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Lithostratigraphy of the Sherwood Sandstone Group of England, Wales and south-west Scotland

Geology and Regional Geophysics Directorate

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Lithostratigraphy of the Sherwood Sandstone Group of England, Wales and south-west Scotland

K Ambrose, E Hough, N J P Smith, and G Warrington

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Front cover

Chester Formation sandstone at Shepley Quarry. Sandstones high in the Chester Formation, Sherwood Sandstone Group. Medium-grained, gently cross-bedded sandstones containing occasional beds of fine conglomerate with 'Bunter' quartzite pebbles. P212558

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1 Introduction

In England, the Sherwood Sandstone Group (SSG; Warrington et al., 1980) is present continuously at the surface and at subcrop from the south Devon coast northwards to Teesside on the north-east coast, Lancashire and Cumbria on the north-west coast, and in the Vale of Eden (Figures 1 and 2). Outcrops occur mainly in east Devon, Somerset, the central and south Midlands (Gloucestershire, Worcestershire, Warwickshire, Leicestershire, Staffordshire, south Derbyshire and north Shropshire), Cheshire, Lancashire, Cumbria, Nottinghamshire, Yorkshire and Durham. The SSG also occurs in south-west Scotland, in Dumfries and Galloway, and on the Isle of Arran. Rocks currently assigned to the Group also crop out in Clwyd, North Wales (Figures 1 and 2). Deposition occurred principally in a number of actively subsiding¸ fault-bounded continental basins (Figure 1); thinner sequences formed in the intervening areas. The current nomenclature for the constituent formations of the SSG reflects distinct depositional areas, with many local names currently in use on BGS maps and in literature. Lithological similarity and borehole geophysical logs have been used to demonstrate continuity of formations between basins and this, combined with the need for a more unified stratigraphical approach for the BGS DiGMapGB and 3D modelling studies, has necessitated this review of the SSG nomenclature. The aim of this discussion document is to determine the scope for rationalising the formation names used in BGS publications and thereby achieve a more unified lithostratigraphical scheme for the Group.

The SSG of England, Wales and south-west Scotland is composed mainly of brown, red, buff, greenish grey and yellow sandstones, commonly with colour mottling. Extra- and intraformational clasts are common in the lower part and are scattered throughout some of the higher formations. Extraformational clasts become less common northwards into Cheshire, south Lancashire, Nottinghamshire and South Yorkshire. Much of the succession is of fluvial origin, deposited from fast-flowing braided rivers that were superseded by meandering river systems in which fining-upward cycles, with subordinate beds of mudstone, were deposited (Warrington, 1970a; Old et al., 1991; Warrington and Ivimey-Cook, 1992; Powell et al., 2000). Aeolian units occur in east Devon, Cheshire, Lancashire, Cumbria, south-west Scotland, the Isle of Arran and offshore, below the East Irish Sea. They may be present but unrecognised in other areas. Palaeontological evidence of temporary marine influence occurs in the upper part of the SSG (Finstall and Sugarbrook members of the Bromsgrove Sandstone Formation) in Oxfordshire, north Worcestershire and south Warwickshire (Warrington, 1967, 1970a, p.21 *in* Williams and Whittaker, 1974; Ivimey-Cook, p.13 *in* Poole, 1978; Old et al*.,* 1991; Benton et al., 1994).

Breccias of Permian and Triassic age occur at the base of the arenaceous sequence but of these, only the Huntley Formation (Ashbourne district, sheet 124; Chisholm et al*.,* 1988) is currently included within the SSG. The Moira Formation in Leicestershire and Derbyshire is demonstrably diachronous, interdigitating with at least two SSG formations in the Coalville (Sheet 155; Worssam and Old, 1988) and Loughborough (Sheet 141; Carney et al., 2001) districts; in the Derby district (Sheet 125; Frost and Smart, 1979) it underlies the Tarporley Siltstone Formation of the Mercia Mudstone Group (MMG). The age range of these breccias is uncertain and they may span the Permian–Triassic boundary. They always occur in isolation from underlying rocks of known Permian age (Appleby, Cumbrian Coast and Zechstein groups), so their relationship to those is not known.

The lower parts of some continuous arenaceous sequences currently included in the SSG are possibly partly of Permian age. These include the Lenton Sandstone in the East Midlands and the Kinnerton Sandstone in the Cheshire Basin (Warrington et al*.,* 1980).

The base of the SSG is currently defined in the BGS Lexicon of Named Rock Units as 'Gradational on the Roxby Formation (formerly the Permian Upper Marls) in the type area of Sherwood Forest, Nottinghamshire, and similar relationship elsewhere, but sharp and unconformable on Carboniferous or older rocks locally'. However, there is a disconformable relationship with the Lenton Sandstone Formation in the eponymous area of Sherwood Forest, Nottinghamshire, and in the West Midlands the

SSG overlies the aeolian Permian Bridgnorth Sandstone Formation; in east Devon, Lancashire and Cumbria it overlies other beds of Permian age. A revised definition is needed to take these variations into account.

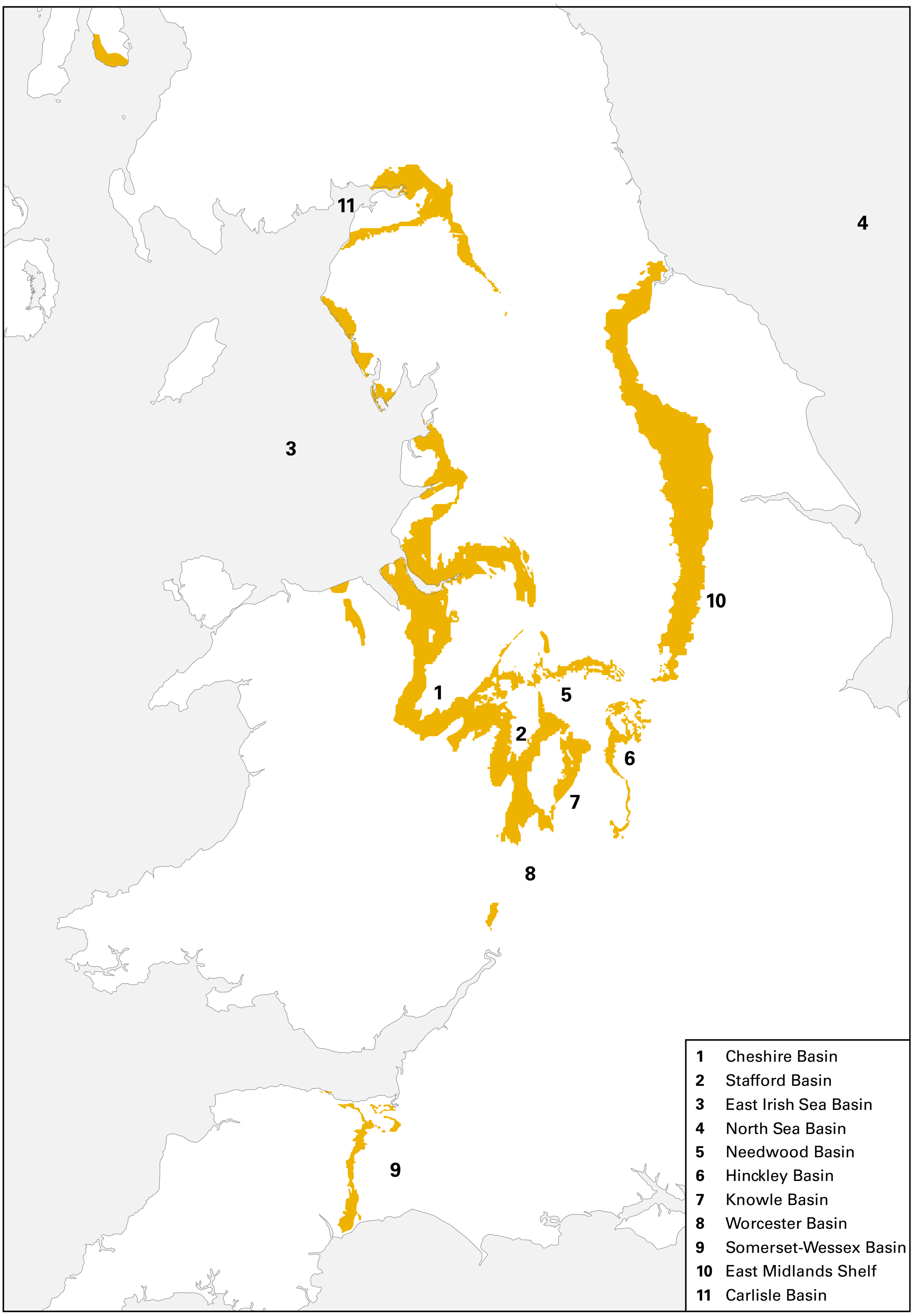

Figure 1 Outcrop of the SSG (onshore only).

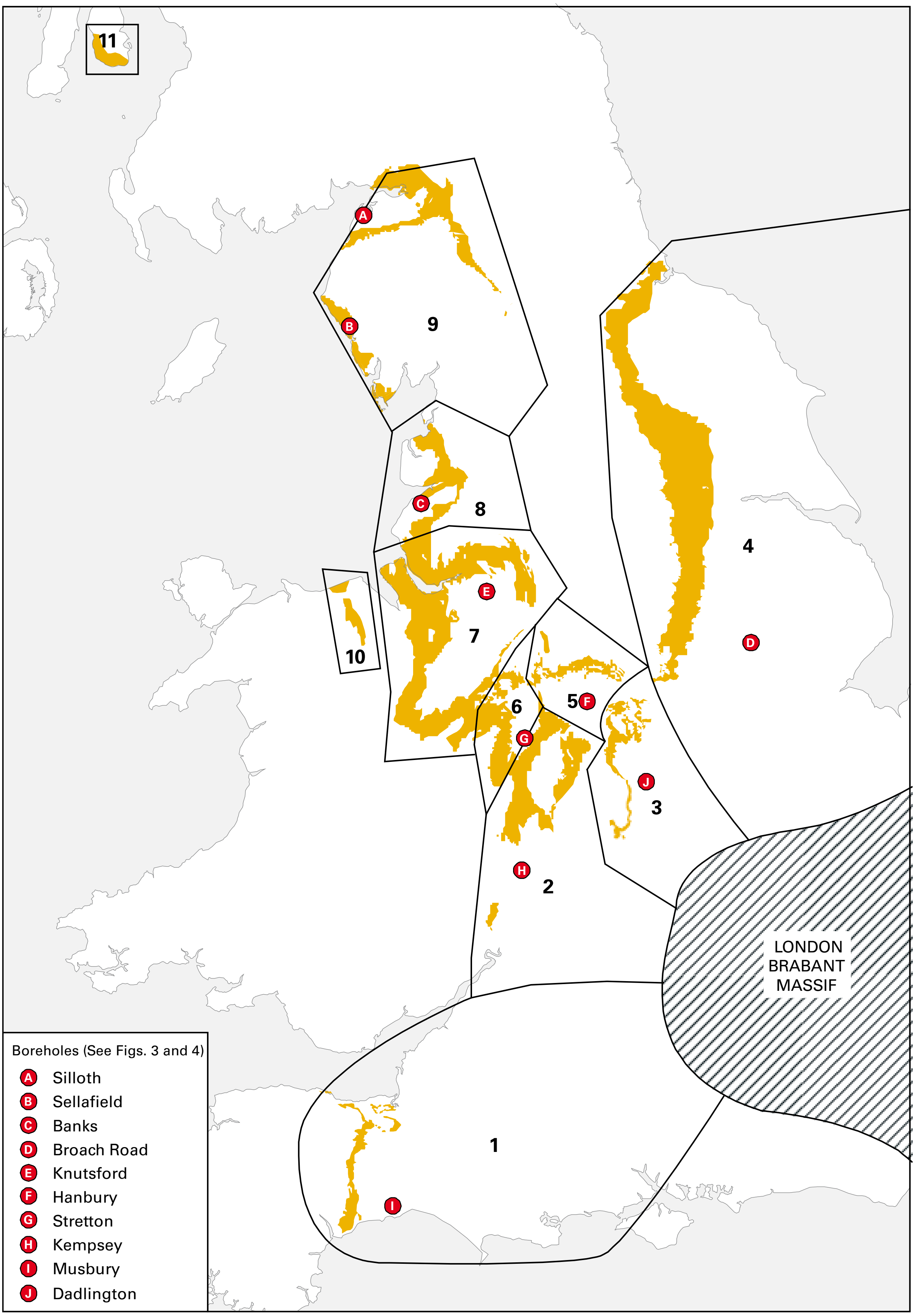

Figure 2 Map showing the 11 regions of the SSG review.

The top of the SSG, and the base of the MMG, is placed 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 diachronous, younging towards the south' (Howard et al., 2008; see also Warrington, 1970b; Warrington and Ivimey-Cook, 1992; Herries and Cowan, 1997; Thompson and Meadows, 1997; Meadows, 2006, fig.8). In the East Midlands, the boundary is sharp and unconformable (Warrington, 1974, fig. 40). In Devon, the boundary is conformable (Gallois, 2004).

The total thickness of the SSG is highly variable. The Knutsford Borehole (Warrington et al. 1999), in Cheshire, proved an incomplete sequence of 1330 m. The thickest known complete sequence is 945.2 m in the Kempsey Borehole (Barclay et al., 1997) Worcestershire, from where substantial thinning occurs towards the south-west, and to the east and south-east where the SSG is overlapped by the MMG around the London–Brabant Massif (Figure 2; Holloway, 1985).

The SSG ranges in age from latest Permian (?) and Early Triassic (Induan to Olenekian) to early Mid Triassic (Anisian). It overlies rocks that range in age from Precambrian to Permian and possibly earliest Triassic.

1.1 TECTONIC AND DEPOSITIONAL SETTING

During Permian and Triassic times, Britain lay in the interior of the Pangaea supercontinent, to the north of the Variscan mountain chain. Both Pangaea and the Variscan mountains were the product of continental collision in the late Carboniferous but, by the early Permian, Pangaea was showing signs of breaking apart. In what is now southern, central and north-west England, crustal tension led to the formation of a series of fault-bounded basins (e.g. McLean, 1978; Chadwick and Evans, 1995; Chadwick, 1997). In contrast, eastern England lay at the western margin of a much larger depocentre (the 'Southern Permian Basin' area; Bachmann et al., 2010) that extended eastwards to Poland. These basins influenced deposition throughout the Permian and Triassic periods. In the Early Triassic, rain falling on the Variscan mountains in northern France fed a major river system that flowed northwards across southern Britain and deposited the thick sequences of sands and gravels that form the SSG (e.g. Wills, 1956, 1970; Audley-Charles, 1970; Warrington, 1970a; Warrington and Ivimey-Cook, 1992; Tyrell et al., 2012). Deposition of the lower formations of the SSG was dominantly fluviatile and largely restricted to the basins, although sediments were transported across the intervening highs; a subordinate part of the succession is likely to be aeolian. However, the upper formations of the SSG, which include both aeolian and fluvial sandstones, overlapped progressively onto the adjacent highs. Temporary marine influence is evident locally in the upper SSG in the Midlands (see **1.2**), and marine environments, represented initially by intertidal deposits in the basal (Tarporley Siltstone) formation of the MMG (e.g. Ireland et al., 1978), gradually encroached on areas of previously mainly fluvial deposition. There is palaeontological and geochemical evidence of marine influence during deposition of the MMG until the end of Carnian times (Warrington, 1970b, 1981; Warrington and Ivimey-Cook, 1992).

1.2 STRATIGRAPHICAL OVERVIEW

The lithostratigraphical classification of Triassic rocks in England and Wales currently adopted by BGS is based on a review carried out by the Triassic Working Group of the Geological Society of London between 1967 and 1979 (Warrington et al., 1980). The terms 'Bunter' and 'Keuper', based on an inferred time correlation with the German Triassic sequence, were abandoned in favour of a rigorous lithostratigraphical approach using the gross lithological characteristics of the various rock units. Parts of the former 'Lower Mottled Sandstone', and all of the former 'Bunter Sandstone', 'Upper Mottled Sandstone' and 'Lower Keuper Sandstone' were combined into the SSG, with the MMG corresponding closely, but not exactly, with the former 'Keuper Marl'.

In some regions, strata of known or probable Permian age have, in the absence of preserved stratigraphical marker beds, been included within the SSG (e.g. the Kinnerton Sandstone of the Cheshire

Basin). In other areas, strata of Permian age are included in the older Exeter and Aylesbeare (Devon), Appleby and Cumbrian Coast (north-west England), and Rotliegendes and Zechstein (East Midlands and north-east England) groups (see 3.2*)*. The current situation is confusing, with sandstones of similar lithology and age being included in different groups. A resolution of this inconsistency is proposed, whereby the SSG does not include units of known or inferred Permian age, and with an upwards change from aeolian to dominantly fluvial sedimentation being a main criterion for defining the base of the SSG.

Chronostratigraphical subdivision and correlation of Triassic rocks in England, Wales and Scotland is hampered by a scarcity of age-diagnostic fossils. The few fossils known from the lower formations of the SSG comprise mostly vertebrate footprints and other trace fossils; a few crustaceans (*Euestheria*) and a fragment of a fish have also been recorded (Wills, 1970; Warrington and Thompson, 1971; Warrington, 1976; Old et al., 1991; Bridge and Hough, 2002). However, in Devon, Gloucestershire, Oxfordshire, Warwickshire, Worcestershire, Staffordshire and Shropshire, the youngest formation has yielded more diverse fossil assemblages. In east Devon, the Otter Sandstone Formation has yielded remains of fish, amphibians and reptiles, in addition to some invertebrates (Benton et al., 1994, 2002). Miospores (plant spores and pollen) and plant debris occur in the Bromsgrove Sandstone Formation in Gloucestershire (Green and Melville, 1956; Warrington, 1970a) and, with *Euestheria*, a brachiopod (*Lingula*), a bivalve, and ostracods, in that formation in Oxfordshire (Worssam, 1963; Poole, 1969; Ivimey-Cook, p.13 *in* Poole, 1978; Warrington, p.22 in Poole, 1978). In north Worcestershire, the same formation has yielded trace fossils, marine microplankton (acritarchs), miospores, plant macrofossils, annelids, molluscs, *Euestheria*, arachnids and remains of fish, amphibians and reptiles; miospores, acritarchs and amphibian and reptilian remains also occur in this formation in south Warwickshire (Warrington, 1967, 1970a, p.21 *in* Williams and Whittaker, 1974, 1976; Old et al., 1987, 1991; Warrington and Ivimey-Cook, 1992; Benton et al., 1994, 2002; Barclay et al*.,* 1997; Powell et al., 2000). The *Euestheria* indicate fresh- to brackish-water conditions; other fossils (e.g. acritarchs and *Lingula*) are indicative of marine environments. In Shropshire (Benton et al., 1994) and Staffordshire (Chisholm et al., 1988) vertebrate remains have been recovered from the Grinshill Sandstone and Hollington formations respectively. In Cheshire the Helsby Sandstone Formation has yielded trace fossils, particularly vertebrate tracks known notably from the Wirral and Runcorn areas (Tresise and Sarjeant, 1997); miospores, macrofloral debris, and *Euestheria* also occur (Warrington et al., 1999).

A review of the borehole geophysical log signatures of the component units of the SSG in different parts of the UK forms part of this report (Figures 3, 4 and 5), with one log illustrating the signatures for each of regions 1 to 7, two for each of regions 8 and 9, but none for regions 10 and 11 (Figure 2), where such data is unavailable.

Many local names have been applied to the constituent formations of the SSG. These names, and their usage on BGS maps, reflect the following factors:

- original depositional restriction of units to individual basins;
- postdepositional, spatial isolation of formations by faulting or erosion;
- 'campaign boundaries' within the BGS mapping programme, resulting in different nomenclatures being introduced for different projects, often many years apart.

With a few notable exceptions, formation names within the SSG are unique to individual basins and in some cases to areas within basins (see Table 1).

1.3 APPROACH TO THE REVIEW

This review follows the approach established and published for the Mercia Mudstone Group by the BGS Stratigraphical Framework Committee (Howard et al., 2008). It aims to meet the following objectives:

- The requirement for a logical nomenclature that adequately describes the range of lithological variability within the SSG.

- The need for stability in nomenclature to avoid confusing users, especially those without specialist understanding of stratigraphical concepts.
- The need for a rationalised nomenclature that enables the compilation of reasonably coherent geological models of UK rock formations in both 2 and 3 dimensions.

Clearly, these objectives are potentially conflicting. In this discussion document the SFC presents three options for rationalising the lithostratigraphy of the SSG of England, Wales and south-west Scotland; in each, different weight is given to the above objectives. To define the options, the SFC has carried out the following analyses:

1. Identified, independently of current nomenclature, five 'framework units' (A to E: see **3.1** and **3.2)** within the SSG – these are units that were in three-dimensional stratigraphical continuity *prior* to any subsequent tectonism or erosion, and that meet the definition of a formation, as expressed in Whittaker et al. (1991) and Rawson (2002). Such units may be diachronous.
2. Determined the present three -dimensional spatial continuity of the 'framework units' in the SSG.
3. Identified the practical needs for rationalising different local names applied to the same 'framework units'. The problem of local names can often be accommodated on 'seamless' geological maps at surface by using convenient natural gaps in outcrop, structures (e.g. faults), or areas of superficial deposit cover to separate formations. This approach may not be applicable for bedrock geology maps or for subsurface models, where different local names for spatially continuous units would have to be separated by arbitrary boundaries of no apparent, or questionable, stratigraphical significance. Within the SSG many of the local names are confined to individual basins, although there is generally continuity of outcrop between the basins and in some areas the local names are used between basins.

2 Current lithostratigraphical framework

2.1 SPATIAL DISTRIBUTION OF THE SSG

The outcrop (Figure 1) of the SSG extends from the south Devon coast, northwards into Somerset. There are scattered isolated outcrops along the east side of the Malvern Hills, in Gloucestershire and Worcestershire. A continuous outcrop commences in north Worcestershire, near Droitwich, extends northwards into Staffordshire and north Shropshire, and encircles the South Staffordshire Coalfield and the Stafford Basin. A narrow outcrop on the south-eastern side of the Cheshire Basin expands around the southern and western sides of that basin and branches onto the Wirral and eastwards from Merseyside to Greater Manchester. From Merseyside it extends northwards, through west Lancashire, to the south side of Morecambe Bay. The outcrop is discontinuous on the north side of Morecambe Bay; it skirts the Cumbrian coast to Whitehaven, then reappears at Maryport from where it extends eastwards, on the south side of the Solway Firth and divides near Carlisle, southwards into the Vale of Eden and northwards to the north side of the Solway Firth in Scotland. The SSG also crops out on the Isle of Arran.

Eastwards from Worcestershire the outcrop extends through Warwickshire, on the eastern side of the Warwickshire Coalfield, into Leicestershire. Farther north it runs nearly continuously eastwards from Staffordshire, through south Derbyshire and into Nottinghamshire. It then forms a broad outcrop running northwards through Nottinghamshire, South, West and North Yorkshire and into Durham, reaching the coast on Teesside. Isolated outcrops occur in North Wales, in the Vale of Clwyd and around Rhyl. Two outliers occur in Staffordshire, in the Leek–Congleton area (Evans et al., 1968; Aitkenhead et al., 1985; Chisholm et al., 1988). Strata equivalent to the SSG also occur on the Isle of Man (Chadwick et al., 2001) and in Northern Ireland (Mitchell, 2004) but these are beyond the scope of this report.

Eastwards from outcrops in central and eastern England, west- and southwards from those in Lancashire and on Arran respectively, and in the centres of the Cheshire and Carlisle basins, the SSG is present in the subsurface beneath the MMG and younger Mesozoic deposits. It thins towards and pinches out at subsurface around the London–Brabant Massif (Figure 2), an ancient cratonic area composed of Lower Palaeozoic rocks (see figures in Hull, 1860a, Holloway, 1985, Warrington and Ivimey-Cook, 1992 and Horton et al., 1995). The SSG successions onshore in England, Wales and south-west Scotland, including Arran, are in continuity with those in the adjacent offshore areas (Evans, 1990; Cameron et al., 1992; Hamblin et al., 1992; Fyfe et al., 1993; Johnson et al., 1994; Tappin et al., 1994; Jackson et al., 1995; Jackson and Johnson, 1996; Chadwick et al., 2001; Bachmann et al., 2010).

Occurrences of the SSG are here divided into 11 spatially distinct regions (Figure 2), some of which represent isolated basins, whereas others represent outcrop areas that are isolated at surface but not in the subsurface. There is subsurface continuity between Regions 1 to 8. Regions 8 to 10, although not in continuity onshore, are in continuity offshore in Liverpool Bay and the East Irish Sea; Region 11 is isolated.

2.2 CURRENT LITHOSTRATIGRAPHICAL NOMENCLATURE

The *current* names adopted in BGS publications for the constituent formations of the SSG and the associated underlying groups of Permian age are shown in Table 1. Further explanation and information sources are given below. Lexicon entries for most of these units can be viewed on the BGS Website:

http://www.bgs.ac.uk/bgs/w3/free/lexicon/lexicon.html

2.2.1 Region 1 – south-west England, Somerset and Wessex basins

Lithostratigraphy based on Warrington et al. (1980), Whittaker and Green (1983), Selwood et al. (1984), Edmonds and Williams (1985), Edwards and Freshney (1987), Bristow et al. (1991, 1995), Edwards (1999), Edwards and Scrivener (1999), Edwards and Gallois (2004), Gallois (2004), Chadwick and Evans

(2005) and Barton et al. (2011). The succession comprises the Budleigh Salterton Pebble Beds Formation (up to 48 m thick) and the overlying Otter Sandstone Formation, a mixed aeolian–fluvial sequence up to 210 m thick. At outcrop the contact between these formations appears disconformable but at subcrop an angular unconformity occurs and an intervening (unnamed) argillaceous unit is present locally (Butler, 1998; Warrington, 2005; Barton et al., 2011).

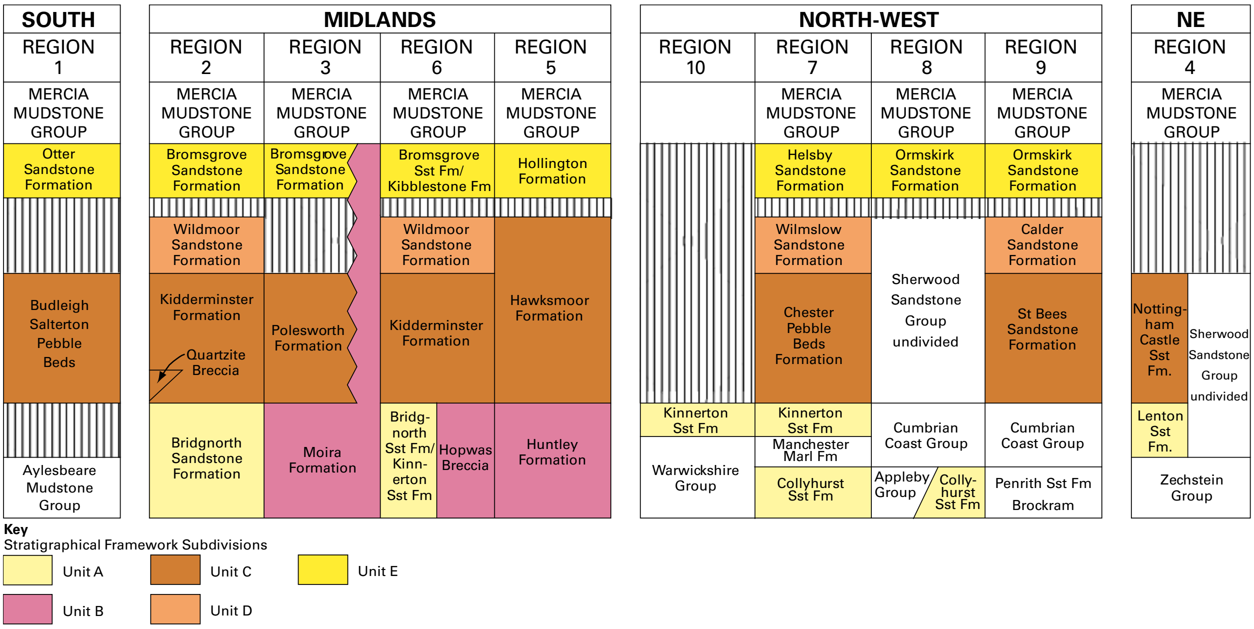

Table 1 The current stratigraphical nomenclature for the SSG review.

Borehole geophysical log characteristics of the SSG in the region were illustrated by Rhys et al. (1982), Penn (1987), Holloway et al. (1989), Bristow et al. (1991) and Butler (1998). The succession is in subsurface continuity with those in Region 2 and offshore, below the Bristol Channel (Tappin et al., 1994) and the English Channel (Evans, 1990; Hamblin et al., 1992).

2.2.2 Region 2 – Worcester and Knowle basins

Lithostratigraphy based on Green and Melville (1956), Warrington et al. (1980), Horton et al. (1987, 1995), Old et al. (1987, 1991), Worssam et al. (1989), Barclay et al. (1997), Powell et al. (2000), Sumbler et al. (2000), Barron et al. (2002) and Sumbler (2002). The succession is based on mapping, particularly in the northern part of this region, on the Kempsey Borehole (Whittaker, 1980) which proved the most complete SSG succession in the Worcester Basin, on boreholes in the Bromsgrove area which proved the Bromsgrove Sandstone Formation (Old et al., 1991), and on seismic data (Chadwick, 1985; Chadwick and Smith, 1988; Chadwick and Evans, 2005). In southern and eastern parts of this region (Gloucestershire and Oxfordshire) the succession has an extensive subcrop beneath younger Mesozoic deposits.

The succession comprises the Hopwas Breccia, of uncertain age, and the Triassic Kidderminster, Wildmoor Sandstone and Bromsgrove Sandstone formations. In the Bromsgrove area a conglomerate unit at the base of, and interdigitating with, the Kidderminster Formation was mapped separately and named the 'Quartzite Breccia' (Old et al., 1991). However, in the Birmingham area this term was not used, 'Hopwas Breccia' being preferred (Powell et al., 2000). In the Bromsgove area, the Bromsgrove Sandstone Formation has been subdivided into the Burcot, Finstall and Sugarbrook members. Borehole geophysical log characteristics of the SSG in the region were illustrated by Green and Melville (1956), Bullerwell (1963), Bennett (1969), Poole (1977, 1978), Horton et al. (1987), Penn (1987), Barclay et al.

(1997), Powell et al. (2000) and Sumbler et al. (2000). The succession is in subsurface continuity with those in regions 1 and 3 and in spatial continuity with those in regions 5 and 6, although not all constituent formations are physically continuous between those areas, the Wildmoor Sandstone being identified only in regions 2 and 6.

2.2.3 Region 3 – Hinckley Basin, with parts of south Derbyshire, north-west Leicestershire and Warwickshire

Lithostratigraphy based on Warrington et al. (1980), Old et al. (1987), Worssam and Old (1988), Bridge et al. (1998), and Carney et al. (2001, 2002, 2009). The formations are largely defined from boreholes and surface mapping in the Warwick, Coventry, Coalville, Loughborough and Leicester areas. The succession includes the Moira, Polesworth and Bromsgrove Sandstone formations. Borehole geophysical log characteristics of the SSG in the region were illustrated by Worssam and Old (1988), Bridge et al. (1998) and Carney et al. (2001). The succession is in subsurface continuity with those in regions 2, 4 and 5, although not all constituent formations are in physical continuity between those areas; the Wildmoor Sandstone is only present in Region 2 and the Bromsgrove Sandstone is largely absent from Region 4.

2.2.4 Region 4 – East Midlands Shelf

Lithostratigraphy based on Elliott (1961), Smith and Warrington (1971), Smith et al. (1973), Warrington et al. (1980), Berridge and Pattison (1994), Gaunt (1994), Berridge et al. (1999), Carney et al. (2004), Hough et al. (2007) and Howard et al. (2009). A clear division into the Lenton Sandstone and Nottingham Castle Sandstone formations can be made in the southern part of this region and as far north as Doncaster. However, northwards from there, to the coast around Hartlepool, pebbles are scarce and the SSG is undivided (Gaunt, 1994; Aitkenhead et al., 2002). The cover of superficial deposits becomes very extensive north of Retford, but considerable information is available from boreholes; in this area the SSG is up to about 400 m thick. Borehole geophysical log characteristics of the SSG in the region were illustrated by Berridge and Pattison (1994), Chadwick et al. (1995), Berridge et al. (1999), Carney et al. (2004) and Howard et al. (2009), The succession is in spatial continuity with that in Region 3; it is in subsurface continuity with the Bacton Group succession in the Southern North Sea Basin (Cameron et al., 1992; Johnson et al., 1994).

2.2.5 Region 5 – Needwood Basin

Lithostratigraphy based on Stevenson and Mitchell (1955), Warrington et al. (1980), Charsley (1982) and Chisholm et al. (1988). The succession includes the Huntley, Hawksmoor and Hollington formations. The succession is in subsurface continuity with that in Region 3 and in spatial continuity with those in regions 2 and 6. The Wildmoor Sandstone Formation is absent in regions 3 and 5.

2.2.6 Region 6 – Stafford Basin

Lithostratigraphy based on Warrington et al. (1980), Rees and Wilson (1998) and Bridge and Hough (2002). The SSG comprises three main formations, together with the Permian Bridgnorth and Kinnerton Sandstone formations. The Hopwas Breccia is also present in this region. The Kidderminster Formation is up to 200 m thick. It is succeeded conformably by the Wildmoor Sandstone Formation which is up to 284 m thick; the junction is gradational and poorly defined. The overlying Bromsgrove Sandstone Formation is up to 500 m thick and rests on a major disconformity; near Stone, an aeolian facies equivalent to this formation has been mapped as the Kibblestone Formation (Rees and Wilson, 1998). Warrington et al. (1980) introduced the 'Cannock Chase Formation' in the eponymous area, with a lower conglomeratic unit and an upper 'pebble free' unit that were considered equivalents of the Kidderminster and Polesworth formations respectively. Borehole geophysical log characteristics of the SSG in the region were illustrated by Bridge and Hough (2002). The succession is in spatial continuity with those in regions 2, 5 and 7; the Wildmoor Sandstone Formation is absent in regions 5 and 7.

2.2.7 Region 7 – Cheshire Basin

Lithostratigraphy based on Thompson (1970a), Warrington et al. (1980, 1999), Earp and Taylor (1986), Evans et al. (1993), Rees and Wilson (1998), Aitkenhead et al. (2002) and Howard et al. (2007). The Cheshire Basin is fault-bounded to the south-east and east. To the north and west it is largely bounded by older rocks on which the basin-fill deposits rest unconformably. The Llŷn–Rossendale ridge, which separates the basin from the East Irish Sea and west Lancashire areas, defines its north-western limit.

The Kinnerton Sandstone Formation, generally regarded as dominantly Permian in age, was included within the SSG by Warrington et al. (1980). This is underlain in parts of the region by the Manchester Marls Formation. Where that formation is not present, the Kinnerton Sandstone includes beds equivalent to the Manchester Marls and underlying Collyhurst Sandstone formations. This part of the group is characterised by fine-grained sandstones deposited as aeolian dunes in a desert environment. The remainder of the SSG comprises three formations, based predominantly on sandstone sedimentology and lithology.

The Chester Pebble Beds Formation comprises red-brown sandstone with sporadic mudstone interbeds; pebbles become rare northwards within the basin (Thompson, 1970a). It is succeeded by the Wilmslow Sandstone Formation, composed of red and orange, fine-grained, poorly cemented, friable and predominantly aeolian sandstones. The Thurstaston Sandstone Member was included in the Wilmslow Sandstone Formation by Howard et al. (2007), rather than in the Helsby Sandstone as originally defined by Thompson (1970a). It comprises a dominantly aeolian sequence with a thin bed (the Thurstaston Hard Sandstone Bed; Thompson, 1970b) of fluvial sandstone at the base of the member, and is similar to the Wilmslow Sandstone. However, borehole geophysical log correlation (Figure 3, Formby Borehole) suggests that this member is better placed in the Helsby Sandstone Formation.

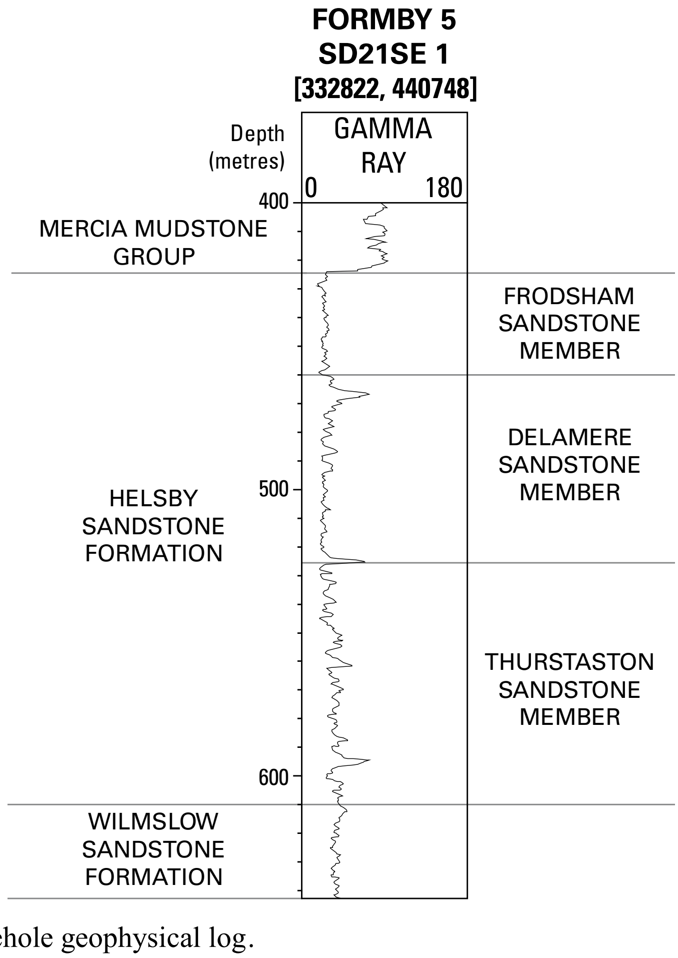

Figure 3 Formby Borehole geophysical log.

The Helsby Sandstone Formation overlies the Wilmslow Sandstone Formation and typically comprises up to 250 m of brown and red-brown, rarely cream coloured, sandstones and pebbly sandstones. Many local names have been used for units or members in this formation, including the Grinshill and Ruyton sandstones of the Wem district (Pocock and Wray, 1925; Thompson, 1993) in the south of the basin, the Bulkeley Hill Formation (Warrington et al., 1980), formerly the 'Keuper Sandstone Passage Beds' of Poole and Whiteman (1966), in the west of the basin, and the 'Engine Vein Conglomerates', 'Beacon Lodge Soft Sandstones', 'Wood Mine Conglomerates', 'West Mine Soft Sandstones' and 'Nether Alderley Red Sandstone' members at Alderley Edge (Thompson, 1970b), in the north-eastern part of the basin. In the north-western part of the basin the formation comprises, in ascending order, the 'Thurstaston Soft Sandstone' (with the 'Thurstaston Hard Sandstone Bed'), the 'Delamere Pebbly Sandstone' and the 'Frodsham Soft Sandstone' members. The 'Delamere Pebbly Sandstone Member' is fluvial in origin and the 'Frodsham Soft Sandstone Member' is largely aeolian (Thompson, 1969, 1970a, 1970b; Mountney and Thompson, 2002).

Borehole geophysical log characteristics of the SSG in the region were illustrated by Colter (1978), Penn (1987), Rees and Wilson (1998), Warrington et al. (1999) and Bloomfield et al. (2006). The succession is in spatial continuity with those in regions 6 and 8, and in subsurface continuity with that offshore, below the East Irish Sea.

2.2.8 Region 8 – West Lancashire

Lithostratigraphy after Warrington et al. (1980), Wilson and Evans (1990) and Jackson et al. (1995). This region is the onshore part of the East Irish Sea Basin (EISB). Outcrops in the Formby and Fylde areas are covered by thick superficial deposits and the formations are defined largely from borehole core. In the southern part of this region recent mapping (E Hough, pers. com) has allowed separation of the Wilmslow Sandstone and overlying Ormskirk Sandstone formations; this division is recognisable as far north as Burscough [SD 43 10]. The Chester Pebble Beds Formation is present at depth but does not crop out. Borehole geophysical log characteristics are illustrated in de Pater and Baisch (2011) (available on the internet at

http://www.cuadrillaresources.com/wp-content/uploads/2012/02/Final_Report_Bowland_Seismicity_02-11-11.pdf).

Figure 3 illustrates the three-fold subdivision of the Helsby Sandstone Formation in the Formby No. 5 borehole from this region, based on that of Thompson (1970a), seen in Region 7 (p.23). The uppermost unit of the SSG comprises a lower fluvial and an upper aeolian unit. Farther north the SSG is poorly exposed, lacks lithological variation, and is undivided.

The succession is in spatial continuity with that in Region 7 and in subsurface continuity with those below the East Irish Sea and in Region 9.

2.2.9 Region 9 – Cumbria, Carlisle Basin and Vale of Eden

Lithostratigraphy after Dixon et al. (1926), Eastwood (1930), Day (1970), Warrington et al. (1980), Barnes et al. (1994), Jackson et al. (1995), Akhurst et al. (1997), Johnson et al. (2001) and Holliday et al. (2004). The SSG crops out on the west coast of the Lake District and eastwards, to Carlisle, then southwards into the Vale of Eden and northwards into Scotland. In the Barrow-in-Furness area only the St Bees Sandstone is recognised (Rose and Dunham, 1977) whereas drilling to the north, around Sellafield, allowed the recognition of three units; in ascending order, the St Bees Sandstone, Calder Sandstone and Ormskirk Sandstone formations (Barnes et al., 1994; Akhurst et al., 1997). These formations can be recognised from Millom to Whitehaven, with thicknesses of 250 to 600 m, 650 m and 150 to 250 m respectively (Akhurst et al., 1997). Borehole geophysical log characteristics of the SSG in the region were illustrated by Barnes et al. (1994), Jones and Ambrose (1994), Chadwick et al. (1995), Akhurst et al. (1997) and Holliday et al. (2001, 2004).

Offshore, below the East Irish Sea, only two formations, the St Bees Sandstone and the Ormskirk Sandstone, are recognised (Jackson and Johnson, 1996; Chadwick et al., 2001), with the Calder Sandstone reduced to member status and forming the upper part of the St Bees Sandstone, the lower part of which is termed the Rottington Sandstone Member.

The lithostratigraphy of the SSG in the Carlisle Basin and Vale of Eden, from Maryport to Carlisle and into south-west Scotland, is uncertain due to a thick cover of superficial deposits, poor exposure, and a scarcity of borehole information (Holliday et al., 2006, 2008). Here two formations have previously been recognised, namely the St Bees Sandstone and Kirklinton Sandstone formations (Dixon et al., 1926; Eastwood, 1930; Day, 1970; Holliday et al., 2004). The SSG is 502 m thick in the Silloth 1A Borehole whereas to the north, in the main part of the Carlisle Basin, and in the Vale of Eden the St Bees Sandstone Formation ranges from 150 to 430 m and the Kirklinton Sandstone Formation is thought to be about 100 m thick (Dixon et al., 1926; Day, 1970). Holliday et al. (2006, 2008) proposed adopting the offshore EISB nomenclature for the Carlisle Basin and Vale of Eden successions, and discarding the term 'Kirklinton Sandstone'.

In the main part of the Vale of Eden, Goodchild (1893) recognised two divisions of the SSG, equivalent to the St Bees Sandstone and the Kirklinton Sandstone formations. Arthurton and Wadge (1981) considered it impractical to map both formations and only the St Bees Sandstone Formation is recognised on recent BGS maps in this area. However, from published descriptions (Goodchild, 1893; Arthurton and Wadge, 1981) it would seem that the Ormskirk Sandstone Formation is present in the Vale of Eden. In the Vale of Eden the St Bees Sandstone Formation varies in thickness from 125 to 600 m (Burgess and Holliday, 1979; Arthurton and Wadge, 1981).

The SSG is in spatial continuity with that in Region 8 and in subsurface continuity with that below the East Irish Sea.

2.2.10 Region 10 – Vale of Clwyd, North Wales

Lithostratigraphy after Ivimey-Cook (1974), Warrington et al. (1980), Warren et al. (1984) and Davies et al. (2004). The Vale of Clwyd is an asymmetric half graben occupied by a sandstone succession up to 800 m thick that comprises aeolian and fluvial red beds and is in spatial continuity with that offshore below the East Irish Sea.

The outcrop, which is largely obscured by superficial deposits, is mapped as Kinnerton Sandstone which was included in the SSG by Warrington et al. (1980) and was therefore considered in this study. However, the Kinnerton Sandstone is here assigned to Framework Unit A (see **3.1**, **3.2**) which is not included in the SSG and the region is not, therefore, considered further.

2.2.11 Region 11 – Isle of Arran, Firth of Clyde, south-west Scotland

Warrington et al. (1980) defined two formations as part of the SSG, the Lamlash Sandstone and the Glen Dubh Sandstone formations. The former comprises sandstones with interbedded conglomerates and mudstones and the latter is a calcareous aeolian sandstone. The Lamlash Sandstone Formation shows similarities to the Kidderminster Formation of England but the pebbles are thought to be largely locally sourced (MacGregor et al., 1983). Because this outcrop is detached and remote from those in England and Wales it is recommended that the local lithostratigraphical nomenclature is retained.

3 Review of Sherwood Sandstone Group lithostratigraphy

3.1 OPTIONS AND RECOMMENDATIONS FOR RATIONALISING SSG LITHOSTRATIGRAPHY

Three options are presented for consideration by the BGS Stratigraphy Committee:

1. ‘Status quo’, with local adjustments (Table 1). This option retains the existing provincial formation names on grounds of maintaining stability of nomenclature.
2. ‘Compromise’ (Table 2). This option uses the ‘framework units’ (**1.3**, **3.2**) to define a simplified formational nomenclature across those basins that are in spatial continuity, but retains the existing local nomenclature where basins are spatially isolated or where there are significant changes in facies between named units of the same age. Other compromise options are possible.
3. ‘Clean slate’. This option uses the ‘framework units’ (**1.3**, **3.2**) to define a simplified single formational nomenclature across all basins. Existing ‘formations’ that represent local subdivisions of the new ‘framework’ formations are downgraded to member status; synonyms are dropped.

The implications of each option are described below.

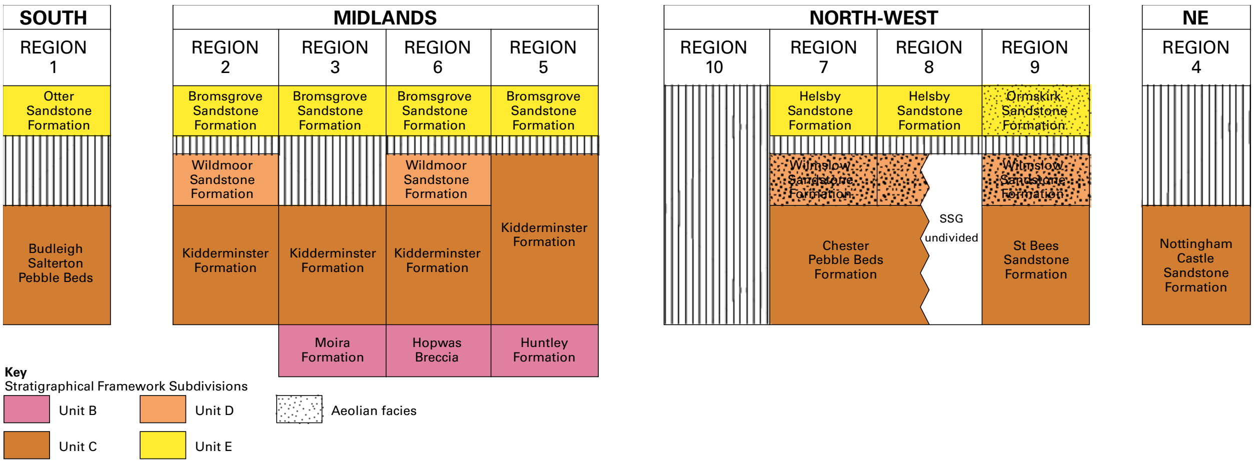

Table 2 Lithostratigraphical nomenclature under Option 2: Compromise.

3.1.1 Option 1 – status quo (Table 1)

Advantages of this option

- Stability of nomenclature used on recently published BGS maps and memoirs is maintained, avoiding accusations of inconsistency.

Disadvantages of this option

- Numerous local names tend to confuse non-specialist map users.
- Spatial mappability of many borehole-defined units is not practicable in some areas.
- Arbitrary lines would need to be created to separate these local units on seamless maps or subsurface models.

3.1.2 Option 2 – compromise (Table 2)

In this option a simplified formational nomenclature is applied across those basins that are in spatial continuity, but the existing local nomenclature is retained where basins are spatially isolated or where there are facies changes.

Advantages of this option

- Production of 'seamless' maps and 3D spatial models to formation level remains possible.
- Changes to the existing nomenclature are less radical than in Option 3 and may therefore confuse users less in the short term.

Disadvantages of this option

- Some further confusion could be added, due to the inconsistency of approach between different basins.
- There is conflict with the stratigraphy published in recent BGS maps and memoirs, leaving BGS open to criticisms of inconsistency.
- Spatial mapping of many borehole-defined 'formations' in the Lancashire and East Midlands Shelf regions is not practicable in some areas.
- Long established names will be abandoned.

3.1.3 Option 3 – clean slate

In this option a single formation name is applied to four of the five 'framework units', from B (oldest) to E (youngest). Unit A is not considered to be part of the SSG and therefore has no recommended name. The units (including Unit A) comprise the following *currently* adopted formations:

Unit A – Bridgnorth Sandstone, Collyhurst Sandstone, Kinnerton Sandstone andLenton Sandstone formations

Unit B – Hopwas Breccia, Moira and Huntley formations

Unit C – Budleigh Salterton Pebble Beds, and Kidderminster, 'Cannock Chase', Polesworth, Hawksmoor, Chester Pebble Beds, Nottingham Castle Sandstone and St Bees Sandstone formations

Unit D – Wildmoor Sandstone, Wilmslow Sandstone and Calder Sandstone formations

Unit E – Otter Sandstone, Bromsgrove Sandstone, Kibblestone, Hollington, Helsby Sandstone, Ormskirk Sandstone and Kirklinton Sandstone formations

The names *currently* used for each unit are listed above. All member names are to be retained for units that have been subdivided.

Advantages of this option

- It presents a 'once and for all' solution that, because of its simplicity, should become readily accepted by users in the long term.
- It is the simplest solution for a seamless geological map.
- It modifies the existing local nomenclature before it becomes too entrenched and enables production of 'seamless' maps and 3D spatial models at formation level.

Disadvantages of this option

- There is conflict with the stratigraphy published in recent BGS maps and memoirs, leaving BGS open to criticisms of inconsistency.
- Changes may confuse users in the short to medium term.
- A number of the units show distinct facies changes along their outcrop that would not be easily identifiable if a single name were used.
- Some long established names will be abandoned.

Under this proposal, the following formation names are recommended for the constituent formations of units B to E:

E – Helsby Sandstone Formation

D – Wilmslow Sandstone Formation

C – Chester Formation*

B – Moira Formation/Hopwas Breccia Formation

*The 'Pebble Beds' lithological epithet is dropped as there are facies changes along the outcrop of the formation.

Table 3 shows the proposed new nomenclature and their former equivalents; Table 4 shows the subdivisions of the new nomenclature.

Option 3 is preferred and recommended by the SFC, and the suggested nomenclature is discussed below. This option has been chosen principally because of the needs of a seamless geological map and 3D models.

Helsby Sandstone Formation	Otter Sandstone Formation Bromsgrove Sandstone Formation Hollington Formation Ormskirk Sandstone Formation Kirklinton Sandstone Formation
Wilmslow Sandstone Formation	Wildmoor Sandstone Formation Calder Sandstone Formation
Chester Formation	Budleigh Salterton Pebble Beds Kidderminster Formation Cannock Chase Formation Polesworth Formation Hawksmoor Formation Chester Pebble Beds Formation Nottingham Castle Sandstone Formation

Table 3 Correlation of the proposed new formations with existing formations in the Sherwood Sandstone Group.

Group	Formation	Member	Bed
Sherwood Sandstone Group	Helsby Sandstone		Burwardsley Hill
		Shepshed Sandstone	
		Burcot	
		Finstall	
		Sugarbrook	
		Thurstaston Sandstone	Thurstaston Hard Sandstone
		Delamere Sandstone	
		Frodsham Sandstone	
		Kibblestone	
		Sellafield	
	Wilmslow Sandstone	Wildmoor Sandstone	
	Chester	St Bees Sandstone	
		Freehay	
		Lodgedale	
		North Head	
	Moira		
	Hopwas Breccia		
	Lamlash Sandstone		
	Glen Dubh Sandstone		

Table 4 Proposed new lithostratigraphy of the Sherwood Sandstone Group.

3.2 STRATIGRAPHICAL FRAMEWORK UNITS

To provide a basis for the potential rationalisation of SSG lithostratigraphy it is necessary to identify a framework of subdivisions that either possess, or can be inferred to have once possessed, a high degree of spatial continuity, i.e. that are mappable both at surface and in the subsurface on a regional rather than a local basis. These ‘framework units’ may have diachronous boundaries but should possess definable lithological characteristics that distinguish them from adjacent units.

The extent to which these units should be formally recognised as formations will depend on:

- The *desirability* of changing the existing provincial nomenclature.
- The *reliability* of the interpretation of primary depositional continuity between what are now spatially isolated basins.
- The facies or facies associations of each group and formation.
- The geophysical log character of each group and formation.

Five ‘framework units’ are recognisable within the SSG as currently defined (Warrington et al., 1980). The boundaries between them are conformable except where stated. All five have distinctive lithological and facies characteristics and geophysical log profiles.

3.2.1 Unit A

This unit is characterised by predominantly orange-red, cross-bedded aeolian sandstones that are considered to be of Permian to Triassic age. The unit has a low gamma-ray response in borehole geophysical logs, reflecting a low mud content due to the dominantly aeolian conditions of deposition. Formerly named the ‘Lower Mottled Sandstone’, four local names have been used for the constituents of this unit: the Bridgnorth Sandstone, Collyhurst Sandstone, Kinnerton Sandstone and Lenton Sandstone formations. Warrington et al. (1980) included the Kinnerton Sandstone and Lenton Sandstone formations in the SSG. The Lenton Sandstone Formation was retained within the SSG by Charsley et al. (1990) and, in part, by Howard et al. (2009). The Collyhurst Sandstone Formation is included in the Appleby Group; the Bridgnorth Sandstone Formation has not been assigned to any group but is included by BGS in a ‘New Red Sandstone Supergroup’, a term (Laming, 1968) that encompasses this formation, the Permian strata of south-west England and all of the Triassic strata.

Unit A is restricted to the following Regions: 2 and 6 (Bridgnorth Sandstone Formation), 7 and 8 (Kinnerton and Collyhurst Sandstone formations) and 4 (Lenton Sandstone Formation). It shows a wide range of thickness variations, from a few metres to a maximum of 938.2 m for the Bridgnorth Sandstone Formation in the Kempsey Borehole (Worcester Basin) (Whittaker, 1980).

The features of the Permian groups are noted here**:**

The Appleby Group (Brandon et al., 1998) comprises aeolian, cross-bedded, millet-seed sandstone, fluviatile sandstone and breccias ('Brockram') interbedded in varying proportions. In the Collyhurst Sandstone and correlatives, grey, white and pale brown colours are common and breccias are rare; some interbedded red mudstones are present locally. The group includes the Penrith Sandstone, ‘Brockram’, Rougholme Point Conglomerate, Collyhurst Sandstone, Locharbriggs Sandstone and Doweel Breccia formations. The base is strongly unconformable, mainly on Carboniferous strata, but locally on older formations. The top is taken at a point in the succession where sandstone becomes subordinate to mudstones, siltstones, carbonates and evaporites of the overlying Cumbrian Coast Group (St Bees Evaporite or Manchester Marls formations).

The Cumbrian Coast Group (Brandon et al., 1998) succession comprises grey mudstones, siltstones and dolomites (Eden Shales and Manchester Marls formations) succeeded by evaporites (St Bees Evaporite Formation) that are overlain by red siltstones, mudstones and calcareous sandstones (St Bees Shale Formation). The base is placed where there is a sharp upwards change from either breccia (‘Brockram’) or red sandstone, to grey siltstones or dolomites. The top tends to be gradational and is therefore taken arbitrarily where sandstone (St Bees Sandstone Formation) becomes predominent over siltstone (St Bees Shale Formation).

The Rotliegendes Group (*auctt*., formalised by Deegan and Scull, 1977) is a succession of aeolian, fluvial and inland lacustrine sandstones and conglomerates with mudstone and subordinate halite. The base is unconformable, resting on strata ranging from Devonian to late Carboniferous in age, and the Group is overlain unconformably by the Kupferschiefer or Marl Slate (or younger strata).

The Zechstein Group (*auctt*., formalised by Deegan and Scull, 1977) is a cyclical succession of marine dolostone, limestone, evaporites, red mudstone and siltstone. The base is unconformable, with the Kupferschiefer or Marl Slate (or younger strata) resting on the Rotliegendes Group or Carboniferous strata. The top is a gradational boundary taken at the base of the SSG onshore and the base of the Bacton and Heron groups offshore.

The Aylesbeare Mudstone Group (Edwards and Scrivener, 1999, after Bristow and Scrivener, 1984) crops out in Devon and is present, at subsurface, in Somerset and Dorset (Barton et al., 2011, fig. 4a). It comprises a succession of dominantly lacustrine playa–sabkha mudstones and siltstones with minor aeolian and fluvial sandstones. It rests unconformably on the Exeter Group (Edwards et al., 1997; Edwards and Scrivener, 1999; Barton et al., 2011).

Recommendations

The SFC recommends that all formations currently forming part of Unit A are no longer included in the SSG, that the definition of the SSG is modified to exclude all dominantly aeolian units thought to be wholly or partially of Permian age, and that the base of the SSG be placed at the incoming of predominantly fluvial facies, recognising that this probably does not equate with the base of the Triassic.

3.2.2 Unit B

This unit is restricted in outcrop and lateral extent but occurs over a wide area in the central and south Midlands. The unit is a heterolithic breccia, usually with a sandstone matrix; the clast composition is very variable and reflects local provenance. It underlies typical SSG sandstones and is generally only up to a few tens of metres in thickness. It has been shown to interdigitate with the Kidderminster Formation in the Redditch (Sheet 183) district and with the Polesworth and Bromsgrove Sandstone formations in the Loughborough (Sheet 141) district, thereby proving a Triassic age in part. Elsewhere, it may be Permian or Triassic in age. It does not occur in association with the Permian sandstones of Unit A and its relationship to those formations is not known. Four local names have been used for this unit:

1. 'Quartzite Breccia' on sheet 183 (Redditch) (Region 2; Old et al., 1991). This name has been abandoned in favour of Hopwas Breccia (Powell et al., 2000).
2. Hopwas Breccia on sheets 154 (Lichfield; Barrow et al., 1919) and 168 (Birmingham; Powell et al., 2000) (both Region 2), and 155 (Coalville; Worssam and Old 1988) and 169 (Coventry; Bridge et al., 1998) (both Region 3).
3. Moira Breccia on sheets 125 (Derby) (Region 3 and 5; Frost and Smart, 1979), 140 (Burton) (Region 5; Stevenson and Mitchell, 1955), and 141 (Loughborough) and 155 (Coalville) (both Region 3; Brown, 1889).
4. Huntley Formation on sheet 124 (Ashbourne) (Region 5; Chisholm et al., 1988).

The unit is characterised by a variable borehole geophysical log response that reflects the diverse range of lithologies present.

Recommendations

It is recommended that the individual formation names are retained as, although all are breccias, each is lithologically distinct in terms of the contained clasts. The breccias are a significantly different facies to other SSG formations, being proximal alluvial fan and debris flow deposits derived almost exclusively from local sources as opposed to the more distant provenance of others in the SSG. It is recommended that the Hopwas Breccia and Moira Formation are retained as part of the SSG as they interdigitate with other units in the group. The Huntley Formation should not form part of the SSG and should stand alone, with no parent group currently recommended.

3.2.3 Unit C

This unit is widespread and occurs in all the regions. It shows a northward facies change. At outcrop in Region 1 it consists of coarse conglomerates, pebbly sandstones and sandstones that show well developed cross-bedding, with conglomerates very much in abundance. Northwards into Regions 2, 3 (southern part) and 6 the lower part of the unit is dominated by conglomerates and the upper part is more arenaceous, with cycles that fine upwards, locally to siltstone and mudstone.

A feature of Unit C on borehole geophysical logs (Figures 4 and 5) is a sonic velocity that is generally higher than that of the bulk of the overlying formation and may be higher than that of the underlying Unit B. The gamma-ray response is more variable; in Kempsey Borehole (Figure 4) it increases slightly upwards, and becomes more serrated, but in Knutsford Borehole (Figure 4) there is little change upwards. In Region 4 the unit has a relatively low gamma-ray response, with some high gamma interbeds, in Broach Road Borehole (Figure 5) the junction with the underlying Lenton Sandstone Formation is marked by a downward increase in gamma-ray values and an increasingly serrated signature. This is comparable with other boreholes in the area (Howard et al*.*, 2009*,* fig. 24).

In Knutsford Borehole (Region 7) the top of Unit C is placed at the downhole appearance of pebbles (see Unit D, **4.3**, **4.4**). There is little upward change on the sonic log at that level. However, in the overlying Unit D there is a gradual decrease in sonic velocity up to a prominent decrease in both that and the gamma-ray response correlated with the 'Top Silicified Zone' ('TSZ'; Figure 4), a seismic reflector in the EISB (Colter and Barr, 1975; Jackson et al., 1987) that shows the same log responses onshore, in Banks 1 Borehole in region 8 and the Silloth 1A and Sellafield 13A boreholes in region 9 (Figure 5). It has been traced southwards into Region 7 (Colter and Barr, 1975) where, however, Jackson et al. (1987) used it to mark the top of the Chester Pebble Beds Formation, above a 'pebble free' succession that Colter and Barr (1975) had included in the Wilmslow Sandstone Formation, an approach that is also adopted in this account (Figure 4). In Region 6, the top of Unit C in Stretton Borehole is placed at a decrease in sonic velocity that is correlated with that at the TSZ in Knutsford, Borehole but the gamma-ray response increases at that level (Figure 4).

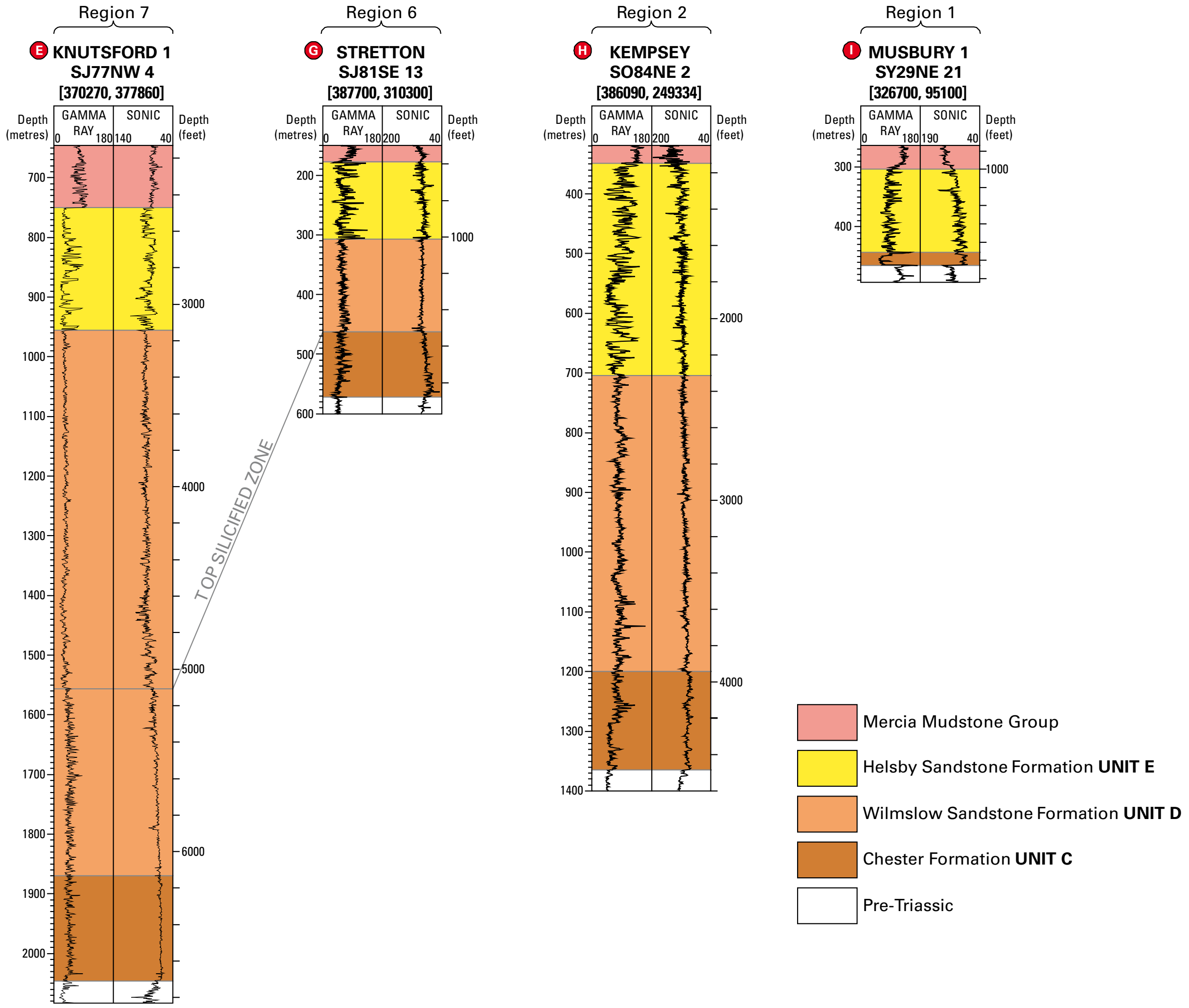

Figure 4 Representative borehole geophysical logs.

In a number of borehole geophysical logs, such as Musbury (Figure 4), there is a distinctive gamma-ray low at the base of the formation, corresponding to a conglomeratic unit; the overlying interbedded conglomerates and sandstones have a generally higher, more serrated gamma-ray signature and the top may be difficult to define on this log response. In the Redditch district, the basal conglomeratic unit has been mapped separately.

Continuing north-eastwards into north Leicestershire and Nottinghamshire, in regions 3 and 4, the unit is a pebbly sandstone. In Region 7 it is a sandstone with a variable pebble content, at least as far north as Liverpool and the Wirral (Howard et al., 2007). In Region 8 the unit is largely unexposed due to a thick cover of superficial deposits. In Cumbria (Region 9) the unit is entirely sandstone, with intraformational mudstone conglomerates and locally granule-rich beds containing fragments of the Ordovician Borrowdale Volcanic Group.

Formerly known as the 'Bunter Pebble Beds', components of this unit are variously named according to facies type. A dominantly conglomeratic facies includes the Budleigh Salterton Pebble Beds, but sandstone is common in the upper part in south-west England (Region 1), in the lower part of the Kidderminster Formation in the Midlands (Region 2 and part of Region 6) and in the Cannock Chase Formation (part of Region 6). A conglomerate was separately mapped at the base of the Kidderminster Formation in the Bromsgrove area but was not named. Subdivisions of the Polesworth Formation are unclear. The Hawksmoor Formation appears to be conglomeratic, mainly in its upper part, with two conglomerate units, the Freehay and Lodgedale members, mapped separately. A pebbly sandstone facies includes the upper part of the Kidderminster Formation in Worcestershire and Staffordshire, the Chester Pebble Beds Formation in the Cheshire Basin and the Nottingham Castle Sandstone Formation in north Leicestershire and Nottinghamshire. This pebbly sandstone facies extends as far north as the Doncaster area of South Yorkshire (Warrington, 1974, fig. 39), and in Merseyside at least as far north as Liverpool. In Cumbria and the Solway Firth area a sandstone facies is represented by the St Bees Sandstone Formation.

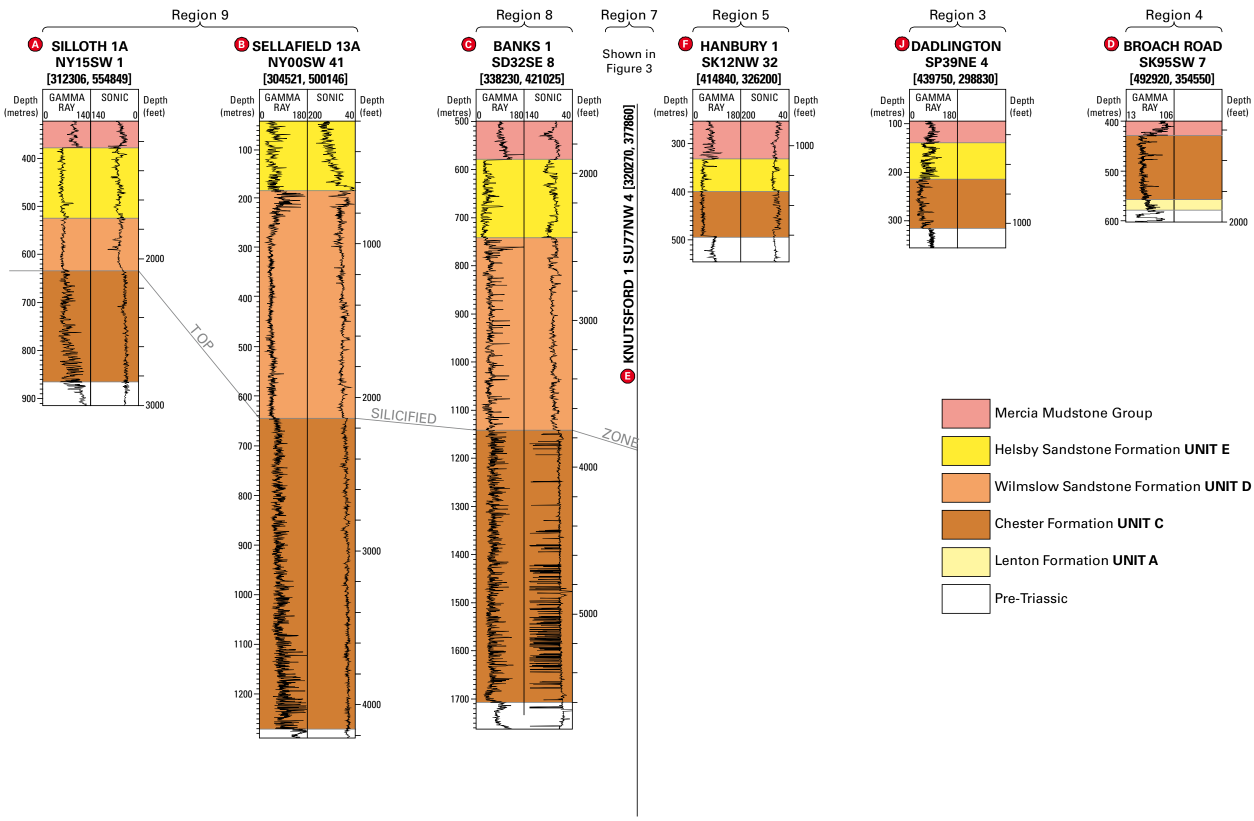

Figure 5 Representative borehole geophysical logs.

In Yorkshire, north of Doncaster, and in Lancashire, the lithological homogeneity of the SSG, in part due to the scarcity of pebbles, means recognition of constituent formations is not possible, and the sandstones between the Roxby, Collyhurst Sandstone and Kinnerton Sandstone formations and the MMG form part of an undifferentiated SSG succession.

In Regions 2, 5 and 6 the term 'Littleworth Beds' (Boulton, 1951; Hoare and Mitchell, 1955; Wills, 1976) has been used for a thin, mainly sandstone and sometimes pebbly unit at the base of the SSG. The term has been used extensively in the logs of borings for coal in these regions but the unit was not identified in all boreholes. The age of the 'Littleworth Beds' remains uncertain; they may be a distal equivalent of the Hopwas Breccia and of Permian age. However, descriptions suggest they include quartzite pebbles typical of the Chester Pebble Beds Formation and a Triassic age seems more likely. For the purposes of this report they are included in Unit C.

Recommendations

It is recommended that this unit be given one formation name and that this should be the **Chester Formation** (**4.4**). This eliminates the use of 'pebble beds' in the title and avoids a lithological epithet for a unit that varies from conglomerate to pebbly sandstone and sandstone from south to north. This name is preferred for historical reasons as the Cheshire area was the first in which a tripartite sequence was recognised in what is now the SSG (Hull, 1860b, 1869 pp.7–8). The formation is also well-exposed in that area. It is recommended that the St. Bees Sandstone is retained as the **St Bees Sandstone Member**, to distinguish the sandstone facies in Cumbria. In the intervening area, in Lancashire, the name adopted should reflect the lithology proven at outcrop or in boreholes.

Within the sequence, all member names are to be retained (**4.4**), including the **North Head Member** in Cumbria and the **Freehay** and **Lodgedale** members in the Ashbourne district. Conglomerate members have been mapped elsewhere, for example in the Redditch district (Old et al., 1991), but have not been named.

The following names are now redundant: the Budleigh Salterton Pebble Beds of south-west England (Region 1), the Kidderminster Formation of Region 2, the 'Cannock Chase Formation' of Region 6 (this has never been formally adopted and used), the Chester Pebble Beds Formation (Region 7), the 'Littleworth Beds' of Regions 2, 5 and 6 (never formally used), the Polesworth Formation of Region 3, the Nottingham Castle Sandstone Formation of the Nottingham area (Region 4), the Hawksmoor Formation of the Ashbourne area (Region 5), and the St Bees Sandstone Formation of Region 9. Following Holliday et al. (2006, 2008), the nomenclature for the SSG of the Carlisle Basin and Vale of Eden (Region 9) now partly follows that used in the EISB (p.26).

3.2.4 Unit D

This unit is discontinuous across the country and everywhere lies below a major unconformity, thought to correspond with the Hardegsen Disconformity of north-west Europe. Below this unconformity there is locally complete erosion of Unit D, for example in the Wessex and Hinckley basins, on the East Midlands Shelf and around Stafford, and also, locally, of Unit C (e.g. in the Wessex Basin). The sequence south of the Cheshire Basin (Regions 2 and 6) consists of heterolithic orange-red, mottled buff and grey, generally fine-grained, cross-bedded and planar laminated, poorly cemented, micaceous sandstones of fluvial origin, with minor thin beds of red-brown mudstone; palaeosols and aeolian sandstones have been reported from the upper part in the Birmingham district (Bouch et al., 2006). This unit has a high silt and clay content and has been extensively used as moulding sand in the West Midlands area. In the Cheshire Basin (Region 7) the unit is a red-brown and orange, medium-grained, poorly cemented, cross-bedded sandstone with sporadic thin beds of grey sandstone and red and green mudstone. Coarser beds are composed of well-rounded grains and are relatively free of mica, characteristics that imply a dominantly aeolian origin. However, well-cemented pebbly sandstones that occur in the upper part in the Wirral and in north Cheshire were deposited by flash floods. In Cumbria (Region 9) it is a red-brown, predominantly aeolian sandstone with a few thin fluvial interbeds.

In borehole geophysical logs (Figures 4 and 5), where dominantly of aeolian facies, the unit is characterised by relatively uniform sonic velocity values when compared to the overlying Unit E, and lower velocities than the underlying Unit C. However, beds with higher velocities that are probably of fluvial origin, may occur at any level within the unit. The gamma-ray values for this unit are generally more constant than in Unit E, probably indicating fewer mudstone interbeds.

Formerly known as the 'Upper Mottled Sandstone', four formation names are currently used for the constituents of this unit: the Wildmoor Sandstone in the West Midlands (Regions 2 and 6), the Wilmslow Sandstone in the Cheshire Basin (Region 7) and the Calder Sandstone in west Cumbria (Region 9). Elsewhere in Region 9, in the Carlisle Basin and Vale of Eden, the name Kirklinton Sandstone has been applied to the uppermost constituent unit of the SSG. The correlation of this unit with formations farther south is uncertain, although the upper part is transitional to the overlying MMG and therefore equivalent to part, at least, of Unit E. The lower part may be related to Unit D although, following Holliday et al. (2006, 2008), for the purposes of this report it is also considered to be part of Unit E (see below).

The unit shows wide and rapid variations in thickness, even within relatively small geographical areas. In the Cheshire Basin the maximum proven thickness is 920 m in the Knutsford Borehole (Figure 4), where pebbles indicative of the underlying Chester Formation (Unit C) appeared downhole at around 1870 to 1878 m depth. This is taken as the base of the formation. The Kempsey Borehole geophysical logs have been reinterpreted from Whittaker (1980), Penn (1987) and Barclay et al. (1997) who placed the top of the Wildmoor Sandstone Formation (now Wildmoor Sandstone Member of the Wilmslow Sandstone Formation; **4.3**) at 915.31 m but this is here revised to 709 m (Figure 4).

Recommendations

There is a clear distinction between the fluvial facies in the Stafford Basin (Region 6) and areas to the south (Regions 2, 5), and the dominantly aeolian sequence in Cheshire and south Lancashire (Region 7) and Cumbria (Region 9). However, large areas of England show an interdigitation of the two facies. The name **Wilmslow Sandstone Formation** (**4.3**) is chosen to represent the whole sequence for the same reason as the naming of Unit C (above). The **Wildmoor Sandstone** is retained as a member where a wholly fluvial facies occurs. The name 'Calder Sandstone Formation' is abandoned.

3.2.5 Unit E

The highest unit of the SSG is traceable through much of England (Regions 1, 2, 3 (part), 5, 6, 7, 8 (part), 9) but has not been identified northwards from Nottingham, in Region 4, and north of Burscough in Region 8. It consists predominantly of buff to greenish grey and red-brown, fine- to medium-grained, cross-bedded, locally micaceous sandstones and subordinate pebbly sandstones. Fining-upward cycles are commonly developed, with thin beds of red-brown or greenish grey siltstone and mudstone present. Extraformational pebbles of quartzite occur in some areas, more commonly in the lower part of the unit, and intraformational mudstone rip-up breccias are commonly developed throughout. This unit is of fluvial origin in regions 1, 2, 3 and 5, with some aeolian beds in regions 1, 7, 8 and 9, and represents an upward transition from a braided to a meandering river system (Warrington, 1970a; Old et al., 1991; Warrington and Ivimey-Cook, 1992; Powell et al., 2000). In Regions 6, 7 and 8 it includes units of aeolian origin. The Bulkeley Hill Formation in the Nantwich–Chester area (Warrington et al., 1980), formerly the 'Keuper Sandstone Passage Beds' of Poole and Whiteman (1966), comprises interbedded fluvial and aeolian sandstones, with a bed of conglomerate. This formation is unmapped apart from the conglomerate, which is not named. In Region 9, Unit E is mainly of aeolian origin.

In borehole geophysical logs the main features of Unit E reflect lithological inhomogeneity, with sandstones showing lower gamma-ray values interbedded with higher gamma-ray mudstones (Figures 3 and 4). Two facies can be present, with higher velocity sandstones probably of fluvial origin and lower velocity sandstones probably of aeolian origin. Often (e.g Stretton Borehole, Figure 4), but not in the Kempsey Borehole, Worcester Basin (Figure 4), the sonic log for Unit E shows a higher velocity than Unit D, reflecting dominantly fluvial sandstones overlying aeolian sandstones.

Formerly known as the 'Keuper Sandstone', five formation names are currently used for the constituents of Unit E (Table 1): Otter Sandstone (Region 1), Bromsgrove Sandstone (Regions 2, 3, 5) Hollington (Region 5), Kibblestone (Region 6) and Helsby Sandstone (Region 7). The SSG is undivided in parts of Region 8 but Ormskirk Sandstone is used in others and in parts of Region 9, with Kirklinton Sandstone used elsewhere in the latter region. Below the East Irish Sea, the Ormskirk Sandstone is very variable, with both dominantly fluvial and dominantly aeolian beds present (Meadows, 2006).

The maximum thickness of Unit E is at least 375.5 m in the Sugarbrook No. 3 Borehole (Old et al., 1991). The greater published thickness of 493.8 m in the Kempsey Borehole (Whittaker, 1980, Penn, 1987, Barclay et al., 1997) has been revised to 360.61 m on the basis of borehole geophysical log interpretation (Figure 4). Beds in Kempsey Borehole that Barclay et al. (1997) assigned to the Burcot Member of the Bromsgrove Sandstone Formation are now included in the Wildmoor Sandstone Member of the Wilmslow Sandstone Formation and the thickness of the Burcot Member in that borehole has been revised to 104 m (605 to 709 m). The 'Keuper' Waterstones' identified by Whittaker (1980) in the Kempsey Borehole are placed in Unit E on geophysical log evidence and are equivalent to the Sugarbrook Member.

Recommendations

Although Unit E shows a progressive northward change from dominantly fluvial to increasingly aeolian facies, a single name, the **Helsby Sandstone Formation** (**4.2**), is recommended for this unit across England. The choice of this name, from the Cheshire Basin sequence, follows the same reasoning as the naming of Units C and D (above). From borehole geophysical log evidence (Figure 3) it appears that the three members established by Thompson (1970a) in the Cheshire Basin can be traced into Region 8 and below the East Irish Sea (Colter, 1978). In the BGS lexicon and this report these units are: **Thurstaston Sandstone Member** (aeolian facies), **Delamere Sandstone Member** (fluvial facies) and **Frodsham Sandstone Member** (aeolian facies). Thompson (1970a) recognised two other members in the Helsby Sandstone in Cheshire, the Nether Alderley Red Sandstone Member and the Alderley Conglomerate Member. These have not been formalised and are not retained in this report. In the Charnwood Forest area, the **Shepshed Sandstone Member**, with pebbles of local Charnian origin, has been defined (Carney et al., 2002) and is retained. In Region 6, the Kibblestone Formation, a unit of aeolian origin that is laterally equivalent to the Bromsgrove Sandstone Formation, has been mapped; retention of this unit, but downgraded to **Kibblestone Member**, is recommended. The Bulkeley Hill Formation (Region 7) is not retained but the mapped conglomerate within this unit should be given a formal name and **Burwardsley Hill Bed (4.9)** is recommended. These member names should all be retained where the units can be recognised. The Grinshill Sandstone and Ruyton Sandstone formations of the Wem district (Region 7) (Pocock and Wray, 1925; Thompson, 1993) are not retained. In Region 9 the aeolian facies of the Ormskirk Sandstone Formation could be retained as a member. However, the name 'Ormskirk Sandstone' is unsuitable as recent work has shown that the exposures at Ormskirk are of typical Helsby Sandstone Formation lithology (i.e. fluvial rather than aeolian sandstones); the name **Sellafield Member** (**4.5**) is recommended for this unit.

The following names are now redundant: Otter Sandstone Formation (Region 1), Bromsgrove Sandstone Formation (Regions 2, 3, 6), Hollington Formation (Region 5), Kibblestone Formation (Region 6) and Ormskirk Sandstone Formation (Regions 8 and 9). The Kirklinton Sandstone of the Carlisle Basin and Vale of Eden is in part equivalent to Unit E. Holliday et al. (2006, 2008) recommended abandoning this name in favour of the Ormskirk Sandstone Formation but, following the recommendation of this committee, this now becomes the Helsby Sandstone Formation.

4 Formal definitions of new and revised stratigraphical units

4.1 SHERWOOD SANDSTONE GROUP

Parent unit

No change to current definition

Previous nomenclature

No change to current definition

Derivation of name

From the eponymous area, SK 57 59 to SK 64 77, Sherwood Forest, Nottinghamshire

Reference Sections

See constituent formations

Extant exposures/sections

No change to current definition

Lithology

Sandstone, red, yellow and brown, part pebbly; conglomeratic in lower part; pebbles generally extraformational quartz and quartzite, with some intraformational clasts; subordinate red mudstone and siltstone.

Lower boundary

Disconformable on the Lenton Sandstone Formation in the eponymous area and on the Kinnerton Sandstone Formation in Cheshire. Unconformable on the Aylesbeare Mudstone Group in east Devon, the Bridgnorth Sandstone Formation in the West Midlands, the Cumbrian Coast Group in Lancashire and Cumbria, and the Zechstein Group in north Nottinghamshire, Yorkshire and Durham. In other areas it rests unconformably on rocks ranging from Precambrian to Carboniferous in age.

Upper boundary

Gradational into the Tarporley Siltstone Formation of the MMG where mudstone/siltstone becomes dominant over sandstone. In the Bristol area it is taken at the upward change to red sandstones of the Redcliffe Sandstone Member of the MMG (Howard et al., 2008). In the East Midlands the boundary with the Tarporley Siltstone Formation is an unconformity.

Thickness

No change to current definition

Age

Induan (?) to Anisian (Early to early Mid-Triassic)

Equivalent units

No change to current definition

Geographical extent

No change to current definition

Subdivisions

Helsby Sandstone Formation (4.2)
- Burcot Member (4.8)
- Delamere Sandstone Member
- Finstall Member (4.7)
- Frodsham Sandstone Member
- Kibblestone Member
- Sellafield Member (4.5)
- Shepshed Sandstone Member
- Sugarbrook Member (4.6)
- Thurstaston Sandstone Member
- Burwardsley Hill Bed (4.9)
- Thurstaston Hard Sandstone Bed

Wilmslow Sandstone Formation (4.3)
- Wildmoor Sandstone Member

Chester Formation (4.4)
- Freehay Member
- Lodgedale Member
- North Head Member

St Bees Sandstone Member
Glen Dubh Sandstone Formation
Hopwas Breccia Formation
Lamlash Sandstone Formation
Moira Formation

4.2 HELSBY SANDSTONE FORMATION

Previous nomenclature

Lower Keuper Sandstone (Hull, 1860a, b)
Waterstones* (Binney, 1846)
Building Stones (Hull, 1869)
Basement Beds (Hull, 1869)
Upper Sandstone(s) (Ussher, 1902, 1913)
Grinshill Sandstone (Pocock and Wray, 1925)
Ruyton Sandstone (Pocock and Wray, 1925)
Otter Sandstones (Laming, 1968)
Otter Sandstone (Henson, 1970)
Waterstones Group (Wills, 1970)
Keuper Sandstone Formation (Thompson, 1970a)
Burcot Breccia (Wills, 1976)
Bulkeley Hill Sandstone Formation (Warrington et al., 1980)

* The beds formerly termed 'Waterstones' have, over most of the country, now been assigned to the MMG although, in the past, they were included in the 'Lower Keuper Sandstone' (various workers) and the Bromsgrove Sandstone (Worssam and Old, 1988). In the Bromsgrove area, this part of the sequence comprises more than 80 per cent sandstone and has been included in the Helsby Sandstone Formation as the Sugarbrook Member (4.6).

Parent unit

Sherwood Sandstone Group

Derivation of name

From the town of Helsby, north Cheshire

Type section

- SJ 495 755: Helsby Hill, Cheshire (Earp and Taylor, 1986, p.26) exposing about 43m of the formation.
- NY00SW/42 35.97 to 176.42 m (Barnes et al., 1994).

Reference sections

- SK 059 388 to SK 072 422: Between Hollington and Alton, Staffordshire.
- SO 96 70: Bromsgrove, north Worcestershire (Warrington, et al., 1980); basal Burcot Breccia exposures (Wills, 1976, p 37); other localities (Old, et al., 1991, p 18–30).
- NY 4000 7240: Small exposures in river banks north of Longtown, Cumbria (Dixon et al, 1926).
- NY 04506 00184: Sellafield Borehole 13B, Cumbria. BGS Registered No. NY00SW/42 35.97 to 176.42 m (Barnes et al., 1994).
- SY 060 816 to SY 130 873: Sea cliffs between Budleigh Salterton and Sidmouth, south Devon (Hounslow and McIntosh, 2003).

Extant exposures/sections

The formation is very well-exposed on the coast between Budleigh Salterton and Sidmouth, south Devon (Barton et al., 2011); a few exposures occur inland in east Devon and Somerset. It is well-exposed in the Warwick (Old et al., 1987), Bromsgrove (Old et al., 1991), Stourport and Kidderminster areas (Mitchell et al., 1962), and across the West Midlands into Staffordshire (e.g. Bridge and Hough, 2002). In north Cheshire, south Lancashire and Merseyside there are numerous exposures, including natural cliff sections at Helsby Hill and sections in disused quarries on Overton Hill, near Frodsham (Woodcock, 2002), and in disused quarries and road cuttings on the Wirral peninsula (Benton et al., 2002). It is also well-exposed at Frogsmouth Quarry, Runcorn (Mountney and Thompson, 2002). The Frodsham Sandstone Member is well-exposed at Frodsham, notably in the railway cutting (Thompson, 1969; Benton et al., 2002). Extensive unweathered sections are accessible in disused mine workings at the Alderley Edge Geological SSSI, north-east Cheshire (Warrington, 2010).

Lithology

Fine- to medium-grained, locally micaceous, cross-bedded and flat-bedded sandstones, weathering to sand near surface. Sandstones are of fluvial (subangular to subrounded grains) and aeolian (well-rounded grains) facies. Pebbles may be common, particularly near the base of the formation, and thin units of hard intraformational conglomerate occur in the south-west. Thin lenticular beds of reddish brown siltstone and mudstone occur and may be common in fining-upward sequences; calcretes and rhizocretions occur at some horizons in the south-west (Purvis and Wright, 1991; Hounslow and McIntosh, 2003; Newell, 2006).

Lower boundary

Rests disconformably on the Wilmslow Sandstone Formation and unconformably on the Chester Formation in different areas of the country. In the West Midlands and Lancashire it is placed at the base of the lowest pebbly bed or conglomerate. In Cumbria it is placed where aeolian sandstones overlie a thick fluvial sandstone sequence assigned to the Wilmslow Sandstone Formation. It is not a formational boundary with characteristic features on borehole geophysical logs.

Upper boundary

Transitional into the overlying Tarporley Siltstone Formation or, where that is absent, the Sidmouth Mudstone Formation of the MMG.

Thickness

It is locally absent in areas that were contemporary high ground such as Charnwood Forest, Breedon Hill and Mountsorrel, and possibly the Lickey Hills. The formation is thinnest in the Warwickshire, Derbyshire and north Staffordshire areas. The thickest known development (up to 500 m) is in the Worcester Basin. It thins northwards to around 250 m in the Cheshire–Lancashire area and is 90 to over 176 m thick in Cumbria. The maximum known thickness there is 176.42 m in the Sellafield 13B borehole where the top was not proved.

Age

Anisian (early Mid Triassic), from bio- and magnetostratigraphy

Equivalent units

- Smith Bank Formation (*pars*.), Heron Group, Central North Sea (Cameron, 1993).
- Dowsing Dolomitic Formation (basal part), Haisborough Group, Southern North Sea Basin (Cameron et al., 1992; Johnson et al., 1994; Bachmann et al., 2010).
- Ormskirk Sandstone Formation, East Irish Sea Basin (Jackson and Johnson, 1996; Chadwick et al., 2001).

Geographical extent

The formation crops out almost continuously from the south Devon coast, northwards, to near Taunton, Somerset. There is one outcrop in north-west Gloucestershire, around Newent, and extensive outcrops in north Worcestershire and in Staffordshire, up to near Stoke-on-Trent. There is continuous outcrop from Warwick to Nuneaton with outcrops elsewhere in Warwickshire and extensive but broken outcrops in south Derbyshire and north-west Leicestershire, including the north side of Charnwood Forest. Further fragmentary outcrops occur in Cheshire and south-west of Manchester, with more continuous outcrops around Merseyside and in southern Lancashire. The formation crops out very locally on the Cumbrian coast and more extensively in the Eden valley.

Subdivisions

Burcot Member (Old et al., 1991)
Delamere Sandstone Member (Thompson, 1970a)
Finstall Member (Old et al., 1991)
Frodsham Sandstone Member (Thompson, 1969)
Kibblestone Member, downgraded from Kibblestone Formation (Rees and Wilson, 1998)
Pennington Point Member (Gallois, 2004)
Shepshed Sandstone Member (Carney et al., 2002)
Sugarbrook Member (Old et al., 1991)
Thurstaston Sandstone Member (Thompson, 1970a)
Thurstaston Hard Sandstone Bed (Thompson, 1970b)

4.3 WILMSLOW SANDSTONE FORMATION

Previous nomenclature

Upper Mottled Sandstone (Hull, 1860a)
Upper Red and Mottled Sandstone (Hull, 1860b)
Moulding Sand Group (Wills, 1948)
Bunter Upper Mottled Sandstone (Thompson, 1970a)
'Upper' St Bees Sandstone (Jackson et al., 1987)
Upper Wildmoor Beds (Wills, 1970)
Lower Wildmoor Beds (Wills, 1970)
Wildmoor Beds (Wills, 1976)

Parent unit

Sherwood Sandstone Group

Derivation of name

From the town of Wilmslow, in north-east Cheshire.

Type section

Wilmslow–Alderley Edge area, north-east Cheshire (Taylor et al., 1963, p.61–62; Thompson, 1970a; Warrington and Thompson, 1971).

Reference sections

- SO 949 762: Wildmoor (Wildmoor Sandstone Member), north of Bromsgrove, Worcestershire (Warrington et al., 1980).
- NY 04268 03080: Bottom part, Sellafield Borehole 10B, Cumbria. BGS Registered No. NY00SW/40, 22.22 to 190.35 m.
- NY 04506 00184: Sellafield Borehole 13B, Cumbria. BGS Registered No. NY00SW/42, 176.42 to 295.70 m.

Extant exposures/sections

The formation is exposed over parts of the West Midlands (mainly Worcestershire and Shropshire) (Whitehead and Pocock, 1947; Mitchell et al., 1962). There are a few exposures in Cheshire, mainly around the Alderley Edge–Wilmslow area. Extensive unweathered sections are accessible in disused mine workings at the Alderley Edge Geological SSSI in north-east Cheshire (Warrington, 2010). In Cumbria there are discontinuous exposures in the River Calder valley (Jones and Ambrose, 1994).

Lithology

In the Cheshire Basin and northwards into Cumbria, the formation comprises red-brown to brick-red, fine- to medium-grained, generally pebble-free, cross-bedded sandstones, with sporadic siltstones. The sand grains are well rounded and indicate an aeolian origin; in Cumbria, they are coarse- to very coarse-grained. There are thin units of fluvial sandstones that have subangular to subrounded sand grains and more common beds of mudstone. Southwards, these pass into bright orange-red to dark brick-red, generally silty or argillaceous, fine- to medium-grained, micaceous sandstones with subordinate siltstone and mudstone beds. The sand grains are subangular to subrounded and pebbles are rare.

Lower boundary

The lower boundary, at the top of a sequence dominated by pebbly sandstones and conglomerates of the Chester Formation, is transitional. It may be taken at the highest occurrence of pebbles, either as a conglomerate or a pebbly sandstone. In Cumbria, it is sharp and is taken at the upward change to typical aeolian sandstones from typical fluvial sandstones, which are finer grained and better cemented.

Upper boundary

It is overlain unconformably by the Helsby Sandstone Formation. In Cumbria, it is placed at the top of a thick (40 to 50 m) fluvial sandstone unit that is well-cemented and overlain by coarser, less well-cemented aeolian sandstones of the Helsby Sandstone Formation. It is not a formational boundary with characteristic features on borehole geophysical logs.

Thickness

Thicknesses are variable across the country. In Cumbria the Sellafield boreholes proved 469 to 529 m. In the west Midlands and the Worcester Basin it is up to 284 m thick. In the Cheshire Basin, in the Knutsford Borehole, pebbles indicative of the Chester Formation were encountered at 1870 to 1878 m depth, giving a thickness of about 920 m for the Wilmslow Sandstone; this includes 325 m of strata below the 'Top Silicified Zone' which, in the EISB and regions 8 and 9, has been used to mark the base of the Wilmslow Sandstone Formation (Jackson et al., 1987).

Age

No direct evidence; probably Olenekian (late Early Triassic)

Equivalent units

- Calder Sandstone Member, St Bees Sandstone Formation, East Irish Sea Basin (Jackson and Johnson, 1996; Chadwick et al., 2001).
- Smith Bank Formation (*pars*.), Heron Group, Central North Sea (Cameron, 1993).
- Bunter Sandstone Formation, Bacton Group, Southern North Sea Basin (Cameron *et al*., 1992; Johnson et al., 1994; Hounslow and Ruffell, 2006).

Geographical extent

The Wilmslow Sandstone is exposed from just south of Stourport, across the West Midlands to Stoke-on-Trent and Lichfield, from Macclesfield to Manchester and Liverpool, and as far north as Ormskirk. In Lancashire, north of Ormskirk, it cannot be distinguished from the Helsby Sandstone and Chester formations. In Cumbria it is a distinctive unit of aeolian facies with thin fluvial interbeds. It is present in the subsurface in the Worcester and Needwood basins but absent in the Wessex and Somerset basins. There is some uncertainty about its presence between the West Midlands and the Needwood Basin. It is absent to the east of the Worcester Basin and up the eastern side of England to Doncaster. North of Doncaster, the SSG is undifferentiated and the Wilmslow Sandstone Formation cannot be distinguished.

Subdivision

Wildmoor Sandstone Member

4.4 CHESTER FORMATION

Previous nomenclature

Conglomerate Beds (Hull, 1860a)
Bunter Sandstone (Hull, 1860b)
Pebble Beds (Hull, 1860b)
St Bees Sandstone (Harkness, 1862)
Bunter Conglomerate/Beds (Bonney, 1880)
Budleigh Salterton Pebble Bed (Irving, 1888)
Budleigh Salterton Conglomerate and Sandstone (Hull, 1892)
Bunter Pebble Beds (Bonney, 1900)
Pebble Beds (Ussher, 1902)
Pebble Bed Group (Wills, 1948)
Budleigh Salterton Pebble Beds (Laming, 1968)
Budleigh Salterton Pebble Beds Formation (Henson, 1970)
Kidderminster Conglomerate Formation (Smith et al., 1974)
Chester Pebble Beds Formation (Warrington et al., 1980)
Kidderminster Formation (Warrington et al., 1980)
Cannock Chase Formation (Warrington et al., 1980)
Nottingham Castle Formation (Warrington et al., 1980)
Hawksmoor Formation (Charsley, 1982)
Polesworth Formation (Worssam and Old, 1988)
Nottingham Castle Sandstone Formation (Charsley et al., 1990)
St Bees Sandstone Formation (Warrington et al., 1980, Barnes et al., 1994)

Parent unit

Sherwood Sandstone Group

Derivation of name

From the City of Chester, Cheshire; renaming the former Chester Pebble Beds Formation

Type area

The City of Chester and vicinity, Cheshire

Type section

SJ 40 71: City of Chester and vicinity (sites in Earp and Taylor, 1986).

The main sections are in Chester, on the railway line [SO 401 666 to 406 671] and the Shropshire Union Canal [SO 401 666 to 406 667]; these show 67 to 76 m of red, cross-bedded sandstones and pebbly sandstones.

Reference sections

- SY 060 816: Sea-cliff at Budleigh Salterton, south Devon; sharp base on the Littleham Mudstone Formation. (Aylesbeare Mudstone Group), and overlain, above a palaeosol and ventifact bed (Wright et al., 1991), by aeolian sands at the base of the Helsby (formerly Otter) Sandstone Formation.
- SK 0392 4422: Hawksmoor Wood, 2.5 km east-north-east of Cheadle, Staffordshire; >11 m of cross-bedded, pebbly sandstones with thin beds of conglomerate (Chisholm et al., 1988).
- SO 83 76: Kidderminster and its vicinity, Worcestershire. Numerous exposures of conglomerate and sandstone in and around the town (Mitchell et al., 1962).
- SK 569 394: Castle Rock, Nottingham; 40 m-high former river cliff with up to 35 m of cross-bedded, pebbly sandstone exposed (Howard et al., 2009).
- SK 3010 1327: disused quarry at Acresford, Leicestershire, exposing about 10 m of interbedded cross-bedded conglomerates, pebbly sandstones and sandstone (Worssam and Old, 1988).
- SJ 303 735: Burton Point, Wirral (Steel and Thompson, 1983).
- NX 960 156 to NX 958 117: coast and quarry sections at St Bees Head, Cumbria, between Saltom Bay and St Bees, exposing >200 m of red, cross-bedded sandstones with thin mudstone beds (Benton et al., 2002).

Extant exposures/sections

The formation is exposed on the south Devon coast, in the Dorset and East Devon Coast World Heritage Site (Barton et al., 2011), but across much of east Devon, Somerset and the south Midlands it is not exposed except in quarries. Quarries in Devon, the Kidderminster area and south Staffordshire show good exposures. There are a few exposures in north Warwickshire and south-west Leicestershire. It is well exposed in the city of Nottingham and in places throughout Nottinghamshire and South Yorkshire, up to Doncaster; the formation cannot be distinguished farther north. There are exposures in Staffordshire and Derbyshire, between Cheadle and Ashbourne, and in Cheshire. The formation is well exposed in Merseyside, particularly on the Wirral peninsula. Through Lancashire the formation is largely obscured by superficial deposits and is difficult to distinguish owing to a northward facies change from pebbly sandstones and conglomerates to sandstones. On the Cumbrian coast, the formation is very well exposed.

Lithology

The formation shows a progressive change in lithology northwards, from a coarse-grained, typically well-cemented proximal facies to a fine-grained, less well-cemented distal facies. The Devon outcrops are closest to the presumed source, in northern France, and comprise brown, horizontally bedded conglomerate with subordinate lenticular beds of trough cross-bedded pebbly sand and sand (Smith, 1990; Smith and Edwards, 1991). The gravel is composed of well-rounded pebbles, cobbles and boulders in a coarse to fine granulestone and silty sandstone matrix. The clasts are mainly (84 to 90 per cent) metaquartzite, together with porphyry, vein quartz, tourmalinite, and conglomerate. From just south of Hillhead, east Devon [ST 067 136], locally derived Devonian and Carboniferous clasts begin to appear. Near Milverton, Somerset, the formation is a massive calcareous conglomerate with limestone clasts.

Northwards into the Worcester Basin, West Midlands, Staffordshire (Steel and Thompson, 1983), Cheshire and Leicestershire, the formation comprises conglomerates and reddish brown, cross-bedded, pebbly sandstones with subordinate beds of red-brown mudstone. The conglomerates have a reddish brown sandy matrix and consist mainly of pebbles of brown or purple quartzite, with quartz conglomerate and vein quartz. In these areas the formation generally fines upwards, from dominantly conglomerates at the base, to interbedded conglomerates and sandstones, with sandstone and pebbly sandstone predominant in the upper part, and rare mudstones. In Nottinghamshire, the formation comprises pinkish red or buff-grey, medium- to coarse-grained, pebbly, cross-bedded, friable sandstone. In north Staffordshire, it consists of red-brown, yellow, or yellow-mottled, very fine- to coarse-grained sandstones that are commonly cross-bedded, locally micaceous, silty or argillaceous, pebbly or conglomeratic, and generally friable.

Northwards from Nottingham the pebbles gradually die out; the farthest north they have been seen consistently is around Doncaster. West of the Pennines they occur in the Wirral–Liverpool area but disappear farther north in Lancashire, where the formation cannot be distinguished. On the Cumbrian coast, the formation is represented by a distal facies comprising red-brown, very fine- to medium-grained, commonly micaceous sandstones, which are generally cross-bedded, with some parallel lamination; mudstone clasts are locally common and subordinate thin beds of greenish grey sandstone occur. The formation has subordinate lenticular beds of reddish brown mudstone or siltstone throughout; these are more common in Cumbria.

Lower boundary

The lower boundary varies across the country. The formation rests conformably, unconformably or disconformably on Permian rocks, and unconformably on rocks of mainly Carboniferous or older Palaeozoic and Precambrian age.

Upper boundary

The upper boundary is, in parts of the country, overlain unconformably by sandstones or pebbly sandstones of the Helsby Sandstone Formation, or generally laminated mudstones, siltstones and sandstones of the MMG. Elsewhere it is conformable and generally transitional to the Wilmslow Sandstone Formation. In places the boundary is taken arbitrarily at the gradational upward change from the highest pebble bed to the overlying silty sandstones of the Wilmslow Sandstone Formation. In Cumbria it is placed at the sharp upward change from generally fine-grained, well-cemented sandstones, with features typical of fluvial deposition, to coarser, more friable sandstones with common well-rounded aeolian grains.

A feature of the Chester Formation on borehole geophysical logs is the sonic velocity which is always higher than in the bulk of the overlying formations, and commonly higher than in the underlying formation. The gamma-ray response is more variable.

The top of the formation is not always clearly defined on the gamma-ray logs when compared to the known downhole appearance of pebbles.

Thickness

The formation shows a wide range of thicknesses across the country. It is thinnest (less than 50 m), in Dorset, and up to 220 m in most other regions. In north Staffordshire it is up to 300 m thick; the thickest proven sequences (340 to 627 m) are in Cumbria.

Age

Early Triassic, Olenekian on magnetostratigraphical evidence (Hounslow and McIntosh, 2003) or older (Warrington, 2005).

Equivalent units

- Rottington Sandstone Member, St Bees Sandstone Formation, East Irish Sea Basin (Jackson and Johnson, 1996; Chadwick et al., 2001).
- Smith Bank Formation (*pars*.), Heron Group, Central North Sea (Cameron, 1993).
- Bunter Sandstone Formation, Bacton Group, Southern North Sea Basin (Cameron *et al*., 1992; Johnson et al., 1994; Bachmann et al., 2010).

Geographical extent

The formation extends from the south Devon coast northwards, up to the Cumbrian coast on the west side of England and to the Doncaster area on the east side. From Doncaster northwards, to Teesside and in parts of Lancashire, the Sherwood Sandstone Group is undivided.

Subdivisions

Freehay Member (Chisholm et al., 1988)
Lodgedale Member (Chisholm et al., 1988)
North Head Member (Ackhurst et al., 1997)
Quartzite Breccia* (Old et al., 1991)
* The status of this unit is uncertain. It was defined by Old et al. (1991) in the Redditch district but renamed the Hopwas Breccia by Powell et al. (2000) in the Birmingham area.

4.5 SELLAFIELD MEMBER

Previous nomenclature

Kirklinton Sandstone (Dixon et al., 1926)
Ormskirk Sandstone Formation (Institute of Geological Sciences, 1977)

Parent unit

Helsby Sandstone Formation

Derivation of name

From the Sellafield area of Cumbria

Type section

NY 04506 00184: Sellafield Borehole 13B, Cumbria. BGS Registered No. NY00SW/42, 0 to 176.42 m.

Reference sections

- NY 0280 0310 to 0255 0274: River Calder, Cumbria (Barnes et al., 1994).
- NY 034 50: Seascale Scar, Cumbria (Gregory, 1915).

Extant exposures/sections

Very scarce exposures in the Sellafield–Seascale–Drigg area, west Cumbria.

Lithology

The dominant lithology is a red-brown, weathering to orange-brown, fine-grained, well-sorted sandstone with well-rounded grains of aeolian origin. It is commonly cross-bedded. This aeolian dune facies is interbedded with an interdune facies comprising well-cemented, fine- to medium-grained, poorly sorted sandstone with common wavy silty laminae. Small-scale convolutions, loading and dewatering structures are common.

Lower boundary

The lower boundary is taken at the sharp upward change from fine- to coarse-grained fluvial sandstone in the underlying part of the Helsby Sandstone Formation to medium-grained, aeolian sandstone. In borehole geophysical logs it is marked by an upward decrease in gamma-ray values and an upward decrease in sonic velocity. Both log signatures are more serrated than in the underlying part of the Helsby Sandstone Formation.

Upper boundary

The upper boundary is not seen but will be marked by the incoming of dominantly red-brown mudstones and siltstones of the MMG.

Thickness

The thickest known sequence is 176.42 m, in the Sellafield 13B Borehole.

Age

Anisian (early Mid Triassic)

Equivalent unit

Helsby Sandstone Formation (*pars.*)

Geographical extent

The member only crops out between Drigg and Sellafield on the Cumbrian coast.

Subdivisions

None

4.6 SUGARBROOK MEMBER (Old et al., 1991)

Previous nomenclature

Waterstones (Binney, 1846)
Passage Beds (Richardson, 1928)
Waterstones Group (Wills, 1970)

Parent unit

Helsby Sandstone Formation

Derivation of name

From the Sugarbrook Pumping Station site [SO 961 681], to the south-west of Bromsgrove, Worcestershire.

Type section

SO 9619 6816: Sugarbrook No. 3 Borehole (BGS Registered No. SO96NE/30), 22.9 to 67.3 m (Old et al., 1991).

Reference sections

None

Extant exposures/sections

Scarce exposures in the Bromsgrove area, south and east of Kidderminster (Mitchell et al., 1962; Old et al., 1991).

Lithology

The dominant lithology is pale red-brown and greenish grey sandstones. The sandstones are finer grained than in the underlying Finstall Member and large-scale cross-bedding is virtually absent. Interbedded red-brown and grey-green mudstones and siltstones are more common than in the Finstall Member. The sequence shows repeated fining-upward cycles, from sandstone to mudstone; intraformational conglomerates occur throughout. Sedimentary structures include ripple marks, flute casts, slump structures, mud cracks and convolute bedding. Micaceous bedding planes are common. In the type section bioturbation, plant remains and *Euestheria* have been found in the lower about15m, and acritarchs and pseudomorphs after halite occur above that level.

Lower boundary

The lower boundary is taken above the highest significant (>1 m) bed of sandstone with large scale cross bedding of the underlying Finstall Member.

Upper boundary

The upper boundary is taken at the top of the highest significant grey sandstone bed, above which red mudstones and siltstones of the MMG predominate over sandstone.

Thickness

The thickest known sequence is 24.4 m, in the Sugarbrook No. 3 Borehole.

Age

Anisian (early Mid Triassic)

Equivalent unit

Tarporley Siltstone Formation (*pars*.), MMG

Geographical extent

The member has only been mapped in the Bromsgrove area of Worcestershire but is likely to extend westwards to Little Witley [SO 78 63], Worcestershire.

Subdivisions

None

4.7 FINSTALL MEMBER (Old et al., 1991)

Previous nomenclature

Building Stones (Hull, 1869)

Parent unit

Helsby Sandstone Formation

Derivation of name

From the Finstall area [SO 980 700], east of Bromsgrove, Worcestershire.

Type section

SO 865 639, disused quarry, Hadley, Worcestershire

Reference section

SO 9619 6816: Sugarbrook No. 3 Borehole. BGS Registered No. SO96NE/30, 67.3 to 206.8 m (Old et al., 1991).

Extant exposures/sections

Scattered exposures in the Bromsgrove area, south and east of Kidderminster.

Lithology

The dominant lithology is planar and trough cross-bedded, irregularly bedded and structureless, pale red-brown and greenish grey sandstones. Subordinate lithologies are red-brown and grey-green mudstone and siltstone. The sequence shows repeated fining-upward cycles, from sandstone to mudstone; there is commonly an intraformational conglomerate at the base of each cycle and the upper beds of sandstone are commonly parallel laminated. Sedimentary structures include ripple marks, flute casts, slump structures, mudcracks and convolute bedding. Micaceous bedding planes are common. Bioturbation occurs in the lower part of the member and plant remains and *Euestheria* have been found in the upper part in the reference section. Elsewhere (**1.2**) the member has yielded acritarchs, miospores, plant remains, annelids, brachiopods, bivalves, *Euestheria*, ostracods, and remains of arachnids, fish, amphibians and reptiles.

Lower boundary

The lower boundary is taken at the base of the cycle above the highest bed of extraformational conglomerate.

Upper boundary

The upper boundary is taken at top of the highest significant (>1 m) bed of sandstone with large scale cross bedding.

Thickness

The thickest known sequence is 139.5 m, in the Sugarbrook No.3 Borehole; the minimum known thickness is 33.6 m, in the Longbridge Laundry Borehole [SP 0201 7847] (Powell et al., 2000).

Age

Anisian (early Mid Triassic)

Equivalent units

None

Geographical extent

The member has only been mapped in the Bromsgrove area of Worcestershire but is likely to extend westwards to Little Witley [SO 78 63], Worcestershire.

Subdivisions

None

4.8 BURCOT MEMBER (OLD ET AL. 1991)

Previous nomenclature

Basement Beds (Hull, 1869)

Parent unit

Helsby Sandstone Formation

Derivation of name

From the Burcot area [SO 98 71], Worcestershire

Type section

Road cutting, Burcot [SO 972 716] (Benton et al. 2002)

Reference section

SO 9619 6816: Sugarbrook No. 3 Borehole BGS Registered No. SO96NE/30, 206.8 to 398.4 m (Old et al., 1991); the base of the member was not proved.

Extant exposures/sections

Scattered exposures south of Kidderminster, Worcestershire.

Lithology

The dominant lithology is planar and trough cross-bedded, irregularly bedded and structureless red-brown sandstones. Subordinate lithologies are conglomerates composed of subrounded to angular clasts. Extraformational clasts include quartz, quartzite, limestone, chert and tuff; intraformational clasts include mudstone, siltstone and sandstone. There are subordinate beds of grey-green mudstone and siltstone. The sequence shows repeated fining-upward cycles, from conglomerate to mudstone; the siltstone and mudstone components of these are commonly absent. Sedimentary structures include ripple marks, flute casts, slump structures and convolute bedding. Micaceous bedding planes are common. A solitary fish spine was recorded from the member (Wills, 1970).

Lower boundary

The lower boundary is taken at the lowest conglomerate resting on soft red sandstones of the Wildmoor Sandstone Member of the Wilmslow Sandstone Formation.

Upper boundary

The upper boundary is taken at the top of the highest bed of extraformational conglomerate, with sandstones and mudstones, of the overlying Finstall Member.

Thickness

The thickest known sequence is 192.4 m, in the Sugarbrook No. 3 Borehole, but the base has not been proved.

Age

Anisian (early Mid Triassic)

Equivalent units

None

Geographical extent

The member has only been mapped in the Bromsgrove area of Worcestershire but is likely to extend westwards to Little Witley [SO 78 63], Worcestershire.

Subdivisions

None

4.9 BURWARDSLEY HILL BED

Previous nomenclature

Keuper Sandstone Conglomerate (Poole and Whiteman, 1966)
Sandstone Conglomerate (Earp and Taylor, 1986)

Parent unit

Helsby Sandstone Formation

Derivation of name

From Burwardsley Hill [SJ5078 5573], where it is well exposed

Type section

Burwardsley Hill, Cheshire [SJ 5086 5562 to 5108 5612] (Earp and Taylor, 1986)

Reference sections

None

Extant exposures/sections

The bed is well-exposed at the type section on Burwardsley Hill, and there are scattered quarry exposures in that area.

Lithology

Conglomerates, pebbly sandstones and sandstones, cross-bedded and coarse-grained. Pebbles are mainly of quartz and quartzite, up to 5 cm in diameter.

Lower boundary

The lower boundary is placed at the downward change from conglomerate and pebbly sandstone to red-brown, fine- to coarse-grained sandstones with thin beds of red-brown mudstone, of the underlying Wilmslow Sandstone Formation.

Upper boundary

At the upward change from mainly conglomerates to sandstones and pebbly sandstones in the Helsby Sandstone Formation.

Thickness

0 to 11 m

Age

Anisian (early Mid Triassic)

Equivalent units

None

Geographical extent

From just south of the village of Penley [SJ 41 39], Cheshire, to near the village of Beeston [SJ 54 58], Cheshire.

Subdivisions

None

Appendix 1 Alphabetical listing of lithostratigraphical units (by group, formation and bed) and their BGS lexicon of named rock units computer codes (where allocated).

Definitive information about all the lithostratigraphical units listed below can be found in the BGS Lexicon of Named Rock Units, accessible on the BGS website at http://www.bgs.ac.uk/lexicon (see also Appendix 2)

Group	Formation	Member	Bed
Sherwood Sandstone Group (SSG)	Helsby Sandstone (HEY)		Burwardsley Hill (BRWH)
		Burcot (BRCT)	
		Delamere Sandstone (DELA)	
		Finstall (FNSTL)	
		Sugarbrook (SGBK)	
		Frodsham Sandstone (FRM)	
		Kibblestone (KBN)	
		Sellafield (SELF)	
		Shepshed Sandstone (SHSA)	
		Thurstaston Sandstone (THUN)	Thurstaston Hard Sandstone (THHB)
	Wilmslow Sandstone (WLSF)	Wildmoor Sandstone (WRS)	
	Chester (CPB)	St Bees Sandstone (SBS)	
		Freehay (FRE)	
		Lodgedale (LOD)	
		North Head (NOHE)	
	Moira (MOI)		
	Hopwas Breccia (HPBR)		
	Lamlash Sandstone (LLSF)		
	Glen Dubh Sandstone (GDSA)		

Appendix 2 Alphabetical listing of obsolete lithostratigraphical terms mentioned in the text, and the units they are now equivalent to or included within

For BGS Lexicon of Named Rock Units computer codes see Appendix 1.

Obsolete term:	**Now equivalent to or included within:**
Bromsgrove Sandstone Formation	Helsby Sandstone Formation
Budleigh Salterton Pebble Beds	Chester Formation
Bulkeley Hill Formation	Helsby Sandstone Formation
Bunter Pebble Beds	Chester Formation
Calder Sandstone Formation	Wilmslow Sandstone Formation
Cannock Chase Formation	Chester Formation
Chester Pebble Beds Formation	Chester Formation
Grinshill Sandstone	Helsby Sandstone Formation
Hawksmoor Formation	Chester Formation
Hollington Formation	Helsby Sandstone Formation
Keuper Sandstone Passage Beds	Helsby Sandstone Formation
Kibblestone Formation	Kibblestone Member, Helsby Sandstone Formation
Kidderminster Formation	Chester Formation
Kirklinton Sandstone Formation	Helsby Sandstone Formation
Lower Keuper Sandstone	Helsby Sandstone Formation
Nottingham Castle Sandstone Formation	Chester Formation
Ormskirk Sandstone Formation	Helsby Sandstone Formation
Otter Sandstone Formation	Helsby Sandstone Formation
Polesworth Formation	Chester Formation
Ruyton Sandstone	Helsby Sandstone Formation
St Bees Sandstone Formation	St Bees Sandstone Member, Chester Formation
Upper Mottled Sandstone	Wilmslow Sandstone Formation
Wildmoor Sandstone Formation	Wildmoor Sandstone Member, Wilmslow Sandstone Formation

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