lower Keuper Sandstone' units were combined to form the Sherwood Sandstone Group. The overlying Mercia Mudstone Group was constituted from strata between the Sherwood Sandstone Group and the Penarth Group (formerly the 'Rhaetic'), corresponding broadly with the former 'Keuper Marl'.

Chronostratigraphical subdivision and correlation of Triassic rocks in England and Wales is hampered by a scarcity of fossils. Chronostratigraphical determinations of the formations in the Mercia Mudstone Group are effected mainly by the use of spore and pollen assemblages (Warrington et al., 1980). Recovery of these fossils varies stratigraphically and geographically, however, and the recognition of 'time lines' within the Mercia Mudstone Group succession is generally approximate. Geophysical log markers and clay mineral stratigraphy have in some cases been used to infer approximate chronostratigraphical correlations where spores and pollen are absent. Magnetostratigraphy is available for the upper part of the Mercia Mudstone Group (Hounslow et al., 2004) and has potential for dating and correlation at other levels.

A plethora of local names has been applied to formations and members within the Mercia Mudstone Group; many of these have been introduced since the Geological Society of London published the special report on the *Correlation* *of Triassic rocks in the British Isles* (Warrington et al., 1980). These local names, and their usage on British Geological Survey (BGS) maps, reflect the following factors:

- original depositional restriction of units to individual basins
- postdepositional, geographic isolation of outcrops by faulting or erosion
- differences in lithostratigraphical approach across boundaries between separate BGS mapping projects, especially where the surveying of adjacent 1:50 000 map sheets was separated by many years and new knowledge became available over the interim period.

With the exception of the Blue Anchor Formation, nomenclature of constituent formations of the Mercia Mudstone Group is unique to individual basins and in some cases to geographical regions within basins. Additionally, some formations were originally defined on lithological or geophysical characteristics recognisable only in borehole core and their mappability at surface has not been tested. This applies, for example, to some of the formations defined in west Lancashire and Cheshire, where exposures are scarce and most of the outcrop lies below thick Quaternary cover. This review presents a rationalisation of existing nomenclature, with the objective of a more unified, lithostratigraphical scheme for the Mercia Mudstone Group in England and Wales.

1.3 APPROACH TO THE REVIEW

The following objectives have guided this review and revision of the lithostratigraphy of the Mercia Mudstone Group in England and Wales:

- the requirement for a logical and robust scheme that adequately describes the range of lithological and stratigraphical variability within the Mercia Mudstone Group
- the need for stability in nomenclature to avoid confusing the users, especially those without specialist understanding of stratigraphical concepts
- the requirement for a rationalised, mappable stratigraphy that is applicable on geological maps throughout England and Wales, eliminating, as far as practicable, changes in nomenclature that currently occur across the boundaries between geological maps of different vintage
- the need for a nomenclature that supports the compilation, by the BGS, of a 'seamless' digital geological map and 3D model of the geology of the UK to formation level

These objectives are potentially conflicting and therefore required appropriate weighting for a review to be effective. Options for rationalising the Mercia Mudstone Group lithostratigraphy of England and Wales were identified using three procedures.

1. Identification, irrespective of current nomenclature, of units within the Mercia Mudstone Group that were likely to have been in stratigraphical continuity *prior* to any subsequent tectonism or erosion, and which therefore correspond to the definition of a formation (North American Commission on Stratigraphic Nomenclature, 1983, 2005; Whittaker et al., 1991; Rawson et al., 2002). Such units may be diachronous.
2. Determination of the present surface and subsurface continuity of these units within the Mercia Mudstone Group.
3. Identification of the practical needs for rationalising local names to ensure that geological maps and digital 3D subsurface models can be linked without involving arbitrary changes in nomenclature across gaps in outcrop or across faults.

2 Review of existing nomenclature

2.1 DISTRIBUTION OF THE MERCIA MUDSTONE GROUP

The Mercia Mudstone Group crops out (Figure 1) in east Devon, Somerset and in the Bristol region, extending westwards into Glamorgan and Gwent, south Wales. The outcrop continues northwards through the Gloucester and Worcester regions before broadening out to underlie much of the central Midlands in Warwickshire, Staffordshire and Leicestershire. Farther north, the outcrop bifurcates around the Pennines. To the east, it extends northwards through Nottinghamshire and Yorkshire and reaches the North Sea coast near Hartlepool. To the west it underlies northern Shropshire, Cheshire and Merseyside and much of the Formby and Fylde peninsulas, passing offshore below the Irish Sea before re-appearing onshore to the south-west of the Lake District at Walney and Barrow-in-Furness, and farther north near Carlisle. In Cheshire, Warwickshire, Yorkshire and the Carlisle area, large parts of the outcrop are masked by thick Quaternary deposits (mainly glacial till), with more patchy cover of superficial deposits elsewhere.

From the outcrop, the Mercia Mudstone Group extends eastwards below younger Mesozoic rocks and pinches out in the subcrop around the London–Brabant Massif (Horton et al., 1987; Sumbler et al., 2000), a cratonic area composed of Palaeozoic rocks (Figure 1; *see also* Warrington and Ivimey-Cook, 1992). Red beds proved beneath the Jurassic by boreholes in Surrey, Sussex and Kent have been tentatively assigned to the Mercia Mudstone Group (Warrington et al., 1980).

The Mercia Mudstone Group crops out in a number of distinct regions (Figure 1); these are named after their areas of outcrop but their extent includes adjacent subcrops. Some of these contain successions that are now geographically isolated within structural basins, but were formerly connected during deposition of the group. Other regions simply represent outcrop areas that are isolated at surface but connected in the subsurface. The entire group is in continuity in the subsurface between Regions 1 to 3 and 5 to 6. The lower part of the Mercia Mudstone Group in Region 4 (Needwood Basin) is also connected in the subsurface with the successions in Regions 3 (Knowle Basin) and 5 (East Midlands Shelf South). The successions in Regions 7 to 10 are isolated either by faulting or by intervening outcrops of older rocks.

2.2 STRATIGRAPHICAL FRAMEWORK

As a basis for the rationalisation of Mercia Mudstone Group lithostratigraphy, we have identified a framework of five lithostratigraphical units (A to E, described below) that either possess, or can reasonably be inferred to have once possessed, a high degree of continuity. These units are mappable both at surface and in the subsurface on a regional rather than local basis, and thus comply with the definition of a formation (*sensu* North American Commission on Stratigraphic Nomenclature, 1983, 2005; Whittaker et al., 1991; Rawson et al., 2002). Each has distinctive lithological characteristics and geophysical log profiles. The lithostratigraphical nomenclature currently applied to these units is shown in Figure 2 and summarised below. A revised nomenclature is considered in Section 3.

Unit A

This heterolithic unit consists of brown mudstone and siltstone interbedded with a variable but approximately equal proportion of paler, grey-brown sandstone. Stratification is generally planar or subplanar, and most sandstone beds are less than 0.5 m thick, with intervening mudstone and siltstone partings of similar thickness. The sandstones are typically very fine to fine-grained, less commonly medium-grained, highly micaceous, and weakly cemented by ferroan calcite or dolomite. Beds of fine- to medium-grained sandstone up to 5 m thick are present locally; these have a lenticular geometry with internal cross-stratification. Sulphates (gypsum and anhydrite) are present as small veins and nodules but are not as abundant as in the higher units. Fossils are generally restricted to miospores (e.g. Fisher, 1972; Charsley, 1982; Earp and Taylor, 1986; Rees and Wilson, 1998; Warrington et al., 1999), but invertebrate trace fossils (Ireland et al., 1978; Pollard, 1981), vertebrate tracks (Sarjeant, 1974) and the brachiopod *Lingula* (Rose and Kent, 1955) have been recorded locally.

The unit is typically a few tens of metres thick, but reaches a maximum of 220 m in the Cheshire Basin.

Unit A was formerly known in many areas as the 'Waterstones', the name originating from its association with springs (Hull, 1869, p. 67) or from an oft-quoted resemblance of the micaceous bedding planes to 'watered silk'. Of the five Mercia Mudstone Group units, this is the most problematical in terms of stratigraphical treatment, and it has not been differentiated in all regions. Where recognised, both the base and top of the unit are gradational, and interdigitate with the upper beds of the Sherwood Sandstone Group and the lower beds of Mercia Mudstone Group Unit B respectively. In southern England and south Wales (Regions 1 and 2, Figure 1), the unit has not been differentiated, and Mercia Mudstone Group Unit B rests directly on the Sherwood Sandstone Group. In the Worcester and Knowle basins (Region 3, Figure 1), Unit A has not been mapped as a formation in its own right and, where the facies has been recognised, it has usually been included within the Bromsgrove Sandstone Formation (or equivalent) in the uppermost part of the Sherwood Sandstone Group. From the Central Midlands northwards (Regions 4–8, Figure 1), Unit A has been mapped as a distinct formation and has been assigned a different name in each basin (e.g. Tarporley Siltstone Formation, Maer Formation, Denstone Formation, Sneinton Formation, *see* Figure 2).

The base of Unit A (or where the unit is not recognised, the base of the Mercia Mudstone Group) is diachronous, becoming generally younger southwards. An exception is Eastern England (Regions 5 and 6), where the base of the Mercia Mudstone Group is unconformable and Unit A onlaps westwards onto the weathered surface of the Sherwood Sandstone Group. This is overlain locally by a thin conglomerate containing re-worked, wind-facetted pebbles, and has long been considered to represent the

Hardegsen Disconformity of north-west Europe (Warrington, 1970; Wills, 1970). Geological mapping and geophysical log correlation suggests that the lower part of Unit A in the Nottingham area was deposited in isolation from coeval strata in the Needwood Basin (Region 4, Figure 1) to the west, but that the upper part is in subsurface continuity between these areas (Howard et al., in press).

Unit A is Mid Triassic (Anisian) in age (Figure 2)

Unit B

Unit B consists mainly of red and, less commonly, green and grey dolomitic mudstones and siltstones. These range from finely laminated to almost totally structureless; in many cases, the primary depositional lamination has been deformed penecontemporaneously by frequent wetting and drying of the substrate and growth and solution of salts. Thin beds of coarse siltstone and very fine-grained sandstone occur at intervals throughout the unit. Individual sandstone beds are typically 0.02 to 0.06 m thick, greenish grey in colour, planar or current ripple laminated and have strong, intergranular dolomite cement. Less commonly, gypsum cement occurs; this is usually dissolved by meteoric waters in the near surface to leave weakly cemented or uncemented sand at outcrop. Sandstones are usually grouped into composite units of three or more beds, with greenish grey mudstone intercalations of equal thickness. These composite units vary in thickness from 0.15 to 1 m and many are sufficiently resistant to form low, cuesta-like landforms; these resistant beds are locally termed 'skerries', the more persistent of which have been named and mapped in some basins. Sulphates (gypsum and anhydrite) are present throughout the unit, but occur as thin veins, small nodules and intergranular cements that are of no economic importance. Plant spores and pollen are virtually the only fossils in this unit.

Deposits of halite, some of substantial thickness and considerable economic importance, occur within the lower to middle part of this unit in the thicker basinal successions of Cheshire, west Lancashire, Carlisle and the East Midlands Shelf North (Figure 2). Higher halite units in the Cheshire, Stafford, Needwood, Worcester and Wessex basins are included in this unit, but may in part be coeval with Unit C (Figures 2; 3). Due to dissolution, the halite beds do not crop out at surface, but their projected surface position is commonly marked by subsidence hollows and collapse breccias formed in overlying strata. These features are formed not only by natural dissolution but also as a result of salt extraction by uncontrolled brine pumping.

Geophysical log markers within the unit can usually be correlated *within* basins, for example the Regional Gamma Ray Marker in Eastern England (Balchin and Ridd, 1970) and the geophysical log units recognised in the Wessex Basin by Lott et al. (1982). However, correlation of the markers within Unit B *between* basins is untenable, mainly due to the local presence of thick halite deposits with low gamma/high sonic signatures that break up and mask any distinctive patterns in the logs.

Unit B is typically 150 to 300 m thick, though with substantial variation between basins. Up to 1600 m occurs in the Cheshire Basin, where two halite units with an aggregate thickness exceeding 600 m are developed.

In the Worcester Basin, Unit B was named the Eldersfield Mudstone, based on a cored and geophysically logged borehole section at Eldersfield (Barclay et al., 1997). Gallois (2001) introduced the name Sidmouth Mudstone Formation for this unit, based on the cliff sections east of Sidmouth, south Devon. In the Cheshire Basin, west Lancashire and the East Midlands Shelf South, Unit B encompasses numerous locally defined formations based on various lithological criteria. In the Cheshire Basin and west Lancashire, the succession was originally subdivided using the major halite units (Pugh, 1960), followed by further subdivision of the mudstones based on lithological character (Wilson, 1990, 1993). In the East Midlands Shelf South, formations were based partly on subtle lithological characteristics evident in borehole core, and partly on the use of 'skerries' as mappable marker beds at surface (Elliott, 1961; Charsley et al., 1990). The unit has not been named elsewhere, though some component units bear names (e.g. Somerset Halite Formation, Droitwich Halite Formation; Figure 2).

Taking the unit as a whole, at least partial depositional continuity was likely to have existed between all basins. However, depositional continuity of the subdivisions currently recognised within this unit, especially the halites, is more questionable. The halites of west Lancashire and the Cheshire Basin have been correlated on the basis of approximate time-equivalence (Wilson, 1993; Jackson et al., 1995), but may not have been in depositional continuity across the high that separates the two basins. Most of the currently recognised subdivisions cannot be correlated between basins either by geological mapping or geophysical log interpretation and their stratigraphical status is re-evaluated accordingly in this report.

Unit B ranges from Anisian to Carnian in age

Unit C

Unit C is distinguished from those below and above on the basis of contrasting colour and a unique combination of lithological, mineralogical, sedimentological and palaeontological features. It is a heterolithic unit that consists predominantly of grey and green mudstone interbedded with paler grey-green to buff-coloured siltstone and fine- to medium-grained, varicoloured (green, brown, buff, mauve) sandstone; pebbly horizons occur locally. Invertebrate and vertebrate macrofossils are present, locally in abundance, and miospores and trace fossils are common. The unit is characterised by an exotic clay mineral assemblage, which is rich in mixed-layer clays and distinct from that of the units below and above (Jeans 1978, Bloodworth and Prior, 1993; Carney et al., 2004; Jeans et al., 2005). Two lithofacies can be distinguished. A mudstone-dominated lithofacies consists of dark greenish grey laminated mudstone and siltstone with subordinate purplish grey mudstone and a few thin beds of very fine- to fine-grained dolomitic sandstone. A sandstone-dominated lithofacies consists mainly of thin- to medium-bedded sandstone that forms discontinuous and lenticular bodies that are enclosed within the mudstone-dominated lithofacies. The sandstone is moderately to strongly calcareous or dolomitic, and the thicker, most resistant beds have been widely used for building stone. In the Wessex Basin and more generally in the English Midlands, the unit has been interpreted as comprising sand-filled distributary channels separated by mudflats within a deltaic or estuarine environment (Ruffell, 1991; Warrington and Ivimey-Cook, 1992). Brecciated units have been recorded at the base and top of the unit (Jeans, 1978; Gallois, 2001) on the south Devon coast.

The thickness of Unit C is typically less than 10 m, but locally ranges up to 21 m in the Worcester Basin and 24 m in the Wessex Basin.

Mapping by the Geological Survey prior to 1980 emphasised the discontinuous sandstone lithofacies, which forms pronounced but localised topographic features. The outcrop was consequentially shown as discontinuous on these older geological maps (e.g. Sheet 295 Taunton). More recent surveys in the Worcester and Knowle basins, where the outcrop is most extensive and continuous, have included the sandstones and the associated distinctive green mudstones and siltstones as a single unit—the Arden Sandstone Formation (Old et al., 1991; Barclay et al., 1997).

Occurrences in the Leicester and Nottingham areas of the East Midlands Shelf South have been termed the Dane Hills Sandstone and Hollygate Sandstone members, respectively (Warrington et al., 1980; Howard et al., in press). The unit has not been mapped in the Needwood, Stafford or Cheshire Basins, or north of Newark in Nottinghamshire. In south-west England the unit encompasses the North Curry Sandstones of Somerset and possibly the Butcombe Sandstone and Stoke Park Rock Bed of the Mendips and Bristol areas, respectively (Green and Welch, 1965; Kellaway and Welch, 1993). On the south Devon coast, it includes the Weston Mouth Sandstone Member of Warrington et al. (1980). The Dunscombe Mudstone Formation of Gallois (2001) is a rather thicker unit (35 m) that is partly equivalent to Unit C but includes, in its upper part, a succession of red-brown and subordinate grey-green mudstones that are more typical of the overlying Unit D (*see* Section 4).

Where borehole geophysical logs can be related to core, Unit C is seen to have a distinctive log signature that enables wider correlation in the subsurface within and between basins. However, in the Cheshire basin and parts of the Wessex Basin, where thick halites are present, the log signature cannot be distinguished, and the unit may, in part, be coeval with the halite (Gallois, 2003). The lack of cored borehole data in the Wessex Basin and adjacent offshore areas has previously led to the miscorrelation of the unit with evaporites at a higher level in the succession (e.g. Lott et al., 1982, Hamblin et al., 1992). The recent availability of core from Wiscombe Park 2 Borehole* in south Devon has enabled the unit to be correctly identified (Warrington, 1999) and correlated within the Wessex Basin (Figure 3). The unit can now be recognised with confidence in boreholes from Devon to the East Midlands (Regions 1, 2, 3 and 5, Figures 1 and 4) and is likely to be continuous in the subsurface between these areas. The unit is late Carnian (Tuvalian) in age, based on palynological evidence (Warrington and Ivimey-Cook, 1992).

Unit D

Unit D superficially resembles Unit B, but resistant dolomitic sandstone-rich units ('skerries') are less common, and structureless red-brown, dolomitic mudstones dominate. Geophysical log interpretation of boreholes in the Wessex Basin (Figure 3; Harvey and Stewart, 1998) suggests that a thin halite may be present locally towards the base of the unit, but the mineral is absent elsewhere (though pseudomorphs after halite occur sporadically). Gypsum and anhydrite are abundant, either as thick beds or as large nodular masses and veins. Locally, gypsum forms deposits of economic importance, for example near Burton on Trent, Nottingham and Newark (Regions 4 and 5, Figure 1). Gypsum is usually absent in the near surface due to dissolution by meteoric water. The unit has a remarkably consistent geophysical log profile, and several log markers, including those recognised by Lott et al. (1982), can be correlated between onshore basins (Figures 3; 4) and with offshore equivalents in the Southern North Sea Basin. The unit is typically devoid of fossils, though plant spores and pollen occur within the higher beds in Somerset and Devon (Region 1, Figure 1).

The unit is represented by the Twyning Mudstone in the Worcester Basin (Barclay et al., 1997), the Brooks Mill Mudstone in the Cheshire Basin (Wilson, 1993), and the Cropwell Bishop Formation in the East Midlands Shelf South (Charsley et al., 1990). In Devon the unit includes the Branscombe Mudstone Formation together with the upper part of the Dunscombe Mudstone Formation of Gallois (2001). Elsewhere it is un-named. As with Unit B (though not as markedly), the unit thickens into the depocentres, with the thickest sequences (up to 240 m) developed in the Wessex Basin and the thinnest (25 m) in the East Midlands.

Depositional continuity can be reasonably inferred for this unit between all the basins (Figure 2). Continuity exists in the subsurface between south Devon and North Yorkshire (Regions 1, 2, 3, 5 and 6, Figure 1), but the successions in the Needwood, Stafford and Cheshire basins, and in west Lancashire and the Carlisle basin (Regions 4, 7, 8, 9 and 10, Figure 1) are isolated by faulting and/or subsequent erosion.

There is no direct evidence of age, but a Norian age is inferred because of palynological evidence—a Carnian and Norian (?) age is indicated for the underlying Unit C and a Rhaetian age for the overlying Unit E.

Unit E

This thin but widespread unit is the uppermost formation of the Mercia Mudstone Group and is recognised in all the regions (Figure 2) except west Lancashire. A single name, the Blue Anchor Formation, has been applied to this unit throughout England and Wales (Warrington et al., 1980). In south-west England and south Wales (Regions 1 and 2, Figure 1) the unit consists of interbedded greenish grey, dark grey and green dolomitic mudstones and dolostones with common gypsum. Elsewhere, it is more homogeneous in lithology and consists of the apparently structureless, pale greenish grey dolomitic mudstones and siltstones known formerly as the 'Tea Green Marl'.

The unit is typically around 30 m thick in south-west England (Region 1, Figure 1), reaching a maximum of 67 m; elsewhere it is generally less than 10 m thick. It was probably deposited in a coastal sabkha environment with periodic marine influence, presaging the widespread marine transgression that deposited dark grey to black mud that formed the lower part of the overlying Penarth Group (Westbury Formation) (Warrington and Ivimey-Cook, 1992). The base of the unit is generally regarded as conformable, though Horton et al. (1987) and Old et al. (1987) refer to significant erosion below this horizon around the margins of the London–Brabant Massif. The base of the overlying Penarth Group is more widely regarded as a non-sequence, and the Blue Anchor Formation typically bears evidence of animal borings and shrinkage cracks on its top surface.

A late Norian (?) to Rhaetian age is indicated by palynological evidence (Hounslow et al., 2004).

Marginal facies

Towards the margins of depositional basins and on the flanks of contemporaneous landmasses such as the Mendips and Charnwood Forest, the Mercia Mudstone Group contains laterally impersistent beds of conglomerate and breccia, commonly cemented strongly by dolomite. These conglomerates were deposited as alluvial fan gravels or screes, and contain abundant, large, commonly angular pebbles of local provenance. They are especially common

* BGS borehole registration numbers and grid references are given in the Appendix

towards the base of the Mercia Mudstone Group where it onlaps onto Carboniferous or older rocks. In south Glamorgan, the marginal facies consists of fenestral and algal carbonates interdigitating with conglomerates and breccias, interpreted as shoreline deposits (Tucker, 1977; Waters and Lawrence, 1987, Benton et al., 2002). Localised pocket deposits filling palaeokarstic cavities in the underlying Carboniferous Limestone occur locally on the Welsh (Wilson et al., 1990), and English flanks of the Bristol Channel (Robinson, 1957; Savage, 1993; Fraser, 1994; Wall and Jenkyns, 2004) and also in Leicestershire (Carney et al., 2001). Sandstone beds also occur locally towards the basin margins in some other areas; the Redcliffe Sandstone Formation of the Bristol area (Kellaway and Welch, 1993), which is up to 50 m thick, is a notable example.

2.3 RECOMMENDATIONS FOR RATIONALISING MERCIA MUDSTONE GROUP LITHOSTRATIGRAPHY

The recognition of framework Units A to E enables consideration of three options for the rationalisation of Mercia Mudstone Group lithostratigraphy and analysis of their relative advantages and disadvantages.

Status quo option

This option would largely retain the existing provincial nomenclature illustrated in Figure 2, with some minor rationalisation of nomenclature within some regions to remove obvious synonyms.

Advantage

- Nomenclature used on recently published BGS maps, memoirs and sheet explanations is maintained.

Disadvantages

- Assigns 'formation' status to units that are mappable only on a local scale.
- Retains inconsistencies in unit status between regions with, for example, halite units being assigned member status in west Lancashire but formation status elsewhere.
- Arbitrary 'boundaries' of little or no stratigraphical significance would need to be created to separate these local formations on 'seamless' digital maps or 3D subsurface models.

Partial rationalisation option

This option rationalises formation names for each of the five 'framework units' where they are in continuity, but retains the existing local nomenclature in successions that are geographically or structurally isolated.

Advantage

- Production of 'seamless' digital geological maps and 3D subsurface models would not be hindered, because all changes in nomenclature would take place across structural or erosional discontinuities between outcrops, removing the need for arbitrary boundaries.

Disadvantages

- Retains inconsistencies in unit status between regions with, for example, halite units being assigned formation status in the Cheshire Basin but member status elsewhere.
- The scheme locally modifies the lithostratigraphy published on recent BGS maps (e.g. Nottingham Sheet 126) and may thus confuse the users of those maps until new editions are published, although the number of sheets affected would be less than for the full rationalisation option (*see below*).

Full rationalisation option

This option applies a formation name to each of the five 'framework units' across all regions. Existing formations that represent local subdivisions of the new 'framework' formations are downgraded to member status. Names that represent junior synonyms are abandoned.

Advantages

- Potentially, it presents a 'once and for all' solution that, because of its simplicity, should become readily accepted and applied by the user community in the medium to long term.
- The formations defined in this scheme are closest in concept to the definitions of the North American Commission on Stratigraphic Nomenclature (1983, 2005), Whittaker et al. (1991) and Rawson et al. (2002).
- Lithostratigraphical divisions maintain a consistency of status between regions; for example equivalent halite units have member status in all occurrences.
- It is the most favourable option for construction of 'seamless' digital maps and 3D subsurface models to formation level.

Disadvantage

- The scheme updates the lithostratigraphy published on recent BGS maps, and may thus confuse the users of those maps until new editions are published.

Conclusion

In consideration of these alternatives, the conclusion of the BGS Stratigraphy Committee is to adopt full rationalisation as the preferred option, on the grounds that it most closely satisfies the objectives stated in Section 1.3, and offers the nearest approach to the formation definitions favoured by Whittaker et al. (1991), Rawson et al. (2002), and the North American Commission on Stratigraphic Nomenclature (1983, 2005). The revised lithostratigraphy arising from this rationalisation is described in Section 3; formal definitions of the five formations are given in Section 4 and in the BGS Lexicon of Named Rock Units, accessible via the BGS website www.bgs.ac.uk/lexicon/lexicon_intro.html.

3 Revised lithostratigraphical framework

3.1 REVISED FORMATION NOMENCLATURE

The following section summarises the revised formation nomenclature for the Mercia Mudstone Group. In choosing the most appropriate name for each of the framework units, we have preferred names that are based on outcrop sections rather than boreholes, with type sections that are readily and permanently accessible to facilitate study. Formal descriptions and diagnoses of each formation are given in Section 4.

UNIT A The name *Tarporley Siltstone Formation*, introduced by Warrington et al. (1980), is applied to this unit. Usage of this name has previously been confined to the Cheshire Basin. The terms Denstone, Maer and Sneinton formations, applied to this unit in other regions, are junior synonyms and are abandoned.

UNIT B The name *Sidmouth Mudstone Formation* has been applied to this unit at outcrop on the south Devon coast (Gallois, 2001). This name is adopted here in preference to the equivalent Eldersfield Mudstone Formation of the Worcester district (Barclay et al., 1997), which was defined based on borehole cores and associated geophysical logs. Existing formations named within this unit in the East Midlands Shelf South, Cheshire Basin and west Lancashire regions are downgraded to members; most subdivisions presently of member status in those areas will retain that status, though with Sidmouth Mudstone as their new 'parent' formation.

UNIT C The name *Arden Sandstone Formation* is preferred for this unit due to its familiarity as a widespread and mappable stratigraphical marker throughout much of the Worcester and Knowle basins, and its use on published geological maps of those regions. Its stratigraphical significance was recognised by Matley (1912), who introduced the name 'Arden Sandstone Group'. The name 'Arden Sandstone Member' was formalised by Warrington et al. (1980), and various sections in the type area, including the stratotype, were described by Old et al. (1991). The name was elevated to formation status by Barclay et al. (1997). Numerous synonyms applied in other regions (Figure 2; *see also* Warrington et al., 1980) are abandoned.

UNIT D The name *Branscombe Mudstone Formation* has been applied to this unit at outcrop on the south Devon coast (Gallois, 2001), where it occurs in discontinuous, faulted sections that are partly obscured by landslides. Both the base and top of the formation are exposed. Predominantly structureless, red-brown and subordinate grey-green mudstones that were included (*see* Section 4) in the upper part of the Dunscombe Mudstone Formation by Gallois (2001) are more typical of the Branscombe Mudstone and are here included in that unit.

This name is preferred to the equivalent Twyning Mudstone Formation of the Worcester district (Barclay et al., 1997), which was based on borehole cores and associated geophysical logs, and to the Cropwell Bishop Formation of the Nottingham area for which no published formal definition exists. The equivalent Brooks Mill Mudstone Formation, introduced by Wilson (1993) in the Cheshire Basin, has been applied to a succession that is atypical, in that the base overlies the Wilkesley Halite Member of the Sidmouth Mudstone Formation, and the Arden Sandstone Formation is not developed in that region.

UNIT E A single name, *Blue Anchor Formation* (Warrington et al., 1980), is already applied to this unit in all regions. No modification is necessary.

MARGINAL FACIES These are mainly dolomitic, arenaceous or conglomeratic deposits of local provenance and distribution; it is considered inappropriate to treat them as formations (cf. Whittaker et al., 1991). Defining them as members would also be unsuitable, because many of these deposits can be shown to be lateral facies equivalents of two or more vertically adjacent formations; some may also be laterally equivalent to parts of the overlying Penarth Group. The use of informal and descriptive local names remains the most practical option for these deposits. Published geological maps in the Bristol area indicate that the Redcliffe Sandstone is a marginal facies equivalent of the Sidmouth Mudstone Formation (Kellaway and Welch, 1993); it is therefore redefined here as a member of that formation.

3.2 REGIONAL LITHOSTRATIGRAPHY AND SUBDIVISIONS

REGION 1 WESSEX BASIN (FIGURE 1)

Former lithostratigraphy after Warrington et al. (1980) and Gallois (2001, 2003)

The outcrop in this area (Figure 1) is isolated from Region 2 by an outcrop of the overlying Penarth and Lias Groups that extends from Glastonbury to Bridgwater Bay. There is, however, continuity in the subsurface with Region 2 and also with the succession proved offshore below the English Channel (Hamblin et al., 1992).

REGION 2 BRISTOL AND SOUTH WALES (FIGURE 5)

Former lithostratigraphy based on Green and Welch (1965), Ivimey-Cook (1974), Warrington et al. (1980), Waters and Lawrence (1987), Wilson et al. (1990) and Whittaker and Green (1983)

The outcrop pattern of the Mercia Mudstone Group in this region is complicated by numerous inliers, outliers and tongues of older and younger rocks. It is separated from Region 3 by an outcrop of Devonian rocks that crosses the River Severn at Sharpness, Gloucestershire, but there is continuity in the subsurface beneath the Cotswolds to the east.

REGION 3 WORCESTER AND KNOWLE BASINS (FIGURE 6)

Former lithostratigraphy based on Green and Melville (1956), Barclay et al. (1997), Worssam et al. (1989), Powell *et al. (2000), Warrington et al. (1980), Old et al. (1987), Old et al. (1991), and Williams and Whittaker (1974)*

The entire succession is in subsurface continuity with that of Region 5 (East Midlands Shelf South), but only the lower part is in continuity with Region 4 (Needwood Basin). The cover of superficial deposits (drift) becomes extensive in east Warwickshire, which hampers correlation with the succession at outcrop to the north-east in the East Midlands Shelf South.

REGION 4 NEEDWOOD BASIN (FIGURE 7)

Former lithostratigraphy based on Warrington et al. (1980), Charsley (1982), Chisholm et al. (1988) and Stevenson and Mitchell (1955)

Only the lower part of the succession is in spatial continuity with Region 3 to the south (Worcester and Knowle basins) and Region 5 (East Midlands Shelf South). A narrow horst of upfaulted Sherwood Sandstone Group separates this region from the Stafford Basin (Region 7) to the west.

REGION 5 EAST MIDLANDS SHELF SOUTH (FIGURE 8)

Former lithostratigraphy based on Elliott (1961), Worssam and Old (1988), Warrington et al. (1980), Charsley et al. (1990), and Howard et al. (in press)

The formations were largely defined from boreholes and surface mapping in south Nottinghamshire and north Leicestershire. The outcrop in Leicestershire and Warwickshire has an extensive cover of superficial deposits. There is full spatial continuity in the subsurface with Region 6 (East Midlands Shelf North) and with the equivalent succession (Haisborough Group, Rhys, 1974) in the Southern North Sea Basin. The formations mapped at surface in this region have not been traced north of Newark.

REGION 6 EAST MIDLANDS SHELF NORTH (FIGURE 8)

Former lithostratigraphy based on Smith and Warrington (1971), Smith et al. (1973), Smith (1980), Riddler (1981) and Warrington et al. (1980)

Superficial deposits cover is extensive north of Retford in north Nottinghamshire. There is full continuity with the succession offshore in the Southern North Sea Basin (Johnson et al., 1994), correlation with which is illustrated in Figure 11 (*see also* Cameron et al., 1992; Warrington, 1974).

REGION 7 STAFFORD BASIN (FIGURE 7)

Former lithostratigraphy based on Warrington et al. (1980) and Rees and Wilson (1998)

The Mercia Mudstone Group succession in the basin is isolated from the adjacent regions by faulting and erosion.

REGION 8 CHESHIRE BASIN (FIGURE 9)

Former lithostratigraphy based on Wilson (1993) and Rees and Wilson (1998)

The Mercia Mudstone Group succession in the Cheshire Basin is spatially isolated from the Stafford Basin by faulting and from west Lancashire (Region 9) by an outcrop of the Sherwood Sandstone Group extending from the Wirral towards Preston (Llŷn–Rossendale Ridge of Jackson et al., 1997). The outcrop is extensively masked by superficial deposits and the existing formations have been mapped mainly using borehole evidence. The halite deposits were used by Pugh (1960) and subsequently Wilson (1993) as dividers for defining a formation-level stratigraphy, with the exception of the Byley and Wych Mudstone formations (Wilson, 1993), which are not separated by a halite and are differentiated on lithological characteristics recognised mainly in borehole core.

REGION 9 WEST LANCASHIRE (FIGURE 10)

Former lithostratigraphy after Warrington et al. (1980), Wilson and Evans (1990) and Jackson et al. (1995; 1997)

The region is the onshore extension of the East Irish Sea Basin, the nomenclature of which (Figure 11) has been defined by Jackson et al. (1997). Onshore, superficial deposits conceal much of the outcrop in the Wirral, Formby, Fylde and Walney to Barrow-in-Furness areas, and the existing formations have been defined and mapped largely using data from cored boreholes (Wilson, 1990; Wilson and Evans, 1990).

REGION 10 CARLISLE BASIN (SEE FIGURE 2)

Lithostratigraphy after Warrington et al. 1980, Barnes et al. (1994), Ivimey-Cook et al. (1995), Jackson et al. (1995; 1997) and Holliday et al. (2004)

The lower part of the Mercia Mudstone Group in this region is partly in continuity with that offshore in the Solway Firth Basin, but both basins are isolated from the East Irish Sea Basin by a sea floor outcrop of the Sherwood Sandstone along the Ramsey–Whitehaven ridge (Jackson et al., 1995). The outcrop in the Carlisle Basin is masked by superficial deposits. The name Stanwix Marls or Stanwix Shales (Holmes, 1881, 1899) has been applied to the Mercia Mudstone Group in the Carlisle Basin but is abandoned in this review. Borehole evidence in this basin provides insufficient detail to differentiate formations within the group, other than the Blue Anchor Formation (Ivimey-Cook et al., 1995).

4 Formal definitions and diagnoses of formations

The following pages provide formal definitions of the Mercia Mudstone Group and its five component formations. These form the basis for the entries in the British Geological Survey Lexicon of Named Rock Units which, when complete, will provide definitions for all the lithostratigraphical terms found on current, published BGS maps. The BGS Lexicon can be searched via the BGS website (http://www.bgs.ac.uk/lexicon/lexicon_intro.html).

4.1 MERCIA MUDSTONE GROUP

Previous nomenclature
Approximately equivalent to:
Upper Red Marls and Gypsum (Sedgwick, 1829)
Red Marl, New Red Marl or Keuper Marl (Hull, 1869)
Keuper Marls (Lamplugh et al., 1908)
Nottingham Group (Balchin and Ridd, 1970)
Stanwix Marls or Stanwix Shales (Holmes, 1881, 1899)

Derivation of name
From Mercia, the Anglo-Saxon kingdom that occupied much of central and southern England.

Primary reference section
South Devon Coast between Sidmouth [SY 129 873] and Haven Cliff [SY 256 898 to 273 894] (Jeans, 1978; Warrington and Scrivener, 1980; Gallois, 2001, 2004).

Reference sections
Fulbeck F/B1 Borehole, Fulbeck, Lincolnshire, from 111.52 to 375.24 m depth (Berridge et al., 1999). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Base of group: surface section, former railway cutting, Colwick Road, Sneinton, Nottingham [SK 5924 3968 to 5920 3980]. Exposes lower boundary and lowermost 20 m of group (Charsley, 1989; Benton et al., 2002; Howard, 2003; Howard et al., in press).

Top of group: St Audrie's Bay [ST 1045 4310], west Somerset coast (Whittaker and Green, 1983; Warrington and Ivimey-Cook, 1995; Benton et al., 2002; Hounslow et al., 2004).

Extant exposures/sections
See above, and entries for constituent formations. All formations within the group are poorly exposed and known largely from boreholes and temporary excavations. Information on inland outcrop or boreholes is mostly contained, or cited, in memoirs or other publications of the British Geological Survey.

Lithology
Dominantly red, less commonly green-grey, mudstones and subordinate siltstones with thick halite-bearing units in some basinal areas. Thin beds of gypsum/anhydrite are widespread; thin sandstones are also present.

Lower boundary
The boundary with the underlying Sherwood Sandstone Group is taken at the upward transition from sandstone to mudstone- or siltstone-dominated lithologies and the incoming of pseudomorphs after halite; the boundary is usually gradational, conformable and markedly diachronous, younging towards the south. In the East Midlands, the boundary with the underlying Sherwood Sandstone Group is sharp and unconformable (Warrington, 1974, fig.40; Howard et al., in press). The base of the group onlaps onto Carboniferous and older rocks at basin margins.

Upper boundary
The boundary with the overlying Penarth Group is typically a slight unconformity marked by an abrupt upward change from the green or grey-green, dolomitic mudstones of the Blue Anchor Formation to black, fossiliferous shales of the Westbury Formation (Penarth Group). The unconformity surface may be slightly irregular and small clasts of Blue Anchor Formation lithologies commonly occur at the base of the Westbury Formation. The Blue Anchor Formation may be burrowed or have animal borings to a depth of several centimetres below the unconformity surface.

Thickness
Thickness variation is considerable, ranging up to 1350 m in the Cheshire Basin.

Age
Mid Triassic (Anisian) to latest Triassic (Rhaetian). The base of the group is diachronous, younging to the south. Age assignments in Warrington et al. (1980) have been revised (Benton et al., 1994; Rees and Wilson, 1998; Warrington et al., 1999).

Equivalent units
Haisborough Group, Southern North Sea Basin (Rhys, 1974; Cameron et al., 1992; Johnson et al., 1994)

Geographical extent
Onshore UK and contiguous offshore areas (equivalent strata in the Southern North Sea Basin are assigned to the Haisborough Group (*see above*).

Subdivisions
Tarporley Siltstone Formation, Sidmouth Mudstone Formation, Arden Sandstone Formation, Branscombe Mudstone Formation, Blue Anchor Formation

4.2 TARPORLEY SILTSTONE FORMATION

Previous nomenclature
Denstone Formation (Charsley, 1982)
Holling Member (Barclay et al., 1997)
Maer Formation (Rees and Wilson, 1998)
Retford Formation plus Colwick Formation (Warrington et al., 1980)

Sneinton Formation (Charsley et al., 1990; Berridge et al., 1999)
Woodthorpe Formation plus Colwick Formation (Warrington et al., 1980)
Woodthorpe Formation plus Waterstones Formation (Elliott, 1961)
Approximately equivalent to:
Keuper Waterstones (Lamplugh *et al*. 1908; Smith, 1912; Swinnerton, 1918; Poole and Whiteman, 1966; Evans et al., 1968)
Waterstones (Hull, 1869; Strahan, 1882; Gibson, 1925)
Waterstones Group (Wills, 1970, 1976)

Parent unit
Mercia Mudstone Group

Derivation of name
From the village of Tarporley, Cheshire

Type area
Several sections (mostly small exposures) around the village of Tarporley, Cheshire (Warrington et al., 1980)

Primary reference sections
Windyharbour Borehole, Staffordshire (SK 04SE/16) [SK 0854 4100] between 51.57 and 103.16 m. (Charsley, 1982). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Surface section, former railway cutting, Colwick Road, Sneinton, Nottingham [SK 5924 3968 to 5920 3980]. Exposes lower boundary and lowermost 20 m of the formation (Charsley, 1989; Benton et al., 2002; Howard, 2003; Howard et al, in press).

Other reference sections
Cropwell Bridge Borehole (SK63NE/28) [SK 6773 3547], Nottinghamshire between 170.70 and 214.33 m (Charsley et al., 1990; Howard et al., in press). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Fulbeck F/B1 Borehole, Lincolnshire (SK 85SE/25) [SK 8889 5053] between 301.58 and 375.24 m (Berridge et al., 1999). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Extant exposures/sections
Cheshire Basin: exposures in the River Dane, north-east of Congleton [SJ 900 656 to 892 657] (Wilson, 1993) and The Dungeon, Wirral, Merseyside [SJ 252 832] (Benton et al., 2002]

Stafford Basin: former railway cutting north of Maer [SJ 7909 3803], and a stream section [SJ 921 353] east of The Hayes, near Oulton (Rees and Wilson, 1998).
Needwood Basin: sections in streams west of Upper Tean [SK 0069 3946 to 0050 3931] and Broadgatehall Drumble, near Hollington [SK 0392 3848 to 0446 3755] (Charsley, 1982).

East Midlands Shelf South: sections in a railway cutting at Sneinton (*see above*) and in a road cutting at Redhill [SK 5837 4713 to 5835 4689] (Rathbone, 1989).

Lithology
Heterolithic, comprising interlaminated and interbedded siltstone, mudstone and sandstone in variable but approximately equal proportions. The siltstones are micaceous and laminated, or interlaminated with mudstones or sandstones; the mudstones usually appear structureless, with a blocky habit. The sandstones are mostly very fine- to fine-grained, well-sorted, and micaceous. They are typically cemented by ferroan calcite or dolomite. Sandstone units are commonly less than 0.5 m thick though composite units, consisting of several individual sandstone beds, may reach over 5 m thick. Intraformational mudclast conglomerates are common, with mudclasts concentrated at the bases of sandstone beds. Conglomerates with extraformational pebbles are rare, and tend to be less than 1 m thick; the 'Waterstones Conglomerate' of Nottinghamshire is a notable example (Elliott, 1961). Most mudstone and siltstone beds are reddish brown, though green-grey mottles and laminae are common. Gypsum occurs sporadically in the mudstone as small nodules. The sandstones are grey-brown in colour and conspicuously paler than the siltstones and mudstones. Bedding is generally planar. Most beds are tabular and laterally extensive, though lenticular channel sandstone bodies occur and typically have incised, erosional bases. The upper surfaces of sandstones and coarse siltstones are commonly wave or current rippled; in section the sandstones are usually planar or ripple-laminated, and exhibit sporadic rootlets. Fossils include miospores (e.g. Fisher, 1972; Charsley, 1982; Earp and Taylor, 1986; Rees and Wilson, 1998; Warrington et al., 1999), invertebrate trace fossils (Ireland et al., 1978; Pollard, 1981), vertebrate tracks (Sarjeant, 1974) and the brachiopod *Lingula* (Rose and Kent, 1955).

Lower boundary
The boundary is diachronous, and in most regions there is interdigitation with the underlying Sherwood Sandstone Group. Within individual sections, the boundary is drawn arbitrarily within an interbedded, generally upward-fining gradation at the level where the micaceous mudstones, siltstones and fine sandstones of the Tarporley Siltstone predominate over the coarser grained, cross-stratified sandstone of the underlying Sherwood Sandstone Group (Warrington et al., 1980). Locally, for example above the Kibblestone Formation of the Stafford basin (Rees and Wilson, 1998), the lowest part of the formation is dominated by sandstones. In these circumstances, the boundary is placed at the base of micaceous, flaggy and fine-grained sandstones, typical of the Tarporley Siltstone Formation, but differing markedly from the coarser, cross-stratified sandstones in the underlying Sherwood Sandstone Group. In the Cheshire Basin the junction between the Tarporley Siltstone Formation and the underlying Helsby Sandstone Formation is complex, being both transitional and diachronous, and locally there is a lateral passage between the two formations. For example, in the south-east of the basin, in the Stoke-on-Trent district (Rees and Wilson, 1998), siltstones, mudstones and thin sandstones (like those of the Tarporley Siltstone) alternate with thicker sandstones of Helsby Sandstone type; here the finer grained lithologies are included within the latter formation. This succession passes laterally into one where mudstones are dominant, assigned to the Tarporley Siltstone Formation. In the Nottingham area, the base of the unit is unconformable and is marked by a patchily distributed basal conglomerate up to 1 m thick with a strong calcareous cement (Howard, 2003; Howard et al., in press).

Where not exposed, the boundary is typically marked by a change in soil type from the sandy soils of the Sherwood Sandstone Group to the heavier, brown sandy clay soils (commonly containing fragments of fine-grained micaceous sandstone) associated with the Tarporley Siltstone Formation. A concave break of slope may mark the boundary in some areas.

Upper boundary
The boundary is diachronous, and interdigitates with the overlying Sidmouth Mudstone Formation. Within individual sections, the boundary is drawn arbitrarily within an upward-fining, interbedded succession at the level where mudstones of the overlying Sidmouth Mudstone Formation predominate over the siltstones and sandstones of the Tarporley Siltstone Formation.

Where not exposed, the boundary is typically marked by a change in soil type from the brown, sandy clay soils of the Tarporley Siltstone Formation to the more clayey, markedly reddish brown soils of the Sidmouth Mudstone Formation. A concave break of slope is associated with the boundary in some areas.

Thickness
Varies from 20 to 60 m in the East Midlands, and 50 to 75 m in Staffordshire, up to a maximum of 220 m in the Cheshire basin. The 273 m-thick succession logged in the Ashley Borehole, Cheshire (Taylor et al., 1963) probably includes a substantial thickness of the overlying Sidmouth Mudstone Formation.

Age
On palynological evidence, the formation is Mid Triassic (Anisian) in age. Both the basal and upper boundaries are diachronous, younging generally towards the south (Warrington, 1970; Warrington et al., 1980; with revisions in Benton et al., 1994; Rees and Wilson, 1998; Warrington et al., 1999).

Equivalent units
None. Coeval strata in contiguous offshore areas are developed in a finer grained lithofacies resembling the overlying Sidmouth Mudstone Formation.

Geographical extent
The outcrop extends northwards from Warwickshire through Staffordshire, Cheshire, Leicestershire, and Nottinghamshire; the formation is also proved by numerous boreholes in the adjacent subcrop. To the south of a line between Wolverhampton and Coventry, the formation passes laterally by interdigitation into the uppermost part of the Sherwood Sandstone Group. Where, south of that line, correlatives of the formation have been recognised, for example the Sugarbrook Member of the Redditch area (Old et al., 1991), they are typically included in the upper part of the Sherwood Sandstone Group and have not been mapped separately. An exception is the Holling Member of the Worcester area, included in the Eldersfield (now Sidmouth) Mudstone Formation by Barclay et al. (1997) and here re-assigned to the Tarporley Siltstone Formation. To the north of the outcrop, the formation passes laterally into a mudstone-dominated facies. It appears to be absent in north and west Lancashire and the central part of the East Irish Sea Basin (Jackson et al., 1987, 1995), where the Sherwood Sandstone Group is directly overlain by a silt and sand-poor sequence typical of the bulk of the Mercia Mudstone Group farther south. However, in the Solway and Carlisle Basins, a 'Waterstones Lithology' has been tentatively identified (Jackson et al., 1995). On the East Midlands Shelf, although the formation is identified in boreholes in the Grantham and Grimsby districts (Berridge et al., 1999; Berridge and Pattison, 1994), it cannot be confidently identified farther north in the Kingston upon Hull district (Gaunt et al., 1992). The lateral transition into mudstone-dominated facies in Eastern England has been described by Smith and Warrington (1971). Coeval strata in the Southern North Sea Basin are in mudstone- and halite-dominated facies (Cameron et al., 1992; Johnson et al., 1994).

Subdivisions
Malpas Sandstone Member [Cheshire Basin] (Stephens, 1961; Poole and Whiteman, 1966; Wilson, 1993)
Woodthorpe Member [East Midlands Shelf South] (formerly Woodthorpe Formation, Elliott, 1961)
Retford Member [East Midlands Shelf South] (formerly Retford Formation, Warrington et al., 1980)
Colwick Member [East Midlands Shelf South] (formerly Colwick Formation, Warrington et al., 1980)

4.3 SIDMOUTH MUDSTONE FORMATION

Previous nomenclature
Radcliffe Formation plus Carlton Formation, Harlequin Formation and Edwalton Formation (excluding Hollygate Skerry) (Elliott, 1961)
Radcliffe Formation plus Gunthorpe Formation and Edwalton Formation (excluding Hollygate Sandstone Member) (Charsley et al., 1990)
Hambleton Mudstone Formation plus Singleton Mudstone Formation, Kirkham Mudstone Formation, and Breckells Mudstone Formation (Wilson and Evans, 1990)
Bollin Mudstone Formation plus Northwich Halite Formation, Byley Mudstone Formation, Wych Mudstone Formation and Wilkesley Halite Formation (Wilson, 1993).
Eldersfield Mudstone Formation (Barclay et al., 1997)
Approximately equivalent to:
Lower Keuper Marl [s] (Brodie, 1870; Matley, 1912)
Mudstone I (Jeans, 1978)
Sub-Arden Keuper Marls (Wills, 1970; 1976)

Parent unit
Mercia Mudstone Group

Derivation of name
From the town of Sidmouth in south Devon, located immediately to the west of the type section.

Type area
South Devon coast

Type section
South Devon coast between Sidmouth [SY 129 873] and Weston Mouth [SY 163 879] (Jeans, 1978; Warrington and Scrivener, 1980; Gallois 2001, 2004).

Primary reference sections
Eldersfield Borehole (SO73SE/6) [SO 7891 3221], Eldersfield, near Tewkesbury, Gloucestershire: from the start of coring to 348.47 m depth (Barclay et al., 1997; Worssam et al., 1989). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Other reference sections
Worcester Borehole (SO85NE/23) [SO 8624 5762], Worcestershire: from surface (core from 30 m) to 293.51 m (Barclay et al., 1997). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Asfordby Hydrogeological Borehole (SK72SW/71) [SK 7252 2061], Asfordby, Leicestershire: from 211.37 to 327.87 m depth (Carney et al., 2004). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Cropwell Bridge Borehole (SK63NE/28) [SK 6773 3547], Cropwell Bishop, Nottinghamshire: from 42.03 m to 170.70 m depth (Howard et al., in press). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Fulbeck F/B1 Borehole (SK85SE/25) [SK 8889 5053], Fulbeck, Lincolnshire: from 158.8 to 301.58 m depth (Berridge et al., 1999). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Wilkesley Borehole (SJ64SW/7) [SJ 6286 4144], Cheshire: from 347.8 to 1527.4 m depth (Poole and Whiteman, 1966; Wilson, 1993).

Home Farm Borehole (SP47SW/72) [SP 4317 7309], near Rugby, Warwickshire: from 76.67 to 201.22 m depth (Old et al., 1987). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Twycross Borehole (SK30NW/13) [SK 3387 0564], Twycross, Leicestershire (Worssam and Old, 1988): from base of Superficial Deposits at 17.40 to 127.97 m depth. Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Leicester Forest East Borehole (SK50SW/71) [SK 5245 0283], Leicestershire: from base of Superficial Deposits at 4.0 m to 119.51 m depth (Worssam and Old, 1988). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Knights Lane Borehole (SP25SW/1) [SP 2242 5497], Stratford-upon-Avon, Warwickshire: from base of Superficial Deposits at 6.1 m to 151.23 m depth (Williams and Whittaker, 1974). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Kirkham Borehole (SD43SW/6) [SD 4324 3247], Lancashire: from base of Superficial Deposits at 36.58 m to 366.19 m depth (Wilson, 1990; Wilson and Evans, 1990). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Extant exposures/sections
The formation is exposed on the south Devon coast in a series of cliff sections extending for 3.5 km between Sidmouth [SY 129 873] and Weston Mouth [SY 163 879] (Jeans, 1978; Warrington and Scrivener, 1980, Gallois, 2001, 2004). Access to the uppermost part of the succession is difficult, although landslipped material can be examined at beach level.

Elsewhere, the formation is generally very poorly exposed at surface. Sections of the lower and middle parts of the formation (Radcliffe and Gunthorpe members) occur alongside the River Trent at Radcliffe on Trent, near Nottingham [SK 6461 3987 and SK 6507 4064] (Howard, 2003), and the middle part of the formation (Gunthorpe Member) is currently exposed in Dorket Head Brick Pit [SK 598 347], near Nottingham (Rathbone, 1989; Howard et al., in press).

Lithology
The formation consists dominantly of red-brown mudstone and siltstone with common grey-green reduction patches and spots. The mudstones are mostly structureless, with a blocky weathering habit, but units up to 15 m thick of interlaminated mudstone and siltstone occur in parts of the formation, notably in the Bollin and Byley Mudstone members of the Cheshire Basin (Wilson, 1993) and in the Radcliffe Member of the East Midlands (Charsley et al., 1990; Howard et al., in press). Heterolithic units consisting of several thin beds of grey-green dolomitic siltstone and very fine-grained sandstone, interbedded with mudstone, occur at intervals throughout the formation. These units range from a few centimetres up to 4 m thick, and locally form mappable cuesta features. Named examples include the Cotgrave Sandstone Member and Clarborough Member of the East Midlands (Smith et al., 1973; Warrington et al., 1980; Charsley et al., 1990) and the Weatheroak Sandstone of the Redditch area (Old et al., 1991). The Redcliffe Sandstone Member, a distinctive, deep red calcareous and ferruginous sandstone, is a marginal facies of the formation developed locally in the Bristol area (Kellaway and Welch, 1993). Units of halite up to 400 m thick are present at several stratigraphical levels in the thicker basinal sequences in west Lancashire and south Cumbria, Cheshire, Staffordshire, north-east Yorkshire, Worcestershire, Somerset and Dorset. Breccias produced by contemporaneous solution of salt are common throughout the formation. In the Cheshire Basin, more recent salt solution (some induced artificially by brine pumping activities) gives rise to solution hollows and collapse breccias associated with the halite members. Gypsum/anhydrite also occurs throughout the formation as nodules and veins.

Lower boundary
The boundary is both gradational and conformable, and is drawn arbitrarily within an upward-fining succession at the level where mudstones predominate over the siltstones and sandstones of the underlying Tarporley Siltstone Formation; the junction is diachronous. Where the underlying Tarporley Siltstone Formation is not differentiated (including at the type section), the boundary is marked by a rapid upward transition from sandstone to mudstone-dominated lithologies immediately above the Sherwood Sandstone Group (Jones, 1993; Gallois, 2001, 2004).

Where not exposed, the boundary is associated with a change from the brown sandy clay soils of underlying formations to the more clayey, distinctively reddish brown soils of the Sidmouth Mudstone Formation. A concave break of slope is associated with the boundary in some areas.

Upper boundary
This boundary is placed at the rapid upward transition from red mudstones or siltstones to the dominantly grey or green, partly or largely arenaceous beds of the overlying Arden Sandstone Formation. At the type section, this boundary coincides with the base of a prominent breccia bed (*see* sections in Jeans, 1978) at the base of the Arden Sandstone Formation. In the Cheshire Basin and parts of the Wessex Basin, where the Arden Sandstone Formation cannot be recognised in the presence of thick halite deposits, the boundary is drawn immediately above the highest halite beds. The boundary is conformable in all areas.

At outcrop, the boundary is typically marked by a change from the reddish brown clayey soils of the Sidmouth Mudstone Formation to the grey, slightly sandy clay soils of the overlying Arden Sandstone Formation. Where the latter forms a marked cuesta feature, the boundary typically lies at a slight concave break in the scarp slope. In the Cheshire Basin, where the Arden Sandstone Formation is absent, the boundary is mapped at the approximate down-dip limit of subsidence hollows and collapse breccias, which are associated with near-surface solution of halites (Wilkesley Halite Member) at the top of the Sidmouth Mudstone (Taylor et al., 1963).

Thickness
The formation is over 200 m thick in south Devon (Figure 3). Elsewhere, it ranges from 120 to 130 m in the East Midlands to 370 m in the Worcester Basin and 1600 m in the Cheshire Basin.

Age
Mid Triassic (Anisian) to Late Triassic (Carnian). Miospore assemblages ranging in age from Anisian to Carnian have been recovered from this formation throughout England. These dates are further constrained by Anisian ages from the underlying Tarporley Siltstone and late Carnian dates from the Arden Sandstone. Magnetostratigraphical correlation (Hounslow and McIntosh, 2003) indicates that the base of the Ladinian lies close to the base of the formation on the south Devon coast.

Equivalent units
Dowsing Formation and Dudgeon Formation [Southern North Sea Basin] (Johnson et al., 1994)
Leyland Formation plus Preesall Halite Formation, Dowbridge Mudstone Formation and Warton Halite Formation [East Irish Sea Basin] (Jackson et al., 1997)

Geographical extent
The surface outcrop extends from the south Devon coast east of Sidmouth northwards into Somerset, Gloucestershire, Worcestershire, Warwickshire, Leicestershire, Nottinghamshire, east and north Yorkshire, and hence westwards into Derbyshire, Staffordshire, north Shropshire, Cheshire and Lancashire. Separate outcrops occur in south Cumbria and the Carlisle Basin. The formation occurs in the subsurface below much of southern England, the south Midlands and eastern England. Equivalents occur below the southern North Sea and eastern Irish Sea.

Subdivisions
* indicates units that were previously defined as formations
Sid Mudstone Member, Salcombe Hill Mudstone Member, Salcombe Mouth Member, Hook Ebb Mudstone Member, Little Weston Mudstone Member [Wessex Basin] (Gallois, 2001)
*Radcliffe Member, *Gunthorpe Member, Cotgrave Sandstone Member, *Edwalton Member, *Clarborough Member, *Seaton Carew Member, *Esk Evaporite Member [East Midlands Shelf North] (Smith, 1980; Warrington et al., 1980, Charsley et al., 1990)
*Bollin Mudstone Member, *Northwich Halite Member, *Byley Mudstone Member, *Wych Mudstone Member, *Wilkesley Halite Member [Cheshire Basin] (Wilson, 1993)
*Hambleton Mudstone Member, Rossall Halite Member, *Singleton Mudstone Member, Mythop Halite Member, Kirkham Mudstone Member, *Breckells Mudstone Member [west Lancashire] (Wilson and Evans, 1990)
*Stafford Halite Member [Stafford Basin] (Warrington et al., 1980)
*Droitwich Halite Member, *Weatheroak Sandstone Member [Worcester and Knowle Basins] (Warrington et al., 1980; Old et al., 1991; Barclay et al., 1997)
*Redcliffe Sandstone Member [Bristol area] (Kellaway and Welch, 1993)
*Somerset Halite Member, Dorset Halite Member [Wessex Basin] (Warrington et al., 1980; Harvey and Stewart, 1998)

4.4 ARDEN SANDSTONE FORMATION

Previous nomenclature
Arden Sandstone Member (Warrington et al., 1980)
Arden Sandstone Group (Matley, 1912)
Arden Sandstone Horizon (Wills, 1970, 1976)
Dane Hills Sandstone Member (Warrington et al., 1980)
Dane Hills Sandstone Group (Horwood, 1913)
Hollygate Skerry (Elliott, 1961)
Hollygate Sandstone Member (Charsley et al., 1990; Howard et al., in press)
Keuper sandstone (Murchison and Strickland, 1840; Symonds, 1855)
North Curry Sandstone Member (Warrington et al., 1980)
Upper Keuper Sandstone (Phillips, 1848; Brodie, 1856; Plant, 1856; Ussher, 1908; Wills and Campbell Smith, 1913)
Approximately equivalent to:
Sandstone Group of the Weston Cycle (Jeans, 1978)
Weston Mouth Sandstone Member (Warrington et al., 1980)
Dunscombe Mudstone Formation (lowest 24 m only) (Gallois, 2001)

Parent unit
Mercia Mudstone Group

Derivation of name
From the Forest of Arden, Warwickshire

Type area
Knowle Basin, Warwickshire

Type section
Canal cutting [SP 2118 6744], Shrewley, Warwickshire (Old et al., 1991, plate 10; Benton et al., 2002)

Primary reference section
Canal cutting [SP 2010 6905], Rowington, Warwickshire (Old et al., 1991)

Other reference sections
Twyning Borehole (SO83NE/5) [SO 8943 3664], Twyning, near Tewkesbury, Gloucestershire: from 310.51 to 315.00 m depth (Barclay et al., 1997). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Cropwell Bridge Borehole (SK63NE/28) [SK 6773 3547] Cropwell Bishop, Nottinghamshire: from 37.50 to 42.03 m depth (Howard et al., in press). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Higher Dunscombe and Weston Cliffs [SY 152 877 to 171 879], south Devon coast (Jeans, 1978; Warrington and Scrivener, 1980; Gallois, 2001).

Newnham river cliff, River Severn, Gloucestershire [SO 6923 1168].

Extant exposures/sections
The formation usually gives rise to a mappable cuesta-type feature (e.g. Old et al., 1991, plate 1) but is not well exposed. Most sections are in former quarries (e.g. at

Inkberrow [SP 009 569], Warwickshire, and Longdon [SO 835 354], Worcestershire), or in road cuttings (e.g. at Inkberrow [SP 004 563; SP 011 577] and roadside exposures (e.g. at Henley-in-Arden [SP 156 654], Warwickshire). Similar exposures of local representatives of the formation occur around Taunton and Bridgwater, Somerset (Buckland, 1837; Warrington and Williams, 1984; Ruffell and Warrington, 1988; Ruffell, 1990), and on the south Devon coast (Jeans, 1978; Warrington and Scrivener, 1980; Gallois, 2001).

Lithology

The Arden Sandstone Formation consists of grey, green and purple mudstone interbedded with paler grey-green to buff-coloured siltstone and fine to medium-grained, varicoloured (green, brown, buff, mauve) sandstone; thin pebble beds occur locally. Breccias occur at the base and top of the formation on the south Devon coast (Jeans, 1978), and may have been formed by penecontemporaneous solution of halite. Laminated and thinly interbedded sediments are commonly extensively bioturbated and show structures indicative of thixotropic deformation. Invertebrate and vertebrate macrofossils are present, locally in abundance, and miospores and burrows are common. The siltstones and finer sandstones show small-scale ripple drift cross-bedding; thicker sandstone beds show trough and planar cross-bedding. The proportion of fine to coarse clastics varies laterally within the formation. The thicker sandstone units, composed of several individual beds, have a lenticular geometry and occupy the inferred former courses of distributary channels in a deltaic or estuarine environment. Less arenaceous, mudstone- and siltstone-dominated successions represent intervening interdistributary areas.

The formation is differentiated from the reddish brown, blocky weathering mudstones of adjacent formations by its predominantly greenish grey colour, the presence of a significant (though commonly subordinate) proportion of sandstone, the predominance of finely laminated lithologies throughout, and its comparatively fossiliferous nature. The formation is characterised by an exotic clay mineral assemblage, which is rich in mixed-layer clays and distinct from the illite-dominated units below and above (Jeans 1978, Bloodworth and Prior, 1993; Carney et al., 2004; Jeans et al., 2005).

Lower boundary

The lower boundary of the formation is placed at an abrupt upward change from the red mudstone or siltstone of the Sidmouth Mudstone Formation to the dominantly grey or green, partly or largely arenaceous beds of the Arden Sandstone Formation. On the south Devon coast, this boundary coincides with the base of a prominent breccia bed (*see* sections in Jeans, 1978), and is conformable in all areas.

Where not exposed, the boundary is typically marked by a change from the reddish brown clayey soils of the Sidmouth Mudstone Formation to the grey, slightly sandy clay soils of the overlying Arden Sandstone Formation. Where the latter forms a marked cuesta feature, the boundary typically lies at a slight concave break in the scarp slope.

Upper boundary

Placed at the base of red, structureless mudstone where it rests on the interbedded dark grey-green siltstone and pale grey sandstone of the underlying Arden Sandstone Formation, the boundary is abrupt or is a rapid interbedded transition. On the south Devon coast, the upper boundary coincides with the top of a prominent breccia bed (*see* sections in Jeans, 1978). This boundary is conformable in all areas.

Where not exposed, the boundary is typically marked by a change from the grey, slightly sandy clay soils of the Arden Sandstone Formation to the reddish brown clayey soils of the Branscombe Mudstone Formation. Where the Arden Sandstone forms a marked cuesta feature, the boundary lies at the down-dip limit of the dip slope.

Thickness

Typically 7 to 8 m, rising to 20 m in the Stowell Park Borehole (SP01SE/1, [SP 0835 1176] (Green and Melville, 1956) towards the south of the Worcester Basin, and 24 m on the south Devon coast (cf. Jeans, 1978). Locally, it thins to 2 to 3 m in parts of the Worcester Basin, Knowle Basin and East Midlands areas.

Age

Late Triassic, late Carnian (Tuvalian), on palynological evidence

Equivalent units

Sandstone groups in Dunscombe and Weston cycles (Jeans, 1978) represent a single unit (Warrington and Scrivener, 1980).

Geographical extent

The outcrop of the formation is traceable nearly continuously from Gloucestershire northward through Worcestershire and eastwards though Warwickshire into Leicestershire and Nottinghamshire. Less continuous outcrop is mapped in Somerset and east Devon. In the subcrop, the formation is proved in several cored and geophysically logged boreholes in the subsurface in the central Midlands (Worcester and Knowle basins), East Midlands, and in southern England (Wessex Basin). It is not recognised in the Cheshire Basin and other basins farther north-west. At depth in Dorset and Somerset, the partly equiavalent Dunscombe Mudstone Formation has been interpreted to pass laterally into halite (Gallois, 2001, 2003).

Subdivisions

None

4.5 BRANSCOMBE MUDSTONE FORMATION

Previous nomenclature

Brooks Mill Mudstone Formation (Wilson, 1993; Rees and Wilson, 1998)
Cropwell Bishop Formation (Charsley et al., 1990; Berridge et al., 1999)
Twyning Mudstone Formation (Barclay et al., 1997)
Trent Formation plus the lower part of the Parva Formation (Elliott, 1961)
Trent Formation plus Glen Parva Formation (Warrington et al., 1980)
Approximately equivalent to:
Mudstone III (Jeans, 1978)
Supra-Arden Keuper Marls (Wills, 1970, 1976)
Upper Keuper Marl[s] of Harrison (1876), Matley (1912)

Parent unit

Mercia Mudstone Group

Derivation of name

From the village of Branscombe, south Devon

Type area
South Devon coast

Type section
South Devon coast between Weston Cliff and Branscombe Mouth [SY 171 879 to 207 881] (lower two thirds of formation) and in Haven Cliff, east of Seaton [SY 256 898 to 260 897] (upper third of formation) (Gallois, 2001).

Primary reference section
Twyning Borehole (SO83NE/5) [SO 8943 3664], Twyning, near Tewkesbury, Gloucestershire: from 141.5 to 310.51 m depth (Barclay et al., 1997; Worssam et al., 1989).

Other reference sections
St Audrie's Bay, north Somerset [ST 120 437 to 106 431]: uppermost 68 m exposed in the cliffs and foreshore (Talbot et al., 1974; Hounslow et al., 2004).

Aust Cliff, south Gloucestershire [ST 5645 8920]: uppermost 35 m is exposed in cliffs on the east side of the River Severn below the Blue Anchor Formation (Hamilton, 1977; Kellaway and Welch, 1993).

Asfordby Hydrogeological Borehole (SK72SW/71) [SK 7252 2061], Asfordby, Leicestershire: from 170.08 to 211.37 m depth (Carney et al., 2004). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Cropwell Bridge Borehole (SK63NE/28) [SK 6773 3547], Cropwell Bishop, Nottinghamshire: from surface to 37.50 m depth (uppermost beds not proved) (Howard et al., in press). Curated core held at the NGRC Core Store, BGS, Keyworth.

Fulbeck F/B1 Borehole (SK85SE/25) [SK 8889 5053], Fulbeck, Lincolnshire: from 117.52 to 156.10 m depth (Berridge et al., 1999). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Wilkesley Borehole (Reg. No. SJ64SW/7) [SJ 6286 4144]: from 186.5 to 347.8 m depth (Poole and Whiteman, 1966; Wilson, 1993).

Extant exposures/sections
The formation is exposed on the south Devon coast between Weston Cliff and Branscombe Mouth [SY 171 879 to 207 881] and intermittently between Beer and Haven Cliff, Seaton [SY 235 896 to 260 897], (Jeans, 1978; Gallois, 2001). The succession generally youngs eastwards in a discontinuous series of cliff exposures; approximately 40 m of strata are obscured towards the top of the formation in Seaton Bay.

Most of the formation is very poorly exposed at surface. There are, however, several good coastal or river cliff sections of the uppermost part of the formation adjacent to the Bristol Channel and River Severn in west Somerset, Gloucestershire and south Glamorgan. These include the sections at Aust Cliff and St Audrie's Bay (*see above*), and also north of Lavernock Point, south Glamorgan (ST 187 682 to 186 690) (Waters and Lawrence, 1987; Warrington and Ivimey-Cook, 1995), Garden Cliff, Westbury-on-Severn [SO 719 126] (Etheridge, 1865; Benton et al., 2002) and Wainlode, near Gloucester [SO 847 259] (Worssam et al., 1989).

Lithology
Mudstone and siltstone, red-brown, with common grey-green reduction patches and spots, comprise the Branscombe Mudstone Formation. The mudstones are mostly structureless, with a blocky weathering habit. Gypsum/anhydrite, locally of economic importance, is common throughout in beds, nodules and veins. Many of these sulphate beds have been named (*see under* Subdivisions) and form distinct markers on geophysical logs. Sporadic thin beds of argillaceous sandstone and silty dolostone occur in the lower part of the formation. In south Devon, Somerset and Gloucestershire, the highest 10 to 20 m of the formation include common beds of greenish grey mudstone, giving rise to markedly colour-banded sections where exposed in coastal or river cliffs. A similar 'colour-banded' unit in the lowest 11 m of the formation was included in the Dunscombe Mudstone Formation by Gallois (2001). In the East Midlands, beds of thinly interlaminated, dark grey-green mudstone and dolomitic siltstone occur locally towards the top of the formation (formerly separated as the Glen Parva Formation, Elliott, 1961, Warrington et al., 1980). Halite is interpreted to occur towards the base of the formation in Dorset (Nettlecombe Borehole SY59NW/1 [SY 5052 9544]; Figure 3) but is absent elsewhere; pseudomorphs after halite are rare.

Lower boundary
The lower boundary of the formation is placed at the base of predominantly red, structureless mudstones where they rest on the interbedded, laminated, dark grey-green siltstones and pale grey fine-grained sandstones of the underlying Arden Sandstone Formation. The boundary is abrupt or a rapid, interbedded transition. Where the Arden Sandstone Formation cannot be recognised with confidence due to the presence of halite (Cheshire Basin and parts of the Wessex Basin), the boundary is placed immediately above the highest halite beds of the Sidmouth Mudstone Formation (Wilkesley Halite Member, Somerset Halite Member, Dorset Halite Member). At the type section, the base of the formation is drawn at a lower stratigraphical level than originally defined by Gallois (2001) in order to encompass some 11 m of reddish brown mudstone with subordinate greenish grey interbeds that Gallois included in the Dunscombe Mudstone Formation. The boundary is conformable in all areas.

Where not exposed, the boundary is marked typically by a change in soil characteristics from grey, slightly sandy clay soils of the Arden Sandstone Formation to the reddish brown clayey soils of the Branscombe Mudstone Formation. Where the Arden Sandstone forms a marked cuesta feature, the boundary lies at the down-dip limit of the dip slope. In the Cheshire Basin, where the Arden Sandstone Formation is not recognisable, the boundary is mapped at the approximate down-dip limit of subsidence hollows and collapse breccias, which are associated with near-surface solution of halite (Wilkesley Halite Member) at the top of the Sidmouth Mudstone (Taylor et al., 1963).

Upper boundary
The upper boundary of the Branscombe Mudstone Formation is placed at an abrupt or rapidly gradational upward transition from the red-brown, silty, mudstones of the Branscombe Mudstone Formation to green or grey-green, dolomitic mudstones of the Blue Anchor Formation. Locally in southern England and Wales, a more gradational transition occurs above interbedded red and green lithologies (e.g. on the west Somerset and south Devon coasts); in these areas the boundary is drawn above the highest significant red mudstone bed. In south Devon, this coincides with a prominent bed of dolomitic limestone (Gallois, 2001). The boundary may be locally erosional around the margins of the London–Brabant Massif (Horton et al., 1987; Old et al., 1987).

Where not exposed, the boundary is marked by a change in soil colour from the reddish brown clayey soils of the Branscombe Mudstone Formation to the grey clayey soils of the overlying Blue Anchor Formation. Typically, this boundary lies near the base of a scarp slope formed by the Blue Anchor Formation and capped by the Penarth Group.

Thickness
Up to 240 m is present in the Wessex Basin, 170 to 190 m in the Worcester Basin, 25 to 60 m in the East Midlands and up to 160 m in the Cheshire Basin.

Age
Late Triassic, Norian to ?Rhaetian. Not independently dated, but the age is inferred from late Carnian dating of the underlying Arden Sandstone Formation (*see above*) and late Norian – Rhaetian dating of the overlying Blue Anchor Formation (*see below*).

Equivalent units
Lower and middle part of Triton Formation, Southern North Sea Basin (Johnson et al., 1994)
Elswick Mudstone Formation of the East Irish Sea Basin (Jackson et al., 1997)

Geographical extent
The surface outcrop extends from south Devon northwards into Somerset, Gloucesterhire, south Glamorgan and Worcestershire. The formation crops out below parts of the Midlands, Cheshire and the Carlisle Basin, and in a strip extending northwards from Nottingham into North Yorkshire. The formation occurs in the subsurface below much of the south Midlands and eastern England. It has equivalents in the Southern North Sea and East Irish Sea Basins.

Subdivisions
Littlecombe Shoot Mudstone Member, Red Rock Gypsum Member, Seaton Mudstone Member, Haven Cliff Mudstone Member [Wessex Basin] (Gallois, 2001)
Units of undefined status include:
Newark Gypsum [East Midlands Shelf South] (Sherlock and Hollingworth, 1938)
Tutbury Gypsum or Tutbury Sulphate Bed [East Midlands Shelf South] (Sherlock and Hollingworth, 1938; Taylor, 1983)
Windmill Skerries [East Midlands Shelf South] (Elliott, 1961)
Woodford Hill Sandstone [Bristol area] (Kellaway and Welch, 1993)

4.6 BLUE ANCHOR FORMATION

Previous nomenclature
Tea Green Marl (Etheridge, 1865)
Tea Green and Grey Marls (Richardson, 1906; Hamilton and Whittaker, 1977)
Grey and Tea Green Marls, and Sully Beds (Richardson, 1911)
Pale Green and Grey Marls (Bristow and Etheridge, 1873; Bristow et al., 1873)
Parva Formation (upper part) (Elliott, 1961)
Sully Beds (lower part) (Warrington et al., 1980, fig.1).
Approximately equivalent to:
Borehole geophysical log unit 'F' (Lott et al., 1982).

Parent unit
Mercia Mudstone Group

Derivation of name
From the type section, Blue Anchor, west Somerset Coast (Warrington et al., 1980; Warrington and Whittaker, 1984)

Type area
West Somerset coastline

Type section
Blue Anchor cliff [ST 0385 4368], Somerset (Warrington and Whittaker, 1984)

Primary reference section
St Audrie's Bay [ST 1045 4310], west Somerset coast (*see* Whittaker and Green, 1983; Warrington and Ivimey-Cook, 1995)

Other reference sections
Lavernock Point [ST 188 682], south Glamorgan (Waters and Lawrence, 1987; Warrington and Ivimey-Cook, 1995).

South Devon coast east of Seaton, between Sparrowbush Ledge [SY 260 897] and Culverhole Point [SY 273 894] (Gallois, 2001).

Fulbeck F/B1 Borehole (SK85SE/25) [SK 8889 5053], Fulbeck, Lincolnshire: from 111.52 to 117.52 m depth (Berridge et al., 1999). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Staithes No.20 Borehole (NZ71NE/14) [NZ 76034 18000], Boulby mine site, North Yorkshire: from 391.36 to 397.00 m depth (Woods, 1973). Curated core held at the National Geosciences Records Centre, BGS, Keyworth.

Extant exposures/sections
Good sections occur at several sites on the west Somerset coast (*see* Whittaker and Green, 1983; Warrington and Whittaker, 1984; Edmonds and Williams, 1985; Edwards, 1999), and in south Glamorgan (Richardson, 1905; Ivimey-Cook, 1974; Waters and Lawrence, 1987). Others occur on the south Devon coast [SY 270 894], east of Seaton (Richardson, 1906; Gallois, 2001), and adjacent to the Bristol Channel or lower River Severn, for example in cliffs at Aust [ST 5645 8920] (Reynolds, 1946; Hamilton, 1977), Garden Cliff, Westbury-on-Severn [SO 719 126] (Etheridge, 1865; Benton et al., 2002) and Wainlode [SO 847 259] (Worssam et al., 1989).

Elsewhere, the formation is poorly exposed and is known largely from boreholes and temporary excavations. A good section is currently (2005) seen in the British Gypsum Bantycock opencast mine [SK 8123 4949] near Newark, Nottinghamshire. Information on inland outcrop or borehole sections elsewhere in England and south Wales is mostly contained, or cited, in memoirs or other publications of the Geological Survey. An occurrence in the Carlisle Basin has been documented by Ivimey-Cook et al. (1995)

Lithology
The formation typically comprises pale green-grey, dolomitic, silty mudstones and siltstones with thin argillaceous or arenaceous laminae and lenses and a few thin, commonly discontinuous, beds of hard, dolomitic, pale-cream to buff, porcellanous mudstone and siltstone ('Tea Green Marl' of Etheridge, 1865). In southern England

and Wales only, the ‘Tea Green Marl’ is overlain by the ‘Grey Marls’ (Richardson, 1906). This unit (equivalent to the upper part of the Rydon Member and the whole of the Williton Member of Mayall, 1981) comprises grey, black, green and, rarely, red-brown dolomitic mudstones with, in the higher beds, yellowish grey dolostones; also present are laminated siltstone beds with mudcracks, scarce pseudomorphs after halite, and locally abundant gypsum; miospores occur sporadically, and bivalve fossils and bioturbation occur locally in the upper beds.

Lower boundary

The lower boundary of the Blue Anchor Formation is placed at an abrupt or rapidly gradational upward transition from the red-brown, silty mudstones of the Branscombe Mudstone Formation to green or grey-green, dolomitic mudstones of the Blue Anchor Formation. Locally in southern England and Wales, a more gradational transition occurs above interbedded red and green lithologies (e.g. on the west Somerset and south Devon coasts); in these areas the boundary is drawn above the highest significant red mudstone bed. In south Devon, this coincides with a prominent bed of dolomitic limestone (Gallois, 2001). The boundary may be locally erosional around the margins of the London–Brabant Massif (Horton et al., 1987; Old et al., 1987).

Where not exposed, the boundary is marked by a change in soil colour from the reddish brown clayey soils of the Branscombe Mudstone Formation to the grey clayey soils of the overlying Blue Anchor Formation. Typically, this boundary lies near the base of a scarp slope formed by the Blue Anchor Formation and capped by the Penarth Group.

Upper boundary

Slighty unconformable or disconformable, the upper boundary is marked by an abrupt upward transition from green or grey-green, dolomitic mudstones of the Blue Anchor Formation to black, fossiliferous shales of the Westbury Formation (Penarth Group). The unconformity surface is commonly slightly irregular and small clasts of Blue Anchor Formation lithologies may occur at the base of the Westbury Formation. The Blue Anchor Formation is both burrowed and bored to a depth of several centimetres below the boundary. In parts of southern England and Wales (e.g. on the west Somerset coast) the upper part of formation (Williton Member; Mayall, 1981) includes lithologies similar to those of the overlying Westbury Formation, giving rise to an apparently gradational and interdigitating upper boundary.

Where not exposed, the boundary is marked by a change in soil type from the generally paler grey clays associated with the Blue Anchor Formation outcrop to the darker grey clays of the overlying Westbury Formation of the Penarth Group. Typically, this boundary lies about half way up a scarp slope capped by limestones of the Penarth Group and lowermost Lias Group.

Thickness

Type section: 36.54 m (Warrington and Whittaker, 1984); primary reference section: 31.18 m Warrington and Ivimey-Cook, 1995).

Maximum recorded thickness: 67.20 m, Winterborne Kingston Borehole, Dorset (Rhys et al., 1982), inferred from geophysical logs.

Elsewhere, the formation typically ranges from 5 to 20 m; it is generally thinner (7 to 10 m) in the more northerly basins.

Age

Late Triassic; late Norian to early Rhaetian on palynological evidence

Equivalent units

Upper part of the Triton Formation, Southern North Sea Basin (Johnson et al., 1994)

Geographical extent

The formation is the highest unit of the Mercia Mudstone Group in the British Isles. The outcrop extends northwards from the south Devon coast, through Somerset, Gloucestershire, Worcestershire, Warwickshire, Leicestershire, Nottinghamshire and Lincolnshire, into Yorkshire. Other outcrops occur in Gwent and Glamorgan, south Wales, and in the Needwood, Cheshire and Carlisle basins. Outcrops in south Devon and Lincolnshire and Yorkshire are in spatial continuity with occurrences of equivalent units offshore in the English Channel and Southern North Sea basins.

Subdivisions

Rydon Member (Mayall, 1981)
Williton Member (Mayall, 1981)

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

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Appendix

List of boreholes

Name	Number	Grid reference and location
Asfordby Hydrogeological	SK72SW/71	[SK 7252 2061] Asfordby, Leicestershire
Chard	ST30NW/7	[ST 3430 0653], south Devon
Cranborne	SU00NW/1	[SU 03408 09073], Hampshire
Cropwell Bridge	SK63NE/28	[SK 6773 3547], Nottinghamshire
Eldersfield	SO73SE/6	[SO 7891 3221], Eldersfield, near Tewkesbury, Gloucestershire
Fulbeck F/B1	SK85SE/25	[SK 8889 5053], Fulbeck, Lincolnshire
Hanbury 1	SK12NW/32	[SK 1484 26200], near Burton-on-Trent, Staffordshire
Home Farm	SP47SW/72	[SP 4317 7309], near Rugby, Warwickshire
Kirkham	SD43SW/6	[SD 4324 3247], Lancashire
Knights Lane	SP25SW/1	[SP 2242 5497], Stratford-upon-Avon, Warwickshire
Knutsford	SJ77NW/4	[SJ 7027 7786] Cheshire
Leicester Forest East	SK50SW/71	[SK 5245 0283], Leicestershire
Netherton	SO94SE/1	[SO 9982 4075], Worcestershire
Nettlecombe	SY59NW/1	[SY 5052 9544], Dorset
Seaborough 1	ST40NW/1	[ST 4348 0620], Dorset
Staithes No. 20	NZ71NE/14	[NZ 76034 18000], Boulby mine site, North Yorkshire
Stowell Park	SP01SE/1	[SP 0835 1176], Gloucestershire
Thornton/Cleveleys	SD34SW/15	[SD 3310 4410], Lancashire
Twycross	SK30NW/13	[SK 3387 0564], Twycross, Leicestershire
Twyning	SO83NE/5	[SO 8943 3664], Twyning, near Tewkesbury, Gloucestershire
Winterborne Kingston	SY89NW/1	[SY8470 9796], Dorset
Wilkesley	SJ64SW/7	[SJ 6286 4144], Cheshire
Windyharbour	SK04SE/16	[SK 0854 4100], Staffordshire
Wiscombe Park 2	SY19SE/2	[SY 18449 92734], south Devon
Worcester	SO85NE/23	[SO 8624 5762], Worcestershire

47/3–1, offshore southern North Sea, 70 km east of Kingston-upon-Hull

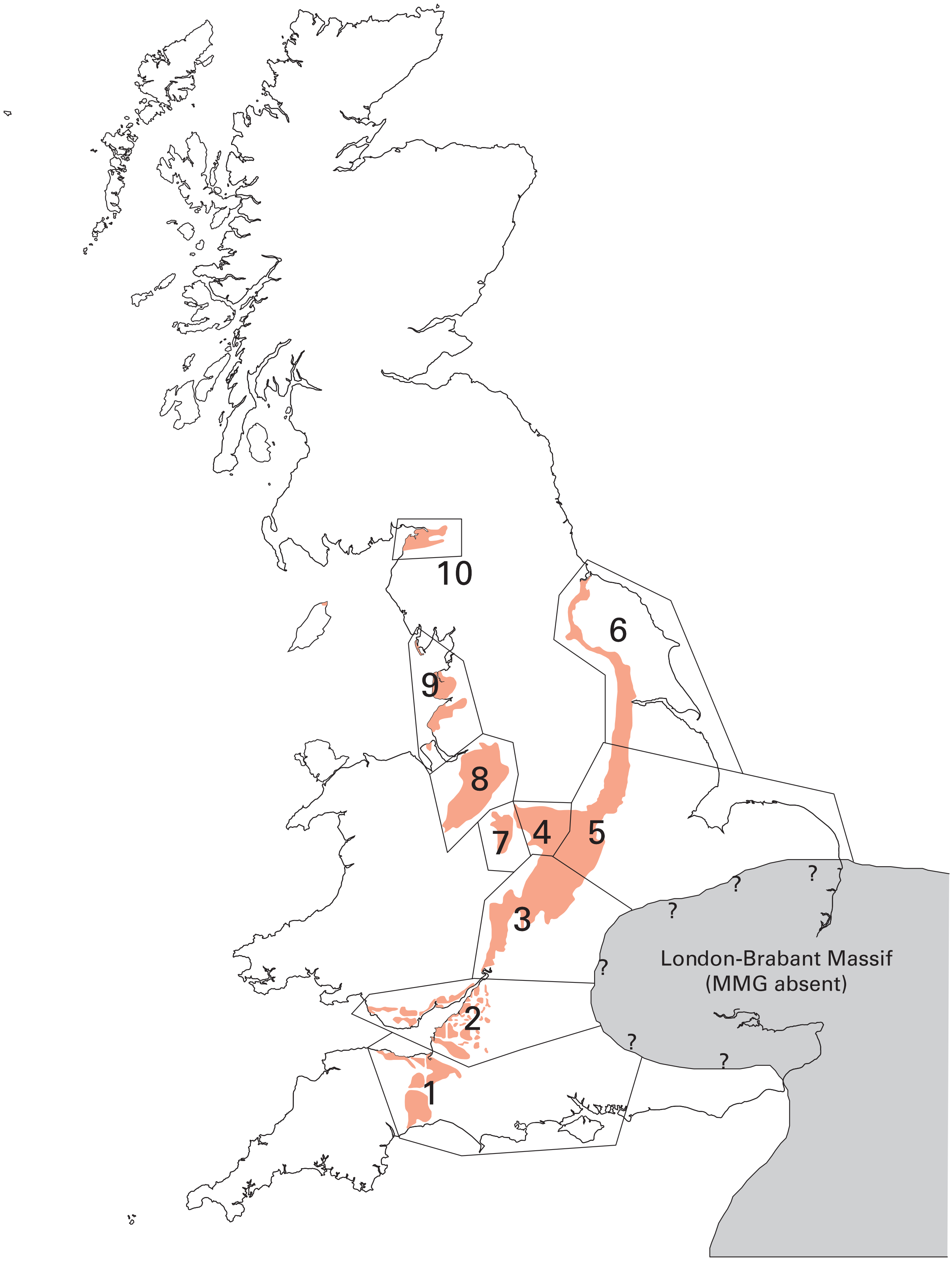

Figure 1 Outcrop of the Mercia Mudstone Group in England and Wales. The numbered regions are as follows: 1 Wessex Basin; 2 Bristol/South Wales; 3 Worcester/Knowle Basins; 4 Needwood Basin; 5 East Midlands Shelf (South); 6 East Midlands Shelf (North); 7 Stafford Basin; 8 Cheshire Basin; 9 West Lancashire; 10 Carlisle Basin

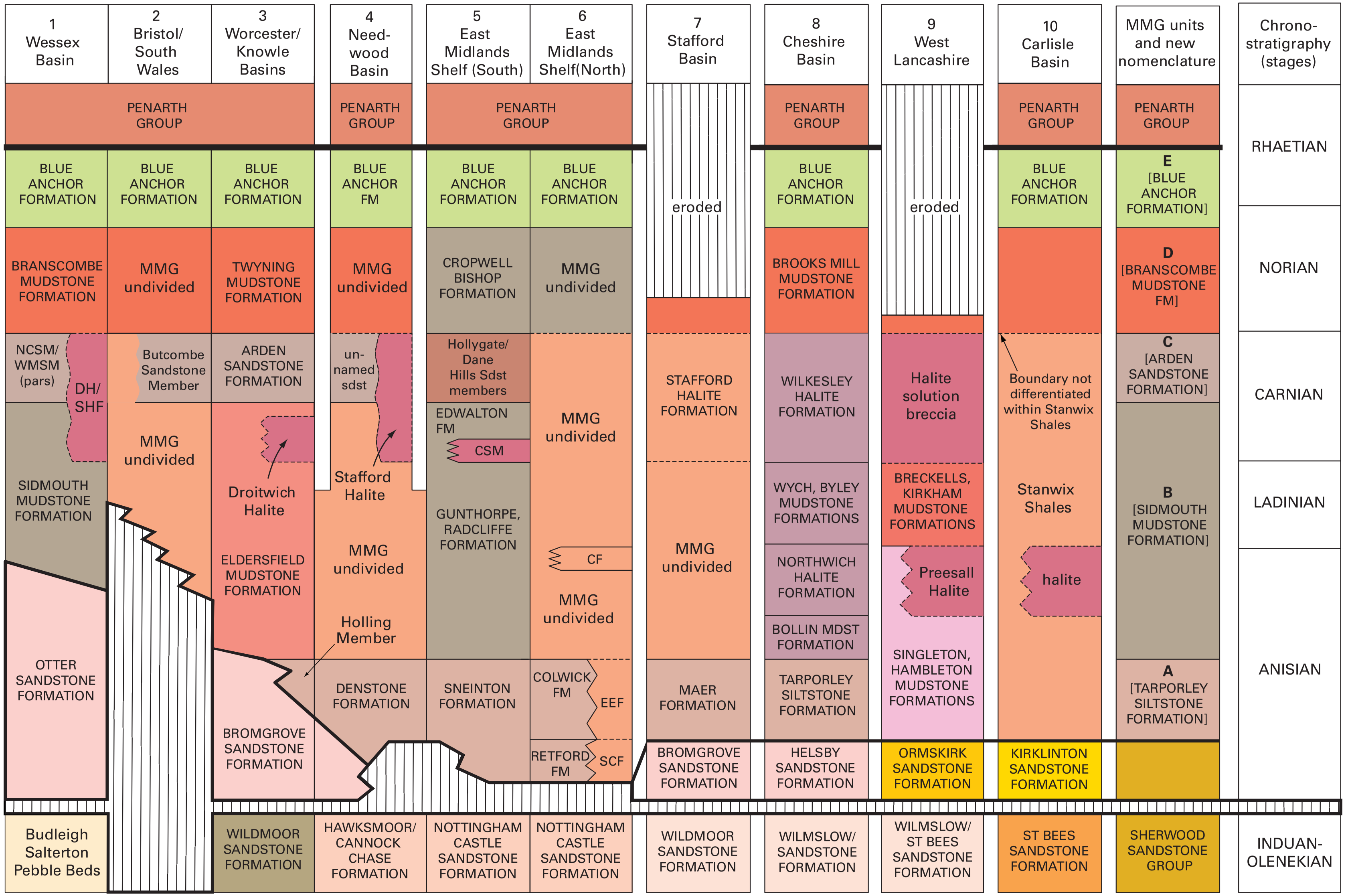

Figure 2 Summary of current Mercia Mudstone Group lithostratigraphy, showing relationship of previous names to the revised nomenclature defined in this report. Gaps between columns denote geographical separation of basins. Broken lines indicate boundaries proved only in boreholes.
CF Clarborough Formation; CSM Cotgrave Sandstone Member; DH Dorset Halite; EEF Esk Evaporite Formation; MMG Mercia Mudstone Group; NCSM North Curry Sandstone Member; SCF Seaton Carew Formation; SHF Somerset halite Formation; WMSM Weston Mouth Sandstone Member
Fm Formation; sdst sandstone

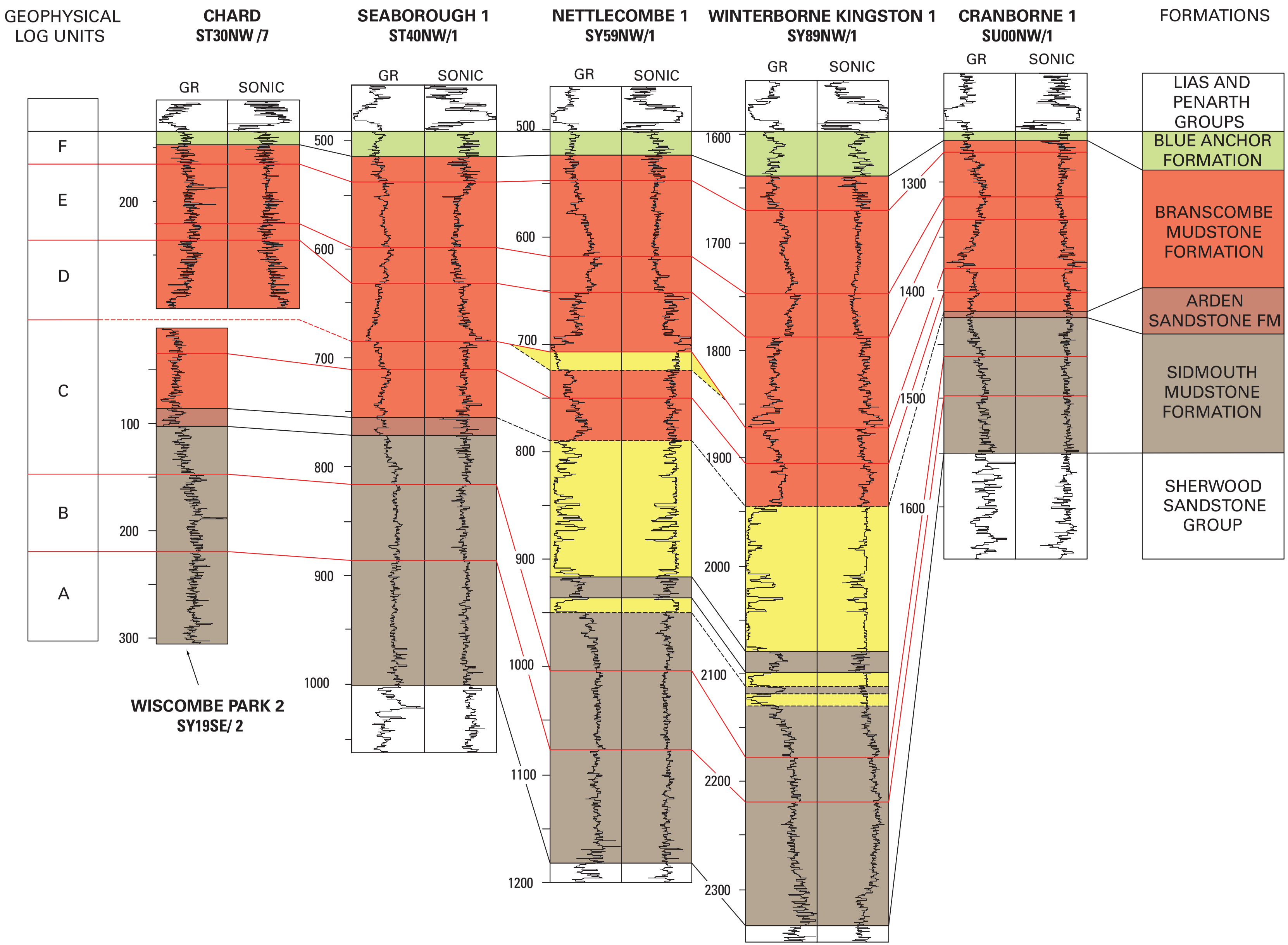

Figure 3 Geophysical log correlation of boreholes proving the Mercia Mudstone Group in the Wessex Basin. Yellow represents interpreted halite units. Red tie-lines represent basin-wide geophysical log markers; log units recognised by Lott et al. (1982) are shown in the left hand column.

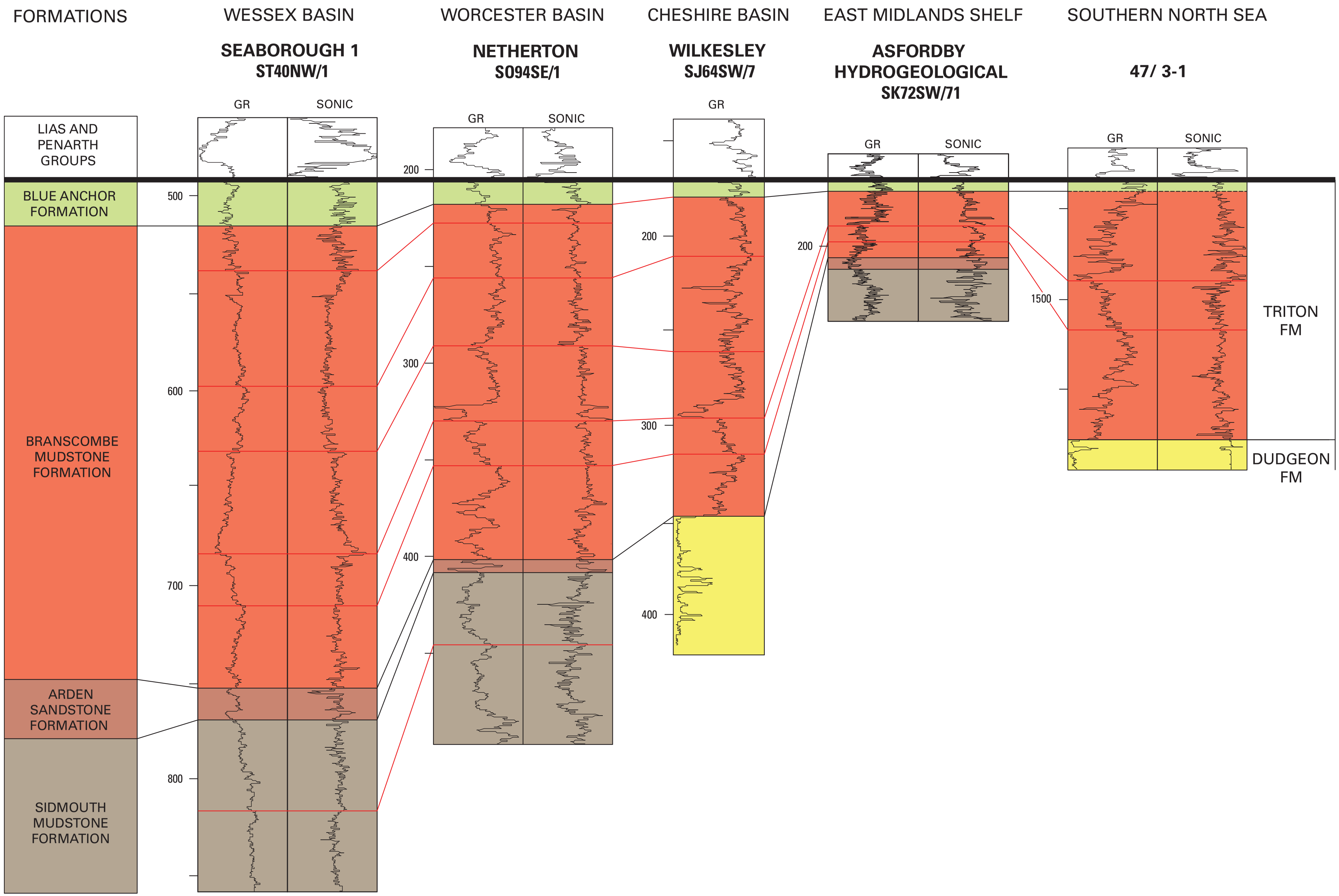

Figure 4 Geophysical log correlation of the upper part of the Mercia Mudstone Group in selected boreholes from major basins. Yellow units represent halite. The red tie-lines correspond to geophysical log markers identified in the Wessex Basin (see Figure 3). Borehole 47/3-1 was drilled in the southern North Sea approximately 70 km east of Kingston-upon Hull.

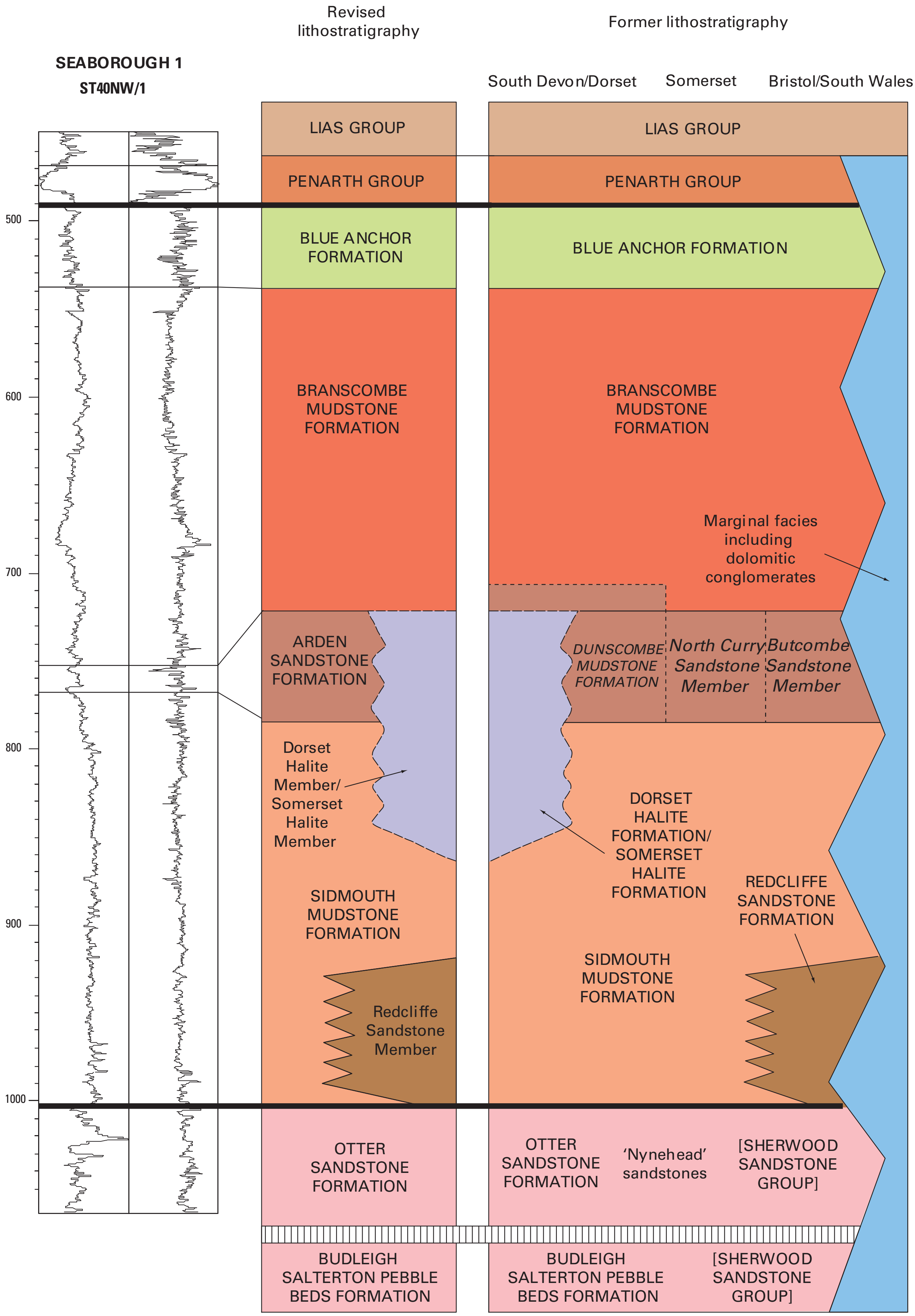

Figure 5 Mercia Mudstone lithostratigraphy of south-west England. Names shown in italics are abandoned in the revised scheme. Boundaries shown as broken lines are identified in boreholes only, others can be mapped at surface. Depths on borehole logs are in metres. Lithostratigraphical columns not to scale.

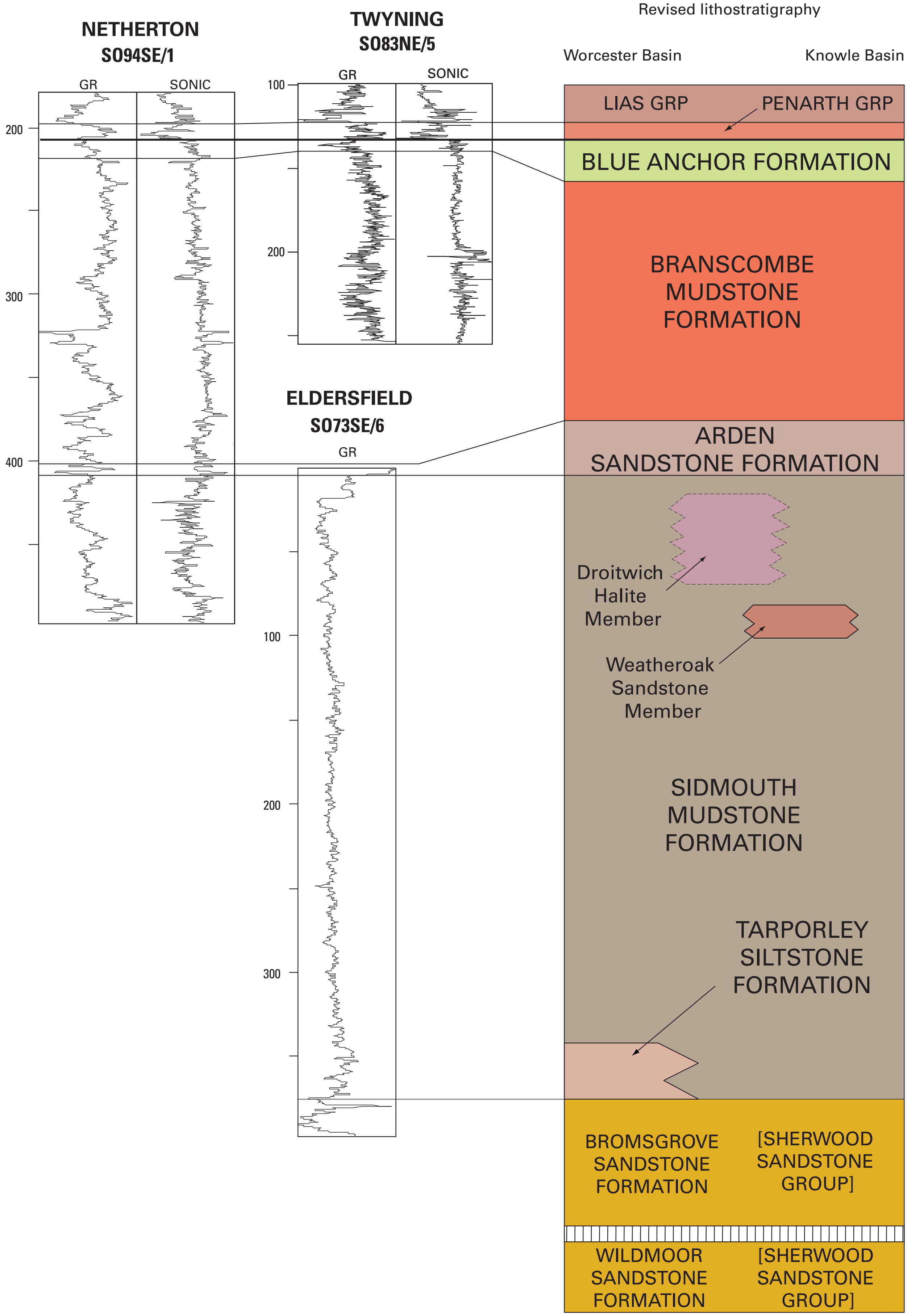

Figure 6 Mercia Mudstone lithostratigraphy of the Worcester and Knowle basins. Boundaries shown as broken lines are identified in boreholes only, others can be mapped at surface. Depths on borehole logs are in metres. Lithostratigraphical column not to scale.

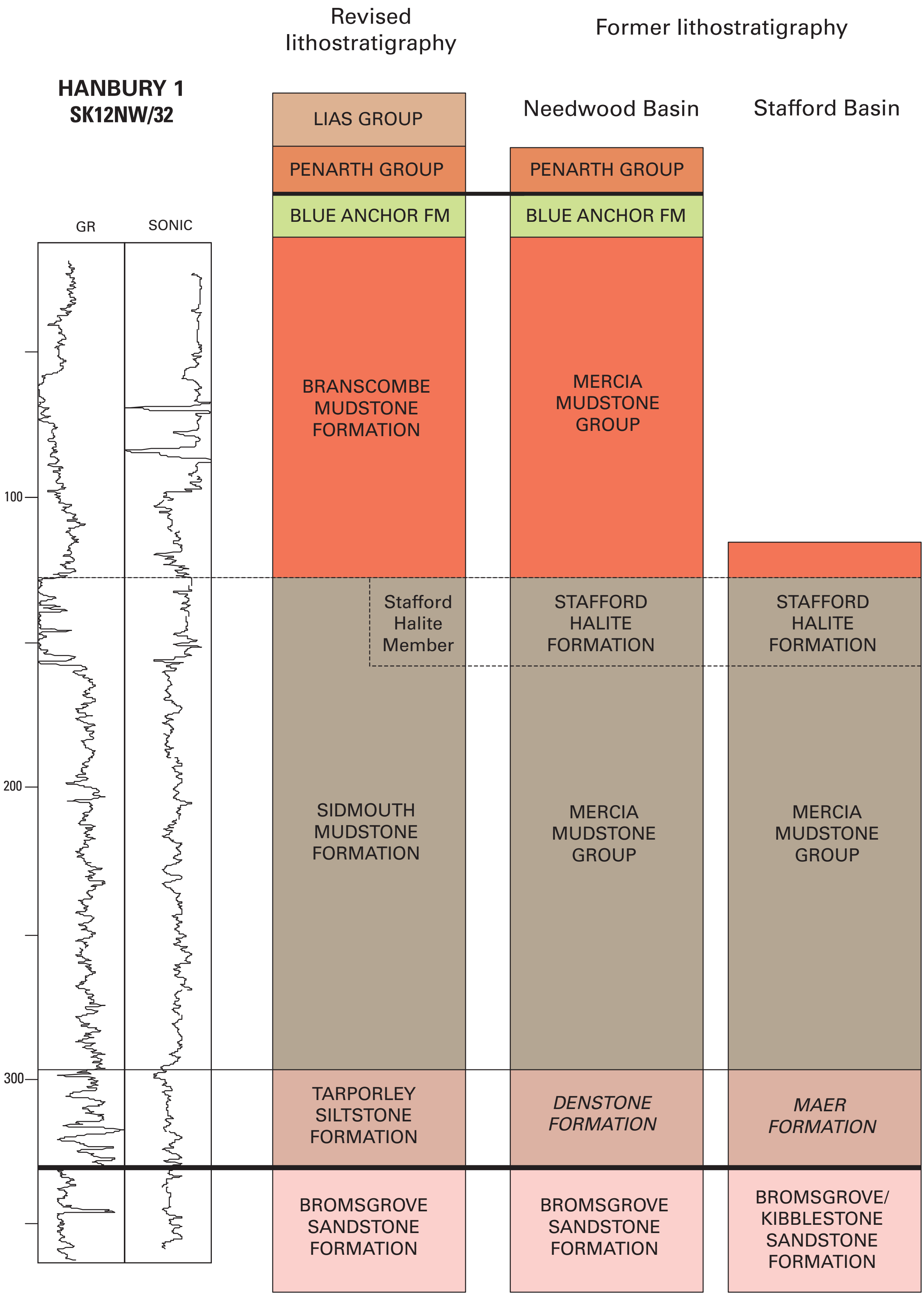

Figure 7 Mercia Mudstone lithostratigraphy of the Needwood and Stafford basins. Existing formation names shown in italics are abandoned in the revised scheme. Boundaries shown as broken lines are identified in boreholes only; others can be mapped at surface. Depths on borehole logs are in metres. Lithostratigraphical columns not to scale.

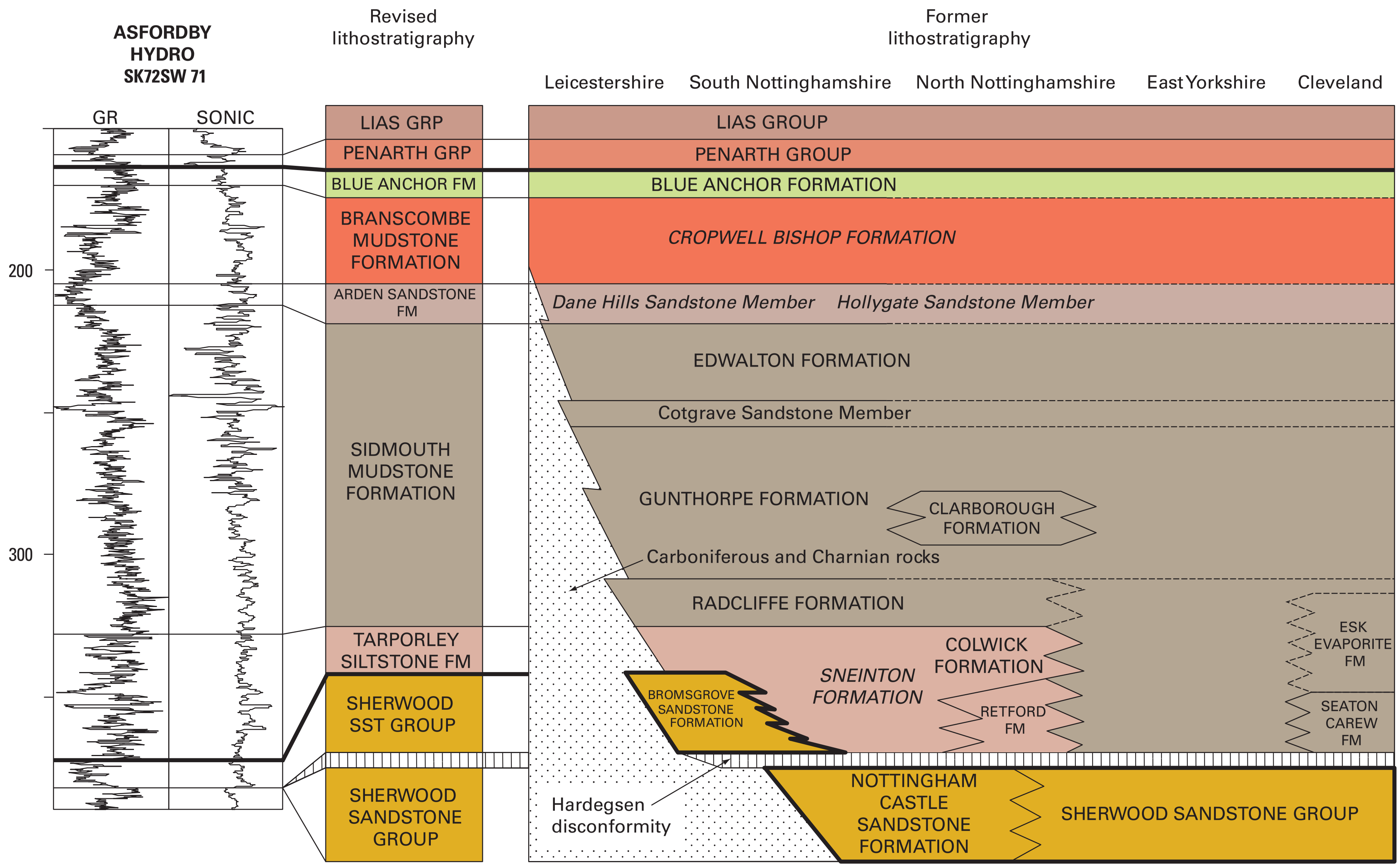

Figure 8 Mercia Mudstone lithostratigraphy of the East Midlands Shelf. Existing formation names shown in italics are abandoned in the revised scheme; names in bold are retained as members. Boundaries shown as broken lines are identified in boreholes only, mainly by geophysical log markers; others can be mapped at surface. Lithostratigraphical columns are not to scale.

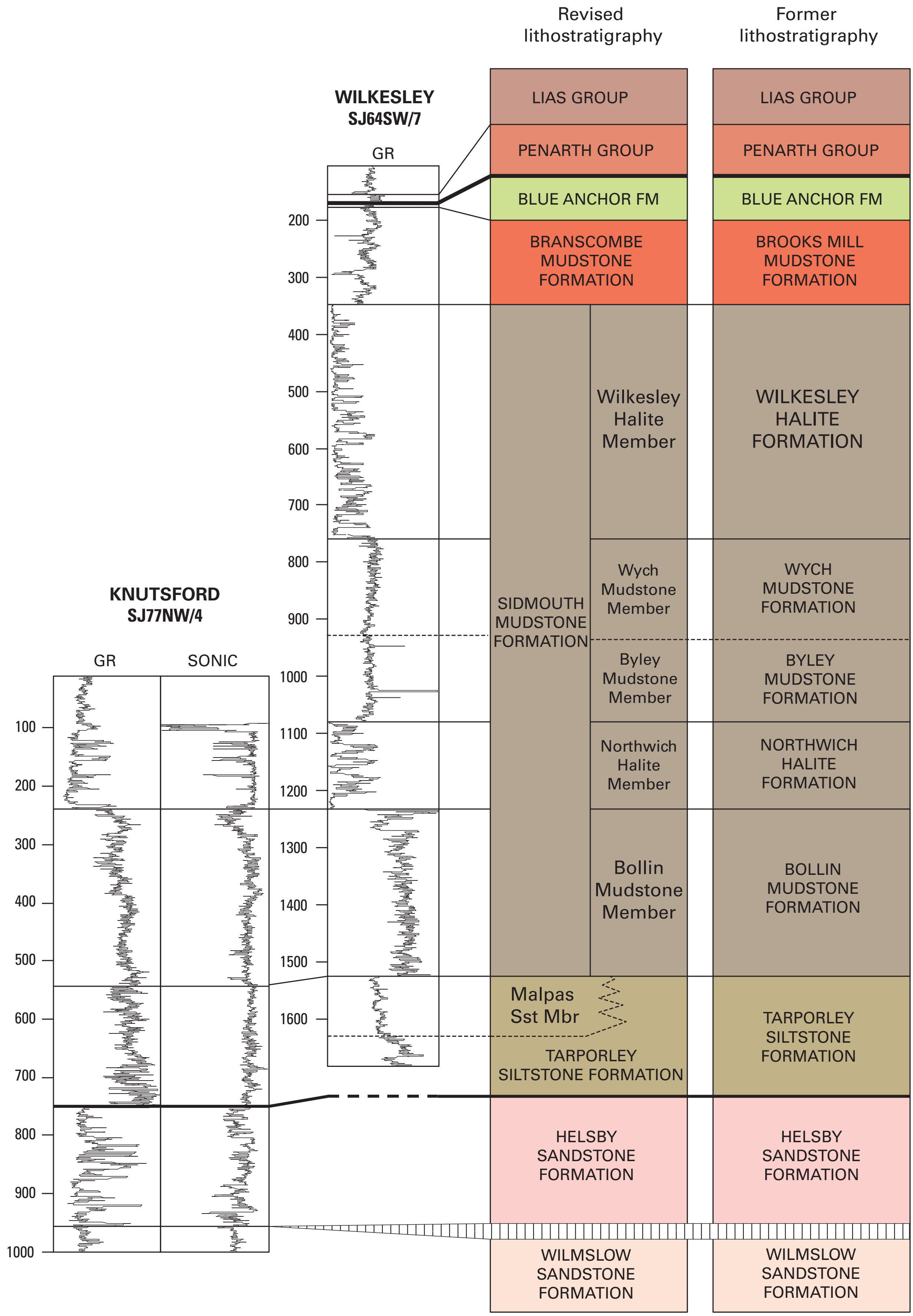

Figure 9 Mercia Mudstone lithostratigraphy of the Cheshire Basin. Boundaries shown as broken lines are identified in boreholes only, others can be mapped at surface. Depths on borehole logs are in metres. Lithostratigraphical columns not to scale.

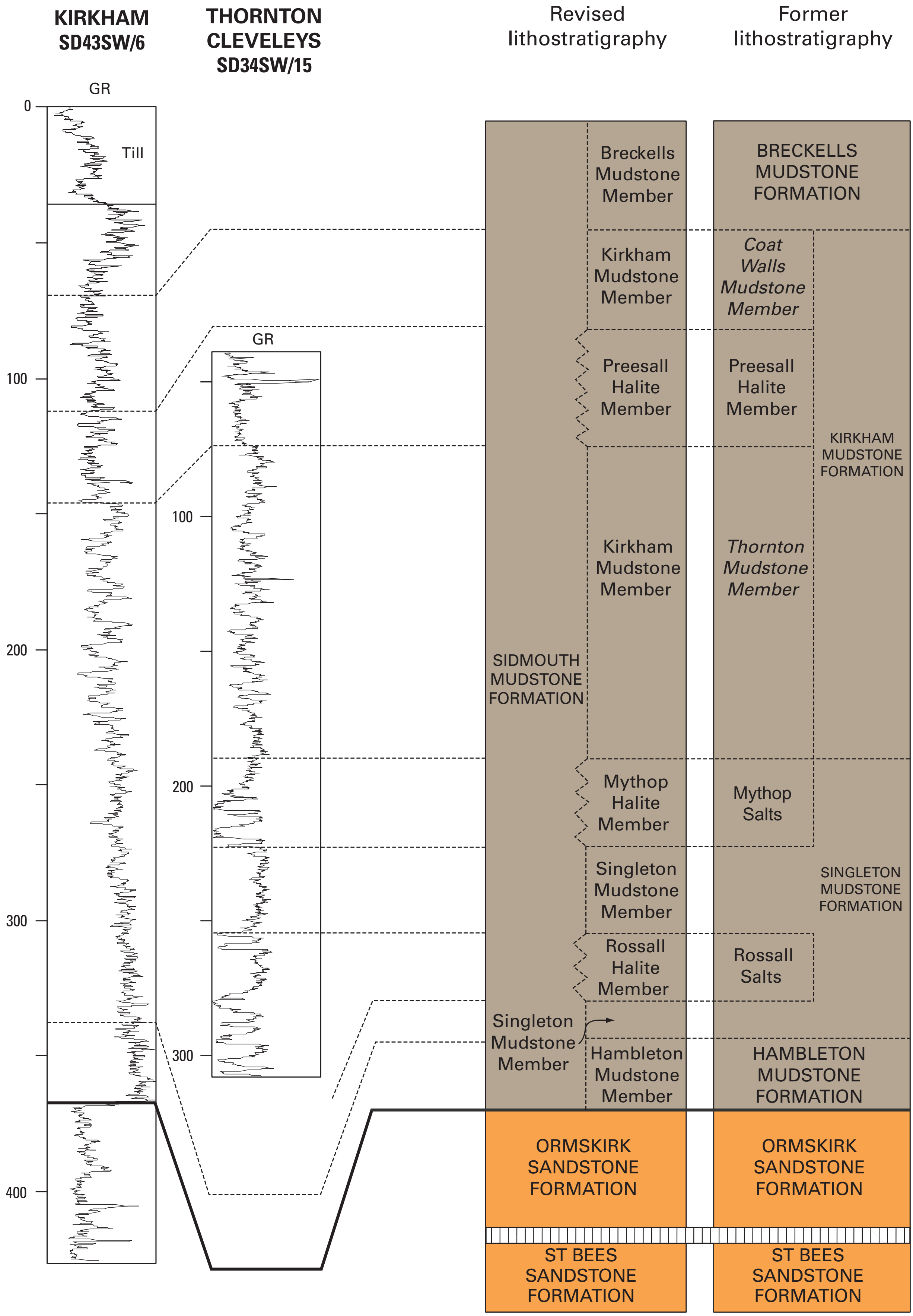

Figure 10 Mercia Mudstone lithostratigraphy of west Lancashire. Existing names shown in italics are abandoned in the revised scheme. All boundaries in the Mercia Mudstone are recognised only in boreholes. Depths on borehole logs are in metres. Lithostratigraphical columns not to scale.

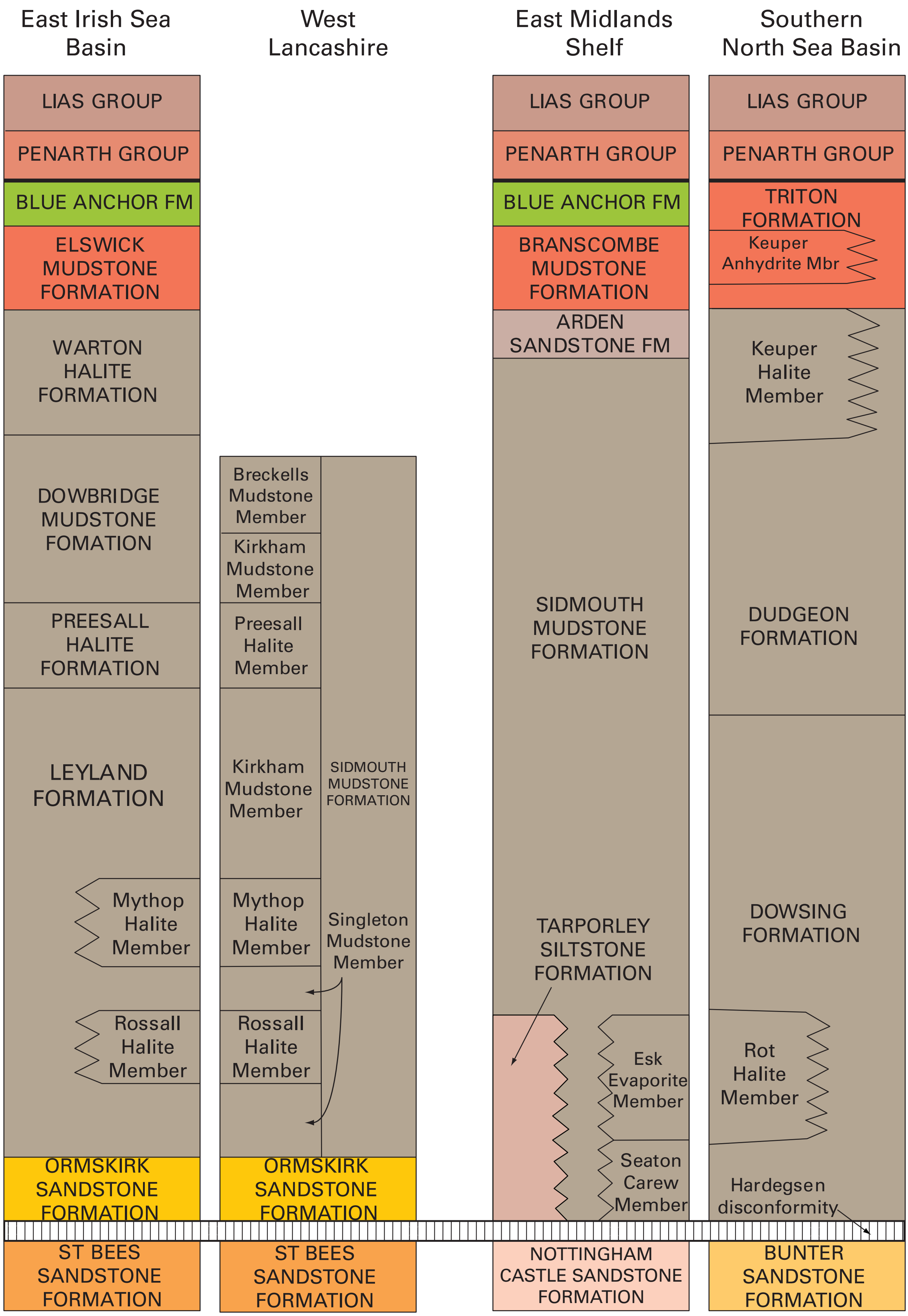

Figure 11 Correlation of revised Mercia Mudstone lithostratigraphy with that of contiguous offshore basins. East Irish Sea Basin after Jackson et al. (1997); Southern North Sea Basin after Johnson et al. (1994).