# The Millstone Grit Group (Pennsylvanian) of the Northumberland-Solway Basin and Alston Block of northern England

C. N. WATERS[1*], D. MILLWARD[2] AND C. W. THOMAS[2]

[1] *British Geological Survey, Environmental Science Centre, Nicker Hill, Keyworth, Nottingham NG12 5GG, UK*

[2] *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK*

**Summary:** In the Northumberland-Solway Basin and Alston Block of northern England, some aspects of the stratigraphical and sedimentological relationships between the Millstone Grit Group, the Stainmore Formation (Namurian part of the Yoredale Group) and the Westphalian Pennine Coal Measures Group are uncertain. Also, confusion has resulted from discontinuation of Millstone Grit as a formal lithostratigraphical term north of the Stainmore Basin. This paper presents the evidence for, and describes the nature of, a Kinderscoutian (early Pennsylvanian) abrupt transition from typical 'Yoredale cyclicity', characterized by marine limestones in a dominantly siliciclastic succession but including marked fluvial channels, to a sandstone-dominated fluvial succession recognizable as the Millstone Grit Group. Sandbodies present in this region are probably the fluvial feeder systems to many of the fluvio-deltaic successions recorded farther south in the Central Pennine Basin. However, onset of the Millstone Grit Group occurs much earlier to the south, during the Pendleian (late Mississippian), despite the entry of fluvial systems into the Central Pennines Basin from the north. In addition to explaining this counter-intuitive relationship, the paper also recognizes continuation of the fluvial regime into the lowermost part of the Pennine Coal Measures Group.

Keywords: Yoredale Group, Millstone Grit Group, Northumberland-Solway Basin, Alston Block

The terms ‘Yoredales’ and ‘Millstone Grit’ have a long association with the Namurian geology of northern England, but the establishment of local lithostratigraphical names over recent decades has diminished appreciation of the relationship between the two units. The lithostratigraphical scheme of Waters *et al*. (2007), detailed in Dean *et al*. (2011), formalized the two units as the Yoredale Group and Millstone Grit Group, but noted that usage of the latter term could not be justified north of the Askrigg Block without further investigation. Of particular concern was the clear presence of coarse-grained sandbodies of ‘Millstone Grit’ affinity throughout much of the Namurian succession, including the Stainmore Formation of the Yoredale Group, and extending into strata of earliest Westphalian age, with no unambiguous boundaries recognized between the groups. The present study provides a detailed appraisal of the distribution of coarse-grained fluvial sandbodies across the Northumberland-Solway Basin and Alston Block, using key boreholes and sections tied to an available framework of marine limestones and shales that constrain the ages of the sandbodies. It sets out to justify the existence of a distinct Millstone Grit Group across northern England and to describe the nature of its relationships with the mainly marine, cyclic strata of the Stainmore Formation beneath.

Whitehurst (1778) first proposed the term ‘Millstone Grit’ as part of the threefold division of the British Carboniferous sequence into Mountain Limestone, Millstone Grit and Coal Measures. The term Yoredale facies is also of significant vintage, based upon the description of Yoredale cycles by Phillips (1836) to characterize the Visean to Namurian strata of northern England, north of the Craven Fault System. By the time of the primary geological survey of the region in the 19$^{th}$ Century, the Yoredale succession was recognized as being distinct from the overlying Millstone Grit. However, the base of the Millstone Grit was not fixed at a particular stratigraphical level, but ranged from the top of the Great Limestone to the base of the sandstone above the 'Grindstone Sill' (Dakyns *et al*. 1891). During the 20$^{th}$ Century, 'Millstone Grit' and 'Yoredales' went out of favour as lithostratigraphical terms. In the Brampton district of Cumbria, the Namurian strata were referred to as the Upper Limestone Group, with the Millstone Grit not recognized (Trotter & Hollingworth 1932). Furthermore, the Millstone Grit developed chronostratigraphical connotations when referred to as a Series, synonymous with the Namurian (e.g. Lumsden *et al*. 1967; Hull 1968; Arthurton *et al*. 1988). However, detailed correlation of marine bands enabled recognition of a 'Millstone Grit' facies in the Kinderscoutian to Langsettian of the Northumberland-Solway Basin and the Alston Block (Hull 1968; Chadwick *et al*. 1995, p. 27). Over recent decades, 'Millstone Grit Group' has not been applied north of the Stainmore Basin, other than informally in the Northumberland Basin (Fig. 1).

Meanwhile, the Yoredale facies received a confusing plethora of localized lithostratigraphical names for the Namurian interval. The Upper Limestone Group was introduced in the Cheviot Block (Fowler 1926) and subsequently applied to parts of the Northumberland Basin, Alston Block and parts of Cumbria. The Hensingham Group was used in the area of the Lake District High (e.g. Eastwood *et al*. 1968; Akhurst *et al*. 1997), and Wensleydale Group on the Askrigg Block (e.g. Arthurton *et al*. 1988) (Fig. 1). The Upper Limestone Group was replaced by the Stainmore Group on the Alston Block, in the Stainmore Basin and in parts of the Northumberland-Solway Basin (e.g. Burgess & Holliday 1979), but an alternative Morpeth Group was also established for part of the Northumberland Basin (Young & Lawrence 1998). These terms have now been rationalized by the new name Yoredale Group, with a component Stainmore Formation of Namurian age (Dean *et al*. 2011; Waters *et al*. 2007, 2011*a*, *b*).

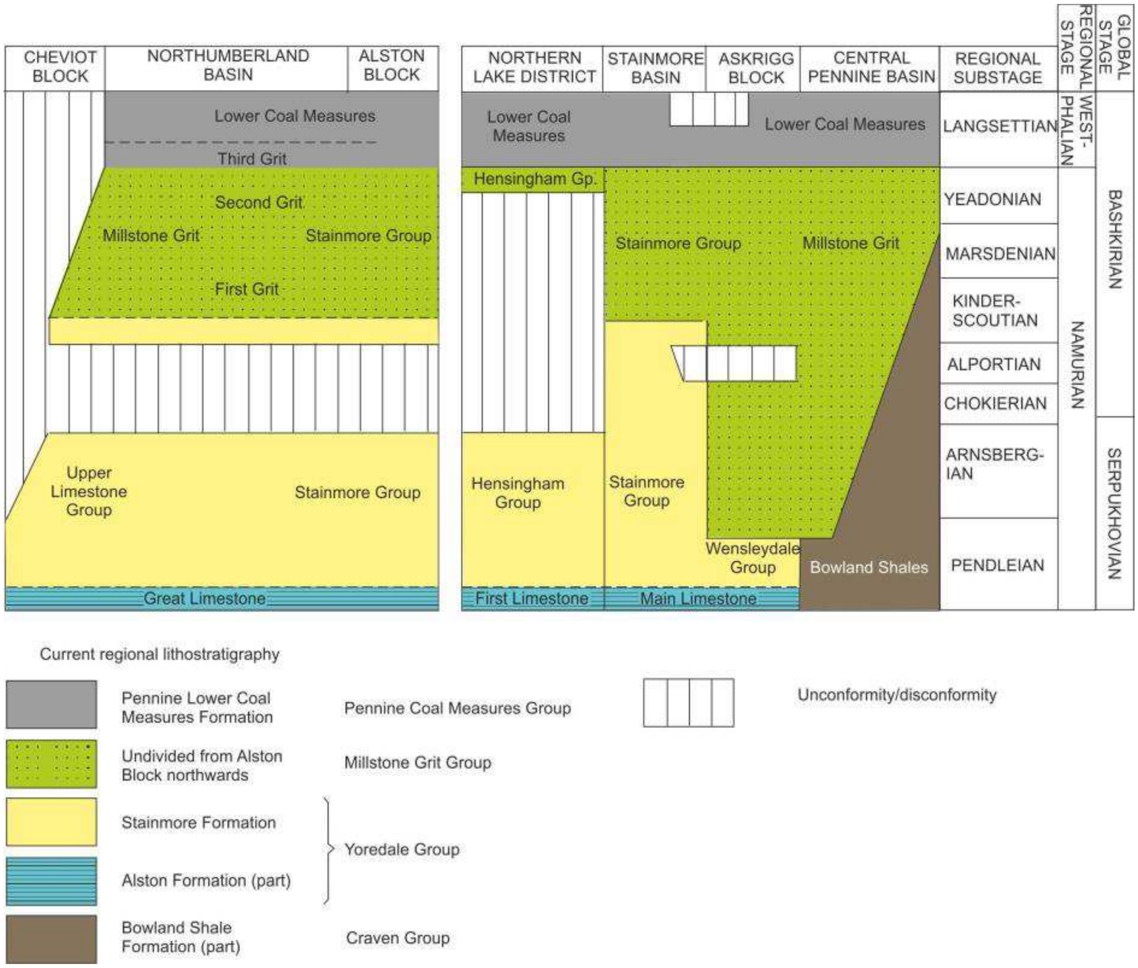



**Fig. 1** Historical stratigraphical nomenclature for the Namurian and lower Westphalian succession in Northern England, with modified current interpretations shown in key (modified from Stone et al. 2010).

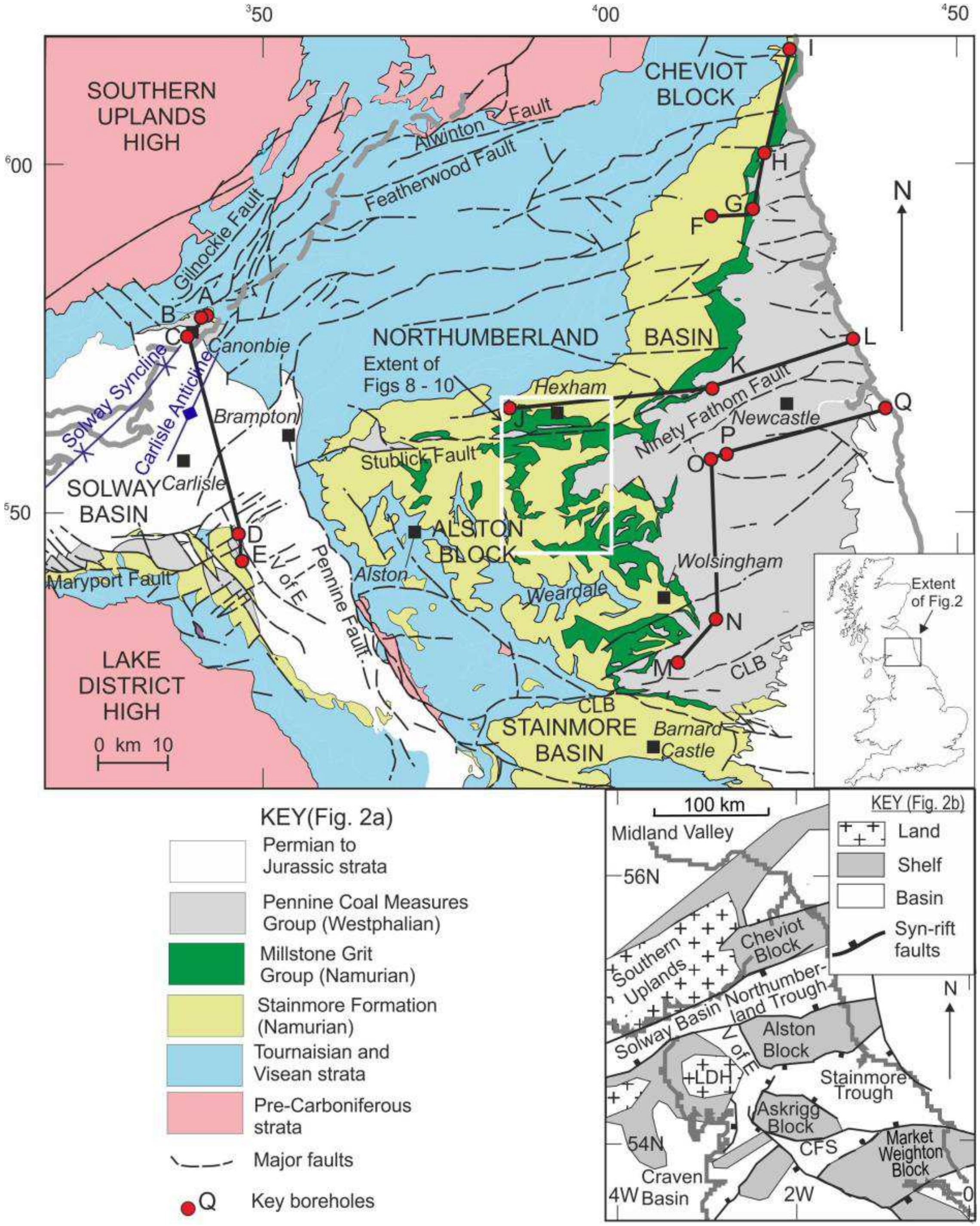



**Fig. 2** Location map showing the extent of Namurian strata, main structures in Northern England and key boreholes and locations: letters refer to logs shown in Figures 3 to 6. Map derived from British Geological Survey (2007). CLB- Closehouse-Lunedale-Butterknowle Fault System; b) distribution of main structural highs and basins in northern England, derived

from Waters et al. (2007); CFS- Craven Fault System, LDH- Lake District High, V of E-Vale of Eden. Geological data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2013.

Heavy mineral analysis of lower Namurian sandstones from the Alston Block by McKervey *et al*. (2010) showed a transition from Low MZi (monazite-zircon)-high RuZi (rutile-zircon), associated with a local Scottish source, to High MZi-low RuZi ratios, representing a diagnostic change in provenance. The transition to higher MZi compositions commences in the Tuft Sandstone, immediately beneath the Great Limestone (McKervey *et al*. 2010). This is slightly earlier (early Pendleian) than in the Millstone Grit Group of the Central Pennine Basin, farther south, where the arrival of detritus relatively rich in monazite (and poor in Cr-spinel) commences in the late Pendleian. Nevertheless, provenance studies establish a clear link between Namurian sandbodies in the study area and the Millstone Grit Group in the Central Pennine Basin, south of the Askrigg Block (Fig. 2b). The monazite-rich sediment has been interpreted as detritus from a distal, northerly source terrain, the product of uplift and erosion in the Norwegian-Greenland Sea region that redirected a northward-flowing fluvial system southward into the Pennine Basin (Morton & Whittam 2002 and references therein).

The Millstone Grit Group in the Central Pennine Basin is divided into six formations, broadly aligned with the Namurian regional substages (see Waters *et al*. 2007). The formations, and the substages, are bounded by key widespread marine bands (see Ramsbottom *et al*. 1978). Where marine bands cannot be recognized and other biostratigraphical data are absent, as is the case in the Northumberland-Solway Basin and on the Alston Block, the group, if recognized, cannot be subdivided.

This study integrates results from recent British Geological Survey (BGS) geological mapping of the Hexham (Sheet 19) and Alston (Sheet 25) areas, and incorporates information available from adjacent areas, including key stratigraphical boreholes (Fig. 2a; Appendix 1).

## 1. STRUCTURAL TRANSITION BETWEEN THE CHEVIOT BLOCK, NORTHUMBERLAND-SOLWAY BASIN AND ALSTON BLOCK

A Late Devonian to Early Carboniferous phase of back-arc extension within the Avalonian part of the Laurussian plate resulted in north–south rifting that affected all of central and northern England, initiating development of a series of graben and half-graben, separated by platforms and tilt-block highs (Leeder 1982, 1988).

In the study area, the dominant basin is the Northumberland-Solway Basin, a combined graben structure (Fig. 2b). The northern margin is taken at a system of *en-echelon* synsedimentary faults, including the Gilnockie, Featherwood and Alwinton faults, considered antithetic to the Maryport–Stublick–Ninety Fathom Fault System (Chadwick *et al*. 1995), which separates the Northumberland-Solway Basin from the Alston Block-Lake District High to the south (Fig. 2). The Stublick Fault forms the southern boundary of the Midgeholme, Plenmeller and Stublick coalfields, throwing strata of Langsettian age down to the north, against Namurian strata to the south. The southern margin of the Alston Block is defined by the Closehouse-Lunedale-Butterknowle Fault System, with the Stainmore Basin present to the south of the fault.

During the Tournaisian and early Visean, the faults were associated with formation of a prominent palaeotopography. The Lake District, Southern Uplands and Alston Block contain pre-Carboniferous granitic intrusions that resisted subsidence during the extensional phase (Leeder 1982), forming structural highs that were emergent for most of the Tournaisian and early Visean. The Southern Uplands underwent marked erosion and shedding of alluvial deposits (the Whita Formation) south-eastwards into the Northumberland-Solway Basin during the early Carboniferous (Leeder 1971). This basinal depression also influenced the focus of fluvial sedimentation, such as the Fell Sandstone Formation, and the thicknesses of cycles.

By late Visean time, the rate of regional north–south extension had greatly reduced. The positive thermal anomaly generated in the lithosphere during the main phase of extension gradually decayed and thermal subsidence dominated during the Namurian and Westphalian (Leeder 1988). By the Namurian interval considered in this study, sedimentation rates broadly matched subsidence rates in both the block and basin locations, resulting in the loss of a palaeotopographical distinction between the two. However, differential compaction of the thicker basinal succession resulted in greater thicknesses for Namurian cycles in the Northumberland Basin compared with the Alston and Cheviot blocks (Chadwick *et al.* 1995). Tectonic activity during the late Namurian is evident in the Canonbie area, where syndepositional folding and local development of an intra-Carboniferous unconformity (Lumsden *et al.* 1967; Picken 1988) has been proposed by Chadwick *et al.* (1995) to reflect dextral strike-slip displacement on the Gilnockie Fault (Fig. 2).

Although the sedimentological distinction between blocks and basins is less pronounced during the Namurian, these structural domains are useful to subdivide and describe the study area, based upon four transects, shown on Fig. 2.

## 2. MARINE FLOODING EVENTS AS KEY CORRELATION SURFACES

Correlation of the sandbodies described in this study depends upon a regional framework of correlatable flooding surfaces, expressed mainly as marine limestones and shales. Despite each limestone historically having several local names, it is possible to rationalize these in a single nomenclature (Table 1), here following that of Brand (2011). Of particular significance to this study are the Kinderscoutian to Langsettian marine bands, which help to define the chronostratigraphical range and allow internal subdivision of the late Namurian sandstone-dominated succession.

**Table 1 (see end of manuscript)**

The distribution of the Namurian to lower Westphalian limestones and marine bands are presented in four correlation panels (Fig. 2), for the Solway Basin (Fig. 3), the Cheviot Block and north-eastern part of the Northumberland Basin (Fig. 4), the southern part of the Northumberland Basin (Fig. 5) and the Alston Block (Fig. 6). The sections are mainly based upon key deep boreholes, with two exposures used (Crossley Burn and Longhoughton Steel) where borehole data are sparse. The BGS reference number (for boreholes), location and key source references for the boreholes and exposures are provided in Appendix 1.

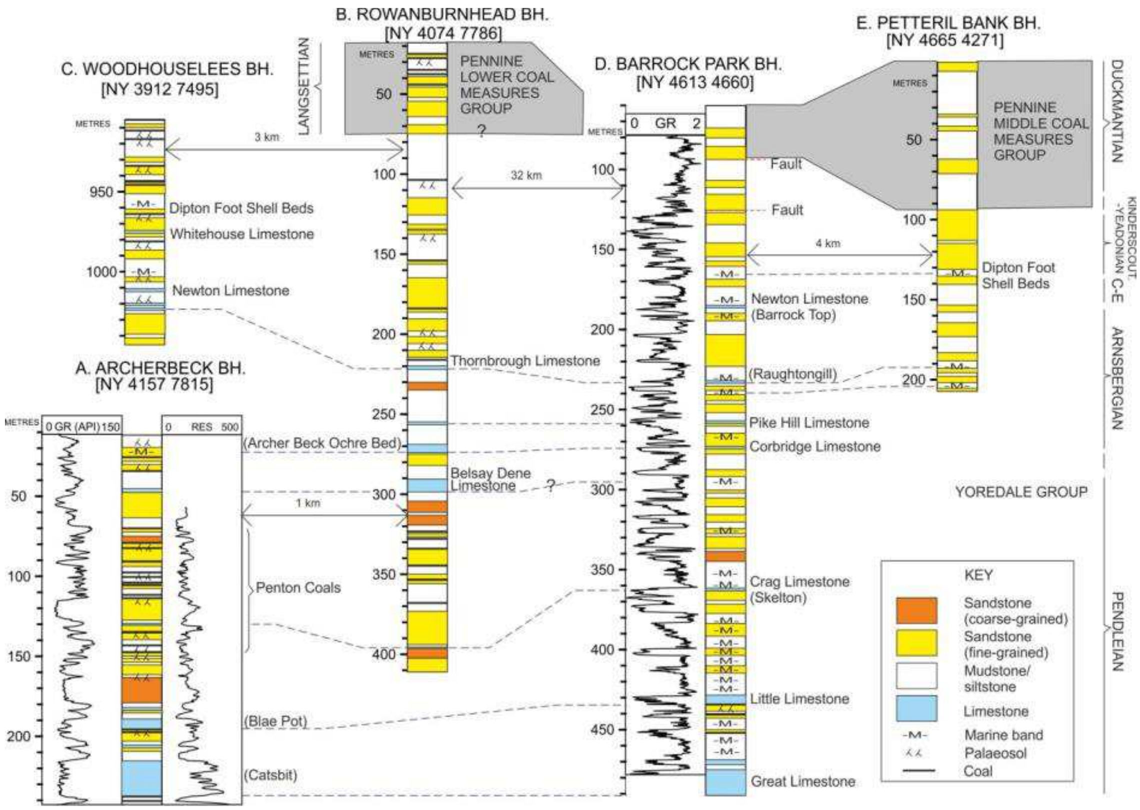



**Fig. 3** Correlation of key boreholes in the Solway Basin-Vale of Eden Basin: Archerbeck, Rowanburnhead, Woodhouselees, Barrock Park, Petteril Bank. * Gamma Ray Log units are API unless stated otherwise. For Barrock Park Borehole it is assumed to be an older scale of micrograms of radium-equivalent per ton, convertable at 11.7 or 16.5 API units per old unit. C-E- Chokierian to early Kinderscoutian.

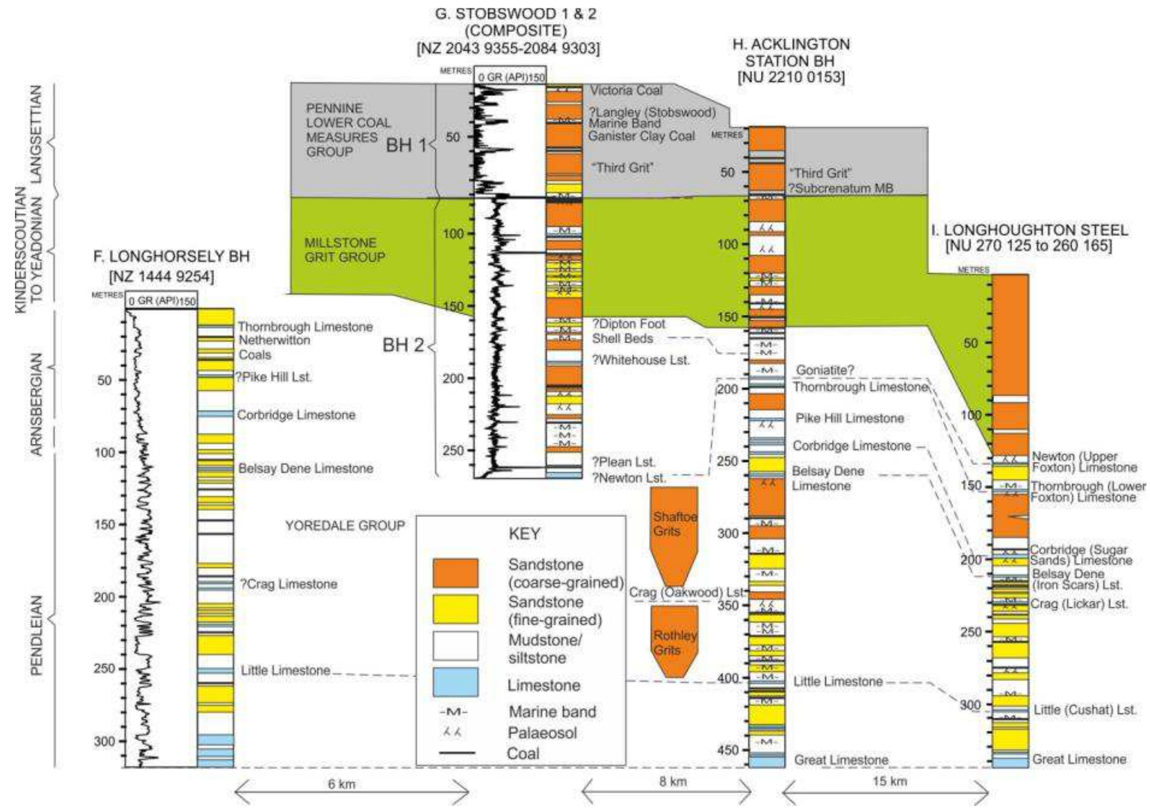
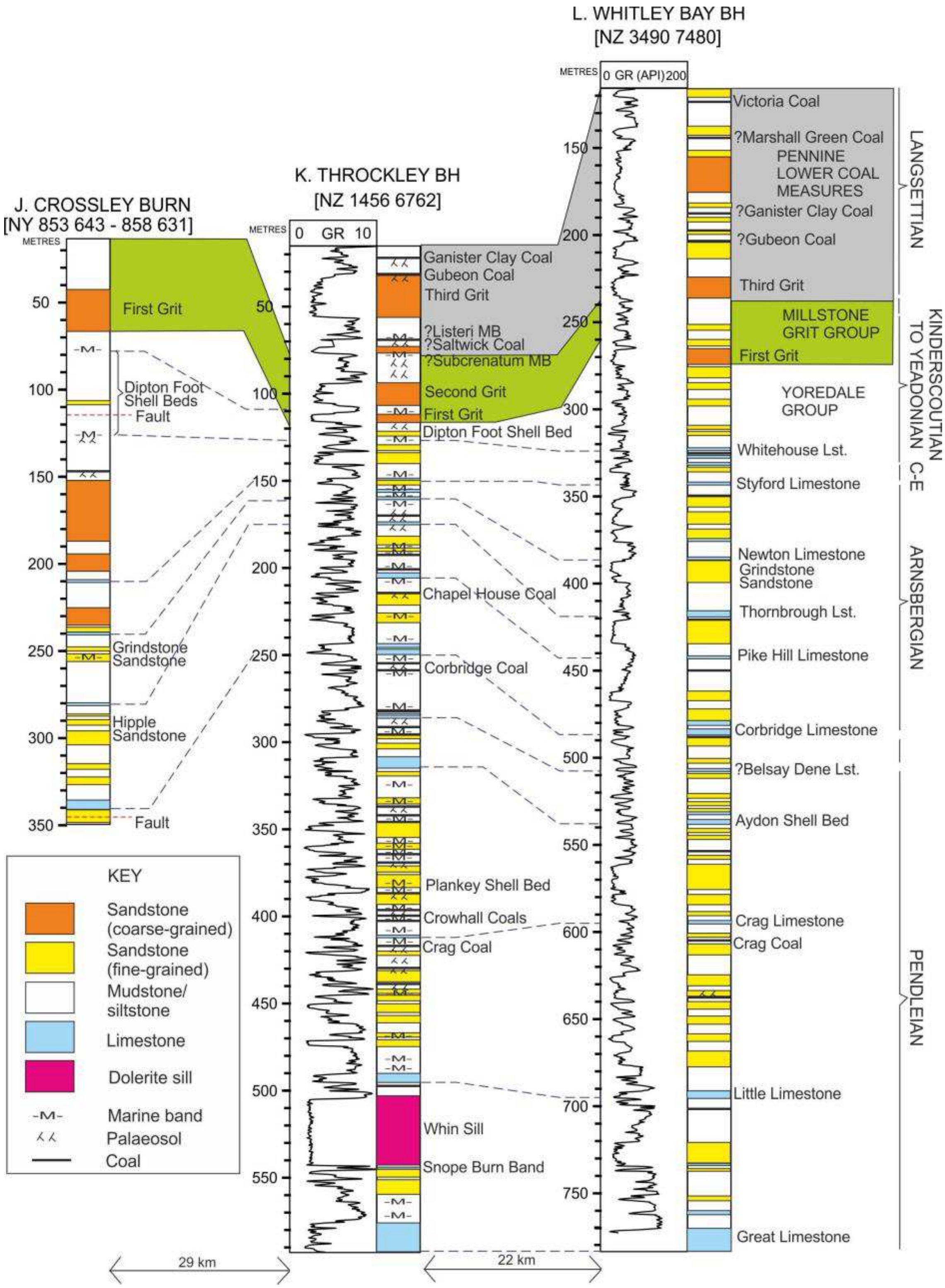



**Fig. 4** Correlation of key boreholes and sections in the NE Northumberland Basin to Cheviot Block: Acklington Station, Stobswood 1 & 2, Longhorsely and Longhoughton Steel.


L. WHITLEY BAY BH
[NZ 3490 7480]
K. THROCKLEY BH
[NZ 1456 6762]
J. CROSSLEY BURN
[NY 853 643 - 858 631]
METRES
0 GR 10
0 GR (API) 200
Victoria Coal
?Marshall Green Coal
PENNINE LOWER COAL MEASURES
?Ganister Clay Coal
?Gubeon Coal
Third Grit
MILLSTONE GRIT GROUP
First Grit
YOREDALE GROUP
Whitehouse Lst.
Styford Limestone
Newton Limestone
Grindstone Sandstone
Thornbrough Lst.
Pike Hill Limestone
Corbridge Limestone
?Belsay Dene Lst.
Aydon Shell Bed
Crag Limestone
Crag Coal
Little Limestone
Great Limestone
LANGSETTIAN
KINDERSCOUTIAN TO YEADONIAN
C-E
ARNSBERGIAN
PENDLEIAN
Ganister Clay Coal
Gubeon Coal
Third Grit
?Listeri MB
?Saltwick Coal
?Subcrenatum MB
Second Grit
First Grit
Dipton Foot Shell Bed
Chapel House Coal
Corbridge Coal
Plankey Shell Bed
Crowhall Coals
Crag Coal
Whin Sill
Snope Burn Band
First Grit
Dipton Foot Shell Beds
Fault
Grindstone Sandstone
Hipple Sandstone
Fault
KEY
Sandstone (coarse-grained)
Sandstone (fine-grained)
Mudstone/ siltstone
Limestone
Dolerite sill
Marine band
Palaeosol
Coal
29 km
22 km

177

**Fig. 5** Correlation of key boreholes and sections in the SE Northumberland Basin: Crossley Burn, Throckley, Whitley Bay. * Gamma Ray Log unit for the Throckley Borehole, see fig. 3. C-E- Chokierian to early Kinderscoutian.

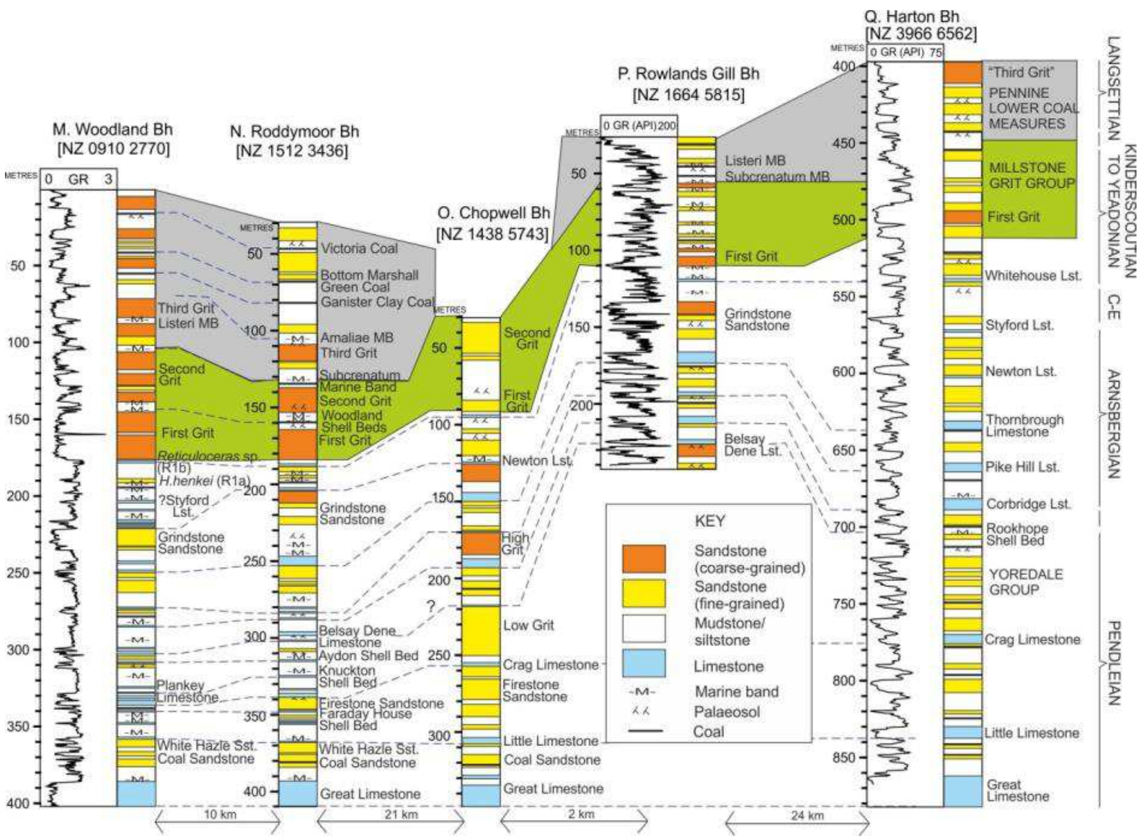



**Fig. 6** Correlation of key boreholes in the Alston Block: Woodland, Roddymoor, Chopwell, Rowlands Gill, Harton. * Gamma Ray Log unit for the Woodland Borehole, see fig. 3. C-E- Chokierian to early Kinderscoutian.

### 2.1 Pendleian cycles

The base of the Serpukhovian Stage was placed by Cózar & Somerville (2012), using foraminiferans, at the base of the Four Fathom Limestone Member (Alston Formation), which extends across parts of Cumbria, Northumberland, Durham and North Yorkshire

(Dean *et al*. 2011). This is lower in the succession than the base of the Pendleian Substage, which is taken at the base of the *Cravenoceras leion* Marine Band (Ramsbottom *et al*. 1978; Waters & Condon 2012). The presence of *C. leion* in mudstones above the Great Limestone in Greenleighton Quarry, Northumberland Basin, proves an $E_{1a}1$ age for this limestone (Johnson *et al*. 1962). The presence of *Cravenoceras* sp. and *C.* aff. *malhamense* above the Little Limestone in Allendale, on the Alston Block (Dunham & Johnson 1962; Johnson *et al*. 1962), suggests an $E_{1c}$ age (Table 1). The presence of *Tylonautilus* sp. nov., located *c.* 16 m below the Crag Limestone in the Woodland Borehole (Fig. 6), suggests that this part of the succession is late Pendleian in age (Mills & Hull 1968). If these correlations are correct, it follows that two late Pendleian flooding surfaces in the Central Pennine Basin ($E_{1c}1$ and $E_{1c}2$; Waters & Condon 2012) equate with up to six distinct marine limestones/shell beds in the north (Table 1). It should be expected that the deeper water Central Pennine Basin would preserve the more complete succession, but it is possible that the greater number of limestones to the north reflects preservation of a higher frequency cyclicity (100 ka or less).

### 2.2 Arnsbergian cycles

The Corbridge Limestone is interpreted as marking the base of strata of Arnsbergian age (Table 1). This is based upon correlation with the Mirk Fell Ironstone of the Stainmore Basin, with associated *Cravenoceras cowlingense* (Rowell & Scanlon 1957; Ramsbottom *et al*. 1978; Brand 2011), diagnostic of the ammonoid $E_{2a}1$ Subzone. The Corbridge Limestone from the Rowlands Gill Borehole (Fig. 6) contains a foraminifer assemblage indicative of Arnsbergian age (Riley 1992). However, the palynomorph assemblages are rather confusing with regards to the age of this limestone and adjacent cycles. In the vicinity of Longhoughton Steel (Fig. 4), the Belsay Dene and Corbridge limestones (Table 1), contain miospore assemblages of the *Stenozonotriletes triangulus–Rotaspora knoxi* (TK) Zone (Turner & Spinner 1992; Table 1), indicating an early Arnsbergian age. The Rookhope Shell

Bed (equivalent to the Belsay Dene Limestone; Table 1) in the Woodland Borehole (Fig. 6) includes late Pendleian foraminifers, but other foraminifers present have first occurrences more typical of the Arnsbergian (Stephenson *et al*. 2010). In contrast, palynological study of the Woodland Borehole (Neves 1968) assigned strata between the Crag and Corbridge limestones to the early Arnsbergian TK Biozone. This suggests the following alternative possibilities: 1) the base of the Arnsbergian substage is lower than the Corbridge Limestone; 2) the correlation of the limestones between the Cheviot Block, southern Northumberland Basin and Alston Block is erroneous; 3) the base of the TK Biozone is below the base of the Arnsbergian Substage; or 4) some of the rocks analysed palynologically did not adequately sample the contemporary microfaunas.

The interval between 358.33m and 243.23m in the Throckley Borehole (Fig. 5) contains palynomorphs typical of the CN biozone of Pendleian age (Stephenson *et al*. 2008). The limestone at 250m depth has commonly been interpreted as the Thornbrough Limestone (Stephenson *et al.* 2008), but this is inconsistent with an interpretation of Pendleian age. It has been reinterpreted by correlation with nearby boreholes as the Corbridge Limestone (Fig. 5), despite the Corbridge Limestone being earliest Arnsbergian in age rather than Pendleian. Above 243.23m (Fig. 5), the palynomorphs indicate the TK biozone up to 136m, just above the base of what was interpreted as the 'Millstone Grit' (Stephenson *et al*. 2008), suggesting an early Arnsbergian age for the interval between these depths. However, the succession between 243.23m and 136m in the Throckley Borehole also includes what Stephenson *et al*. (2008) identified as the Whitehouse Limestone at *c*. 175m, typically considered to be Kinderscoutian in age (see below). In a revised interpretation (Fig. 5), this limestone is now correlated with the Thornbrough Limestone, consistent with an early Arnsbergian ($E_{2a}$) age.

Mudstones associated with the Newton Limestone of the Alnwick area (Table 1), at Longhoughton Steel, contain miospore assemblages of the *Lycospora subtriquetra*–

*Kraeuselisporites ornatus* (SO) Zone, suggesting a latest Arnsbergian to Alportian age (Turner & Spinner 1992). Mudstones within the overlying 'Millstone Grit' contain 15 first appearances of new miospore species, including *Crassispora kosankei* (Turner & Spinner 1992), which is characteristic of the KV miospore zone of Kinderscoutian to early Marsdenian age. However, the absence of other characteristic KV zone species led Turner & Spinner (1992) to attribute an SO Zone age to the 'Millstone Grit', though we contend that a later Kinderscoutian age is preferred. The Newton Limestone of the Barrock Park Borehole (Brand 2011; Fig. 3) includes *Tylonautilus nodiferus*, indicative of an $E_{2b}$ age (Arthurton & Wadge 1981). In the Throckley Borehole (Fig. 5), the first appearance of the palynomorph *Lycospora subtriquetra* at a depth of 136m marks the base of the SO Biozone (Stephenson *et al*. 2008), but it occurs above the inferred position of both the Newton and Styford limestones.

The strata of early and mid Arnsbergian ($E_{2a}$ and $E_{2b}$) age are here considered to include six limestones/shell beds and three unnamed marine bands, compared with the eight marine bands recognized in the Central Pennine Basin (Waters & Condon 2012). Late Arnsbergian strata, associated with four marine bands in the Central Pennine Basin ($E_{2c}$1-4; Waters & Condon 2012), are considered to be absent in northern England. The late Arnsbergian is interpreted to be an interval between Gondwanan glaciations in which base-level falls and rises are significantly subdued (Waters & Condon 2012), potentially to the point that marine conditions were unable to extend across those parts of the Pennine Basin where subsidence rates were lower, i.e. north of the Craven Fault System.

### 2.3 Chokierian and Alportian cycles

Within the study area, there is only limited palaeontological evidence for strata of Chokierian and Alportian age (Hull 1968). The absence of ammonoids diagnostic of this interval precludes identification of strata from these substages. There is a condensed 17m thick succession in the Woodland Borehole (Fig. 6) between the occurrence of *Posidonia corrugata*, indicative of Arnsbergian strata, 8.4m above the Newton Limestone, and the presence of *Homoceras* cf. *henkei,* which indicates strata of early Kinderscoutian ($R_{1a}$) age, 13.3m below the Whitehouse Limestone (Mills & Hull 1968). The upper 1.5m of this succession is dominated by seatearth palaeosols, thin coals and marine shales and the remainder dominated by grey mudstone, in part with marine fauna, with subordinate thin marine limestone, fine-grained sandstone and ironstone beds (Mills & Hull 1968).

### 2.4 Dipton Foot Shell Beds (Kinderscoutian)

The Dipton Foot Shell Beds, a term more widely used in description of the stratigraphy of the Northumberland Basin, commonly comprise three distinct bands, varying laterally from shale with marine fauna to thin limestone. The ammonoid *Reticuloceras stubblefieldi* has been found in this interval, indicating an $R_{1b}$ age (Ramsbottom *et al*. 1978). The Dipton Foot Shell Beds typically occur 10m or less below the base of the Millstone Grit Group around Hexham, and between 8m and 20m below that unit north-west of the Newcastle area. The Alston Block term, 'Whitehouse Limestone' (Mills & Hull 1976), refers to the basal thin limestone, representing the oldest Pennsylvanian flooding event in the region.

In a tributary stream of West Dipton Burn [NY 9273 6131], the Dipton Foot Shell Beds comprise three shelly calcareous mudstones in a *c*. 7m mudstone succession. Above the uppermost of the shell beds is a broadly upward-coarsening succession, at least 6.9m thick, comprising silty mudstone, upward-fining siltstone-mudstone couplets and, at the top, a thin, planar-bedded, fine-grained sandstone. In Crossley Burn (Figs 5, 7), three distinct marine bands were recognized by Brand (1991*a*), spanning a *c*. 35m thickness, with intervening fine-grained quartzitic sandstones.

In the Throckley Borehole (Fig. 5), the presence of *Homoceratoides* sp. at 143.4m (Ramsbottom *in* Richardson 1966) indicates an early Kinderscoutian ($R_{1a}$) age for the succession immediately above what is interpreted in the current study to be the Styford Limestone. In the same borehole, a distinctive palynostratigraphical level is marked by the first appearance of common *Crassispora kosankei* at 126.5m, defining the base of the KV Biozone (late Alportian to Marsdenian age) (Stephenson *et al*. 2008). This is close to a brachiopod-bearing mudstone at 127.8m depth. The palynological interpretation above is consistent with this mudstone being one of the Dipton Foot Shell Beds (Fig. 5).

The uppermost of the recognized flooding events in the west Solway Basin area (Fig. 2) was taken to be equivalent to the Dipton Foot Shell Beds by Brand (2011). The Mousegill Marine Beds of the Stainmore area (Table 1) include *Homoceras henkei* and are therefore of $R_1$ age (Burgess & Holliday 1979). They were also considered to be equivalents of the Dipton Foot Shell Beds by Brand (2011).

## 2.5 Sharnberry, Woodland and Spurlswood Shell Beds (Kinderscoutian–Yeadonian)

The Sharnberry Shell Beds are recorded in the Wolsingham area (Fig. 2), at the Sharnberry Beck type locality, occurring within what was previously termed the First Grit. *Reticuloceras* sp. has been recorded, suggesting an $R_1$ age (Mills & Hull 1976). In the Woodland Borehole (Fig. 6), the fossiliferous marine mudstone of the Woodland Shell Bed occurs between what has been broadly mapped as the First Grit and Second Grit (Mills & Hull 1968). It lacks a diagnostic fauna, but is interpreted as equivalent to the *Bilinguites superbilinguis* ($R_{2c}1$) Marine Band (Brand 2011). This suggests that lower Marsdenian ($R_{2a}$ and $R_{2b}$) strata, which comprise up to eight flooding surfaces in the Central Pennine Basin (Waters & Condon 2012), lack marine bands in the region (Table 1).

The Spurlswood Shell Beds of the southern part of the Alston Block and northern part of the Stainmore Basin, which comprise two thin fossiliferous beds with *Lingula* and productoids separated by 5m of barren mudstones (Mills & Hull 1976), are a possible equivalent of the *Cancelloceras cumbriense* ($G_{1b}1$) Marine Band (Brand 2011). They occur within the Second Grit, although the upper part of this sandstone locally cuts out the fossiliferous beds.

## 2.6 Subcrenatum (Quarterburn) Marine Band (Langsettian)

The base of the Pennine Lower Coal Measures (and Langsettian Substage) is taken at the base of the Subcrenatum Marine Band (Waters *et al*. 2007; Dean *et al*. 2011). In the Alston Block area, this marine band, despite lacking the diagnostic ammonoid, is recognized in the Woodland Borehole at 101.4m depth, in the Roddymoor Borehole at 127.1m, and in the Rowlands Gill Borehole at 57.08m (Fig. 6). In the Durham Coalfield (east of Wolsingham on Fig. 2), the Quarterburn Marine Band is considered to be the local correlative of the Subcrenatum Marine Band (Ramsbottom *et al*. 1978; Table 1), and it rests upon what has been mapped historically as the Second Grit. In the west Newcastle area, the Quarterburn Marine Band comprises 5m of mudstone and silty shale with *Lingula* fragments, and locally with brachiopods, molluscs, echinoderms, sponge spicules, crinoid columnals, fish and plant debris. Fragments of *Gastrioceras*? are present in Mere Burn [NZ 0886 5485], although *Gastrioceras subcrenatum* has nowhere been recorded (Mills & Holliday 1998). The interval is associated with seatearths and ironstone bands or nodules, and with a rooted, commonly calcareous sandstone with *Zoophycos*. The Quarterburn Marine Band has not been recognized with certainty north of the River Tyne.

## 2.7 Higher Langsettian marine bands

Above the Subcrenatum Marine Band, up to three marine bands are recognized within the Langsettian succession of the region: in ascending order, the Listeri, Amaliae and ?Langley marine bands (Table 1). This compares with the up to 10 flooding surfaces recognized within the central part of the Pennine Basin (Waters & Condon 2012). The Listeri Marine Band, referred to in the Stainmore Basin as the Kays Lea Marine Band (Table 1), is inferred to be present in the Throckley Borehole (Fig. 5), and has been recorded in the Woodland and Rowlands Gill boreholes (Fig. 6). The Amaliae Marine Band is recognized as the Gubeon Marine Band in the Northumberland Coalfield and as the Roddymoor Marine Band in the Roddymoor Borehole (Fig. 6, Table 1). The Stobswood Marine Band, recognized in the Stobswood 1 Borehole (Fig. 4), is tentatively correlated with the Langley Marine Band and is thought to equate with the Templeman's Marine Band of the Canonbie area (Waters *et al*. 2011*b*).

In the Hexham area, much significance has been placed on biostratigraphical information provided by Brand (1991*a*) for the proposed Acton Fell Opencast site. This has allowed broad correlation of Langsettian marine flooding surfaces and has resulted in mapping of a more extensive development of the Pennine Lower Coal Measures across the northern part of the Alston Block. Both the Subcrenatum and Listeri marine bands have now been recognized as *Planolites* bands, separated by 6m of mudstone. The Amaliae (Gubeon) Marine Band is here represented by a *Lingula* band, recorded from the eastern end of Acton Burn Quarry [NY 98195 53930].

## 3. EARLY NAMURIAN (PENDLEIAN TO ARNSBERGIAN) FLUVIAL SYSTEMS

### 3.1 Sedimentological overview

The Alston Formation (Yoredale Group), a mainly Brigantian succession with Yoredale cycles dominated by comparatively thick marine limestones, extends to the top of the Great Limestone, and hence into earliest Pendleian times (Fig. 1). However, this section focuses on the nature of the overlying early Namurian Stainmore Formation (Yoredale Group).

The Stainmore Formation comprises typically upward-coarsening cyclic successions. The cycles comprise marine limestone (deposits of a Transgressive Systems Tract) and mudstone/siltstone, overlain by thin tabular quartzitic sandstones up to medium-grained, in part also of shallow marine origin (deposits of a Highstand Systems Tract). The cycles are commonly capped by seatearth palaeosols (representing a Lowstand Systems Tract) and thin coals (representing an Initial Flooding Surface). In many cases, the limestones show a broadly similar thickness across the Northumberland Basin and Alston Block and are laterally persistent (Dunham 1990, fig. 4). The mudstones are commonly laminated to massive, probably representing variably bioturbated suspension deposits in a shallow bay (Elliott 1975, 1976).

The cycles represent the alternation between deposition on a shallow clear-water carbonate shelf and clastic incursions deposited by fluvial deltas (Moore 1959; Elliott 1975). Variations in the upward-coarsening character (e.g. Fig. 7a), described by Elliott (1976), might reflect progradation of minor deltas, minor overbank sheet floods and crevasse splay lobes. Thicker cycles typically occur above transgressive marine limestones (Elliot 1976) in response to greater accommodation space. These upward-coarsening cycles were deposited in slightly deeper water with low wave energies, with the topmost sandstones of the cycles possibly forming in low energy beaches (Elliott 1976). Small-scale distributary channel sandbodies are often highly sinuous (Elliott 1976).

Locally, very thick-bedded, cross-bedded, granule-rich and pebbly, coarse- to very-coarse-grained, quartz-feldspathic sandstones occupy fluvial channels. These sandstone bodies, which exhibit many ‘Millstone Grit’ characteristics such as strongly erosive bases and channel-like morphologies, are present within the Stainmore Formation. The erosive surfaces are interpreted as Type I sequence boundaries (sensu Posamentier & Vail 1988), cut into the delta plain as a consequence of a fall in relative sea-level. The inferred palaeovalley subsequently filled with very coarse, rapidly deposited fluvial detritus that typically fines upwards in response to a rise in relative sea-level. The nature and distribution of these fluvial sandbodies are described in turn for the four regions covered in this study.

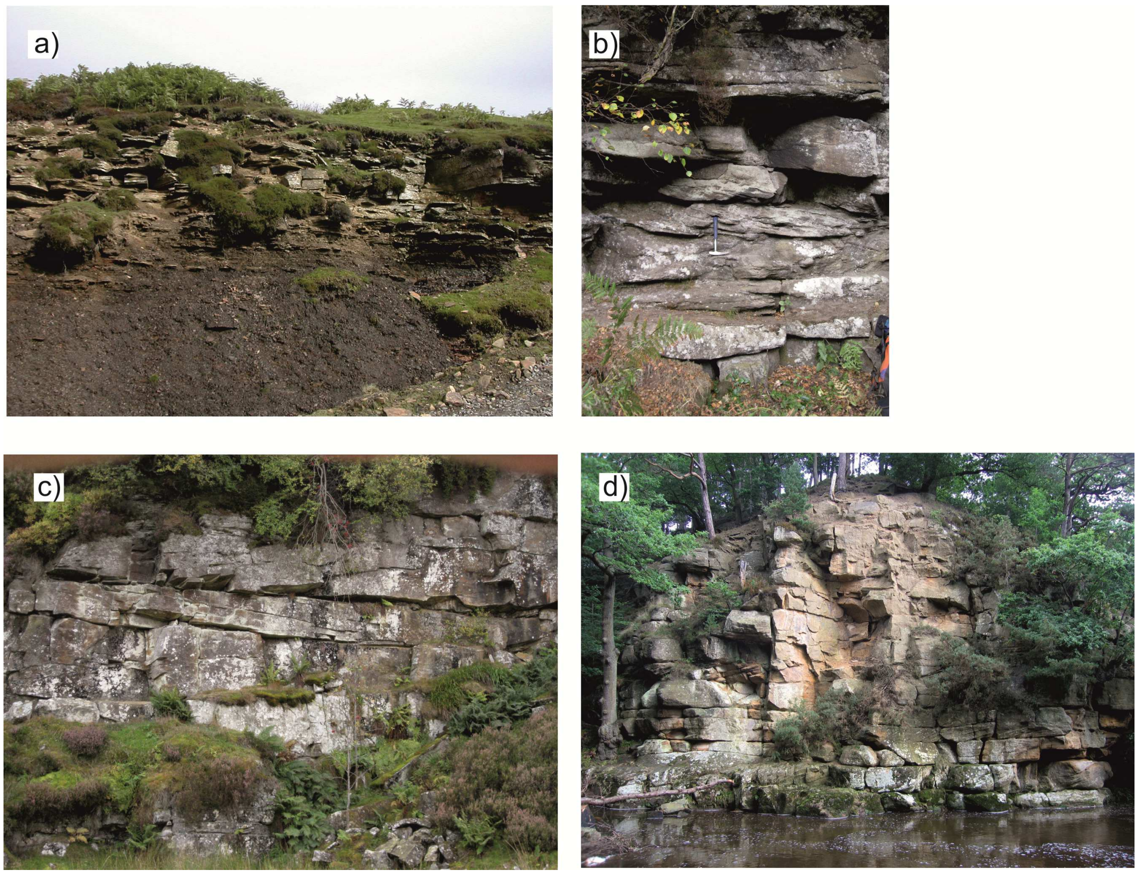



**Fig.** 7a) Thin, coarsening upward cycle from the Stainmore Formation, above the Thornbrough Limestone; Heathery Burn [NY 9069 4979], section c. 4 m high; 7b) Fluvial channel facies of laterally accreting sandbodies exposed in a c. 6 – 7 m high section at Castleberry Cleugh, south bank, Beldon Burn [NY9293 4947]. Thick to very thick bedded, lenticular sand bodies wedge out laterally. Beds are commonly conspicuously cross-bedded internally, though some are massive or faintly parallel-laminated. The sandstone is poorly–sorted, feldspathic, coarse to very coarse, with granules and pebbles, the latter chiefly of vein quartz; 7c) The basal sandstone of the Millstone Grit Group at the Devil's Water [NY 9584 6232], in a cross-bedded, pebbly very coarse-grained sandstone facies c. 12 m high.

### 3.2 Solway Basin to north Lake District High

The lowermost 60m of the Namurian succession in the Archerbeck and Barrock Park boreholes show typical Yoredale cyclicity. This early Pendleian succession is dominated by the marine Great Limestone and Little Limestone, with limited siliciclastic input (Fig. 3). Mudstone intervals in the Barrock Park Borehole also contain marine fauna. The upper *c.* 10m of the Great Limestone cycle are marked by development of coals and seatearths (Arthurton & Wadge 1981), indicating a period of widespread emergence prior to the Little Limestone flooding event.

The succeeding, 160m-thick, upper Pendleian succession in the Archerbeck Borehole shows a marked change in depositional style, being dominated by sandstone with numerous seatearths and thin coals, but with only a single thin marine unit, the Crag Limestone (Brand 2011; Table 1). In this borehole, fluvial, quartz-feldpathic, coarse-grained sandstones only occur between the Little Limestone and Crag Limestone, below the main development of Penton Coals and seatearths, and as a thin development between the Crag and ?Belsay Dene limestones at the top of this coal-rich succession (Fig. 3). Coarse-grained sandstones are recognized at equivalent intervals in the Rowanburnhead Borehole (Fig. 3). The succession appears to reflect limited marine inundation, but repeated emergence with development of coals and associated palaeosols. In contrast with these successions in the northern part of the Solway Basin, the Vale of Eden succession is predominantly marine with no indications of emergence. The equivalent 160m succession above the Little Limestone in the Barrock Park Borehole, for example, is dominated by marine sandstone and mudstone. Within this interval, a 37.9m-thick, fine- to medium-grained sandstone, coarse-grained in the lower part (Arthurton & Wadge 1981), occurs between the Crag Limestone and Corbridge Limestone and might equate with the Low Grit sandstones of the Alston Block (see below).

The succeeding >110m succession, seen in the Archerbeck Borehole as the Archer Beck Ochre Bed and in the Woodhouselees Borehole extending up to the uppermost of the recognized flooding events, taken to be equivalent to the Dipton Foot Shell Beds by Brand (2011), is marked by laterally correlatable flooding events, variably marine limestone or mudstone. Sandstones within this succession are mainly fine- to medium-grained and quartzitic.

The western flank of the Lake District High shows a thin Namurian succession, 110m and 140m thick in the Distington [NX 997 233] and Rowhall Farm [NY 085 366] boreholes respectively (Akhurst *et al*. 1997). The Rowhall Farm Borehole displays five Yoredale-type cycles, ranging in age from Pendleian to Arnsbergian; the Distington Borehole is interpreted as showing the same five cycles, but with the limestone absent (Akhurst *et al*. 1997). A major non-sequence is inferred at the top of cyclic succession which contains a limestone that is inferred to be equivalent to the Thornbrough Limestone of early Arnsbergian ($E_{2a}$) age (Akhurst *et al*. 1997).

### 3.3 Cheviot Block to northern Northumberland Basin

In northern Northumberland, the Stainmore Formation is c. 243−259m thick (Westoll *et al*. 1955) and includes a number of coarse-grained, quartzo-feldspathic sandbodies. Coastal exposures near Alnwick typically comprise 2.0 to 8.5m-thick, upward-coarsening cycles that represent shallow-water deltaic deposition (Elliott 1976). Above the Corbridge Limestone (Table 1) is a *c.* 18m-thick, coarse-grained sandstone, which is tabular cross-bedded and normal-graded, and an overlying coarse-grained sandstone with slump folds at least 8m thick; both sandstones show markedly erosive bases (Farmer & Jones 1968).

The Acklington Station Borehole shows the development of thick, cross-bedded, typically normal-graded, coarse- to medium-grained sandstone within the cycles present beneath the

Belsay Dene and Thornbrough limestones (Fig. 4). These sandstones might equate with the fluvial Low Grit and High Grit (Fig. 6) of the Alston Block. Erosion at the base of the sandstone beneath the Belsay Dene Limestone might be responsible for the absence of the Crag Limestone in the Acklington Station Borehole.

The Pendleian Rothley Grits and Arnsbergian Shaftoe Grits of the Morpeth and Rothbury areas exhibit deep erosive bases close to the levels of the Little Limestone and Oakwood (= Crag) Limestone respectively (Young & Lawrence 1998, 2002), the Shaftoe Grits being associated with removal of the Belsay Dene, Corbridge and Thornbrough cycles (Fig. 4). The grits are coarse- and very coarse-grained and pebbly sandstones containing substantial amounts of feldspar; locally, grains of pale purple garnet are seen in the Shaftoe Grits. The units are cross-bedded with trough and planar forms. Palaeocurrent measurements for the Rothley Grits indicate south-easterly flow (Young & Lawrence 1998), whereas those for the Shaftoe Grits indicate flow to the south-west (Jones 1996). Both units are interpreted as multi-storey, low sinuosity channel deposits (Jones 1996), which might constitute further examples of palaeovalley fills.

In Stobswood 2 Borehole, immediately beneath the Whitehouse Limestone, is a 14m thick, very coarse-grained, feldspathic sandstone, becoming fine-grained upwards (Fig 4). The base is conglomeratic with pebbles up to 6mm; elsewhere the coarsest grains are granules up to 3mm with limestone clasts up to 20mm.

## 3.4 Southern part of the Northumberland Basin

North of Haltwhistle, at Haltwhistle Burn [NY 7093 6556], and around Fourstones [NY 880 675], north-east of Hexham, the *c.* 60m succession between the Little Limestone and Crag (Oakwood) Limestone is sandstone-dominated and includes two massive sandstones, the lower sandstone 18m thick and the upper 12m thick, comprising medium- to coarse-grained sandstone (Clarke 2007). The upper sandstone is apparently equivalent to the Firestone Sandstone of the Alston Block (Clarke 2007). Just to the north and west of Hexham, two units of fluvial, cross-bedded, locally conglomeratic or pebbly, very coarse-grained sandstone occur immediately above the Crag Limestone.

The Throckley and Whitley Bay boreholes both show significant thicknesses of sandstone between the Little Limestone and the Crag Limestone (Fig. 5), though none has coarse-grained fluvial characteristics. The upper part of the succession below the Crag Limestone shows an upward increase in abundance of thin coals and palaeosols. In the Throckley Borehole, between the Crag Limestone and the Newton Limestone, the succession is extensively marine, although with common coals and palaeosols, but with no coarse-grained fluvial sandstones, something that is also observed in the Whitley Bay Borehole and the Crossley Burn section (Fig. 5). The interval between the Corbridge Limestone and the Thornbrough Limestone in the Throckley Borehole is comparatively sand-poor (Fig. 5).

Between the Thornbrough and Newton limestones, the Grindstone Sandstone, present in Crossley Burn [NY 8548 6397], comprises 5m of pale grey, possibly hummocky cross-bedded, fine-grained sandstone, with locally bi-directional foresets and *Rhizocorallium* traces, indicating that the sandstone is marine and at least in part tidal- and storm-influenced.

Between the Newton Limestone and the Styford Limestone in the Hexham area is a thick channel sandstone. At Devil's Water [NY 970 627], the base of this sandstone appears to cut out the underlying Newton Limestone (Mills & Holliday 1998). In the Corbridge area, the cycle, dominated by sandstone, is estimated to be 30m thick. This sandstone is evident at Crossley Burn, where the cycle is only 8m thick (Figs 5, 8).

Between the Styford Limestone and Dipton Foot Shell Beds, an additional 22m-thick, quartz-feldpathic sandstone is present in the Crossley Burn section (Fig. 5). In the lower 5m, the sandstone is very coarse-grained, thick to very thick-bedded and cross-bedded. The overlying 9.6m of sandstone are mainly coarse-grained and thin to thick-bedded. The overlying 5.8m comprise intermittent exposure of fine-grained sandstone with dispersed sand grains up to 0.5mm in diameter. The sandstone succession is capped by iron-rich, diagenetic peloidal, coarse-grained sandstone. The upward-fining succession is interpreted as a fluvial channel-fill deposit.

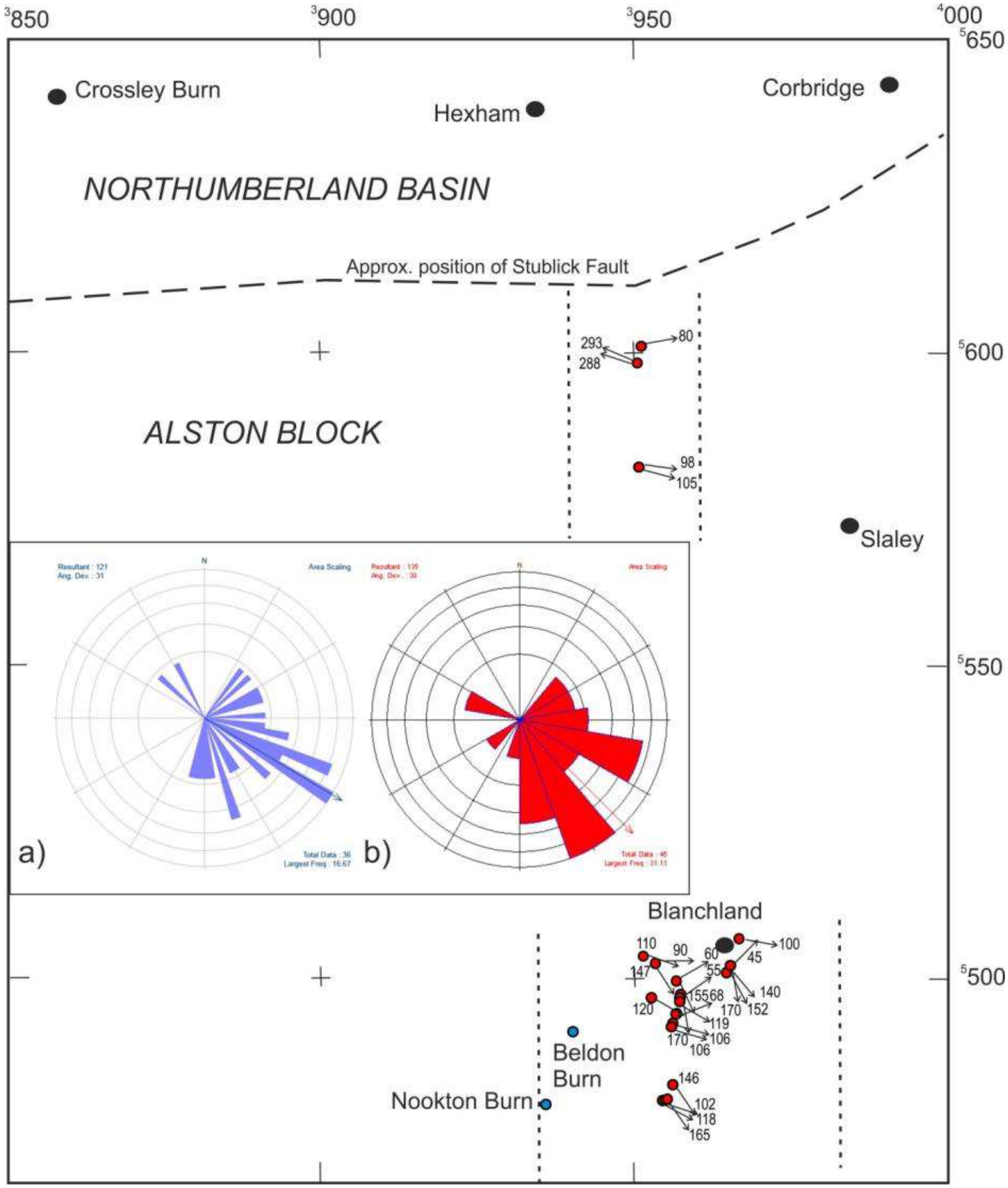



**Fig. 8** Palaeocurrent data for the Rogerley Channel a) in the area between Hexham and Blanchland for the upper fluvial channel, and b) from Beldon and Nookton burns for the lower fluvial channel.

### 3.5 Alston Block

Between the Great Limestone and Little Limestone, a succession up to 37m thick (average 24m) extends across the Alston Block (Fig. 6; Dunham 1990, fig. 5). A thick, pebbly, coarse-grained sandstone, up to 30m thick (Hodge 1965), was considered by Dunham (1990) to occupy an erosive channel with a sinuous course, extending south-west of Blanchland to Barras in Stainmore. The channel cuts through the sheet sandstones of the Low and High Coal sandstones, but pre-dates deposition of the High Coal (Hodge 1965). A further belt of thick sandstone, the White Hazle Sandstone (Fig. 6), lies to the south-east and is approximately parallel with the distributary channel. This upward-coarsening sandstone body is interpreted as a barrier island deposit (Elliott 1975). At Scarrowmanwick Fell, in the Penrith area, the High Coal Sandstone is up to 12m thick, coarse-grained and massive (Arthurton & Wadge 1981). However, the interval between the Great Limestone and the Corbridge Limestone is dominantly marine, as indicated in the Goldfields Extension boreholes near Swinhope [NY 450 830] (Dunham & Johnson 1962), in the Allenheads boreholes [NY 8604 4539, NY 8715 4505] and extending at least as far north as Sipton Cleugh [NY 852 500]. In addition to a fauna that includes brachiopods, crinoids and trilobites, sedimentological evidence includes the presence of hummocky cross-stratification, particularly in the last named section.

The Firestone Sandstone, locally known as the Crag Sandstone, occurs beneath the Crag (Oakwood) Limestone. Two distinct facies can be recognized (Dunham 1990): a) coarse-grained and pebbly in Alston Moor, along the Teesdale-Weardale watershed and around Middleton-in-Teesdale; b) siliceous, medium-grained sandstone with a marked ganister top in Rookhope and the Derwent valley (Percival 1986) and medium-grained sandstone in the Cross Fell–Dun Fell outlier (Arthurton & Wadge 1981). The medium-grained sandstone might pass laterally in the Allenheads area into *c*. 12m of interbedded shale and sandstone

(Dunham & Johnson 1962). Clarke (2008) recorded a laterally extensive sandstone, 10–15m thick, well exposed at Firestone Bridge [NY 7885 4353], near Alston. Here, the sandstone has an erosional base, overlain by a 0.3m basal lag of rounded to sub-rounded quartz grains and siltstone intraclasts, succeeded by coarse- to very coarse-grained sandstone, mainly cross-bedded, with foresets dipping towards the SSW (228°). The uppermost 1m is medium-grained, fining upwards, and becoming planar bedded. Clarke (2008) recognized an approximately north–south orientation of these sandstones at Blaeberry Burn [NY 7595 5556], Hareshaw Cleugh [NY 7570 5145] and Allen Gorge [NY 7975 5957]. Within the axis of this channel, a thin coal, seen elsewhere beneath the Firestone Sandstone, appears to be cut out by erosion, but fragments of coal are present locally at the base of the sandbody (Clarke 2008).

The succession between the Crag and Pike Hill limestones is associated with a complex relationship between fluvial channel sandstone bodies, commonly referred to as the Low Grit and High Grit sandstones (Fig. 6). Dunham (1990) considered there to be a single, major, kilometre-scale palaeochannel, which he referred to as the Rogerley Channel, trending roughly north–south through the Hunstanworth–Blanchland area towards Middleton-in-Teesdale. However, the current study in the Hexham and Alston areas suggests the presence of at least two major channels, with the upper channel locally eroding into the fill of the lower channel.

The lower major channel fill comprises very coarse-grained, granule-rich and pebbly, feldspathic sandstone in cross-bedded, thick to very thick beds, forming a multi-storey sandbody at least 15 to 20 m thick; this is exposed in Nookton and Beldon burns and in the headwaters of Derwent Water, west of Blanchland. In Nookton Burn [NY 9359 4799], the erosive base of this sandstone cuts down through the marine sequence above the Crag Limestone, which includes a fine-grained sandstone interpreted as comprising shoreface or beach swash/backswash sands, and is locally separated by only 0.6m from the underlying Crag Limestone. The coarse, pebbly nature of the sandstone and the relatively steeply dipping foresets (generally 15–25°, Fig. 7b) suggests that the foresets result from downstream accreting barforms in a relatively deep channel system. The foreset dip direction data (Fig. 8a) reveal a predominantly south-easterly palaeocurrent direction, although here and in the northern part of the observed channel, a small number of opposing values show palaeocurrent directions to the west and north-west, probably reflecting localized counter-currents. The coarse pebbly facies was previously considered to be either the Low Grit or High Grit sandstones, or both combined (Dunham 1990; fig. 4, column 11). However, both of these sandstones, exposed about 500m to the west of the fluvial succession at Nookton Burn, are relatively thin, up to 5m, and neither are notably pebbly, though both contain granules. Although the palaeocurrent data range widely for the Low Grit and High Grit sandstones, the contrast in grainsize and palaeocurrent directions suggest that the pebbly sandstone pre-dates, and is distinct from, the Low Grit and High Grit sandstones.

Erosion is also seen at a comparable level in Weardale, with the Knucton Shell Beds cut out in a 4 km wide belt and the Crag Limestone removed within the axis of this belt (Dunham 1990). At Round Hill Ganister Quarry, south-east of Stanhope, the base of the sandstone is seen cutting out the Crag Limestone and underlying Firestone Ganister (Dunham 1990). At Stanhope, erosion associated with the channel is inferred to be at least 76m deep (Dunham 1990).

To the west of Newcastle, the late Pendleian interval between the Crag and Corbridge limestones comprises a 62–110m-thick succession with several coarse-grained sandstones that form complex sandbodies. The sandbodies show little evidence of deep channelling at their bases and only rarely unite to form laterally continuous arenaceous sequences (Mills & Holliday 1998). The sandstones equate with the Low Grit Sandstone and with the Low Slate and High Slate sandstones of the western part of the Alston Block (Dunham 1990). A 20 m-thick succession of coarse-grained and pebbly sandstone interbedded with argillaceous beds and coals occurs above the Aydon Shell Bed at Aydon Dene [NY 9952 6588 to NZ 0054 6673] (Mills & Holliday 1998). Near Croglin Water [NY 6312 4620], between the Crag and Corbridge limestones, the Low Slate Sandstone comprises up to 12m of cross-bedded, fine- to medium-grained sandstone with a shelly top and with a markedly erosive base that has cut out the Knucton Shell Beds (Arthurton & Wadge 1981). The High Slate Sandstone comprises up to 14m of locally coarse-grained, feldspathic sandstone with a shelly top, possibly equivalent to the Rookhope Shell Beds and with an erosive base (Arthurton & Wadge 1981).

The localized absence of the Corbridge (Lower Felltop) Limestone across parts of the Alston Block was used by Carruthers (1938, p.236) as evidence of a regional unconformity, but is here interpreted as marking the erosive base of the upper fluvial channel. In the Derwent Valley, such erosion removed both the Corbridge Limestone and Rookhope Shell Bed. Around Blanchland, the erosion surface is overlain by a multi-storey sandstone body, at least 50 m thick, comprising thick to very thick (0.3 − >1.0m) beds of very coarse, granule-rich and pebbly, quartz-feldspathic sandstone. The lower part of the sandstone is mainly coarse- and very coarse-grained, with granules and small pebbles, up to 25 mm, present as isolated pebbles or as pebble lag deposits. Cross-stratification, both tabular and trough cross-bedding, typically forms sets about 1m thick. Foreset dip direction data for the coarse and pebbly lithologies (Fig. 8b) reveal a predominantly south-easterly flow direction, although there is a range from north-east to southerly. The upper part of the sandstone is typically very fine- to medium-grained, micaceous and thinly planar-bedded, with low angle, tabular cross-stratification in sets up to 0.4m and with thin mudstone interlaminae, indicative of waning flow regime. The ultimate flooding of the channel might be evident at the top of the sandstone, where a medium grey, weathered limestone bed, 0.5m thick, possibly the Pike Hill Limestone, was recorded west of Blanchland [NY 9566 5010]. Outside of the channel, the Corbridge Limestone is overlain by the Coalcleugh Beds, a limonite-stained, medium- to coarse-grained, locally ganisteroid sandstone (Dunham 1990). The sandstone is capped by the Coalcleugh Shell Bed (Table 1; Brand 2011). This succession is interpreted as a transgressive interval (Dunham 1990).

The Grindstone Sandstone, occurring between the Thornbrough and Newton limestones (Fig. 6), is typically thin to thick bedded, fine- to medium-grained, quartzitic and commonly ganisteroid. In a quarry [NY 8642 4595] above Allenheads, low-angle cross-lamination in the lowest part of the unit is associated with very shallow channels. By contrast, in the uppermost 3m, bedding is conspicuously lenticular, with foreset cross-beds dipping and troughs aligned to the west-north-west (300°). About 1km to the east, there is a facies change, with development of very coarse-grained and pebbly sandstone. Farther east, in the Chopwell Borehole, there are 10.04m of very coarse-grained, feldspathic sandstone, whereas in the Rowlands Gill Borehole, there are 8.26m of medium- and thick-bedded, mostly coarse-grained feldspathic sandstone (Fig. 6). The Wolf Crag Grit of the Brampton (Trotter & Hollingworth 1932) and Penrith (Arthurton & Wadge 1981) areas comprises 11m of massive, coarse-grained and pebbly feldspathic sandstone is of equivalent age to the Grindstone Sandstone.

The interval between 209.5m and 192.5m in the Woodland Borehole, between strata of known Arnsbergian and Kinderscoutian ages, comprises marine shales, barren mudstones and subordinate thin limestones, coals and seatearths, and is not considered to relate to an unconformity (Dunham 1990). In the Rowlands Gill Borehole, the same interval, undated, comprises 13.5m of siltstone with interbeds of mudstone and sandstone, a thin seatearth and a *Lingula* Band.

# 4. LATE NAMURIAN (KINDERSCOUTIAN TO YEADONIAN) FLUVIAL SYSTEMS

## 4.1 Stratigraphical overview

The Millstone Grit Group (s.s.) forms broad upland tracts within the studied area. The group is dominated by very thick-bedded, very coarse-grained, granule-rich and pebbly arkosic or sub-arkosic sandstones (formerly referred to as grit). Beds of fine- and medium-grained and thin-bedded sandstone are also present within the succession, together with subordinate interbeds of mudstone and siltstone. Marine bands, comprising dark grey to black, calcareous, shaly mudstone, about 0.5 m thick, record transgressive events.

In the Central Pennine Basin, south of the Craven Fault System (Fig. 2b), the Millstone Grit Group was deposited by repeated progradation of deltas, predominantly from the north and east (Collinson 1988; Martinsen 1993; Aitkenhead *et al*. 2002). North of the Craven Fault System, delta-top sub-facies dominate, characterized by condensed, predominantly cyclic successions of braided fluvial channel sandstone fining upward to shallow-water deltaic mudstones, siltstones and fine sandstones (Martinsen *et al*. 1995). Thick, high-alumina seatclay, fireclay and bauxitic clay are common, with sporadic beds of ironstone, cannel and coal (Waters *et al*. 2007). Many of the sandbodies are linear, occupying incised valleys (e.g. Martinsen *et al*. 1995), with well-developed palaeosols developed on the interfluves. Sheet-like and laterally extensive deltaic sandbodies, upward-coarsening units, typically show a lower part dominated by mouth-bar deposits overlain by distributary sands. These are typical of the late Namurian succession of the Central Pennine Basin (Collinson 1988) and southern margin of the Askrigg Block. However, such sandbodies are not typical of the Northumberland Basin and Alston Block. Similarly, deep-water deltaic sequences deposited on a delta-front apron of coalescing turbidite lobes, and typical of the lower part of the group in the Central Pennine Basin, are absent north of the Craven Fault System (Martinsen *et al*. 1995).

Historically, from the Northumberland Basin south to the Stainmore Basin, the succession between the Dipton Foot Shell Beds and Subcrenatum Marine Band has been mapped as two beds of medium- or coarse-grained sandstone, commonly pebbly and separated by subordinate argillaceous beds. The terms First Grit and Second Grit were widely used during the initial phase of mapping by the Geological Survey for the lower and upper sandstones, respectively. However, this is now considered an oversimplification, with little evidence of lateral continuity of sandbodies (Hull 1968), and mudstone intervals are more persistent and extensive than previously thought (Dunham 1948; Mills & Holliday 1998). Although the sandstones commonly show sharp and erosive bases, there is little evidence to suggest any significant incision (Mills & Holliday 1998).

The thick basal sandstone, typically referred to as the 'First Grit' (Ramsbottom *et al*. 1978), is commonly seen to occur at, or just above, the Dipton Foot Shell Beds. However, this thick basal sandstone is not seen everywhere, suggesting that it does not represent a simple sheet sandbody. A 'Second Grit' has traditionally been recognized, occurring within late Marsdenian to Yeadonian strata (Ramsbottom *et al*. 1978). Again, the sandbody is somewhat intermittently developed, and can only be unequivocally recognized when seen above the Woodland Shell Beds in the Stainmore Basin and on the Alston Block. The Millstone Grit Group thins markedly to the south of Hexham, to as little as 20m.

Historically, the top of the Millstone Grit was taken at the top of the coarse-grained sandstone-dominated facies commonly referred to as the 'Third Grit', of mid to late Langsettian age. However, the base of the Pennine Coal Measures Group is taken regionally at the base of the Subcrenatum (formerly Quarterburn) Marine Band (Waters *et al*. 2007; Dean *et al*. 2011). In the Canonbie area, the development of a growth anticline, probably in response to dextral strike-slip displacement on the Gilnockie Fault (Chadwick *et al*. 1995), has resulted in the development of an intra-Carboniferous unconformity (Lumsden *et al*. 1967; Picken 1988). The unconformity is taken as the local base of the Pennine Coal Measures Group, with strata of the Stainmore Formation down to a level of the Great Limestone locally absent (Picken 1988). Elsewhere, where the Subcrenatum/Quaterburn Marine Band is missing, the base of the group is now taken arbitrarily at the base of the Third Grit where this can be recognized.

### 4.2 Solway Basin to north Lake District High

The uppermost *c*. 150m of the Rowanburnfoot Borehole are dominated by interbedded quartzitic sandstone and mudstone, with numerous rooted beds up to 2.4m thick and thin coals. The absence of marine flooding events makes correlation particularly difficult; the position of the Subcrenatum Marine Band is inferred.

Above the Newton Limestone in the Barrock Park Borehole, there are some 79m of sandstone, fine- and medium-grained, locally coarse-grained and interbedded with siltstone and mudstone (Fig. 3). The top of the succession is faulted against Coal Measures. A comparable, though unfaulted succession, at least 114m thick, is seen in the Petteril Bank Borehole, dominated by fine-grained and siliceous sandstone. This suggests that no equivalent of the Millstone Grit Group is present in the Solway Basin area and the Pennine Coal Measures Group rests directly upon the Stainmore Formation.

In west Cumbria, on the western flank of the Lake District High, a major non-sequence upon Arnsbergian strata is overlain by an 8m-thick succession of carbonaceous mudstone, siltstone and seatearth of Yeadonian age (Distington Borehole [NX 997 233]) and basal sandstone of the Pennine Coal Measures of Langsettian age (Rowhall Farm Borehole [NY 085 366]) (Akhurst *et al*. 1997). The equivalent of the Millstone Grit Group is present locally in the

Bigrigg area [NY 001 130], evident above the *Cancelloceras cumbriense* Marine Band as a 5.6m-thick sandstone that includes a middle component of granular feldspathic sandstone (Eastwood *et al*. 1931, p.111).

## 4.3 Cheviot Block to northern Northumberland Basin

The base of the Millstone Grit Group in Stobswood 2 Borehole (Fig. 4), resting immediately upon the Dipton Foot Shell Beds, is marked by a 5.5m thick sandstone, coarsening upwards from fine-grained at the base to a very coarse-grained sandstone with some feldspar pebbles. The overlying 13.5m of sandstone show an upward fining, cross-bedded succession, coarse-grained and pebbly with large mudstone clasts at the base, passing up to fine-grained sandstone with very thin subordinate siltstone and mudstone beds with a seatearth at the top. This equivalent of the First Grit is overlain by about 19m of strata that include five marine bands, dominated by the presence of *Lingula mytilloides*. A further marine band, with *Lingula mytilloides*, is overlain by a 16m succession of cross-bedded sandstone that equates with the Second Grit, comprising upward fining beds that range from pebble conglomerates at the base of each bed to fine- to medium-grained at the top.

The three *Lingula* Bands between 140m and 121m in the Acklington Station Borehole are correlated with the five marine bands recorded in Stobswood 2. The overlying, 54m-thick succession is dominated by two coarse-grained, fining upward to medium-grained sandstones, interbedded with mainly siltstone and seatearth (Fig. 4). The upper sandbody is also considered to represent the Second Grit.

The Longhoughton Grits of the Alnwick area comprise up to 150m of channel-based, cross-bedded, coarse-grained, pebbly sandstone with conglomerate beds, with intercalated shale beds (Leeder *et al*. 1989), and were formerly referred to as 'Millstone Grit' (Westoll *et al*. 1955; Farmer & Jones 1968). As noted above, these beds were attributed to the SO Miospore

Biozone by Turner & Spinner (1992), but the style of sedimentation as multi-storey sheet sands of fluvial braidplain origin (Leeder *et al*. 1989) is more typical of the Kinderscoutian First Grit.

## 4.4 Southern part of the Northumberland Basin

Along the southern margin of the Northumberland Basin, the multi-storey basal sandstone ranges in thickness from about 10m to 40m and comprises upward fining beds with sharp bed bases. A basal, very coarse-grained, granular, pebbly and locally conglomeratic sandstone, with rounded to sub-rounded quartz pebbles up to 25mm in diameter, passes up into cross-bedded, coarse-grained sandstone. The uppermost part of the unit is commonly fine- to medium-grained and planar-bedded or cross-laminated, and the top is marked locally by a rooted palaeosol overlain by a thin coal.

In the Throckley Borehole, a bioturbated, fine- to medium-grained sandstone, with its base at 141.3m, was taken as the base of the First Grit by Stephenson *et al*. (2008), although the facies and age are inconsistent with it being that sandstone. A revised interpretation is that the 5.1m-thick sandstone, with a base at 116.9m, represents the First Grit, with the *Lingula* Band at 110.4m separating it from the upper 11.3m-thick feldspathic and garnetiferous sandstone of the Second Grit (Fig. 5).

At West Dipton Burn [NY 8961 6160], west of Hexham, the base of the basal sandstone is marked by scours with a relief up to 10cm. The lowermost 5m of the sandstone are trough cross-bedded and very coarse-grained to conglomeratic, with rounded quartz pebbles up to 15mm in diameter and ironstone clasts up to 0.12m in diameter. In contrast, in nearby Crossley Burn [NY 8575 6337 to NY 8579 6316], the base of the basal sandstone is gradational. There, the 7m succession above the uppermost Dipton Foot Shell Bed passes up from mudstone to siltstone. The overlying sandstone succession consists of 1.5m of very thinly planar-bedded, very micaceous, very fine-grained sandstone with wave ripples, overlain by 2m of low-angle, cross-bedded, very micaceous, fine-grained sandstone, in turn overlain by about 10m of cross-bedded, medium- to coarse-grained sandstone.

The basal sandstone shows a dramatic thinning across the Stublick Fault and into the relay ramp area between the Stublick and Ninety Fathom faults (Fig. 2). The basal sandstone is close to the maximum thickness of 40m at the Devil's Water [NY 9584 6232], south-east of Hexham, in a pebbly, very coarse-grained sandstone facies (Fig. 7c). Just over 2km to the south, the minimum thickness of 10m is seen around Dipton Head [NY 9615 6002], where up to two leaves are present, comprising 5m of medium- to very coarse-grained sandstone with isolated rounded quartz pebbles up to 1cm in diameter. The sharp bases of coarse-grained sandstone beds locally include *Asterichnus* trace fossils, suggesting that the base was not erosive, but gently filled the surface traces of burrows.

Cross-bedding foresets within the basal sandstone show a mean palaeocurrent direction towards the south-west (Fig. 9a). Detailed analysis of the palaeocurrent data shows localized variations ranging from westerly and southerly palaeocurrents, but with few readings towards any other sector. This reflects deposition within a low sinuosity fluvial system that shows no deflection as it crossed from the Northumberland Basin to the Alston Block, confirming that no palaeoslope associated with the former high existed at the time of deposition.

In the Hexham-Corbridge area, the succession overlying the basal sandstone is about 50m to 80m thick. Historically, this succession was considered to be dominated by a coarse pebbly sandstone referred to as the Second Grit. However, the succession comprises a complex interbedding of sandstones, in part lenticular and ranging from fine-grained to coarse-grained and pebbly, and mudstones and siltstones. Although there is a dominance of palaeocurrents towards the south-west and SSE, the palaeocurrent direction is less strongly developed in comparison with the basal sandstone.

## 4.5 Alston Block

To the west of Newcastle, the interval between the Whitehouse Limestone and base of the Quarterburn Marine Band ranges from 62m to 90m (Mills & Holliday 1998). In the Harton Borehole, an interval of 70.1m comprises mainly fine- to medium-grained sandstone, only locally coarse-grained, with interbedded siltstone, and lacks any marine fauna. The base of the First Grit is taken 27.7m above the proposed Whitehouse Limestone (Fig. 6). In the Rowlands Gill Borehole, the base of the First Grit is taken 7.86m above the Whitehouse Limestone and the Millstone Grit Group is 54m thick (Fig. 6). The sandstones are mainly fine- to medium-grained, only the basal sandstone being coarse-grained, and the intervening mudstones and siltstones commonly contain marine fauna (brachiopods, including *Lingula*).

The equivalent of the Millstone Grit Group in the Barnard Castle area ranges from 60m to 100m (Mills & Hull 1976). At Crag Gill the First Grit occurs closely above the Whitehouse Limestone, with an intervening succession of 2m of mudstone overlain by 2.7m of thin-bedded silty sandstone (Mills & Hull 1976). The basal unit of the First Grit forms a continuous sheet of weakly graded, cross-bedded, medium- to coarse-grained sandstone with small quartz pebbles, seen in the Roddymoor Borehole to be 18m thick (Woolacott 1923), and with a thin shale parting and a seatearth on top (Fig. 6).

In the Woodland Borehole (Fig. 6), the upper part of the First Grit has cut out the Sharnberry Shell Bed, and rests on the lower part to form a composite sandstone 33m thick (Mills & Hull 1968). In the north-western part of the Barnard Castle area, this upper unit of the First Grit is some 20–22m thick and comprises thin-bedded, pebbly and coarse-grained sandstone (Mills & Hull 1976). Above the Woodland Shell Beds, the lower part of the Second Grit is 19.5m thick in the Woodland Borehole (Mills & Hull 1968). The Spurlswood Shell Beds are absent in this borehole, interpreted as being cut out by the upper part of the Second Grit, which is some 15m thick, but is locally up to 31.6m thick. In the Hexham district, the basal sandstone is found on the flanks of the Derwent Valley on Cocklake [NY 941 475], about 1km south-west of Hunstanworth, and comprises very coarse-grained and granule-rich pebbly sandstone. Prominent cross-stratification reveals palaeoflow directions towards the south-east (Fig. 9b), almost identical to the underlying 'Rogerley' palaeovalley succession within the Stainmore Formation (Fig. 8b), suggesting an identically orientated distributary system, but at a higher stratigraphical level. However, the spread of palaeocurrent directions indicated by cross-bedding is greater for the basal unit of the Millstone Grit Group than for the Rogerley Channel, which can be expected for an unconfined distributary. Around Buckshott Fell [NY 960 480], the entire thickness of the Millstone Grit Group is only 20m, comprising a single sandstone with a laterally impersistent mudstone interbed. An exposure [NY 9618 4854] comprises 2.5m of coarse-grained sandstone, with pebbles up to 10 mm in diameter. Tabular cross-bed sets up to 1.1m thick show palaeocurrents towards the SSE (Fig. 9).

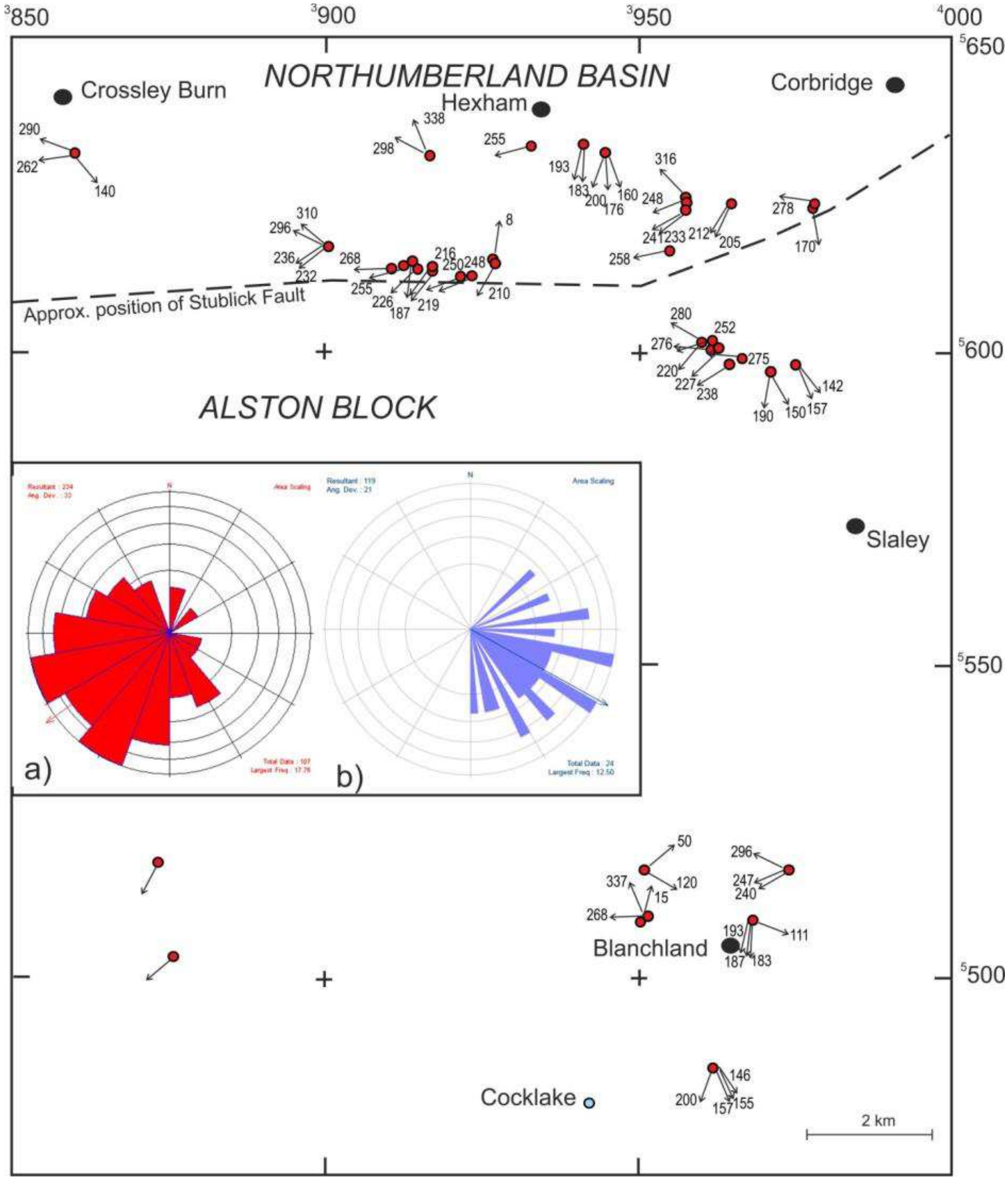



**Fig. 9** Palaeocurrent data for the basal unit of the Millstone Grit Group (First Grit): a) basal sandstone in the Hexham to Blanchland area; b) Cocklake [NY 941 475] locality.

An extensive sheet of locally conglomeratic and pebbly, coarse- and very coarse-grained feldspathic sandstone caps the summits of the hills around Hexhamshire Common [NY 850

590 – NY 870 510 – NY 930 505] and on Acton Moor [NY 810 530] to the south-west of Allendale Town. Subround to round, polycrystalline quartz pebbles up to at least 10mm in diameter are common. At least two sandstone units are recognized, separated by some 10m of poorly exposed, dark grey mudstone with brachiopods (borehole NY85NW/9) [NY 8216 5922]. The sandstones are trough cross-bedded and locally convolute bedded. The lower sandstone unit consistently overlies about 40–50m of poorly exposed shales that overlie the Thornbrough Limestone. In this area, the Newton, Styford and Whitehouse limestones are not usually present, as illustrated by Dunham (1990, fig. 4). However, farther east and south, where this interval is thicker, these higher marine beds are present, as illustrated in the Woodland, Roddymoor and Harton boreholes (Fig. 6). There is no evidence therefore for incision associated with the basal unit of the Millstone Grit Group, and the attenuated sequence beneath it is probably related to palaeogeographical factors such as emergence rather than incision.

Farther west in the Hexham district, capping the hills of Whitfield Common [NY 720 540], are further exposures of sandstone, similar in facies to that seen on Hexhamshire Common and Acton Moor. Cross-beds indicate palaeoflow directions to the west-north-west. The bed tops in the Whitfield exposures are commonly rooted and at least one of the units is capped locally by a layer rich in large brachiopod shells (Clarke 2008). In contrast to those on Hexhamshire Common, significant incision is apparently associated with the base of the Whitfield Common outcrops, starting from above the Thornbrough Limestone in the north to just below the Corbridge Limestone at the southern extent of the outcrop. As the top of the sandstone on Whitfield Common is not seen, it is unclear whether it is part of the Millstone Grit Group or a channel-fill within the Stainmore Formation. Further west, on the north-western part of the Alston Block, the Millstone Grit Group succession is absent (Trotter & Hollingworth 1932).

# 5. PENNINE COAL MEASURES GROUP

Historically, the top of the Millstone Grit was mapped at the Ganister Clay Coal, above the Third Grit. However, recognition that this part of the succession is Westphalian in age (Mills & Hull 1968) has resulted in it being included within the Pennine Coal Measures Group. The Third Grit occurs above the Listeri (Kays Lea) Marine Band and below the Amaliae (Roddymoor or Gubeon) Marine Band, indicating that the Millstone Grit facies of coarse-grained sandbodies persists later in this area compared with the coalfields of the Central Pennines, where coarse-grained facies, e.g. Crawshaw Sandstone, occur beneath the Listeri Marine Band (Aitkenhead *et al.* 2002).

## 5.1 Solway Basin to north Lake District High

The Petteril Bank Borehole (Fig. 3) includes 90.37m of red-mottled and rooted mudstones, containing non-marine bivalves of the Lower *similis-pulchra* Zone, and subordinate fine-grained sandstone (Arthurton & Wadge 1981). The apparent absence of Coal Measures strata of Langsettian and early Duckmantian age, including the basal Langsettian Subcrenatum Marine Band, might indicate an unconformity at the base of the group. Similarly, in the Canonbie area, the basal Coal Measures include non-marine bivalves of the *Anthraconaia modiolaris* Zone, suggesting that much of the Langsettian succession is absent, probably on the axis of a growth fold, the Carlisle Anticline (Fig. 2). However, Owens (1980) recorded miospores of the RA Biozone (late Langsettian) in the Rowanburnfoot Borehole, 5m beneath the supposed unconformity, suggesting that the base of the Westphalian succession is here conformable within the complementary Solway Syncline and that the Coal Measures onlap and overlap the flanks of the anticline (cf. Chadwick *et al.* 1995).

On the western flank of the Lake District High, the Harrington Four Foot Rock is a 30m-thick, coarse-grained and pebbly sandstone, which passes northwards into a mudstone succession containing, in ascending order the Honley, Listeri, Amaliae and Langley marine bands (Akhurst *et al*. 1997). The relationship is not described, but it is inferred that the Harrington Four Foot Rock post-dates the Langley Marine Band and occupies a palaeovalley cutting through the early Langsettian succession to below the level of the Honley Marine Band.

### 5.2 Cheviot Block to Northern Northumberland Basin

In Stobswood 1 Borehole, much of the Langsettian succession between the proposed Subcrenatum Marine Band and the Victoria Coal is some 72m thick and dominated by sandstone, equated with the Third Grit (Fig. 4). The basal part is some 16m thick, fine- to medium-grained, with mudstone rip-up clasts. The overlying 14 m are dominated by upward-fining beds, ranging from conglomerate to fine-grained sandstone. The coarsest beds, from the possible Ganister Clay to the Langley (Stobswood) Marine Band, comprise some 18m of mainly conglomerate and very coarse-grained sandstone, with pebbles up to 15mm in diameter.

### 5.3 Southern part of Northumberland Basin

Areas of Pennine Coal Measures Group are located to the north of the Stublick Fault in the Midgeholme, Plenmeller and Stublick coalfields, and locally to the south of Hexham from Currick Hill [NY 890 620] to Dukeshouse Wood [NY 953 628]. In the absence of the Subcrenatum Marine Band, the base of the group is nominally taken at the base of a dominantly argillaceous coal-bearing succession. About 90m of Pennine Lower Coal Measures of the Communis and Modiolaris zones are recorded in the Plenmeller Coalfield (Turner 1999), suggesting an absence of lower Langsettian strata. The lowermost coarse-grained sandstone occurs above the Amaliae Marine Band (Turner 1999) and is hence at a higher level than the traditional Third Grit.

In the Throckley Borehole, two *Lingula* Bands at 79.6m and 69.1m are interpreted as possible Subcrenatum and Listeri marine bands, separated by a 4.2m-thick, coarse-grained sandstone (Fig. 5). The Third Grit is dominantly coarse-grained sandstone with small quartz pebbles, 24.5m thick, above the Listeri Marine Band.

### 5.4 Alston Block

In the Woodland Borehole, the Listeri Marine Band is separated from the Subcrenatum Marine Band by a 13.5m-thick, fine- to coarse-grained sandstone. The Listeri Marine Band is in turn overlain by an 11.5m, upward-fining, fine- to coarse-grained sandstone, interpreted as the Third Grit. The Listeri Marine Band in the Rowlands Gill Borehole, seen as a *Lingula* Band, occurs 12.3m above the Subcrenatum Marine Band, with no coarse-grained sandstone either below or above.

In the Acton Fell area, south of Hexham, the biostratigraphical interpretation of boreholes (Brand 1991*a*) and subsequent mapping have determined that a ~22m-thick succession is present between the Listeri and Amaliae marine bands, which at Acton Burn Quarry includes an 8m high face in weakly cemented, pale grey, orange and pink sandstone. The sandstone is medium-grained, well-sorted with trough cross-bedding, and is interpreted as the local representative of the Third Grit. Palaeocurrents determined from foresets within the Third Grit (Fig. 10) indicate a dominant palaeoflow towards the south, with no deflection associated with the fluvial system crossing from the Northumberland Basin to Alston Block.

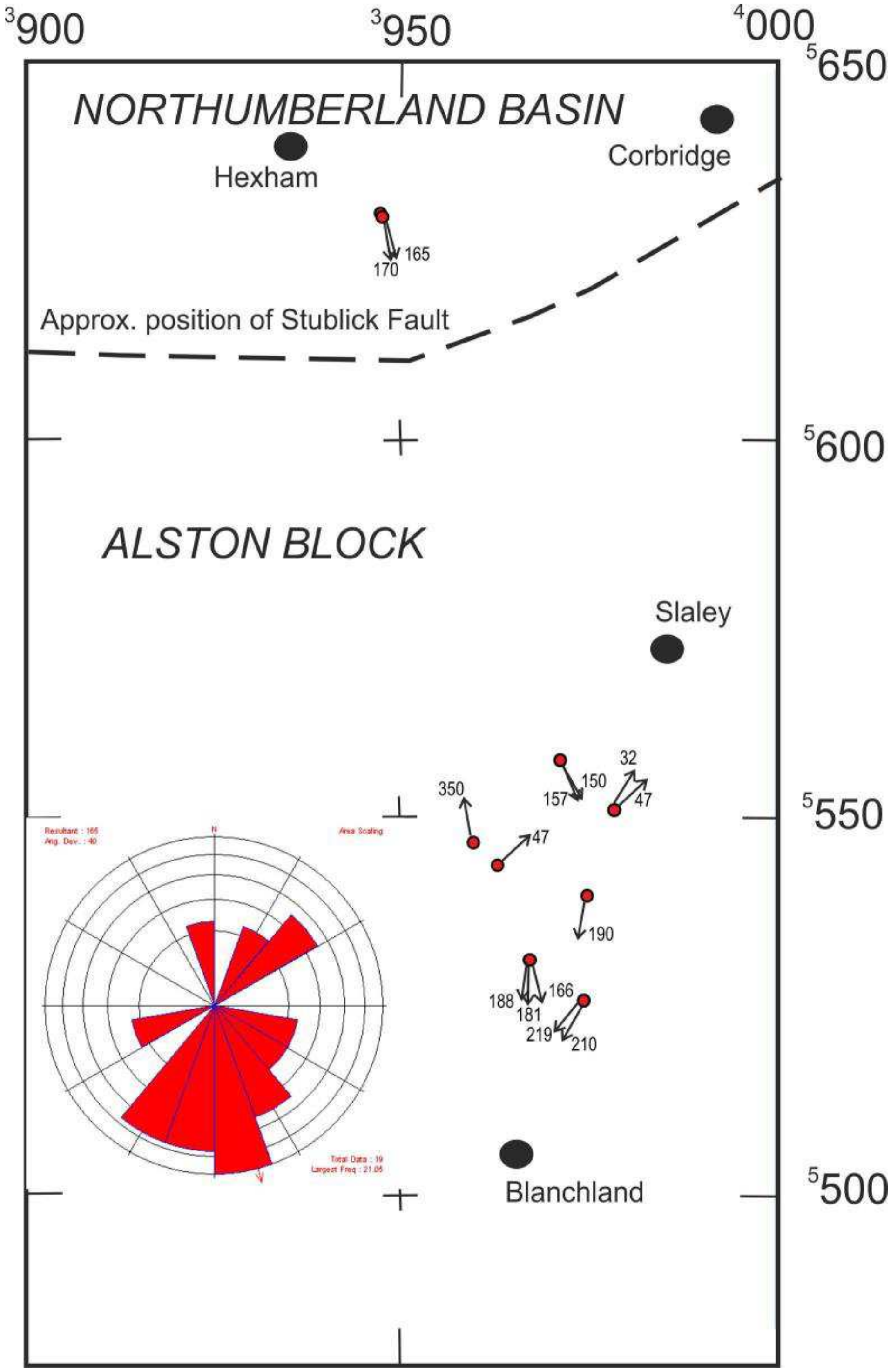
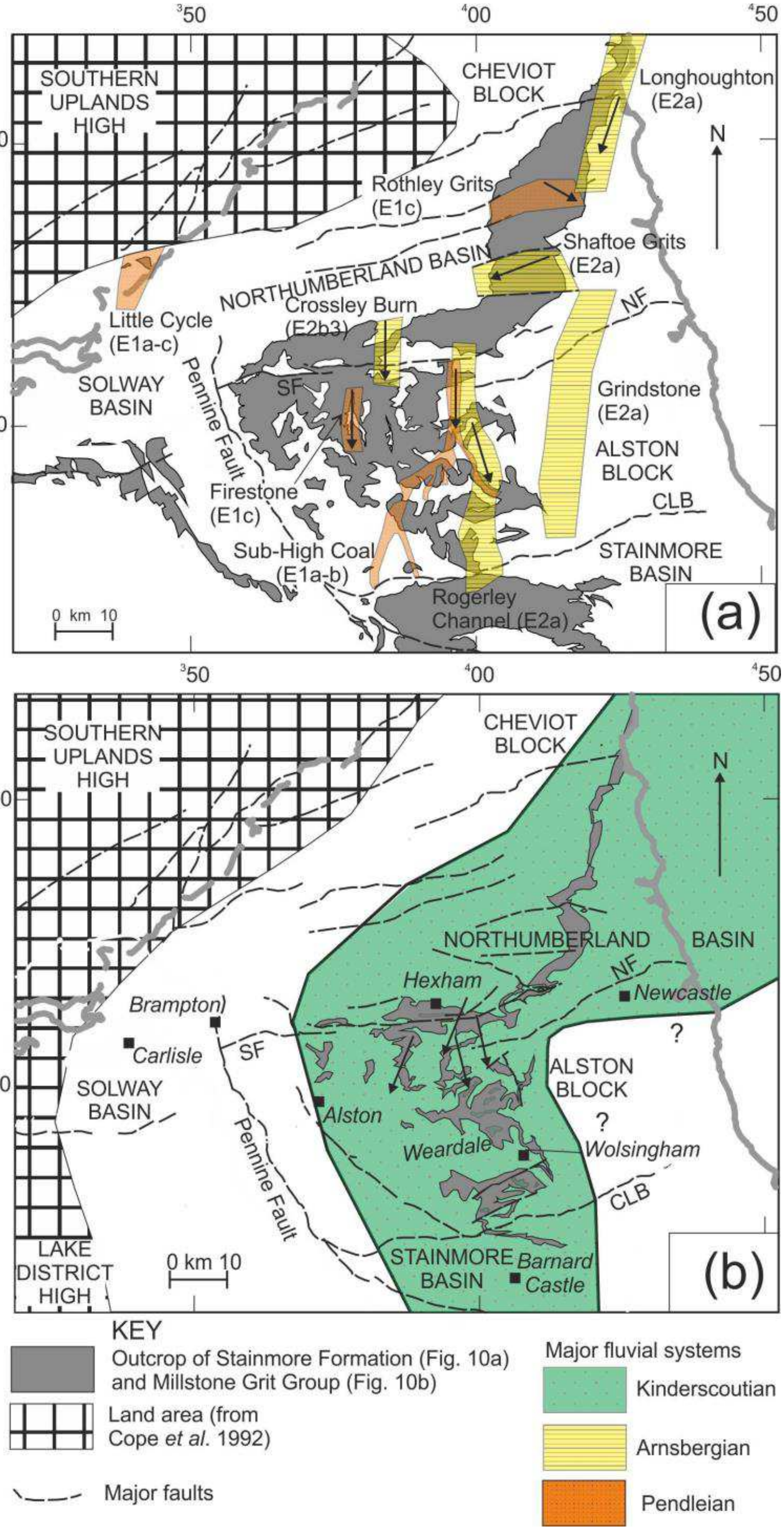



**Fig. 10** Palaeocurrent data for the Third Grit.

## 6. DISCUSSION

Regionally, the lower Pendleian ($E_{1a}$–$E_{1b}$) succession shows a typical Yoredale cyclicity, dominated by thick marine limestone with variable siliciclastic input and with some emergence below the Little Limestone. Within the study area, fluvial channel development in this interval is typically present only on the Alston Block, with development of the Sub-High Coal and White Hazle channels, and in the Canonbie area (Fig. 11a). This conforms with evidence from the Central Pennine Basin, to the south of the study area, in which the $E_{1a}$ and $E_{1b}$ succession is mudstone-dominated with marine flooding events, equating with the marine limestones of the shelf area, but lacking influx of significant fluvio-deltaic deposits (Martinsen 1993; Waters *et al.* 2007).


SOUTHERN UPLANDS HIGH
CHEVIOT BLOCK
Longhoughton (E2a)
Rothley Grits (E1c)
Shaftoe Grits (E2a)
NORTHUMBERLAND BASIN
Little Cycle (E1a-c)
Crossley Burn (E2b3)
NF
SOLWAY BASIN
SF
Pennine Fault
Grindstone (E2a)
ALSTON BLOCK
Firestone (E1c)
CLB
Sub-High Coal (E1a-b)
STAINMORE BASIN
Rogerley Channel (E2a)
0 km 10
(a)
Hexham
Brampton
Newcastle
Carlisle
Alston
Weardale
Wolsingham
Barnard Castle
LAKE DISTRICT HIGH
(b)
KEY
Outcrop of Stainmore Formation (Fig. 10a) and Millstone Grit Group (Fig. 10b)
Land area (from Cope et al. 1992)
Major faults
Major fluvial systems
Kinderscoutian
Arnsbergian
Pendleian

925

**Fig. 11** Palaeogeographical reconstructions of the extent of fluvial systems in the Northumberland-Solway Basin and Alston Block during a) Pendleian–Arnsbergian, and b) Kinderscoutian. Distribution of land areas based upon Cope et al. (1992) for the Arnsbergian and Marsdenian, respectively. The distribution of the Sub-High Coal channel is from Hodge (1965) and for the Rogerley Channel in part from Dunham (1990). CLB- Closehouse-Lunedale-Butterknowle Fault System, NF- Ninety Fathom Fault, SF-Stublick Fault.

The late Pendleian ($E_{1c}$) in the northern part of the Solway Basin is associated with fluvio-deltaic infill of a brackish inter-distributary bay, emergent intervals with peat and palaeosol development and local fluvial distributary development (Fig. 3), though there is no evidence of major incised valley fills. Within the southern part of the Solway Basin, a marine succession dominates, with only limited evidence of emergence and fluvial input. Thick fluvial sandbodies, including the Rothley Grits in the north-eastern part of the Northumberland Basin (Fig. 4) and Firestone Sandstone of the Alston Block (Fig. 11a), are locally present below the Crag Limestone and its equivalents. Similar fluvial sandbodies are developed above the Crag Limestone on the Cheviot Block, including the Shaftoe Grits and in the Acklington Station Borehole and on the Alston Block (the Low Grit and High Grit). These fluvial sandbodies are likely to represent the feeders of the major turbidite system of the Pendle Grit Member and the fluvial system of the Warley Wise Grit of $E_{1c}$ age developed within the Central Pennine Basin (Martinsen 1993; Martinsen *et al*. 1995; Waters *et al*. 2007).

An early component of the Rogerley Channel (Fig. 11a) has been proposed as the feeder of the Lower Howgate Grit-Grassington Grit of the Askrigg Block (Mills & Hull 1976). However, it is clear that the incision of the Corbridge Limestone, interpreted as the equivalent of the *Cravenoceras cowlingense* Marine Band (Dunham 1990; Brand 2011), indicates an $E_{2a}$

age for erosion of a later valley. Fluvial sandstones of this age are also common on the Cheviot Block, including development within strata above the equivalent of the Corbridge Limestone (Figs 4, 11a). Similarly, in the north-east part of the Northumberland Basin, fluvial sandstones are evident as the Shaftoe Grits (Young & Lawrence 2002), and on the Alston Block as a fluvial sandstone equivalent to the Grindstone Sandstone (Fig. 6), below the Newton Limestone (Fig. 11a). One or more of these channels is likely to have fed the Upper Howgate Edge Grit-Tan Hill Grit ($E_{2a}1$) (Martinsen *et al.* 1995) and Marchup (Red Scar) Grit of the Askrigg Block ($E_{2a}2$). The Grindstone Sandstone rests upon a significant intra-Arnsbergian unconformity (Brandon *et al.* 1995), inferred to be a major incised valley (Waters & Condon 2012). The Solway Basin shows the continuation of typical Yoredale cyclicity during the early Arnsbergian, with no significant development of fluvial channels (Fig. 3).

In the southern part of the Northumberland Basin, the fluvial facies commences above the Newton Limestone ($E_{2b}$), e.g. in Crossley Burn (Fig. 5). An important phase of channel sandstone development occurred in the Midland Valley of Scotland above the Castlecary Limestone (equivalent to the *Cravenoceratoides nitidus* ($E_{2b}2$) Marine Band; Read 1981), at or about the late Arnsbergian interval associated with the first input of fluvial sandstones in other sections in Northumberland (Chadwick *et al.* 1995, p.32). However, no significant influx of fluvio-deltaic deposits into the Central Pennine Basin occurred at that time. There, the minor sand influxes are of $E_{2b}3$ and $E_{2c}4$ age in the Bradford area (Waters 2000).

Strata of Chokierian and Alportian age are nowhere proved conclusively. This interval might be represented by a condensed argillaceous succession that lacks marine limestones, e.g. in the Barrock Park Borehole (Fig. 3), the Throckley (as proposed by Hull 1968) and Whitley Bay boreholes (Fig. 5) and the boreholes located on the Alston Block (Fig. 6). Alternatively, the succession might be represented by fluvial sandstones, or might have been removed through erosion in incised valleys, e.g. in the Stobswood 2 Borehole and at Longhoughton Steel (Fig. 4) and Crossley Burn (Fig. 5). The equivalent of this fluvial succession in the Central Pennine Basin, where Chokierian and Alportian strata are proved, is the Brocka Bank Grit (Waters 2000).

A significant change in the style of sedimentation occurs during the Kinderscoutian, above the Whitehouse Limestone/Dipton Foot Shell Beds, from Yoredale-type cyclicity to Millstone Grit Group facies. The typical upwards-coarsening cycles with marine carbonates are absent. Instead, marine flooding events are represented by shelly mudstones rich in benthic fauna, indicating a continuation of relatively shallow marine waters but without the formation of carbonate platforms. These marine bands are likely to be laterally equivalent to the ammonoid-bearing, hemi-pelagic, marine shales typical of the deeper basinal areas of the Central Pennine Basin. The greatest contrast is that the Kinderscoutian to Yeadonian succession is sandstone-dominated, typically upward-fining with basal very coarse-grained sandstones, and that the sandbodies have greater lateral continuity and show less evidence of significant incision than other fluvial sandbodies present lower in the succession. The strata in this interval, interpreted to be the Millstone Grit Group, are widely recognized across the region in the north-east part of the Northumberland Basin, e.g. in the Acklington Station and Stobswood 2 boreholes (Fig. 4), and in the southern part of the Northumberland Basin, e.g. Crossley Burn and the Throckley Borehole (Fig. 5) and the boreholes of the Alston Block (Fig. 6). The Kinderscoutian First Grit forms an extensive braidplain some 40km wide (Fig. 11b). Only the Solway Basin area (Fig. 3) lacks the development of thick, coarse-grained sandstones (Fig. 11b) and it is accepted that there is no evidence for the presence of the Millstone Grit Group across this area. The extent of this group across the eastern part of the Alston Block is unknown.

The transition to sandstone-dominated and typically coarser grained and pebbly successions during the late Kinderscoutian coincides with a significant event within the Central Pennine Basin. At the time, a very large volume of coarse and pebbly fluvial sand built out across most of the basin, prograding much farther than the fluvio-deltaic deposits of Pendleian and Arnsbergian age. Waters & Condon (2012) have proposed that this sudden influx and rapid progradation of fluvial deposits might have been initiated by a late Namurian to earliest Westphalian glaciation in Gondwana. This interval would be associated with more extreme fluctuations in sea-level, with base level falls resulting in incision and rejuvenation of fluvial systems. A global change in climate might also have enhanced development of monsoonal systems, enhancing the discharge and flow velocities of major rivers that could carry greater volumes of bedload with coarser grainsize. This glacially induced climatic perturbation is considered to extend into the early Westphalian, at which time the Third Grit is evident below the Amaliae Marine Band, notably in the Stobswood 1 and Acklington Station boreholes (Fig. 4), the Throckley and Whitley Bay boreholes (Fig. 5) and the Woodland, Roddymoor and Harton boreholes (Fig. 6), in an area similar in extent to that of the First Grit. No equivalent of the Third Grit is evident in the Solway Basin (Fig. 3). The Amaliae Band and overlying cycles coincide with a short interglacial interval, which across the Pennine Basin coincides with a marked diminution of sandbody dimension and grainsize (Waters & Condon 2012), and the deposition of a fluvio-lacustrine facies with the development of thick histosols more typical of the Pennine Coal Measures Group.

## 7. CONCLUSIONS

The Pendleian to early Kinderscoutian cycles of the Stainmore Formation (Yoredale Group) are dominated by relatively thick and laterally continuous marine carbonates and marine, fine- to medium-grained, quartzitic sandstone bodies. Fluvial, quartz-feldspathic sandbodies are locally recognized as incised valley fills within the lower Namurian Stainmore Formation, but are not a diagnostic feature of the formation. There is a clear lithological distinction with the overlying late Kinderscoutian to Yeadonian strata, which are dominated by thick, sheet-like, fluvial, coarse-grained, quartz-feldspathic sandstones, with thin marine mudstone flooding surfaces. The differences warrant definition of a distinct Millstone Grit Group over most of the Northumberland Basin and Alston Block. This strong, late Namurian fluvial signature is, however, absent in the Solway Basin. Both the early Namurian incised valley fills and late Namurian sheet-like sandstones are inferred to feed the sandbodies of the Millstone Grit Group of the Central Pennine Basin, to the south of the study area. The change in depositional style used to distinguish the two groups reflects an increased influx and rapid progradation of fluvial sands in the mid Namurian to early Westphalian, considered to be the far-field expression of glaciations in Gondwana. The glaciations might have resulted in more extreme fluctuations in sea-level and enhancement of monsoonal climatic conditions, both leading to rejuvenation of fluvial systems across northern England.

*Acknowledgements*. Dave Lawrence is acknowledged for his advice concerning the Stobswood boreholes. Mr and Mrs Michael Loyd are thanked for providing permission to access the Crossley Burn section. We thank Neil Jones and John Collinson for their reviews and Jochem Bijkerk and Oliver Wakefield for their helpful comments on an earlier draft of the manuscript. The authors publish with the permission of the Executive Director, British Geological Survey, Natural Environment Research Council.

## Appendix 1 Key boreholes and surface geological sections referred in the text and used to compile figs. 3−6.

| Name | BGS Reg. No. | Grid Ref | Depth range (m) | References |
|---|---|---|---|---|
| **Acklington Station BH** | NU20SW53 | [NU 2210 0153] | 19.8-462.0 | Chadwick *et al*. (1995) |
| **Archerbeck BH** | NY47NW14 | [NY 4157 7815] | 11.5-238.3 | Lumsden & Wilson (1961) |
| **Barrock Park BH** | NY44NE28 | [NY 4613 4660] | 95.1-490.9 | Arthurton & Wadge (1981); Chadwick *et al*. (1995) |
| **Chopwell BH** | NZ15NW46 | [NZ 1438 5743] | 5.0-349.9 | Simpson (1902); Chadwick *et al*. (1995) |
| **Crossley Burn** | | [NY 8530 6433 to 8579 6316] | 280 | |
| **Harton BH** | NZ36NE80 | [NZ 3966 6562] | 261.5-448.4 | Ridd *et al*. (1970); Chadwick *et al*. 1995) |
| **Longhorsely BH** | NZ19SW6 | [NZ 1444 9254] | 0-318.5 | Chadwick *et al*. (1995) |
| **Longhoughton Steel** | | [NU 243 155] | | Farmer & Jones (1968); Turner & Spinner (1992) |
| **Petteril Bank BH** | NY44SE77 | [NY 4665 4271] | 3.2-207.2 | Arthurton & Wadge (1981) |
| **Roddymoor BH** (Crook) | NZ13NE146 | [NZ 1512 3436] | 0-322.5 | Woolacott (1923); Mills & Hull (1968) |
| **Rowanburnfoot BH** | NY47NW27 | [NY 4103 7574] | 4.5-876.9 | Lumsden *et al*. (1967) |
| **Rowanburnhead BH** | NY47NW13 | [NY 4074 7786] | 34.5-410.7 | Peach & Horne (1903); Barrett & Richey (1945) |
| **Rowlands Gill BH** | NZ15NE276 | [NZ 1664 5815] | 26.7-242.9 | Mills & Holliday (1998) |
| **Stobswood 1 BH** | NZ29SW121 | [NZ 2043 9355] | 0-100.3 | Brand (1991b) |
| **Stobswood 2 BH** | NZ29SW122 | [NZ 2084 9303] | 50.0-269.2 | Brand (1991b) |
| **Throckley BH** | NZ16NW45 | [NZ 1456 6762] | 1.5-590.6 | Mills & Holliday (1998) |
| **Whitley Bay BH** | NZ37SW56 | [NZ 3490 7480] | 0-735 | |
| **Woodhouselees BH** | NY37SE1 | [NY 3912 7495] | 907.4-1046.0 | Lumsden *et al*., (1967) |
| **Woodland BH** | NZ02NE4 | [NZ 0910 2770] | 3-402.4 | Mills & Hull (1968) |

## REFERENCES

Aitkenhead, N., Barclay, W.J., Brandon, A., Chadwick, R.A., Chisholm, J.I., Cooper, A. H. & Johnson, E.W.. 2002. *British Regional Geology: The Pennines and adjacent areas.* HMSO (for the British Geological Survey), London.

Akhurst, M.C., Chadwick, R.A., Holliday, D.W., McCormac, M., McMillan, A.A., Millward, D. & Young, B. 1997. *Geology of the west Cumbria district*. Memoir of the British Geological Survey, Sheets 28, 37 and 47 (England & Wales).

Arthurton, R.S. & Wadge, A.J. 1981. Geology of the country around Penrith. *Memoir of the British Geological Survey*, Sheet 24 (England and Wales).

Arthurton, R.S., Johnson, E.W. & Mundy, D.J.C. 1988. *Geology of the country around Settle*. Memoir of the British Geological Survey, Sheet 60 (England and Wales).

Barrett, B.H. & Richey, J.E. 1945. Economic geology of the Canonbie Coalfield. *Wartime Pamphlet of the Geological Survey of Great Britain*, **42**.

Brand, P.J. 1991*a*. Report on faunas from various localities contained in the collection of BGS Keyworth from the area of Sheet 19, England. *BGS Technical Report, Stratigraphy Series*, WH/91/75R.

Brand, P.J. 1991*b*. Report on faunas collected from Stobswood Nos. 1 & 2 Boreholes. *BGS Technical Report, Stratigraphy Series*, WH/91/324R.

Brand, P.J. 2011. The Serpukhovian and Bashkirian (Carboniferous, Namurian and basal Westphalian) faunas of northern England. *Proceedings of the Yorkshire Geological Society*, **58,** 143-165.

Brandon, A., Riley, N.J., Wilson, A.A., & Ellison, R.A. 1995. Three new early Namurian (E1c-E2a) marine bands in central and northern England, UK, and their bearing on correlations with the Askrigg Block. *Proceedings of the Yorkshire Geological Society*, **50**, 333-355.

BRITISH GEOLOGICAL SURVEY 2007. Bedrock Geology UK North, 1:625 000 Scale. (5th Edition).

BURGESS, I.C. & HOLLIDAY, D.W. 1979. *Geology of the country around Brough-under-Stainmore.* Memoir of the Geological Survey of Great Britain, Sheet 31 and parts of 25 and 30 (England and Wales).

CARRUTHERS, R.G. 1938. Alston Moor to Botany and Tan Hill: an adventure in stratigraphy. *Proceedings of the Yorkshire Geological Society*, **23**, 236-253.

CHADWICK, R.A., HOLLIDAY, D.W., HOLLOWAY, S., & HULBERT, A.G. 1995. *The structure and evolution of the Northumberland-Solway Basin and adjacent areas*. British Geological Survey Subsurface Memoir. HMSO, London.

CLARKE, S.M. 2007. The geology of NY76NW (S) Cawfields, Northumberland. *British Geological Survey Open Report* OR/07/034.

CLARKE, S.M. 2008. Geology of 1:10 000 sheets NY74NE, NW and NY75NE, SW, SE, Alston, Cumbria. *British Geological Survey Open Report* OR/07/032.

COLLINSON, J.D. 1988. Controls on Namurian sedimentation in the Central Province basins of northern England. *In:* BESLY, B.M, & KELLING, G (eds), *Sedimentation in a synorogenic basin complex: the Upper Carboniferous of Northwest Europe*, 85-101. Blackie, Glasgow and London.

COPE, J.C.W., INGHAM, J.K. & RAWSON, P.F. (eds) 1992. *Atlas of palaeogeography and lithofacies*. Geological Society, London, Memoir **13**.

CÓZAR, P. & SOMERVILLE, I.D. 2012. The Carboniferous Archerbeck Borehole, near Canonbie (Dumfriesshire, southern Scotland): biostratigraphic revision of the late Asbian to early Pendleian succession using foraminiferans and regional correlations. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **103**, 1-18.

DAKYNS, J.R., TIDDEMAN, R.H., RUSSELL, R., CLOUGH, C.T. & STRACHAN, A. 1891. *The geology of the country around Mallerstang, with parts of the Wensleydale, Swaledale and Arkendale*. Memoir of the Geological Survey (Explanation of Quarter-Sheet 97NW, New Series, Sheet 40, England and Wales). HMSO, London.

DEAN, M.T., BROWNE, M.A.E., WATERS, C.N. & POWELL, J.H. 2011. *A lithostratigraphical framework for the Carboniferous successions of Northern Great Britain (onshore)*. British Geological Survey Research Report, RR/10/07.

DUNHAM, K C. 1948 *Geology of the Northern Pennine Orefield , Volume 1: Tyne to Stainmore*. Memoir of the Geological Survey of Great Britain. (First Edition). HMSO, London

DUNHAM, K.C. 1990. *Geology of the Northern Pennine Orefield, Volume 1: Tyne to Stainmore (2nd Edition)*. Economic Memoir of the British Geological Survey, England and Wales, Sheets 40, 41 and 50. HMSO, London.

DUNHAM, K.C. & JOHNSON, G.A.L. 1962. Sub-surface data on the Namurian strata of Allenheads, south Northumberland. *Proceedings of the Yorkshire Geological Society*, **33**, 235-254.

EASTWOOD, T., DIXON, E.E.L., HOLLINGWORTH, S. & SMITH, B. 1931. *The geology of the Whitehaven and Workington District*. Memoir of the Geological Survey, England and Wales, Sheet 28. HMSO, London.

EASTWOOD, T., HOLLINGWORTH, S.E., ROSE, W.C.C. & TROTTER, F.M. 1968. *Geology of the country around Cockermouth and Caldbeck*. Memoir of the Geological Survey, England and Wales, Sheet 23. HMSO, London.

ELLIOTT, T. 1975. The sedimentary history of a delta lobe from a Yoredale (Carboniferous) cyclothem. *Proceedings of the Yorkshire Geological Society*, **40**, 505-536.

ELLIOTT, T. 1976. Sedimentary sequences from the Upper Limestone Group of Northumberland. *Scottish Journal of Geology*, **12**, 115-124.

FARMER, N. & JONES, J.M. 1968. The Carboniferous Namurian rocks of the coast section from Howick Bay to Foxton Hall, Northumberland. *Transactions of the Natural History Society of Northumberland*, **17**, 1-27.

FOWLER, A. 1926. *The geology of Berwick on Tweed, Norham and Scremerston*. Memoir of the Geological Survey of Great Britain, England and Wales, Sheets 1 and 2 . HMSO, London.

HODGE, B.L. 1965. The Great Cyclothem of northern England. *Unpublished PhD thesis, University of Durham*.

HULL, J.H. 1968. The Namurian Stages of North-Eastern England. *Proceedings of the Yorkshire Geological Society*, **36**, 297-308.

JOHNSON, G.A.L., HODGE, B.L. & FAIRBAIRN, R.A. 1962. The base of the Namurian and the Millstone Grit in north-east England. *Proceedings of the Yorkshire Geological Society*, **33**, 341-362.

JONES, N.S. 1996. Report on the sedimentology of Namurian strata examined at selected localities on the Morpeth and Rothbury sheets. *British Geological Survey Technical Report*, WH/96/87R.

LEEDER, M.R. 1971. Initiation of the Northumberland basin. *Geological Magazine*, **108**, 511-516.

LEEDER, M.R. 1982. Upper Palaeozoic basins of the British Isles: Caledonide inheritance versus Hercynian plate margin processes. *Journal of the Geological Society, London*, **139**, 481-494.

LEEDER, M.R. 1988. Recent developments in Carboniferous geology: a critical review with implications for the British Isles and N.W. Europe. *Proceedings of the Geologists Association*, **99**, 73-100.

LEEDER, M.R., FAIRHEAD, D., LEE, A., STUART, G., CLEMMEY, H., EL-HADDAKEH, B. & GREEN, C. 1989. Sedimentary and tectonic evolution of the Northumberland Basin. In: ARTHURTON, R.J., GUTTERIDGE, P. & NOLAN, S.C. (eds), *The role of tectonics in Devonian and Carboniferous sedimentation in the British Isles*.. Yorkshire Geological Society Occasional Publication **6**, 207-223.

LUMSDEN, G.I. & WILSON, R.B. 1961. The stratigraphy of the Archerbeck Borehole, Canonbie, Dumfriesshire. *Bulletin of the Geological Survey of Great Britain*, **18**, 1-89.

LUMSDEN, G.I., TULLOCH, W., HOWELLS, M.F. & DAVIES, A. 1967. *The geology of the neighbourhood of Langholm*. Memoir of the Geological Survey of Great Britain, Scotland, Sheet 11. HMSO, Edinburgh.

MARTINSEN, O.J. 1993. Namurian (late Carboniferous) depositional systems of the Craven-Askrigg area, northern England: implications for sequence stratigraphic models. *In:* POSAMENTIER, H.W., SUMMERHAYES, C.P., HAQ, B.U. & ALLEN, G.P. (eds), *Sequence stratigraphy and facies associations*. International Association of Sedimentologists, Special Publication **18**, 247-281.

MARTINSEN, O.J., COLLINSON, J.D. & HOLDSWORTH, B.K. 1995. Millstone Grit cyclicity revisited, II: sequence stratigraphy and sedimentary responses to changes of relative sea-level. *In:* PLINT, A.G. (ed.) *Sedimentary facies analysis*. International Association of Sedimentologists, Special Publication **22**, 305-327.

MCKERVEY, J.A., CLARKE, S.M. & VYE, C. 2010. Heavy mineral analysis of Carboniferous sandstones from the north Pennines. *British Geological Survey Internal Report,* IR/08/023. 41pp.

MILLS, D.A.C. & HOLLIDAY, D.W. 1998. *Geology of the district around Newcastle upon Tyne, Gateshead and Consett*. Memoir of the British Geological Survey, England and Wales, Sheet 20. The Stationery Office, London.

MILLS, D.A.C. & HULL, J.H. 1968. The Geological Survey Borehole at Woodland, Co. Durham (1962). *Bulletin of the Geological Survey of Great Britain*, **28**, 1-34.

MILLS, D.A.C. & HULL, J.H. 1976. *Geology of the Country around Barnard Castle*. Memoirs of the Geological Survey, England and Wales, Sheet 32. HMSO, London.

MOORE, D.G. 1959. Role of deltas in the formation of some British Lower Carboniferous cyclothems. *Journal of Geology*, **67**, 522-539.

MORTON, A.C. & WHITTAM, A.G. 2002. The Millstone Grit of northern England: a response to tectonic evolution of a northern sourceland. *Proceedings of the Yorkshire Geological Society*, **54**, 47-56.

NEVES, R. 1968. The palynology of the Woodland Borehole, Co. Durham. *Bulletin of the Geological Survey of Great Britain*, **28**, 55-60.

OWENS, B. 1980. Palynological report on basal Westphalian samples from Rowanburn Foot Borehole. *Report of the Palaeontological Department, Institute of Geological Sciences*. No. PDL/80/224 (unpublished).

PEACH, B.N. & HORNE, J. 1903. The Canonbie Coalfield: its geological structure and relations to the Carboniferous rocks of the North of England and Central Scotland. *Transactions of the Royal Society of Edinburgh*, **40**, 835-877.

PERCIVAL, C. 1986. Paleosols containing an albic horizon: examples from the Upper Carboniferous of Northern England. *In:* WRIGHT, V.P. (ed.), *Palaeosols - their recognition and interpretation*, 87-111. Blackwell Scientific Publications, Oxford.

PICKEN, G.S. 1988. The concealed coalfield at Canonbie: an interpretation based on boreholes and seismic surveys. *Scottish Journal of Geology*, **24**, 61-71.

Phillips, J. 1836. *Illustrations of the geology of Yorkshire. Part 2, The Mountain Limestone District*. John Murray, London.

Posamentier, H.W. & Vail, P.R. 1988. Eustatic controls on clastic deposition II-sequence and tract models. *In:* Wilgnus, C.K., Hastings, C.G.S.C, Kendall, H.W., Posamentier, H.W., Ross, C.A. & Van Wagoner, J.C. (eds), *Sea-level changes: an integrated approach.*. Society for Economic Palaeontologists and Mineralogists, Special Publication **42,** 124-154.

Ramsbottom, W.H.C, Calver, M.A., Eagar, R.M.C, Hodson, F., Holliday, D.W., Stubblefield, C.J. & Wilson, R.B. 1978. A correlation of Silesian rocks in the British Isles. Geological Society, London, Special Report **10**.

Read, W.A. 1981. Facies breaks in the Scottish Passage Group and their possible correlation with the Mississippian-Pennsylvanian hiatus. *Scottish Journal of Geology*, **17**, 295-300.

Richardson, G. 1966. *Geological Survey Borehole*. Summary of Progress of the Geological Survey of Great Britain for 1965, 56.

Ridd, M.F., Walker, D.B. & Jones, J.M. 1970. A deep borehole at Harton on the margin of the Northumbrian Trough. *Proceedings of the Yorkshire Geological Society*, **38**, 75-103.

Riley, N.J. 1992. Foraminiferal and algal biostratigraphy of the Rowlands Gill Borehole (BGS BH reference NZ15NE/276). *Palaeontological Department, British Geological Survey Report PDL 92/132R*.

Rowell, A.J. & Scanlon, J.E. 1957. The relation between the Yoredale Series and the Millstone Grit on the Askrigg Block. *Proceedings of the Yorkshire Geological Society*, **31**, 79-90.

Simpson, J.B. 1902. The probability of finding working seams of coal in the Carboniferous Limestone or Bernician Formation, beneath the regular Coal-Measures of Northumberland and Durham, with an account of a recent deep boring, in Chopwell Woods, below the Brockwell seam. *Transactions of the Institution of Mining Engineers*, **25**, 549-571.

Stephenson, M.H., Millward, D., Leng, M.J. & Vane, C.H. 2008. Palaeoecological and possible evolutionary effects of early Namurian (Serpukhovian, Carboniferous) glacioeustatic cyclicity. *Journal of the Geological Society, London*, **165**, 993-1005.

Stephenson, M.H., Angiolini, L., Cózar, P., Jadoul, F., Leng, M.J., Millward, D. & Chenery, S. 2010. Northern England Serpukhovian (early Namurian) farfield responses to southern hemisphere glaciation. *Journal of the Geological Society, London*, **167**, 1171-1184.

Stone, P., Millward, D., Young, B., Merritt, J.W., Clarke, S.M., McCormac, M. & Lawrence, D.J.D. 2010. *British Regional Geology: Northern England* (Fifth edition). British Geological Survey, Keyworth, Nottingham.

Trotter, F.M. & Hollingworth, S.E. 1932. *The geology of the Brampton district.* Memoir of the Geological Survey of Great Britain, England and Wales, Sheet 18. HMSO, London.

Turner, N. & Spinner, E. 1992. Palynological evidence for the early Namurian age of the "Millstone Grit" and Upper Limestone Group around Longhoughton Steel, Northumberland. *Proceedings of the Yorkshire Geological Society*, **49**, 11-22.

Turner, B.R. 1999. Geology of the Plenmeller opencast coal site, southwest Northumberland. *British Geological Survey, Onshore Geology Series, Technical Report WA/99/42*.

WATERS, C.N. 2000. Geology of the Bradford district - a brief explanation of the geological map. *Sheet Explanation of the British Geological Survey*, 1:50 000 Sheet 69 Bradford (England and Wales).

WATERS, C.N. & CONDON, D.J. 2012. Nature and timing of Late Mississippian to Mid-Pennsylvanian glacio-eustatic sea-level changes of the Pennine Basin, UK. *Journal of the Geological Society, London*, **169**, 37-51.

WATERS, C.N., BROWNE, M.A.E, DEAN, M.T. & POWELL, J.H. 2007. Lithostratigraphical framework for Carboniferous successions of Great Britain (Onshore). *British Geological Survey Research Report, RR/07/01*, 60.

WATERS, C.N., DEAN, M.T., JONES, N.S. & SOMERVILLE, I.D. 2011*a*. Chapter 12: Cumbria and the northern Pennines. *In:* WATERS, C.N., SOMERVILLE, I.D., JONES, N.S., CLEAL, C.J., COLLINSON, J.D., WATERS, R.A., BESLY, B.M., DEAN, M.T., STEPHENSON, M.H., DAVIES, J.R., FRESHNEY, E.C., JACKSON, D.I., MITCHELL, W.I., POWELL, J.H., BARCLAY, W.J., BROWNE, M.A.E, LEVERIDGE, B.E., LONG, S.L. & MCLEAN, D. *A Revised Correlation of Carboniferous Rocks in the British Isles.* Geological Society, London, Special Report **26**, 82-88.

WATERS, C.N., DEAN, M.T., JONES, N.S., & SOMERVILLE, I.D. 2011*b*. Chapter 13: Northumberland Trough and Solway Basin. *In:* WATERS, C.N., SOMERVILLE, I.D., JONES, N.S., CLEAL, C.J., COLLINSON, J.D., WATERS, R.A., BESLY, B.M., DEAN, M.T., STEPHENSON, M.H., DAVIES, J.R., FRESHNEY, E.C., JACKSON, D.I., MITCHELL, W.I., POWELL, J.H., BARCLAY, W.J., BROWNE, M.A.E, LEVERIDGE, B.E., LONG, S.L. & MCLEAN, D. *A Revised Correlation of Carboniferous Rocks in the British Isles.* Geological Society, London, Special Report **26**, 89-95.

WESTOLL, T.S., ROBSON, D.A. & GREEN, R. 1955. A guide to the geology of the district around Alnwick, Northumberland. *Proceedings of the Yorkshire Geological Society*, **30**, 61-100.

WHITEHURST, J. 1778. *An inquiry into the original state and formation of the Earth*. London.

WOOLACOTT, D. 1923. A boring at Roddymoor Colliery, near Crook, Co. Durham. *Geological Magazine*, **60**, 50-62.

YOUNG, B. & LAWRENCE, D.J.D. 1998. The Morpeth Group of 1:50 000 scale sheet 14 (Morpeth): lithostratigraphy and local details. *British Geological Survey Technical Report,* WA/98/10.

YOUNG, B. & LAWRENCE, D.J.D. 2002. *Geology of the Morpeth district*. Sheet description of the British Geological Survey 1:50 000 Series Sheet 14 Morpeth (England & Wales). British Geological Survey, Keyworth, Nottingham.

## Figures

Fig. 1 Historical stratigraphical nomenclature for the Namurian and lower Westphalian succession in Northern England, with modified current interpretations shown in key (modified from Stone *et al*. 2010).

Fig. 2 Location map showing the extent of Namurian strata, main structures in Northern England and key boreholes and locations: letters refer to logs shown in Figures 3 to 6. Map derived from British Geological Survey (2007). CLB- Closehouse-Lunedale-Butterknowle Fault System; b) distribution of main structural highs and basins in northern England, derived from Waters *et al*. (2007); CFS- Craven Fault System, LDH- Lake District High, V of E-Vale of Eden. Geological data, BGS © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2013.

Fig. 3 Correlation of key boreholes in the Solway Basin-Vale of Eden Basin: Archerbeck, Rowanburnhead, Woodhouselees, Barrock Park, Petteril Bank. * Gamma Ray Log units are API unless stated otherwise. For Barrock Park Borehole it is assumed to be an older scale of micrograms of radium-equivalent per ton, convertable at 11.7 or 16.5 API units per old unit. C-E- Chokierian to early Kinderscoutian.

Fig. 4 Correlation of key boreholes and sections in the NE Northumberland Basin to Cheviot Block: Acklington Station, Stobswood 1 & 2, Longhorsely and Longhoughton Steel.

Fig. 5 Correlation of key boreholes and sections in the SE Northumberland Basin: Crossley Burn, Throckley, Whitley Bay. * Gamma Ray Log unit for the Throckley Borehole, see fig. 3. C-E- Chokierian to early Kinderscoutian.

Fig. 6 Correlation of key boreholes in the Alston Block: Woodland, Roddymoor, Chopwell, Rowlands Gill, Harton. * Gamma Ray Log unit for the Woodland Borehole, see fig. 3. C-E- Chokierian to early Kinderscoutian.

Fig. 7a) Thin, coarsening upward cycle from the Stainmore Formation, above the Thornbrough Limestone; Heathery Burn [NY 9069 4979], section c. 4 m high; 7b) Fluvial channel facies of laterally accreting sandbodies exposed in a c. 6 – 7 m high section at Castleberry Cleugh, south bank, Beldon Burn [NY9293 4947]. Thick to very thick bedded, lenticular sand bodies wedge out laterally. Beds are commonly conspicuously cross-bedded internally, though some are massive or faintly parallel-laminated. The sandstone is poorly–sorted, feldspathic, coarse to very coarse, with granules and pebbles, the latter chiefly of vein quartz; 7c) The basal sandstone of the Millstone Grit Group at the Devil's Water [NY 9584 6232], in a cross-bedded, pebbly very coarse-grained sandstone facies c. 12 m high.

Fig. 8 Palaeocurrent data for the Rogerley Channel a) in the area between Hexham and Blanchland for the upper fluvial channel, and b) from Beldon and Nookton burns for the lower fluvial channel .

Fig. 9 Palaeocurrent data for the basal unit of the Millstone Grit Group (First Grit): a) basal sandstone in the Hexham to Blanchland area; b) Cocklake [NY 941 475] locality.

Fig. 10 Palaeocurrent data for the Third Grit.

Fig. 11 Palaeogeographical reconstructions of the extent of fluvial systems in the Northumberland-Solway Basin and Alston Block during a) Pendleian–Arnsbergian, and b) Kinderscoutian. Distribution of land areas based upon Cope et al. (1992) for the Arnsbergian and Marsdenian, respectively. The distribution of the Sub-High Coal channel is from Hodge

(1965) and for the Rogerley Channel in part from Dunham (1990). CLB- Closehouse-Lunedale-Butterknowle Fault System, NF- Ninety Fathom Fault, SF-Stublick Fault.

Table 1 Correlation of marine limestones (in blue) and marine bands (symbolized with "M" where present as marine shales) in northern England. Adapted from Brand (2011) and Waters *et al*. (2011*a*, *b*). Lst- Limestone; MB- Marine Band; SB- Shell Bed. *B*- *Bilinguites*; *C*- *Cravenoceras*; *Ct.*- *Cravenoceratoides*.

| Preferred name | Solway Basin | Eden Valley | Cheviot Block | Northumberland Trough | Alston Block | Stainmore Trough | Central Pennine Basin MBs | Goniatite Biozone | Miospore Biozone | N W European Substage | Stage | Sub-system |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Langley MB | Templeman's MB | | Stobswood MB | | | | | G2 (part) | SS (part) | **Langsettian (part)** | **BASHKIRIAN (PART)** | **PENNSYLVANIAN (PART)** |
| Amaliae MB | | | | Gubeon MB | | Roddymoor MB | Amaliae MB | | | | | |
| Listeri MB | | | | | | Kays Lea MB | Listeri MB | | | | | |
| Subcrenatum MB | ? | Quarterburn MB | Saltwick E MB | Quarterburn MB | Quarterburn MB | Swinstone Top MB | Subcrenatum MB | | | | | |
| | | ? | M | M | Spurlswood SB | Swinstone Middle MB | *Cancelloceras cumbriense* MB | G1b1 | FR | **Yeadonian** | | |
| | | | M | | | Swinstone Bottom MB | *Cancelloceras cancellatum* MB | G1a1 | | | | |
| | | | M<br>M | M<br>M | Woodland SB | | ?*B.superbilinguis* MB | R2c | | **Marsdenian** | | |
| | | | | | Sharnberry SB | | | | KV | **Kinder-scoutian** | | |
| Dipton Foot SB | M | | Pisgah Hill Lst | Dipton Foot SB | Whitehouse Lst Beds | Mousegill MB | | R1c – R1a | | | | |
| ?Absent | | | | | | | | H2<br>H1<br>E2c | | **Alportian – Late Arnsbergian** | | |
| | | | M | M | M | Peasah Wood Lst | | | SO | **Arnsbergian** | **SERPUKHOVIAN (PART)** | **MISSISSIPPIAN (PART)** |
| Styford Lst | | | M | Dalton; Styford Lsts | | | ?*Ct. nititoides* MB | E2b3 | | | | |
| | | M | M<br>M | M<br>M | | | | | | | | |
| Newton Lst | M | Barrock Top Lst | Upper Foxton Lst | Newton Lst | Grindstone Lst (Botany Lst) | High Wood MB | | E2b | | | | |
| | | M | | M | | M | | | | | | |
| Thornbrough Lst | M | Raughtongill Lst | Lower Foxton Lst | Thornbrough Lst | Upper Felltop Lst | Upper Felltop Lst | | E2a | TK | | | |
| | M | M | M | Pike Hill Lst | Coalcleugh SB | Holme Wood MB | | | | | | |
| Corbridge Lst | Archerbeck Ochre Bed | M | Sugar Sands Lst | Corbridge Lst | Lower Felltop Lst | Mirk Fell Ironstone | *C. cowlingense* MB | E2a1 | CN-TK | | | |
| Belsay Dene Lst | M | M | Iron Scars Lst | Belsay Dene Lst | Rookhope SB | Upper Stonesdale Lst | | | | **Pendleian (part)** | | |
| | M | M | ? | Aydon Shell Bed | M | Hunder Beck Lst | | | CN (part) | | | |
| | | | | Plankey Lst | Knucton SB | Lower Stonesdale Lst | | | | | | |
| Crag/Crow Lst | Lower Oakwood Lst | Skelton Lst | Hazon Lea Lst | Oakwood Lst | Crag Lst | Crow Lst | | | | | | |
| | ? | M<br>M | ? | M<br>M | Faraday House SB | Faraday House SB | | | | | | |
| Little Lst | Blae Pot Lst | Little Lst | Cushat Lst | Little Lst | Little Lst | Little Lst | *C. malhamense MB* | E1c | | | | |
| | ?<br>? | ?<br>M | ?<br>? | M<br>M | ?<br>? | M<br>M | | ?E1b | | | | |
| Great Lst | Catsbit Lst | Great Lst | Great Lst | Great Lst | Great Lst | Great Lst (Main Lst) | *C. leion* MB | E1a1 | | | | |