Lithostratigraphical subdivision of the Sherwood Sandstone Group (Triassic) of the north-eastern part of the Carlisle Basin, Cumbria, and adjacent parts of Dumfries and Galloway, UK

Geology & Landscape Northern Britain Programme

Internal Report IR/05/148

BRITISH GEOLOGICAL SURVEY

GEOLOGY & LANDSCAPE NORTHERN BRITAIN PROGRAMME

INTERNAL REPORT IR/05/148

Lithostratigraphical subdivision of the Sherwood Sandstone Group (Triassic) of the north-eastern part of the Carlisle Basin, Cumbria, and adjacent parts of Dumfries and Galloway, UK

D.W. HOLLIDAY, N.S. JONES and A.A. MCMILLAN

Keywords

Lithostratigraphy, Sherwood Sandstone Group, St Bees Sandstone Formation, Kirklinton Samndstone, Triassic, Carlisle Basin, Cumbria, Dumfries and Galloway.

Front cover

Cover picture details, delete if no cover picture.

Bibliographical reference

HOLLIDAY, D.W., JONES, N.S. & MCMILLAN, A.A. 2005. Lithostratigraphical subdivision of the Sherwood Sandstone Group (Triassic) of the north-eastern part of the Carlisle Basin, Cumbria, and adjacent parts of Dumfries and Galloway, UK. *British Geological Survey Internal Report*, IR/05/148. 43pp.

Keyworth, Nottingham British Geological Survey 2005

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desks at Nottingham, Edinburgh and London; see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications including maps for consultation.

The Survey publishes an annual catalogue of its maps and other publications; this catalogue is available from any of the BGS Sales Desks.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE

☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

☎ 028-9038 8462 Fax 028-9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff, CF15 7NE

☎ 029–2052 1962 Fax 029–2052 1963

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Acknowledgements

The authors would like to thank Dave Millward and Graham Lott of BGS for their encouragement and support, and Dr M Brookfield (University of Guelph, Canada) and Mr D I Jackson (Edinburgh) for valuable discussion and comment. Thanks are also due to Blockstone Ltd, particularly Tina Bailey, for granting permission to visit Cove Quarry.

Contents

FIGURES

TABLES

Summary

This report presents a review of the history of the lithostratigraphical subdivision of the Triassic Sherwood Sandstone Group of the north-eastern part of the Carlisle Basin, Cumbria, and adjacent parts of Dumfries and Galloway, UK. Two formations, the St Bees Sandstone and Kirklinton Sandstone, have been mapped in the past. However, previous workers have found considerable difficulty in consistently identifying, defining and mapping the Kirklinton Sandstone Formation. Moreover, previous accounts of the sandstones in the Carlisle area appear to suggest that the succession there differs in several key aspects from its correlatives in other parts of Cumbria and, in particular, the adjacent offshore area. As a result of a short period of field work in the area, it is concluded that the principal lithological change is between mainly fine-grained sandstones, that are generally or commonly micaceous and contain common or numerous mudstone interbeds, in the lower and middle parts of the group, and fine- to coarse-grained sandstones with rare or no mica and mudstone partings at the top of the group. This change occurs within the Kirklinton Sandstone Formation as previously mapped, and it is suggested that this unit is now invalid. Several options are considered as to how the group should be subdivided and the nomenclature to be adopted. All options presently have some associated problems, but the adoption of the same terminology as in the continuous offshore is suggested, i.e. St Bees Sandstone Formation below (subdivided where possible into Rottington Sandstone and Calder Sandstone Members) and Ormskirk Sandstone Formation above.

1 Introduction

Current lithostratigraphical subdivision of Triassic rocks in Britain follows the framework established by Warrington *et al*. (1980). The terms in common usage prior to these proposals, such as ‘Bunter’, ‘Keuper’ and ‘Rheatic’ had acquired mixed litho- and chronostratigraphical connotations. The lithostratigraphical scheme of Warrington *et al*. (1980) avoids the use of such names and clearly separates litho- and chronostratigraphical divisions. They (*op. cit*., p. 13) proposed the term Sherwood Sandstone Group (SSG) broadly to encompass arenaceous “formations previously assigned to the ‘Bunter’ and the arenaceous (lower) part of the ‘Keuper’ in Britain”. The 'Bunter' and 'Keuper' rocks are thought to be separated by a widespread hiatus, the Hardegsen Disconformity. The Sherwood Sandstone Group is overlain by the dominantly argillaceous beds of the Mercia Mudstone Group (MMG). Where argillaceous beds rest on the disconformity, the junction between the two groups is likely to be sharp, but, where arenaceous rocks of the Sherwood Sandstone Group (such examples were formerly called Keuper Sandstone) occur above the Hardegsen surface, the boundary between the groups is likely to be gradational and diachronous.

Prior to the Warrington *et al*. (1980) nomenclature, the arenaceous part of the Triassic succession in Cumbria, including the Carlisle and Vale of Eden basins and the eastern margin of the East Irish Sea Basin (EISB), was largely assigned to a single division, the St Bees Sandstone (SBS) (Figs 1, 2; Tables 1, 2) (Harkness 1862; Dixon *et al*. 1926; Eastwood 1930; Eastwood *et al*. 1931; Trotter and Hollingworth 1932; Trotter *et al*. 1937; Arthurton and Wadge 1981). A higher unit, the Kirklinton Sandstone (KS) (Holmes 1881, 1899; Dixon *et al*. 1926; Trotter and Hollingworth 1932; Day 1970) was also recognised in the Carlisle Basin (Table 1). As reviewed below, the status of the KS, whether it can be recognised in other areas and its relationship with both the SBS and the overlying strata have been called into question. Notwithstanding these difficulties, Arthurton et al. (1978) and Warrington *et al*. (1980, table 4 column 7) included the St Bees and Kirklinton sandstones as component formations (SBSF and KSF) of the Sherwood Sandstone Group in the Carlisle Basin.

Since 1980, much new information has come to hand relating to the lithostratigraphy and sedimentology of the Sherwood Sandstone Group of Cumbria and adjacent areas (Tables 1-3). This is particularly the case in the EISB, the Solway Firth Basin (SFB) and other offshore areas following extensive offshore hydrocarbon exploration (Colter 1997; Quirk *et al*. 1999) and the onshore investigation of the area around Sellafield, west Cumbria, as a potential repository or store site for radioactive waste (Michie and Bowden 1994; Bowden *et al*. 1998). As a result, a more detailed subdivision of the Sherwood Sandstone Group is now employed in these areas (Tables 1-3). However, the relationship between this more recently proposed lithostratigraphy in the EISB and the older subdivisions elsewhere in Cumbria remains uncertain. In particular, the age, stratigraphical relations and correlation of the KS have not been resolved. In this account, we briefly review the literature on the KS and report on reconnaissance field investigations of the Sherwood Sandstone Group in NE Cumbria and adjacent areas of Dumfries and Galloway, including the eponymous area of the KS and other significant nearby exposures. We also discuss the local and regional lithostratigraphical implications of the field observations.

2 Previous investigations

2.1 ONSHORE PRIOR TO *C.* 1980

The Permo-Triassic (New Red Sandstone) rocks of Cumbria attracted considerable interest during the 19th century. A list of the principal contributions during this period is given by Dixon *et al*. (1926, pp. 103-105). The stratigraphical order, classification and structural relationships of the various argillaceous, evaporitic and arenaceous units observed at outcrop and in boreholes were a matter of considerable debate, which was not satisfactorily resolved until the publication of the 2nd edition of the Carlisle Memoir (Dixon *et al*. 1926) (Table 1). The broad stratigraphical succession in the Permo-Triassic rocks of the Carlisle Basin was confirmed by the Silloth 1-A Borehole (Fig. 3), drilled in 1973 by Ultramar Exploration. In this borehole, the Sherwood Sandstone Group was proved to be 502 m thick (381-883 m).

The 'red sandstone of St Bees Head' was well known to early workers, e.g. Sedgwick (1836). The first use of the term St Bees Sandstone seems to have been by Harkness (1862) and Murchison and Harkness (1864) in the area around St Bees Head, west Cumbria, and was quickly applied elsewhere in NW England to lithologically similar correlatives. The distinctive sandstone lithofacies seen on the coast and in quarries around the eponymous locality can be recognised in west and south Cumbria, and the Carlisle and Vale of Eden basins. The name Annan Sandstone was suggested by Horne and Gregory (1916) for the sandstone in the Scottish part of the Carlisle Basin, but the continuity with the St Bees Sandstone immediately across the border in England led Barrett (1942) to discontinue its use. The St Bees Sandstone Formation of west Cumbria is typically fine-grained, with angular detritus. Siltstone and mudstone partings are common in its lower part which is gradational with underlying Permo-Triassic argillaceous rocks of the St Bees or Eden Shales (Dixon *et al*. 1926; Trotter and Hollingworth 1932; Holliday *et al*. 2001; Brookfield 2004).

Holmes (1881, 1899) proposed that another sandstone unit, the Kirklinton Sandstone, softer and less well-cemented, and commonly with medium to coarse, rounded sand grains, was present in the Carlisle Basin, unconformably overlying the SBS (Table 1). Goodchild (1893) observed some lithological similarities between parts of the KS and the Waterstones (Keuper) of the English Midlands. However, the St Bees Sandstone and Kirklinton Sandstone were later shown to be essentially conformable and the latter was seen by many as being only a local lithofacies variation of the SBS in its upper part, since the two lithological types apparently could be seen alternating at many localities (e.g. Gregory 1915b; Dixon *et al*. 1926; Trotter and Hollingworth 1932; Barrett 1942). Certainly, it is difficult to understand from the written accounts and surviving maps the reasons why Holmes (1881, 1899) included some exposures within the Kirklinton Sandstone, rather than the St Bees Sandstone. Indeed, Trotter and Hollingworth (1932, p. 141) suggested that there was little justification for retaining the term Kirklinton Sandstone except as a means of broadly separating the generally stratigraphically higher softer and less well-cemented sandstones. Thus, although the Geological Survey maps of the eastern Carlisle Basin show the Kirklinton Sandstone and St Bees Sandstone as separate lithostratigraphical units (Dixon *et al*. 1926; Trotter and Hollingworth 1932; Day 1970), the bipartite subdivision was not continued into the western part of the basin partly due to poor exposure (British Geological Survey 1995, 1997). In west Cumbria (Eastwood *et al*. 1931; Trotter *et al*. 1937) and the Vale of Eden (Arthurton and Wadge 1981), the Sherwood Sandstone Group was shown as comprising only an undivided SBS on the published geological maps (Table 2). Even though rocks of Kirklinton Sandstone-type lithofacies are exposed in these areas, it was argued that the inferred diachronous and gradational boundary between the divisions could not be adequately and consistently mapped in the field because of local structural complexity and the relatively thick and persistent drift cover. Some attempts were made to extend the use of the term Kirklinton Sandstone for the higher, less well-cemented sandstones in these areas, e.g. Gregory (1915a) in west Cumbria and Goodchild (1893) in the Vale of Eden, but were supported by few workers (Table 2).

The KS is overlain in the Carlisle Basin by argillaceous rocks of the Stanwix Shales, previously regarded as part of the 'Keuper Series' and now taken as a component part of the Mercia Mudstone Group. The top of the KS was thought by Holmes (1891, 1899) to be also at an unconformity. However, Dixon *et al*. (1926), Trotter and Hollingworth (1932) and Brookfield (2004) interpreted the field evidence as indicating a gradational junction. The Mercia Mudstone Group is not found elsewhere onshore in west and north Cumbria.

The age of the sandstones in Cumbria and adjacent areas has been much debated in the past. They have been variously ascribed to either the Permian or the Triassic, but, because of the lack of firm biostratigraphical and chronostratigraphical information, much of the discussion was based on lithological criteria of dubious value and on supposed correlations with sequences elsewhere in Britain. The general consensus, pre-1980, was that the sandstones are of Triassic age and correlatives of the 'Bunter' Sandstone of the English Midlands (reviewed by Dixon *et al*. 1926, chapter II). This view was broadly supported by the more detailed review of Warrington et al. (1980), who placed the Permian-Triassic boundary within the argillaceous beds of the St Bees and Eden shales, which have a gradational and diachronous junction with the overlying Sherwood Sandstone Group. However, Warrington *et al*. (1980, table 4, column 7) suggested that the Kirklinton Sandstone Formation could be a correlative of the ‘Keuper Sandstone’, possibly separated from the St Bees Sandstone Formation by the Hardegsen Disconformity. This view is supported by the lithological similarities with the (Keuper) Waterstones noted by Goodchild (1893), and the apparent transition between the Kirklinton Sandstone and overlying Mercia Mudstone Group, but is contradicted by the claimed diachronous junction, with alternating lithofacies, with the St Bees Sandstone.

2.2 OFFSHORE WEST CUMBRIA TO *C.* 1990

Analysis of borehole cores and cuttings, down-hole geophysical logs and seismic reflection profiles, obtained during the exploration for oil and gas in the EISB (Colter 1978, 1997), offshore NW England, beginning in the 1970s, led to the next major advance in the lithostratigraphical analysis of the Sherwood Sandstone Group of Cumbria.

In early studies on the geology of the EISB (Colter and Barr 1975; Colter 1978) the Triassic sandstones were assigned to three informal lithostratigraphical units of unequal thickness, the St Bees Sandstone, the (Lower) Keuper Sandstone and the Keuper Waterstones. The term Sherwood Sandstone Group was used first in the EISB by Ebbern (1981), and the succession was subdivided into the St Bees Sandstone Formation, the Keuper Sandstone Formation and the Keuper Waterstones Formation (Ebbern 1981; Burley 1984; Bushell 1986) (Table 2). Later, Jackson *et al*. (1987), noting the obsolescence of the terms 'Keuper' and 'Waterstones', following the recommendations of Warrington et al. (1980), proposed a two-fold subdivision, retaining St Bees Sandstone Formation and extending the term Ormskirk Sandstone (Formation) (OSF) (Institute of Geological Sciences 1977; Warrington *et al*. 1980) to offshore areas, as a replacement for the combined Keuper Sandstone Formation and Keuper Waterstones Formation (Table 2) Later workers (e.g. Cowan 1993; Meadows and Beach 1993a) generally followed the classification of Jackson et al. (1987). Colter and Barr (1975) and Colter (1978) noted a widely recognised shift in the geophysical log traces (particularly gamma and sonic), the so-called Top Silicified Zone, in the St Bees Sandstone Formation of the EISB. Jackson *et al*. (1987) used this marker to informally subdivide the St Bees Sandstone Formation into ‘lower’ and 'upper' units.

Detailed sedimentological studies have helped to differentiate the subdivisions of the Sherwood Sandstone Group offshore (Meadows and Beach 1993a, 1993b; Cowan 1993; Cowan *et al*.

1993). Much of the St Bees Sandstone Formation comprises the deposits of a major northwards flowing river system, in a semi-arid continental setting, but aeolian deposition became increasing important in the higher part of the formation, particularly towards the basin margins. The ‘Lower’ St Bees Sandstone Formation is almost everywhere fluvial in origin, whereas the ‘Upper’ part commonly exhibits alternating fluvial and aeolian facies. The Ormskirk Sandstone Formation also contains the deposits of a major river system, subjected to periodic aeolian deposition, particularly towards the basin margin and over interfluves.

2.3 ONSHORE: THE NIREX INVESTIGATIONS AROUND SELLAFIELD AND LATER INVESTIGATIONS

As part of the Nirex investigation of the geology of west Cumbria (Michie and Bowden 1994; Bowden *et al*. 1998), the area between Whitehaven and Seascale was resurveyed in 1991 (Nirex 1992). This work supported Gregory's (1915a) suggestion that the finer grained sandstones, typical of the coastal exposures to the north of St Bees, were overlain towards the south by less well exposed, softer and coarser sandstones. The term Calder Sandstone (CSF), of formational status, was introduced for these higher sandstones, and the name St Bees Sandstone Formation (SBSF) restricted to the lower unit, i.e. the sandstones that are so prominent around St Bees Head itself.

Examination of the more complete sections provided by the several kilometres of core from boreholes drilled around Sellafield (Michie and Bowden 1994), allowed Barnes *et al*. (1994) to propose a formal lithostratigraphical subdivision, with, for the first time, designated type and reference sections for the St Bees Sandstone Formation and Calder Sandstone Formation. Study of borehole core and of outcrops, also geophysical log correlation and seismic reflection data, showed that the boundary between these two formations corresponded to Colter and Barr's (1975) Top Silicified Zone, and that correlatives of Jackson et al.'s (1987) Ormskirk Sandstone Formation also occurred onshore. A marked lithological contrast was found between the St Bees Sandstone Formation and and Calder Sandstone Formation with a sharp erosional contact, whereas the OS could only be separated with difficulty from the CS on lithological criteria, and was recognised principally by its finer grain size, geophysical log pattern and from seismic reflection data. From the wide range of data available, it proved possible to map all three formations in the subsurface and at outcrop (Akhurst *et al*. 1997) (Tables 2, 3).

As offshore, the onshore subdivisions of the Sherwood Sandstone Group in west Cumbria can be characterised by their different sedimentological origin (Jones and Ambrose 1994). The onshore deposits form part of the same northwards flowing fluvial system as offshore, but aeolian deposition is of much greater significance, particularly in the upper half. The St Bees Sandstone Formation is almost totally fluvial in origin with only rare (<1%) aeolian interbeds. In contrast, the and Calder Sandstone Formation and Ormskirk Sandstone Formation largely comprise aeolian deposits with, in the and Calder Sandstone Formation, some notable fluvial interbeds. The and Calder Sandstone Formation and Ormskirk Sandstone Formation boundary onshore is taken at the top of one prominent, persistent fluvial unit (Barnes *et al*. 1994).

The borehole cores, geophysical logs and seismic reflection data indicate that the boundaries between the St Bees Sandstone Formation, and Calder Sandstone Formation and Ormskirk Sandstone Formation are sharp and laterally persistent. Barnes *et al*. (1994) suggested that these boundaries are disconformities, the higher corresponding to the Hardegsen Disconformity. These observations contradicted the previous investigations of Eastwood *et al*. (1931) and Trotter *et al*. (1937), who had concluded that there were no major breaks in the sequence and that the aeolian beds are a local lithofacies of the fluvial rocks and cannot be separately mapped at surface. The alternations of facies cited by these authors in support of their case can now be identified with the and Calder Sandstone Formation, particularly its lower part, where such alternations are common (Barnes *et al*. 1994, fig. 1).

Barnes et al. (1994, pp. 58-59, fig. 2) discussed the correlation of the newly established west Cumbrian Sherwood Sandstone Group succession with other parts of Cumbria, in particular with the Carlisle and Vale of Eden basins. They, and Jackson *et al*. (1995), noted that the mud log and geophysical logs of the Silloth 1-A Borehole proved the presence of the offshore "Top Silicified Zone" log marker of Jackson *et al*. (1987), providing the basis for the recognition of equivalents of the St Bees Sandstone Formation and the and Calder Sandstone Formation (Fig. 3). The presence of an Ormskirk Sandstone Formation equivalent was also tentatively proposed. They broadly correlated the Ormskirk Sandstone Formation and Kirklinton Sandstone Formation, and compared the 'transitional' interbedding of St Bees Sandstone Formation - and Kirklinton Sandstone-type strata, described by Dixon et al. (1926), with the alternating fluvial and aeolian facies of the and Calder Sandstone Formation around Sellafield. Studies of seismic reflection data have indicated that the correlatives of the west Cumbrian Sherwood Sandstone Group formations can be mapped in the subsurface of the Carlisle Basin (Chadwick *et al*. 1995, fig. 38; Akhurst *et al*. 1997, fig. 28; Holliday *et al*. 2004) (Table 1). Further investigation (see below) is required to determine whether these divisions can be recognised and mapped at the surface. Barnes *et al*. (1994) drew attention to the records of similar SBS and KS facies alternations in the Sherwood Sandstone Group of the Vale of Eden (Arthurton and Wadge 1981), suggesting the possible presence here also of equivalents of the and Calder Sandstone Formation and, perhaps, the Ormskirk Sandstone Formation.

More recently, Brookfield (2004) has revived the term Annan Sandstone in the Carlisle Basin and applied it, for the first time, to the English outcrops. Though not explicitly stated, his Annan Sandstone apparently is not strictly used in its original (Horne and Gregory 1916) sense, and not only comprises strata previously regarded as St Bees Sandstone Formation, but also includes beds previously mapped by Holmes (1899), Dixon *et al*. (1926) and Trotter and Hollingworth (1932) as forming the lower part of the Kirklinton Sandstone and 'transitional strata'. The Kirklinton Sandstone is retained by Brookfield (2004) but used, in a more restricted sense, for only the higher parts of the formation as previously recognised. No type sections were designated by Brookfield (2004) for the Annan Sandstone or the revised Kirklinton Sandstone Formation.

2.4 OFFSHORE: INTEGRATED LITHOSTRATIGRAPHICAL SCHEME OF JACKSON AND JOHNSON (1996) AND LATER STUDIES

The establishment of a fully formalised lithostratigraphical scheme by Jackson and Johnson (1996) is the latest advance in the subdivision of the Sherwood Sandstone Group in the offshore East Irish Sea Basin (Tables 2, 3). Chadwick *et al*. (2001) have since extended the use of this nomenclature to much of the northern part of the Irish Sea, including the SFB. Although the same lithostratigraphical units were recognised as in the onshore scheme of Barnes et al. (1994), some different names and a different hierarchy were proposed. Jackson and Johnson (1996) preferred to continue to use the extended definition of St Bees Sandstone Formation of Jackson et al. (1987), with the 'Top Silicified Zone' separating units given member status. The 'lower' St Bee's Sandstone Formation has now been formally defined as the Rottington Sandstone Member (RSM) and the 'upper' lower' St Bee's Sandstone Formation as the Calder Sandstone Member (CSM). Because of the greater proportion of fluvial strata in the CSM and its general finer grained nature, compared with the and Calder Sandstone Formation, this boundary is less of a lithological contrast than is the case onshore in west Cumbria. The CSM was subdivided into four units, CR1 to CR4, based principally on the study of wireline logs and depositional environment analysis. It is probable that these divisions can also be recognised onshore in the Sellafield and Silloth 1-A boreholes; for example the dominantly fluvial CR4 is probably the correlative of the fluvial beds at the top of the and Calder Sandstone Formation of west Cumbria (Fig. 3). For the first time, the Ormskirk Sandstone Formation has been given a formal definition and type section. Jackson *et al*. (1995) and Jackson and Johnson (1996, p. 70) have proposed that the Ormskirk Sandstone Formation "corresponds approximately" with the Kirklinton Sandstone Formation of the Carlisle area, whereas Chadwick et al. (2001) suggested that the Kirklinton Sandstone Formation includes equivalents of both Calder Sandstone Member and Ormskirk Sandstone Formation.

Jackson and Johnson (1996) and Chadwick *et al*. (2001) have suggested, mainly from the character of the geophysical log traces, that in some offshore areas both the top and bottom of the Sherwood Sandstone Group may be non-sequences. This contrast with the onshore where, as noted above, the gradational base of the Sherwood Sandstone Group is exposed at several localities and revealed in numerous borehole cores, and the top is said to be gradational.

2.5 SUMMARY AND CURRENT PROBLEMS RELATING TO THE KIRKLINTON SANDSTONE

1. A broad but consistent tripartite division of the Sherwood Sandstone Group has been recognised and mapped offshore and onshore, at surface and in the subsurface, in the EIS and SF basins. The same divisions occur in the subsurface of the Carlisle Basin, but the upper two have not been substantiated at outcrop in this basin or in the Vale of Eden Basin (Table 3).

2. The lowest division, equivalent to the St Bees Sandstone Formation onshore west Cumbria and to the Rottington Sandstone Member of the offshore East Irish Sea and Solway Firth basins, comprising very fine to fine-grained sandstones of fluvial origin, has been identified in all areas. It has a gradational base with the underlying argillaceous strata, at least in onshore areas.

3. The middle division, equivalent to the and Calder Sandstone Formation of onshore west Cumbria and Calder Sandstone Member offshore, has a sharp, disconformable boundary with the underlying strata. In west Cumbria it comprises up to medium-grained sandstones, commonly bimodal, with prominent rounded 'millet seed' quartz grains, and is characterised by alternating fluvial and aeolian facies. Offshore, in the EIS and SF basins, it is more generally fine-grained and less clearly lithologically distinct from the sandstones of the lowest division. The presence of the middle division has been demonstrated in the subsurface of the Carlisle Basin (Silloth No. 1 Borehole and seismic reflection data) (Fig. 3), but, prior to the present study, its equivalent at outcrop were uncertain. It seemed likely to be at least in part a correlative of the Kirklinton Sandstone Formation and/or the 'transitional beds' between the St Bees Sandstone Formation and Kirklinton Sandstone Formation.

4. The upper division, Ormskirk Sandstone Formation, has a sharp, disconformable boundary with the underlying strata. In west Cumbria, it is generally finer grained and better sorted than the and Calder Sandstone Formation, and is dominantly of aeolian origin. In the offshore EIS and SF basins, the Ormskirk Sandstone Formation is generally coarser grained than the underlying Calder Sandstone Member. The presence of strata equivalent to the Ormskirk Sandstone Formation has been demonstrated in the subsurface of the Carlisle Basin (seismic reflection data and Silloth No 1 Borehole) (Fig. 3). It seemed likely to be at least in part a correlative of the Kirklinton Sandstone Formation of the Carlisle Basin, and could possibly be present in the Vale of Eden Basin.

5. The Sherwood Sandstone Group is overlain by the Mercia Mudstone Group. Offshore, the junction is said to be erosional, but onshore, in the Carlisle Basin, the boundary appears from descriptions of surface exposures to be gradational.

6. The main, current problems of lithostratigraphical division in Cumbria result principally from the uncertain nature and status of the KS. This derives mainly from the lack of modern information on the sequence, lithology and sedimentology of the Kirklinton Sandstone Formation at outcrop in the Carlisle and perhaps Vale of Eden basins. Key questions include:
   - Is the Kirklinton Sandstone Formation a valid lithostratigraphical division and can it be adequately defined and distinguished from the St Bees Sandstone Formation?
   - Can the Calder Sandstone Member (and/or Calder Sandstone Formation) and Ormskirk Sandstone Formation lithofacies be recognised in the outcrops previously referred to the Kirklinton Sandstone?
   - Can the basal and Calder Sandstone Formation and Ormskirk Sandstone Formation disconformities be recognised within the inferred equivalent strata at outcrop?
   - Which if any of these divisions constitute mappable formations at the surface in the Carlisle Basin as well as in the subsurface?

3 Field investigations

In an attempt to answer the above questions, and determine whether the current lithostratigraphical nomenclature remains the most appropriate at outcrop in the Carlisle Basin, or whether new nomenclature should be adopted, some of the outcrops of the St Bees Sandstone Formation and Kirklinton Sandstone Formation to the north and east of Carlisle, around Annan, Longtown, Brampton and Canonbie have been examined (Fig. 2). This area contains the eponymous locality for the Kirklinton Sandstone Formation and other excellent exposures (Holmes 1881, 1889; Dixon *et al*. 1926; Trotter and Hollingworth 1932; Barrett 1942; Day 1970). Comparison was made between the lithology and sedimentology of the sandstones in this area with that of the Sherwood Sandstone Group in west Cumbria (Jones and Ambrose 1994; Akhurst *et al*. 1997) and in adjacent offshore areas (Jackson and Johnson 1996; Chadwick *et al*. 2001). It should be stressed that the following descriptions and conclusions are based on preliminary investigations, of only a few days duration, of only a limited number of the more accessible available exposures that were believed to be typical and representative. The authors recognise that more extensive investigations may lead to somewhat different conclusions to those expressed below.

3.1 ST BEES SANDSTONE FORMATION

The St Bees Sandstone Formation (SBSF) is exposed in several quarries and natural exposures in the study area (Horne and Gregory 1916; Dixon *et al*. 1926; Trotter and Hollingworth 1932; Barrett 1942; Holliday *et al*. 2001; Brookfield 2004). Some of the most extensive, complete and continuous exposures are seen in the cliffs and quarries on the sides of the gorge cut by the River Gelt, *c*. 2-3 km S of Brampton (Trotter and Hollingworth 1932). Observations here have been supplemented by information from several other localities, in particular Cove Quarry [NY 254 710], which presently provides one of the best examples of strata in the lower part of the formation. The St Bees Sandstone Formation is also seen in discontinuous exposures in Carwinley Burn (Dixon *et al*. 1926; Trotter and Hollingworth 1932). Beds mapped as being at or near the top of the St Bees Sandstone Formation are shown as occurring in the burn where it is crossed by the Longtown-Penton road [NY 407 732] (Dixon *et al*. 1926; Day 1970).

At Cove Quarry, *c*. 35 m of the lower part of the St Bees Sandstone Formation can be seen (Figs 4, 5). Brookfield (2004) included a sedimentary log. The sandstones are typically reddish-brown, fine-grained or fine- to medium-grained and micaceous. Thin sections reveal that the rocks are significantly feldspathic (Fig. 6). In the lower part of the quarry, sheet sandstones are interbedded with laterally continuous mudstones that are extensively desiccation cracked. Trough and planar tabular cross-bedding and ripple lamination are the main sedimentary structures with planar lamination, rip-up clasts, ripple form sets, load casts and possible annelid tracks also common features. The facies present include sheetflood sandstones, playa mudstones and minor channel sandstones. Measured palaeocurrents from these structures indicate a unidirectional flow towards the north-west and west-north-west. In the upper part of the quarry, the sandstones are thicker bedded, more channelised with overbank playa mudstone becoming less common and much less persistent. Extensive quarry sections, each typically up to 25 m in thickness, in the gorge of the River Gelt, e.g. at [NY 5287 5864], reveal sandstones of similar lithology and sedimentological character to those towards the top of Cove Quarry (Fig. 7). Thick bedded (commonly >1 m), reddish brown, cross-bedded, fine- to medium-grained, micaceous, fluvial channel sandstones, are dominant with only rare mudstone. Laterally persistent (tens to hundreds of meters) erosion surfaces form noticeable features of these quarries (Fig. 7). Palaeocurrents suggest flow towards the north-west and west-north-west.

The overall lithological and sedimentological characters of the beds seen at these and other localities are closely comparable to those of the of the St Bees Sandstone Formation in the outcrops at the type locality of the formation near St Bees, west Cumbria, and in the nearby Nirex boreholes at Sellafield (Barnes *et al*. 1994; Jones and Ambrose 1994). The dominance of sheetflood sandstones over minor channel sandstones in the lower part of the formation at Cove Quarry suggests that the beds there belong to a sheetflood facies association, similar to, or part of that recognised in the lower part of the St Bees Sandstone Formation (North Head Member) in west Cumbria by Jones and Ambrose (1994) and Akhurst *et al*. (1997). This facies association has been interpreted as forming the earlier deposits of a northward advancing sandy braidplain that comprises the bulk of the St Bees Sandstone Formation, such as seen at the top of Cove Quarry and in the River Gelt. The laterally persistent erosion surfaces present in the River Gelt sections are surfaces cut by individual channels as they migrated across the floodplain. Extensive reworking of floodplain sediments is indicated by the paucity, thinness and limited extent of shale partings, and the total dominance of fluvial channel facies. This suggests that these latter exposures occur in the middle or upper part of the St Bees Sandstone Formation. They are comparable to the fluvial channel facies association of the St Bees Sandstone Formation in west Cumbria (Jones and Ambrose 1994; Akhurst *et al*. 1997), and most likely formed part of the same northerly or north-westerly flowing braided fluvial system.

Exposures [NY 123 648] of sandstone in the tidal flats of the Solway Firth, *c*. 3 km WSW of Powfoot, do not seem to have been described previously. They were located by Dr R. A. Hughes and shown in British Geological Survey (1998) as belonging to the Penrith Sandstone (Appleby Group) of Permian age. The restricted nature of these partially sand- and water-covered outcrops, and the relatively small thickness of beds exposed, limit detailed comment on their origin and stratigraphical position. Their overall reddish brown colour, fine grain size, lithological character and inferred fluvial origin strongly suggest that they belong to the St Bees Sandstone Formation, rather than the Penrith Sandstone or the Locharbriggs Sandstone of the nearby Dumfries Basin (c.f. British Geological Survey 1998). Primary current lineation and trough cross-bedding in these sandstones indicate that palaeocurrent flows were directed towards the north-west to west. By comparison with west Cumbria, and other occurrences in the Carlisle Basin described above, the limited occurrence of shale partings and the dominance of minor channel sandstones suggest that these exposures belong to the middle or upper part of the St Bees Sandstone Formation. The location and probable stratigraphical position of these beds suggests that they may be faulted against Carboniferous strata to the west by a NE-trending structure, a probable continuation of the offshore North-East Axial Fault and the onshore Gilnockie Fault (Jackson *et al*. 1995). On this view, this fault would lie immediately to the west of the outcrops, as in Holliday *et al*. (2004), rather than several kilometres to the SE as shown on British Geological Survey (1998).

3.2 LOWER PART OF THE KIRKLINTON SANDSTONE

Strata, previously mapped (Holmes 1899; Dixon *et al*. 1926; Trotter and Hollingworth 1932) as occurring in the lower part of the Kirklinton Sandstone Formation, crop out in several stream and river sections in the study area. As noted previously, Brookfield (2004) has excluded these strata from the Kirklinton Sandstone and placed them in the upper part of his Annan Sandstone. Though of similar grain size and petrological character as the St Bees Sandstone Formation, these rocks probably contain less mica than the St Bees Sandstone Formation. Many beds are soft and not as well cemented as the St Bees Sandstone Formation; this restricted their use as building stone in the past and is reflected by the lack of quarries.

Around 15 m of very fine to medium-grained sandstone is exposed in the River Lyne [NY 431 677 to 432 675] to the WNW of the ruined Kirklinton Hall. A conspicuous feature here is the presence of numerous laterally continuous, subhorizontal bedding surfaces (Fig. 8). Facies variations are subtle and are particularly difficult to recognise in the cliff sections in poor exposure or difficult light conditions. The rock platforms at or near river level are commonly more informative. Both fluvial (sandflat) and probable aeolian (sandsheet) facies are present, though large dune sets are apparently absent. The fluvial facies comprises fine-grained, reddish brown, micaceous sandstones with well-defined flaggy lamination, ripple cross-lamination and ripple form sets suggesting flow towards the WNW (Fig. 9). These are interpreted as sandflat deposits. Interbedded with these are softer and less well cemented, moderately to well sorted, moderately to well-rounded, fine to medium-grained, orange-brown to reddish-brown sandstones in beds ranging from 2-5 cm thick. These beds are thought to be sandsheet deposits. Low angle cross-bedding and adhesion ripples are common in the sandsheet facies (Figs 10, 11). Mica is rare or absent. Associated with this facies are some interbedded siltstones and mudstone laminae showing desiccation cracks. Brookfield (2004), p. 289) recorded palaeocurrent directions ranging from south-east through south to west, whereas the limited work carried out here suggests cross-bedding azimuths dip to the north-west for the aeolian facies and to the west for the fluvial facies.

Sandsheets and sandflats are characteristic features of modern semi-arid deserts. Sandflats are deposited during periodic floods or high lake levels but are commonly dry for much of the time, permitting aeolian reworking of sediment. Sandsheets can develop in such situations, typically where there is limited sand supply and the water table relatively high, but the formation of large dunes is restricted by periods of frequent flooding (Kocurek and Neilsen 1986; Kocurek 1996).

Sandstones exhibiting similar alternating fluvial and aeolian lithofacies can be seen in Carwinley Burn [NY 403 729] and are thought to be at a stratigraphical position comparable to those in the River Lyne described above. The alternation of fluvial and softer, apparently aeolian rocks at these localities is thought to be an example of the strata described by Trotter and Hollingworth

(1932) as ‘transitional’ between the SBS and KS.

3.3 UPPER PART OF THE KIRKLINTON SANDSTONE

The sandstones in the River Lyne at Cliff Bridge [NY 4136 6619], and nearby in Hether Burn, were thought by Holmes (1881) to be among the best exposures of the KS (Fig. 12). Close by, these sandstones are conformably overlain by argillaceous rocks of the Mercia Mudstone Group, demonstrating that the outcrops are towards the top of the KS. Other significant exposures of similar sandstones occur at several localities, e.g. Redkirk Point [NY 3023 6507], Rockcliffe [NY 3555 6183] and Longtown [NY 379 689] (Holmes 1899; Dixon *et al*. 1926; Trotter and Hollingworth 1932; Brookfield 2004). Indeed, it is only these higher strata that Brookfield (2004) included in his restricted KS.

Although there is some lithological variation from locality to locality, these sandstones are characteristically fine to medium-grained, orange brown, feldspathic, moderately to well sorted, with common, well-rounded, coarse to very coarse, frosted grains (Fig. 13). The sandstones are generally soft and friable, and seem to have been little quarried. In thin section they are highly porous (Fig. 13). At several of the above localities, notably Cliff Bridge, the sandstones typically comprise large (up to 2 m) trough cross-bedded sets with swept-out toesets (Fig. 12). There are also numerous smaller scale sets, 0.1-0.5 m in thickness. Locally, some asymmetrical ripple-form sets, with no internal foreset lamination, occur on some toesets. In some instances, these have thin clay drapes. Otherwise, mica and clay are absent from these sandstones, which, together with the common coarse, frosted grains, serve to distinguish these rocks from the St Bees Sandstone Formation and the lower parts of the Kirklinton Sandstone Formation. A section at Rockcliffe exposes *c*. 4 m of pinkish brown to orange-brown very fine- to fine-grained sandstones that are typically dominated by small-scale trough cross-bedding, in sets that range from 10 to 20 cm, rarely up to 40 cm, in thickness (Figs 14, 15). These outcrops are interpreted as comprising an aeolian dune facies. Interestingly, subangular grains (Fig. 15) are a common feature of the sandstones at Rockliffe that are in general not as well sorted as those at Cliff Bridge.

The strata at Cliff Bridge are interpreted as good examples of aeolian dune facies, with the asymmetrical ripple form sets present in the toesets inferred to be wind ripples. The sedimentary structures here suggest that the palaeowind direction blew from the NE. At Rockcliffe, smaller dune sets are present and, from foreset dips, a wind blowing from east to west is inferred. A similar aeolian origin is inferred at the other localities named above, although, as at Rockcliffe, large dune sets are not everywhere present.

4 Discussion

The fieldwork described above suggests that the Sherwood Sandstone Group north and east of Carlisle can be divided into three distinct lithological and sedimentological units, the lower corresponding to the St Bees Sandstone Formation as previously recognised, and the middle and upper units together making up strata previously mapped as Kirklinton Sandstone Formation. The lower and middle units correspond with the Annan Sandstone of Brookfield (2004) and the upper with his more restricted KS. No contacts between the subdivisions were seen during the field studies and previous investigations suggest that such are not anywhere satisfactorily exposed (Dixon *et al*. 1926; Trotter and Hollingworth 1932). Although previous investigators inferred gradational contacts, the evidence of the Silloth No. 1 Borehole (Fig. 3) and the seismic reflection data, as noted previously, suggests that the junctions are more probably at sharp disconformities as in west Cumbria and the East Irish Sea Basin (Barnes et al. 1994; Holliday et al. 2004).

The three divisions recognised in the Sherwood Sandstone Group of the north-eastern part of the Carlisle Basin would appear to broadly correspond and equate with the three formations identified in west Cumbria by Barnes et al. (1994), and, more particularly, with the similar units recognised offshore (Jackson and Johnson 1996) (Table 3). The lower and upper units in particular closely match the St Bees Sandstone Formation and Ormskirk Sandstone Formation respectively. Although at a similar stratigraphical level as the and Calder Sandstone Formation, the middle unit differs significantly in lithology from its west Cumbrian equivalent, its relatively fine-grained nature and inferred alternating sandflat/sandsheet depositional environment being more like the contemporary strata (Calder Sandstone Member) described offshore in the EISB and SFB by Jackson *et al*. (1995), Jackson and Johnson (1996) and Chadwick *et al*. (2001).

The principal, readily recognised, non-genetic lithological distinction within the Sherwood Sandstone Group of the Carlisle Basin is between the generally coarser sandstones of the upper division, with more rounded grains, and largely devoid of clay and mica, and the underlying finer grained micaceous sandstones of the lower and middle divisions with sporadic to common mudstone interbeds (Brookfield 2004). The distinction between the lower and middle divisions is in large measure genetic and based on subtle sedimentological features and lithological features not always well displayed at every locality or in all weather and light conditions. The differences between the upper and combined middle/lower divisions are thought to be sufficiently distinctive enough potentially to allow the definition of two separate formations, whereas the more subdued differences between the lower and middle units potentially permit the definition of two members within the lower formation. This situation is similar to that in the contiguous offshore EIS and SF basins (cf. Jackson and Johnson 1996; Chadwick *et al*. 2001) (Table 3).

It is not now clear whether the higher potential formation was what Holmes (1881, 1899) intended as the KS, but, if so, it was not what he mapped. His and later worker's inclusion within the KS of fine-grained micaceous sandstones of the middle division has been a source of much subsequent confusion about the KS and its use. The mapped boundaries on current Geological Survey maps (Holmes 1899, Dixon *et al*. 1926; Trotter and Hollingworth 1932; Day 1970) do not correspond with the main lithological change. They probably broadly correspond with the boundary between the members of the potential lower formation, though it is not certain that this is the case at all mapped localities.

4.1 LITHOSTRATIGRAPHICAL SUBDIVISION OF THE SHERWOOD SANDSTONE GROUP IN THE CARLISLE BASIN

There are several options available for the lithostratigraphical subdivision of the Sherwood Sandstone Group on British Geological Survey maps of the Carlisle Basin, taking into account that the area has not been remapped in recent years and that the only available surveyed geological boundaries are *c*. 80 years old and based on a now discredited premise. None of these options is totally satisfactory at the present time. The options considered are:

1. Show an undivided Sherwood Sandstone Group (cf. Barnes *et al*. 1994).
2. Ignore the new information and follow the status quo, showing St Bees Sandstone Formation and Kirklinton Sandstone as mapped by previous workers (Holmes 1899; Dixon *et al*. 1926; Trotter and Hollingworth 1932).
3. Redefine the St Bees Sandstone Formation (or Annan Sandstone) and Kirklinton Sandstone Formation to match the main lithological and sedimentological change (cf. Brookfield 2004).
4. As 3) above, recognising essentially the same two formations as Brookfield (2004) but giving

them either (a) new names or (b) adopting the current offshore classification.

Given the lack of modern mapping and the unsatisfactory basis for the recognition of the only mapped boundary within the Sherwood Sandstone Group, at the base of the KS, option 1 should be seriously considered. However, its adoption, could be seen as a major step backwards, with the new maps showing less detail than the old, and leave large areas on the geological maps with little form or indication of structure. Option 2, keeping existing linework, however, does provide some form to the maps, even if the basis on which the formations shown are divided is invalid. Options 3 and 4 have the advantage that they would attempt to show real lithological differences. However, it is debatable whether sufficient information is yet available to map the boundaries between these divisions in detail (at the 1:10 000 scale) and designate fully representative type sections for all units, because of the lack of detailed investigation on the ground and the extensive drift cover. Nevertheless, despite such difficulties, it may be possible to map the formation boundary (at 1:50 000) largely as a desk exercise from existing information and some limited field proving. Option 3 has the advantage that it recognises the main lithological changes but retains the old, familiar St Bees (or Annan) and Kirklinton sandstones terminology (Brookfield 2004). However, the various uses of these terms, particularly KS, in the past by previous workers has led to much confusion that may be compounded by their reintroduction with new definitions. If that argument were accepted, then option 4(a), introducing totally new names with no previous connotations, would be a better choice, though nominating type sections could be problematical. Option 4(b) has the merit of not requiring new names, and would apply to the Carlisle Basin essentially the same classification (St Bees Sandstone Formation overlain by Ormskirk Sandstone Formation) as that of the adjacent EIS and SF offshore basins. Although the Sherwood Sandstone Group onshore in the Carlisle Basin, at 250-525 m thick, is significantly thinner than in much of the offshore area (e.g. *c*. 1250 in Borehole 112/15-1, Fig. 3), the close lithological similarities with west Cumbria, and more especially with the EIS and SF basins (Fig. 3), support the view that the St Bees Sandstone Formation and Ormskirk Sandstone Formation are appropriate formational terms in the Carlisle Basin, particularly as there is continuity of outcrop between the basins, albeit in part (*c*. 20 km) subsea. Another advantage is that both formations already have formally defined type sections (Barnes *et al*. 1994; Jackson and Johnson 1996) with numerous reference sections. Thus Option 4(b) is thought to provide the most practical way forward and is the recommended method of subdivision of the Sherwood Sandstone Group in the Carlisle area (Table 4).

The North Head Member of the St Bees Sandstone Formation was designated principally for subsurface investigations in west Cumbria, with its upper boundary imprecisely defined on geophysical log character (Akhurst *et al*. 1997). It has not been mapped at the surface in west Cumbria. Similarly, there is insufficient information and exposure to attempt to map this unit at outcrop anywhere in the Carlisle Basin, and there is thought to be no case for its introduction into the Carlisle Basin at the present time. Barrett (1942) and later workers found little justification for the more local lithostratigraphical units within the Annan Sandstone (St Bees Sandstone Formation) proposed by Horne and Gregory (1916). However, as noted above, equivalents of the offshore members of the St Bees Sandstone Formation, Rottington Sandstone Member and Calder Sandstone Member, have been recognised in the subsurface of the Carlisle Basin (Fig. 3). At surface, the Rottington Sandstone Member appears to be the St Bees Sandstone Formation of previous mapping and the Calder Sandstone Member equivalent to the lower part of the Kirklinton Sandstone Formation, the boundary probably being close to the current base Kirklinton Sandstone Formation line (Table 4). Type sections for the Rottington Sandstone Member and Calder Sandstone Member have already been designated (Jackson and Johnson 1996). Jackson and Johnson (1996) and Chadwick *et al*. (2001) recognised 4 subdivisions of the Calder Sandstone Member (CR1-4) in the East Irish and Solway Firth basins, principally from wireline log patterns. These units may also be present in the Silloth No. 1A

Borehole (Fig. 3) but they cannot yet be recognised at outcrop.

5 Conclusions

1. It is concluded that the most practical solution to current problems of lithostratigraphical subdivision of the Sherwood Sandstone Group in the Carlisle Basin is to adopt the nomenclature presently employed in the contiguous offshore SF and EIS basins. Two formations are recognised, St Bees Sandstone Formation (SBSF) below and the Ormskirk Sandstone Formation (OSF) above. If this recommendation were accepted, it would permit the lithostratigraphical subdivision of the Carlisle area to conform to the lithostratigraphical subdivision adopted over a wide area in most other parts of nearby NW England and adjacent offshore areas.
2. The St Bees Sandstone Formation is typically very fine- to fine-grained, locally medium-grained, commonly micaceous with mudstone and siltstone interbeds and partings. It is largely of fluvial origin.
3. The Ormskirk Sandstone Formation is typically fine- to medium-grained, commonly with coarse to very coarse rounded grains. Mica and mudstone are very rare to absent. In exposures seen in the Carlisle Basin it is dominantly of aeolian origin.
4. The Kirklinton Sandstone of Holmes (1881, 1899) was not adequately defined and has been a source of considerable confusion as the formation, as mapped, includes sandstones of quite different lithology and depositional environment, as recognised by Dixon et al. (1926) and Trotter and Hollingworth (1932). The main lithological change within the Sherwood Sandstone Group occurs within the Kirklinton Sandstone Formation.
5. The mapped base of the Kirklinton Sandstone Formation probably is close to the boundary between the two members, Rottington Sandstone Member and Calder Sandstone Member, of the St Bees Sandstone Formation.
6. These conclusions probably also have implications for the Vale of Eden Basin where only St Bees Sandstone Formation is presently recognised. From the published descriptions of Goodchild (1893) and Arthurton and Wadge (1981), it would seem that Ormskirk Sandstone Formation lithologies are present here also.

References

Most of the references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

AKHURST, M.C., CHADWICK, R.A., HOLLIDAY, D.W., MCCORMAC, M., MCMILLAN, A.A., MILLWARD, D., and YOUNG, B. 1997. Geology of the west Cumbria district. *Memoir of the British Geological Survey*, Sheets 28, 37 and 47 (England and Wales). ISBN 0 85272 300 8

ARTHURTON, R.S., BURGESS, I.C., AND HOLLIDAY, D.W. 1978. Permian and Triassic. 189-206 in *The geology of the Lake District*. MOSELEY, F. (editor). Yorkshire Geological Society Occasional Publication 3. ISBN 0 9501656 2 X

ARTHURTON, R.S. and WADGE, A.J. 1981. Geology of the country around Penrith. *Memoir of the Geological Survey of Great Britain*, Sheet 24 (England and Wales). ISBN 0 11 884142 4

BARNES, R.P. AMBROSE, K., HOLLIDAY, D.W., AND JONES N.S. 1994. Lithostratigraphical subdivision of the Triassic Sherwood Sandstone Group in west Cumbria. *Proceedings of the Yorkshire Geological Society*, Vol. 50, 51-60.

BARRETT, B.H. 1942. The Triassic rocks of the Annan Basin, Dumfriesshire. *Transactions of the Geological Society of Glasgow*, Vol. 20, 161-179.

BOWDEN, R.A., BUMPUS, C. AND LITTLEBOY, A.K. 1998. An overview and update of the site characterization studies at Sellafield. *Proceedings of the Yorkshire Geological Society*, Vol. 52, 125-137.

BRITISH GEOLOGICAL SURVEY 1995. Maryport. England and Wales Sheet 22. 1:50 000. Ordnance Survey for British Geological Survey.

BRITISH GEOLOGICAL SURVEY 1997. Cockermouth. England and Wales Sheet 84. 1:50 000. Ordnance Survey for British Geological Survey.

BRITISH GEOLOGICAL SURVEY 1998. Kirkbean. Scotland Sheet 6W. Solid Geology. 1:50 000. (British Geological Survey: Keyworth, Nottingham.)

BROOKFIELD, M.E. 2004. The enigma of fine-grained alluvial basin fills: the Permo-Triassic (Cumbrian Coastal and Sherwood Sandstones Groups) of the Solway Basin, NW England and SW Scotland). *International Journal of Earth Sciences (Geologische Rundschau)*, Vol. 93, 282-296.

BURLEY, S.D. 1984. Patterns of diagenesis in the Sherwood Sandstone Group (Triassic), United Kingdom. *Clay Minerals*, Vol. 19, 403-440.

BUSHELL, T.P. 1986. Reservoir geology of the Morecambe Field. 189-208 in BROOKS, J., GOFF, J.C. AND VAN HOORN, B. (editors) *Habitat of Palaeozoic gas in northwest Europe*. Geological Society of London Special Publication 23. ISBN 7073 0491 1

CHADWICK, R.A., HOLLIDAY. D.W., HOLLOWAY, S. and HULBERT, A.G. 1995. *The structure and evolution of the Northumberland-Solway Basin*. Subsurface Memoir of the British Geological Survey. ISBN 0 11 884501 2

CHADWICK, R.A., JACKSON, D.I., BARNES, R.P., KIMBELL, G.S., JOHNSON, H., CHIVERRELL, R.C., THOMAS, G.S.P., JONES, N.S., RILEY, N.J., PICKETT, E.A., YOUNG, B., HOLLIDAY, D.W., BALL, D.F., MOLYNEUX, S.G., LONG, D., POWER, G.M. AND ROBERTS, D.H. 2001. *Geology of the Isle of Man and its offshore area*. British Geological Survey Research Report, RR/01/06.

COLTER, V.S. 1978. Exploration for gas in the Irish Sea. *Geologie en Mijnbouw*, Vol. 57, 503-516.

COLTER, V.S. 1997. The East Irish Sea Basin – from caterpillar to butterfly, a thirty-year metamorphosis. 1-9 in MEADOWS, N.S., TRUEBLOOD, S.P., HARDMAN, M. AND COWAN, G. (editors) *Petroleum Geology of the Irish sea and adjacent areas*. Special Publication of the Geological Society, London **124**. ISBN 1 897799 84 5

COLTER, V.S. AND BARR, K.W. 1975. Recent developments in the geology of the Irish Sea and Cheshire Basins. 61-75 in WOODLAND, A.W. (editor) *Petroleum and the Continental Shelf of North-west Europe, Vol. 1, Geology*. Applied Science Publishers, London. ISBN 0 85334 648 8

COWAN, G. 1993. Identification and significance of aeolian deposits within the dominantly fluvial Sherwood Sandstone Group of the East Irish Sea Basin, UK. 231-245 in NORTH, C.P. AND PROSSER, D.J. (editors) *Characterization of fluvial and aeolian reservoirs*. Special Publication of the Geological Society, London, 73. ISBN 0 903317 90 7

COWAN G., OTTESEN, C. AND STUART, I.A. 1993. The use of dipmeter logs in the structural interpretation and palaeocurrent analysis of Morecambe Fields, East Irish Sea Basin. 867-882 in PARKER, J.R (editor) *Petroleum geology of north-west Europe: Proceedings of the 4th Conference*. Geological Society (London). ISBN

DAY, J.B.W. 1970. Geology of the country around Bewcastle. *Memoir of the Geological Survey of Great Britain,* Sheet 12 (England and Wales). SBN 11 880075 2

DIXON, E.E.L., MADEN, J., TROTTER, F.M., HOLLINGWORTH, S.E. and TONKS, L.H. 1926. The geology of the Carlisle, Longtown and Silloth district. *Memoir of the Geological Survey of Great Britain,* Sheets 11, 16 and 17 (England and Wales).

EASTWOOD, T. 1930. The geology of the Maryport district. *Memoir of the Geological Survey of Great Britain,* Sheet 22 (England and Wales).

EASTWOOD, T., DIXON, E.E.L., HOLLINGWORTH, S.E. AND SMITH, B. 1931. Geology of the Whitehaven and Workington District. *Memoir of the Geological Survey of Great Britain*, Sheet 28 (England and Wales).

EBBERN, J. 1981. The geology of the Morecambe Gas Field. 485-493 in ILLING, L.V. AND HOBSON, G.D. (editors) *Petroleum Geology of the continental shelf of north-west Europe*. Institute of Petroleum, London. ISBN

GOODCHILD, J.G. 1893. Observations on the New Red Series of Cumberland and Westmorland, with special reference to classification. *Transactions of the Cumberland and Westmorland Association for the Advance of Literature and Science*, Vol. 17, 1-24.

GREGORY, J.W. 1915a. A deep bore at Seascale in Cumberland. *Geological Magazine*, Vol. 52, 146-149.

GREGORY, J.W. 1915b. The Solway Basin and its Permo-Triassic sequence. *Geological Magazine,* Vol. 52, 241-249.

HARKNESS, R. 1862. On the sandstones and their associated deposits in the Vale of Eden, the Cumberland Plain, and the south-east of Dumfriesshire. *Quarterly Journal of the Geological Society*, *London*, Vol. 18, 205.

HOLLIDAY, D.W., WARRINGTON, G., BROOKFIELD, M.E., MCMILLAN, A.A AND HOLLOWAY S. 2001. Permo-Triassic rocks in boreholes in the Annan-Canonbie area, Dumfries and Galloway, southern Scotland. *Scottish Journal of Geology*, Vol. 37, 97-113.

HOLLIDAY, D.W., HOLLOWAY, S., MCMILLAN, A.A., JONES, N.S., WARRINGTON, G., AND AKHURST, M.C. 2004. The evolution of the Carlisle Basin, NW England and SW Scotland. *Proceedings of the Yorkshire Geological Society*, Vol. 55, 1-19.

HOLMES, T.V. 1881. The Permian, Triassic and Liassic rocks of the Carlisle Basin. *Quarterly Journal of the Geological Society*, *London*, Vol. 37, 286-298.

HOLMES, T.V. 1899. The geology of the country around Carlisle. *Memoir of the Geological Survey of Great Britain,* Sheet 17 (England and Wales).

HORNE, J and GREGORY, J W. 1916. The Annan Red Sandstone Series of Dumfriesshire. *Transactions of the Geological Society of Glasgow*, Vol. 15, 374-386.

INSTITUE OF GEOLOGICAL SCIENCES 1977. *Wigan*. England and Wales Sheet 84. 1:50 000. Ordnance Survey for Institute of Geological Sciences.

JACKSON, D.I., MULHOLLAND, P., JONES, S.M. AND WARRINGTON, G. 1987. The geological framework of the East Irish Sea Basin. 191-203 in BROOKS, J. AND GLENNIE, K. (editors) *Petroleum Geology of North-west Europe*. Graham and Trotman, London.

JACKSON, D.I., JACKSON, A.A., EVANS, D., WINGFIELD, R.T.R., BARNES, R.P. and ARTHUR, M.J. 1995. *United Kingdom offshore regional report: the geology of the Irish Sea*. HMSO for the British Geological Survey, London.

JACKSON, D.I. and JOHNSON, H. 1996. *Lithostratigraphic nomenclature of the Triassic, Permian and Carboniferous of the UK offshore East Irish Sea Basin*. British Geological Survey, Nottingham.

JONES, N.S. and AMBROSE, K.1994. Triassic sandy braidplain and aeolian sedimentation, the Sherwood Sandstone Group, west Cumbria. *Proceedings of the Yorkshire Geological Society*, 50, 61-76.

KOCUREK, G. 1996. Desert aeolian systems. *In*: READING, H.G. (editor) *Sedimentary environments: processes, facies and stratigraphy*. 3rd Edition. Blackwell Science, Oxford, 125-153.

KOCUREK, G. AND NEILSEN, J. 1986. Conditiond favourable for the formation of warm-climate aeolian sand-sheets. *Sedimentology*, Vol. 33, 795-816.

MEADOWS, N.S. AND BEACH. A. 1993a. Structural and climatic controls on facies distribution in a mixed fluvial and aeolian reservoir: the Triassic Sherwood Sandstone Group in the Irish Sea. 246-264 in NORTH, C.P. AND PROSSER, D.J. (editors) *Characterization of fluvial and aeolian reservoirs*. Special Publication Geological Society, London, 73. ISBN 0 903317 90 7

MEADOWS, N.S. AND BEACH. A. 1993b. Controls on reservoir quality in the Triassic Sherwood Sandstone of the Irish Sea. 823-833 in PARKER, J.R (ed) *Petroleum geology of north-west Europe: Proceedings of the 4th Conference*. Geological Society (London).

MICHIE, U.MCL. AND BOWDEN, R.A. 1994. UK NIREX geological investigations at Sellafield. *Proceedings of the Yorkshire Geological Society*, Vol. 50, 5-9.

MURCHISON, R.I. AND HARKNESS, R. 1864. On the Permian rocks of the north-west of England and their extension into Scotland. *Quarterly Journal of the Geological Society, London, Vol.* 20, 144-165.

NIREX 1992. *A revised geological map (solid) of the Sellafield District*. Nirex Report No. 524.

QUIRK, F.G., ROY, S., KNOT, I., REDFERN, J. AND HILL, L. 1999. Petroleum geology and future hydrocarbon potential of the Irish Sea. *Journal of Petroleum Geology*, Vol. 22, 243-260.

SEDGWICK, A, 1836. On the New Red Sandstone Series in the basin of Eden, and north-western coasts of Cumberland and Lancashire. *Transactions of the Geological Society of London, Vol.* 4, 383-407.

TROTTER, F.M. AND HOLLINGWORTH, S.E. 1932. The geology of the Brampton district. *Memoir of the Geological Survey of Great Britain*, Sheet 18 (England and Wales).

TROTTER, F.M., HOLLINGWORTH, S.E., EASTWOOD, T. AND ROSE, W.C.C. 1937. Gosforth District. *Memoir of the Geological Survey of Great Britain*, Sheet 37 (England and Wales).

WARRINGTON, G., AUDLEY-CHARLES, M.G., ELLIOTT, R.E., EVANS, W.B., IVIMEY-COOK, H.C., KENT, P.E., ROBINSON, P.L., SHOTTON, F.W. and TAYLOR, F.M. 1980. *A correlation of Triassic rocks in the British Isles*. Special Report of the Geological Society, London 13.

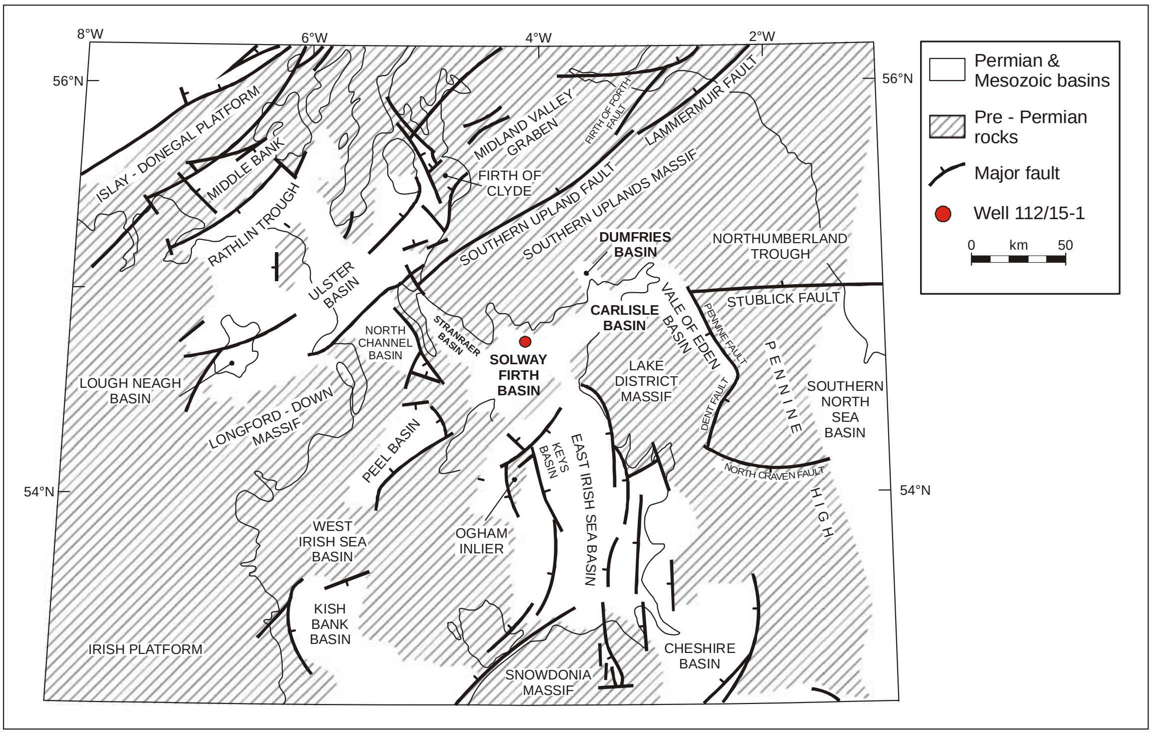

Fig. 1. Regional setting of the Carlisle Basin and other Permo-Triassic basins around the Irish Sea

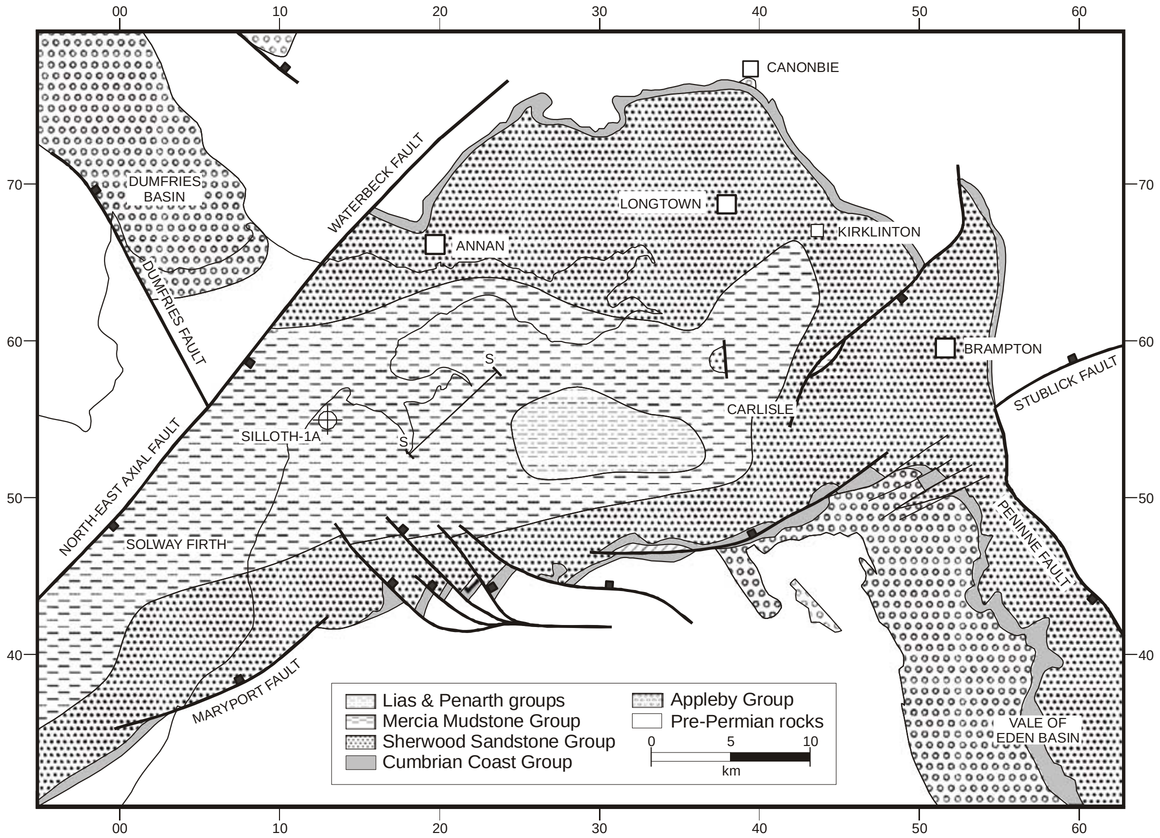

Fig. 2. Carlisle Basin; location and simplified geological map

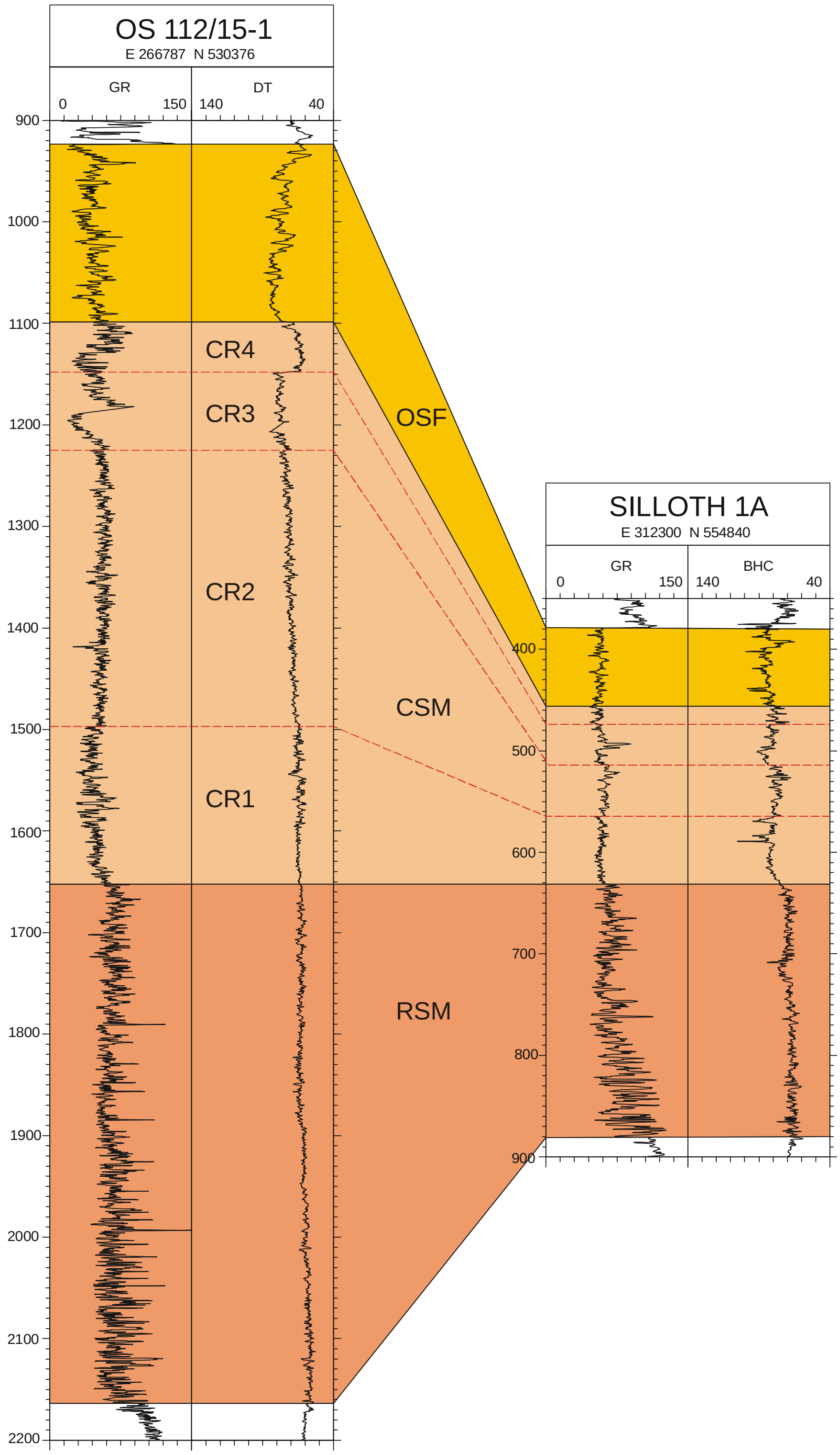

Fig. 3. Subdivision of the Sherwood Sandstone Group (SSG) in offshore well 112/15-1 and the Silloth No. 1A Borehole. RSM Rottington Sandstone Member (St Bees Sandstone Formation); CSM Calder Sandstone Member (St Bees Sandstone Formation); OSF Ormskirk Sandstone Formation; CR1-4 divisions of the Calder Sandstone Member recognised by Jackson and Johnson (1996). All depth is metres below Kelly Bushing.

Fig. 4. Cove Quarry; sheet and semi-confined sandstones towards the base of the St Bees Sandstone Formation (Rottington Sandstone Member)

Fig. 5. General view of Cove Quarry showing sheet sandstones near base of quarry overlain by channelised sandstones towards the base of the St Bees Sandstone Formation (Rottington Sandstone Member) (P621360)

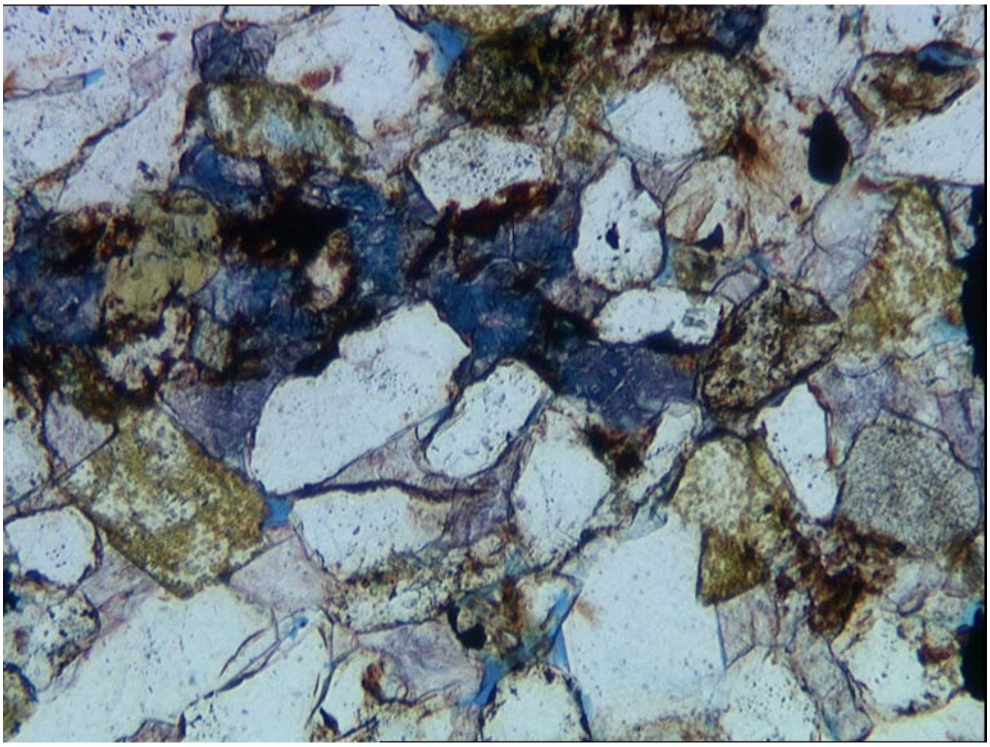

Fig. 6. Photomicrograph of St Bees Sandstone Formation**.** Cove Quarry. The thin section is dominated by quartz grains, although feldspar (stained yellow) forms an appreciable component

Fig. 7. St Bees Sandstone Formation, Gelt quarries, River Gelt. Note the laterally extensive erosion surfaces (often forming overhangs) spaced every few metres or so vertically

Fig. 8. Kirklinton Sandstone exposed in the River Lyne, Kirklinton. Note the sheet like, thinly bedded nature of the sandstone (P621359)

Fig. 9. Rippled flaggy sandstones, Kirklinton Sandstone, River Lyne, Kirklinton (P621361)

Fig. 10. Adhesion ripples, Kirklinton Sandstone, River Lyne, Kirklinton (P621363)

Fig. 11. Small-scale aeolian cross-beds, Kirklinton Sandstone, River Lyne, Kirklinton (P621362)

Fig. 12. Large aeolian cross-beds from the upper part of the Kirklinton Sandstone, Cliff Bridge

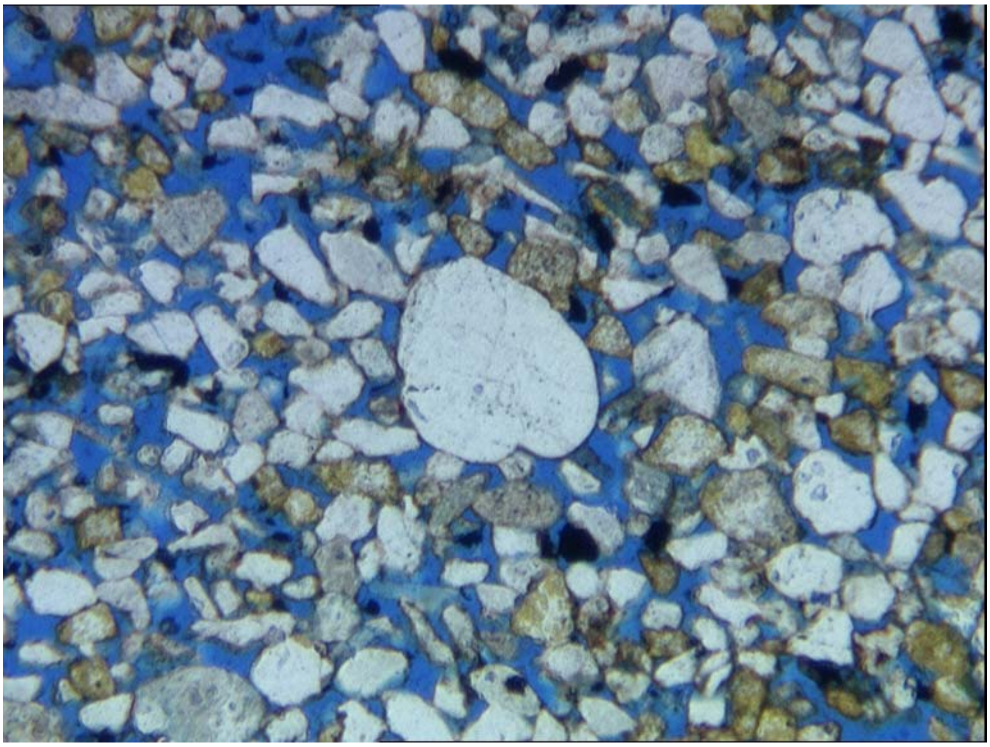

Fig. 13. Thin section photomicrograph of the Kirklinton Sandstone at Cliff Bridge. The sandstone is moderately to well sorted with distinct well rounded coarse grains giving a bimodality to the grain size. The blue dye indicates void space and shows that the sandstone is highly porous

Fig. 14. General view of the Kirklinton Sandstone at Rockcliffe

Fig. 15. Close up of the Kirklinton Sandstone at Rockcliffe. Note the sandstone predominantly comprises trough cross-bedding, in sets 10-30 cm in size

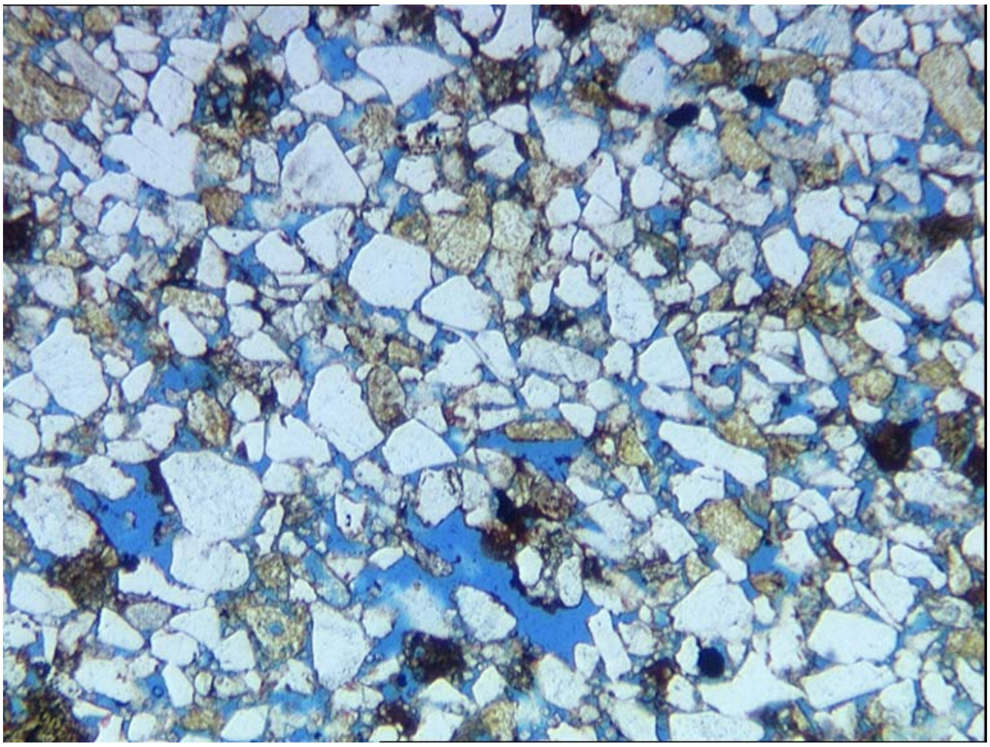

Fig. 16. Thin section photomicrograph of the Kirklinton Sandstone at Rockcliffe

Table 1 Evolution of lithostratigraphical classification of Triassic sandstones in the Carlisle and Vale of Eden basins

<table>
<tr><th>Holmes (1881, 1899)</th><th>Goodchild (1893); Gregory (1915b)</th><th>Dixon et al. (1926)</th><th colspan="2">Arthurton et al. (1978); Warrington et al. (1980)</th><th>Barnes et al. (1994); Akhurst et al. (1997)</th></tr>
<tr><td>Stanwix Shales</td><td>Stanwix Shales</td><td>Stanwix Shales</td><td colspan="2">Mercia Mudstone Group (Stanwix Shales)</td><td>Mercia Mudstone Group (Stanwix Shales)</td></tr>
<tr><td>Kirklinton Sandstone</td><td rowspan="3">Kirklinton Sandstone
? ? ? ? ? ? ? ?
St Bees Sandstone</td><td rowspan="3">Kirklinton Sandstone
? ? ? ? ? ? ? ?
St Bees Sandstone</td><td rowspan="3">Kirklinton Sandstone Formation
? ? ? ?
St Bees Sandstone Formation</td><td rowspan="3">Sherwood
Sandstone
Group</td><td>Ormskirk Sandstone Formation equivalent*</td></tr>
<tr><td>Upper Gypsiferous Shales</td><td>Calder Sandstone Formation equivalent*</td></tr>
<tr><td>St Bees Sandstone</td><td>St Bees Sandstone Formation</td></tr>
<tr><td>Lower Gypsiferous Shales</td><td>Gypsiferous Shales</td><td>St Bees Shales</td><td colspan="2">St Bees Shale/Eden Shales formations</td><td>St Bees Shale/Eden Shales formations</td></tr>
</table>

* Identified so far in subsurface only

Table 2 Evolution of lithostratigraphical classification of Triassic sandstones in the East Irish Sea Basin

<table>
<tr><th>Gregory (1915a)
[onshore]</th><th>Eastwood et al. (1931); Trotter et al. (1937)
[onshore]</th><th>Colter (1978); Ebbern (1981)
[offshore]</th><th colspan="2">Jackson et al. (1987)
[offshore]</th><th>Barnes et al. (1994); Akhurst et al. (1997)
[onshore]</th><th colspan="2">Jackson and Johnson (1996); Chadwick et al. (2001)
[offshore]</th></tr>
<tr><td></td><td></td><td>Mercia Mudstone Group</td><td colspan="2">Mercia Mudstone Group</td><td></td><td colspan="2">Mercia Mudstone Group</td></tr>
<tr><td rowspan="4">Kirklinton Sandstone
? ? ? ? ?
St Bees Sandstone</td><td rowspan="4">St
Bees
Sandstone</td><td>Keuper Waterstones Formation</td><td colspan="2" rowspan="2">Ormskirk Sandstone Formation</td><td rowspan="2">Ormskirk Sandstone Formation</td><td colspan="2" rowspan="2">Ormskirk Sandstone Formation</td></tr>
<tr><td>Keuper Sandstone Formation</td></tr>
<tr><td rowspan="2">St Bees Sandstone Formation</td><td rowspan="2">St Bees Sandstone Formation</td><td>'upper'</td><td>Calder Sandstone Formation</td><td rowspan="2">St Bees Sandstone Formation</td><td>Calder Sst Mb</td></tr>
<tr><td>'lower'</td><td>St Bees Sandstone Formation</td><td>Rottington Sst. Mb</td></tr>
<tr><td>Gypsiferous Shales</td><td>St Bees Shales</td><td>St Bees Shale Formation</td><td colspan="2">St Bees Shale Formation</td><td>St Bees Shale Formation</td><td colspan="2">Barrowmouth Mudstone Formation</td></tr>
</table>

Table 3 Summary of the current lithostratigraphical subdivision of the Sherwood Sandstone Group and associated strata in Cumbria

<table>
<tr><th rowspan="2">GROUP</th><th colspan="4">EAST IRISH SEA and SOLWAY FIRTH BASINS</th><th colspan="2" rowspan="2">CARLISLE BASIN
(Dixon et al. 1926; Barrett 1942; Holliday et al. 2001)</th><th rowspan="2">VALE OF EDEN BASIN
(Arthurton and Wadge 1981)</th></tr>
<tr><th colspan="2">OFFSHORE
(Jackson and Johnson 1996)</th><th colspan="2">ONSHORE
(West Cumbria)
(Barnes et al. 1994)</th></tr>
<tr><td>Mercia Mudstone Group</td><td colspan="2">Mercia Mudstone Group
(MMG)</td><td colspan="2"></td><td colspan="2">Stanwix Shales</td><td></td></tr>
<tr><td rowspan="3">Sherwood Sandstone Group
(SSG)</td><td colspan="2">Ormskirk Sandstone Formation (OSF)</td><td colspan="2">Ormskirk Sandstone Formation (OSF)</td><td colspan="2" rowspan="3">Kirklinton Sandstone (KSF)
? ? ? ? ? ? ? ? ?
St Bees Sandstone Formation
(SBSF)</td><td rowspan="3">?Kirklinton Sandstone
? ? ? ? ?
St Bees Sandstone Formation</td></tr>
<tr><td rowspan="2">St Bees Sandstone Formation
(SBSF)</td><td>Calder Sandstone Member
(CSM)</td><td colspan="2">Calder Sandstone Formation
(CSF)</td></tr>
<tr><td>Rottington Sandstone Member
(RSM)</td><td colspan="2">St Bees Sandstone Formation
(SBSF)</td></tr>
<tr><td rowspan="2">Cumbrian Coast Group</td><td colspan="2">Barrowmouth Mudstone Formation</td><td>St Bees Shale Formation</td><td rowspan="2">Brockram</td><td colspan="2" rowspan="2">Eden Shales Formation</td><td rowspan="2">Eden Shales Formation</td></tr>
<tr><td colspan="2">St Bees Evaporite Formation</td><td>St Bees Evaporite Formation</td></tr>
<tr><td>Appleby Group</td><td></td><td>Collyhurst Sandstone Formation</td><td colspan="2">Brockram</td><td>Penrith Sandstone Formation and Brockram</td><td></td><td>Penrith Sandstone and Brockram</td></tr>
</table>

Table 4. Suggested new subdivision of the Sherwood Sandstone Group in the Carlisle Basin

<table>
<tr><td></td><td>Previous Nomenclature</td><td colspan="2">Proposed Nomenclature</td></tr>
<tr><td rowspan="3">Sherwood Sandstone Group (SSG)</td><td rowspan="2">Kirklinton Sandstone Formation (KSF)</td><td colspan="2">Ormskirk Sandstone Formation (OSF)</td></tr>
<tr><td rowspan="2">St Bees Sandstone Formation (SBSF)</td><td>Calder Sandstone Member (CSM)</td></tr>
<tr><td>St Bees Sandstone Formation</td><td>Rottington Sandstone Member (RSM)</td></tr>
</table>