The stratigraphy and sedimentology of Upper Carboniferous Warwickshire Group red-bed facies in the Canonbie area of S.W. Scotland

Geology and Landscape Northern Britain Programme

Internal Report IR/06/043

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Keywords

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Summary

This work was carried out initially as part of the Southern Scotland and N England Integrated Surveys project (Integrated Geoscience Surveys (Northern Britain) Programme), under the leadership of D Millward and more recently falls within the South of Scotland – Tweed basin project (Geology and Landscape Northern Britain Programme), managed by Andrew McMillan.

The Canonbie Coalfield is one of the few areas in the UK outside of the English Midlands where late Carboniferous red-beds can be directly examined at outcrop. The authors carried out fieldwork in the Canonbie area during March 2004 and July 2005, the main aim being to examine this late Carboniferous red-bed succession which was exposed in part along the River Esk at Canonbie. These occur stratigraphically above the Cambriense Marine Band and have previously been referred to the Upper Coal Measures or Barren Red Coal Measures. Fieldwork has been able to establish that much of the succession actually comprises red-bed strata that show evidence for primary oxidation, i.e. the reddening formed at or soon after deposition. Thus these strata are better referred to the Warwickshire Group.

Around 700 m of strata are present of which the lower 290 m are exposed in the River Esk. Boreholes and seismic reflection data supplement information on the remainder. The strata are preserved in the Solway Syncline a long-lived structural feature in the area, probably linked to dextral displacement on basin-bounding faults with associated syndepositional thickening of strata from Late Visean (Asbian) until end-Carboniferous times. Detailed analyses of the River Esk sections, combined with data from British Coal exploration borehole has allowed three new formations to be defined from the Warwickshire Group in this area, namely the Eskbank Wood Formation, the Canonbie Bridge Sandstone Formation and the Becklees Sandstone Formation. These three formations have distinctive geophysical log signatures and hence are readily correlatable in the subsurface around Canonbie. These are defined and described in detail for the first time here and comparisons made with other areas of the Great Britain and offshore East Irish Sea and Southern North Sea, where equivalent Upper Carboniferous strata are also known.

Warwickshire Group sedimentation largely took place on a well-drained alluvial plain, characterised by an early, primary oxidation of the strata. Large braided river systems were common features on this alluvial plain, with palaeocurrent data from the Canonbie Bridge Sandstone showing channels flowed towards the north. Overbank and floodplain fines were commonly deposited laterally to channels and soils were able to form during intervals of low sediment aggradation.

Comparisons with other areas, where Upper Carboniferous red-beds are present, suggest that the Canonbie succession includes some of the youngest Carboniferous preserved in UK. Strata similar to the Eskbank Wood Formation occur in Ayrshire and it is of similar Bolsovian age to the Etruria Formation of the English Midlands and Ketch Formation of the southern North Sea, although there appears to be some significant lithological differences. Metasediment-dominated litharenites from the Halesowen Formation, the Pennant Sandstone Formation of South Wales and the offshore Boulton Formation appear to be similar to those of the Canonbie Bridge Sandstone Formation. This suggests that southerly-derived detritus was able to travel

considerable distances from the Variscan highlands across the southern North Sea and UK areas, to a position some hundreds of kilometres north of what has previously been recognised. The Becklees Sandstone Formation has much in common with the Salop Formation of the English Midlands and would appear to have no equivalent in the southern North Sea.

1. Introduction

The sub-Permian unconformity is one of the more pronounced large-scale features of the geological map of northern England and southern Scotland. The unconformity formed during a long period (several tens of millions of years) of regional uplift and transpression, basin inversion and erosion during and following the Variscan Orogeny (Taylor et al., 1971; Chadwick et al., 1995), and resulted in strata ranging from probable Mid Permian to Early Triassic in age resting discordantly on rocks of Early Ordovician to Westphalian D age. As a consequence of this long period of erosion, the youngest, largely red-bed Carboniferous succession (Bolsovian-Westphalian D) are only locally preserved in the region. Thus, little is known of the sediments laid down during the latest part of the Carboniferous in northernmost England and southernmost Scotland, particularly in comparison with the more extensively preserved Dinantian and earlier Silesian strata.

The largest area in the northernmost counties of England and environs where Upper Carboniferous (Bolsovian-Westphalian D) strata have been preserved is in a NNE-trending synclinal tract (Solway Syncline) that is mainly concealed by the younger Permo-Triassic rocks of the Carlisle Basin (Chadwick et al., 1995) (Figure 1). For much of this area, seismic reflection data are the main source of information on the Carboniferous rocks. However, in a relatively small area straddling the England-Scotland border near Canonbie, they come to the present-day surface and are exposed in several river and stream sections, notably that in the River Esk (Figure 1), which provide a rare opportunity in this region to examine Bolsovian and Westphalian D rocks in the field. These sections are supplemented by information from a number of boreholes, drilled into the coal-bearing Langsettian-Duckmantian strata (Table 1), and by seismic reflection surveys. Previous research in the area has concentrated on these coal-bearing rocks because of their potential economic importance (Peach and Horne, 1903; Barrett and Richey, 1945; Lumsden et al., 1967; Picken, 1988). Apart from the establishment of a broad, generalised lithological sequence, and the presentation of some fauna and flora data, little has been published on the largely red-bed strata above the Cambriense Marine Band. Many of the boreholes were open-holed through these mainly red rocks as they were regarded as being of little economic interest. Where cores were taken, most have since been discarded, and core descriptions are of variable quality. Fortunately, some of the more recent boreholes, mainly drilled in the 1980s (Picken, 1988), have geophysical log suites through this part of the succession.

Stratigraphic subdivision of the younger parts of the Carboniferous is often hampered by the common occurrence of reddening of the strata. Coal seams, which are commonly used to assist stratigraphic subdivision, are often oxidised by this process. Where the reddening occurs soon after deposition it is termed primary. This contrasts with later, diagenetic reddening events, which are termed secondary. Both processes have been recorded from the Carboniferous of the UK. The main features of primary red-beds have been described in detail by Besly (1988), Besly and Turner (1983) and Besly et al. (1993). It is also well known that, during the Permian, there occurred widespread secondary reddening of Carboniferous rocks below the sub-Permian unconformity, linked to the ingress of oxidizing groundwaters as a result of periods of subaerial exposure (Bailey, 1926; Besly, 1990). This penetrative oxidation has been described in detail by Trotter (1953, 1954), Turner (1980) and Mykura (1960). It typically affects the uppermost 50 m or so of the Carboniferous succession below the Permian unconformity but, depending on the elevation of the land surface above the Permian groundwater table, may occur down to depths of

500 m or more (Mykura, 1960; Besly, 1998). Such deep penetrative oxidation is also favoured along fault planes and along permeable sandstone horizons (Mykura, 1960; Besly, 1990). This late diagenetic process occurs by the conversion of original diagenetic siderite and/or pyrite to hematite (Mücke, 1994).

Coals can also be affected by secondary reddening; the most comprehensive description of this process comes from the Ayrshire Coalfield (Mykura, 1960). Typically the coals are either removed by dissolution or they are replaced by limestone or siderite. The transformation of coal into siderite appears to be a common reaction under oxygenated conditions that lack significant lime-rich fluids (Mykura, 1960). The transformation of coal into limestone can occur over relatively short distances (a few hundred metres) and alteration appears to have taken place at a low temperature. Coal is initially replaced by calcite and may subsequently be replaced by dolomite or siderite (Mykura, 1960). This process appears to be dependant on the presence of calcium- and magnesium-rich fluids which, in the case of the examples described by Mykura (1960), were supplied from surface decomposition of Permian olivine-basalts.

In this account, we review current information on the Silesian rocks of the Canonbie area and, in particular, present the results of an outcrop study of the Upper Carboniferous red-beds that occur above the Cambriense Marine Band. At the time of field investigation (1-4 March 2004; 15-16 July 2005), the strata were particularly well exposed along the River Esk as river levels were low and relatively little river sediment was present. This has allowed us to provide much new information on those parts of the sequence apparently not exposed at the time of earlier surveys and to present here a more detailed description than given previously by Barrett and Richey (1945) and Lumsden et al. (1967) of the main River Esk section at Canonbie. In addition to the outcrops along the River Esk, data from 17 boreholes of differing vintage were used to supplement our observations (Table 1). Exploration boreholes to the south of Canonbie show that at least 200 m of strata, also of probable late Carboniferous age, conformably overly those of the river section; seismic reflection surveys indicate that this is could be up to c.700 m along the axis of the Solway Syncline (Chadwick et al., 1995). Although these strata cannot be examined directly, their wireline log and seismic reflection character suggest that they are similar in character to the youngest Carboniferous red-beds seen at outcrop (Figure 2).

Borehole Name	Quarter Sheet	Numb	Easting	Northing	Length (m)	Total depth (m)	Date of drilling	Ground level (m)	Rotary table or kelly bushing depth (m)	Datum
BECKHALL	NY37NW	2	333924	575733	420	421	1980	89.34	92.94	Ground level
BECKLEES	NY37SE	3	335166	571578	1370	1370.6	1982	35.25	Unknown	Ground level
BOGRA	NY37NW	3	332864	575529	447	448.3	1983	82.89	Unknown	Ground level
BROADMEADOWS	NY37NE	15	337646	576265	791	791.57	1979	80	83	Kelly bushing
CRANBERRY BORE	NY36NW	3	330724	569485	300	300.1	1982	40.8	Unknown	?Ground level
CROOKHOLM FARM	NY47NW	26	342452	576555	632	632	1956	54.86	Unknown	?Ground level
EVERTOWN	NY37NE	14	336390	575938	777	780.3	1979	92.8	95.8	Kelly bushing
FORGE DIAMOND BORE	NY37NE	7	339456	576720	458	458.47	1893	c.30	Unknown	Unknown
GLENZIERFOOT BORE	NY37SE	2	336514	574275	869	869.39	1980	64.93	68.53	Kelly bushing
KNOTTYHOLM	NY37NE	6	339501	577124	649	649.83	1955	42.67	Unknown	Unknown
RIDDINGS BOREHOLE	NY47SW	2	340300	574530	143.26	143.26	1914	28.96	Unknown	Ground level
RIDDINGS NO. 1 (COAL BORE)	NY47SW	16	340310	574480	126.79	126.8	1914	c.27.43	Unknown	Ground level
ROWANBURN DIAMOND BORE	NY47NW	21	340896	577014	481	481.46	1890	c.57	Unknown	Unknown
ROWANBURNFOOT BORE	NY47NW	27	341031	575743	876	876.91	1955	31.7	Unknown	Unknown
STAFFLER	NY37SW	1	332973	572267	708	711.43	1980	52.2	55.2	Ground level
TIMPANHECK	NY37SW	2	332207	574677	558	563.27	1983	83.99	Unknown	?Ground level
WOODHOUSELEES	NY37SE	1	339119	574951	1045	1045.9	1956	57.91	Unknown	?Ground level

Table 1. Boreholes used in this study.

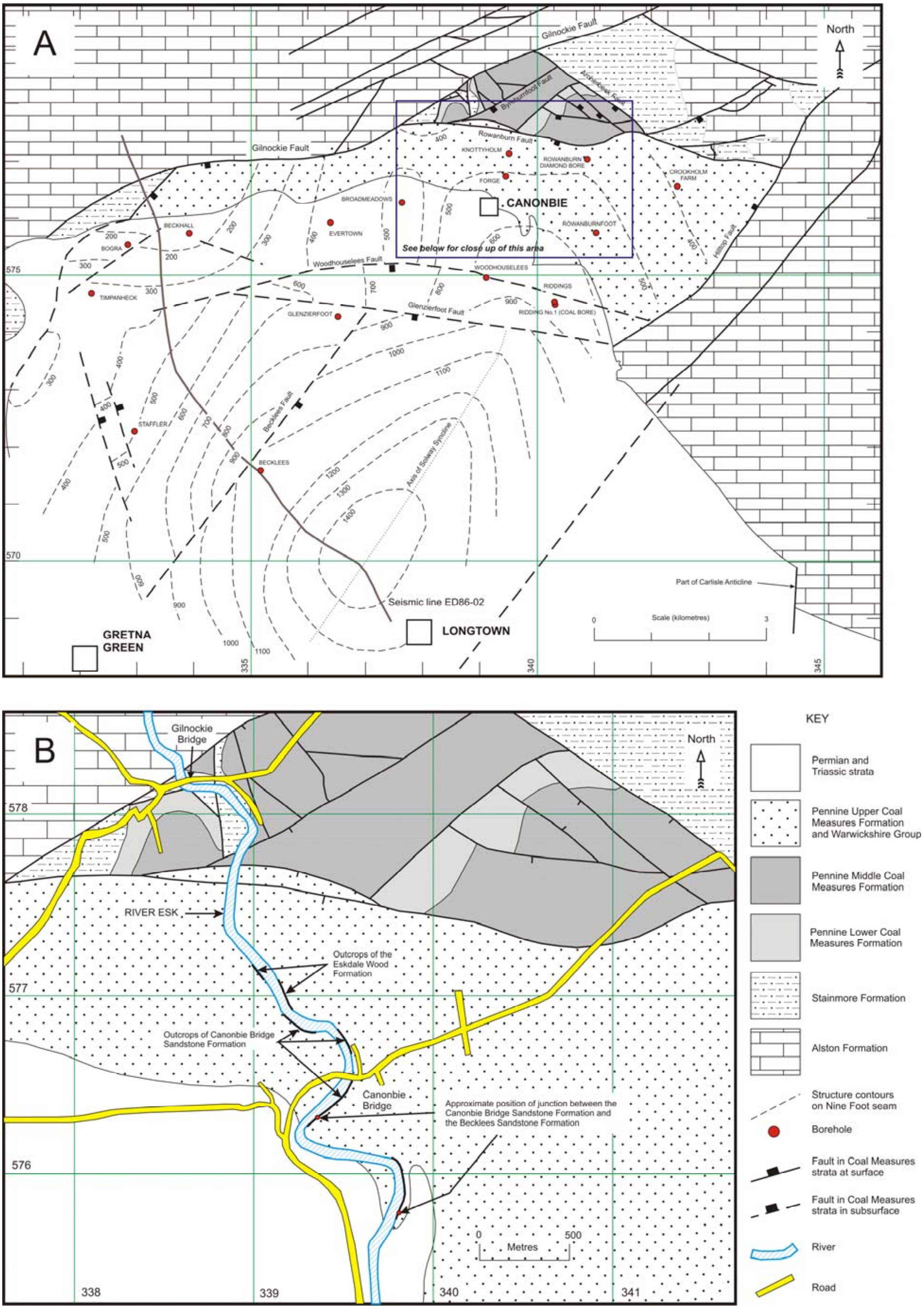

Figure 1. A. Geological map of the Canonbie Coalfield and adjacent areas. The positions of the main boreholes used in the study are also marked. B Close up of outcrop localities studied.

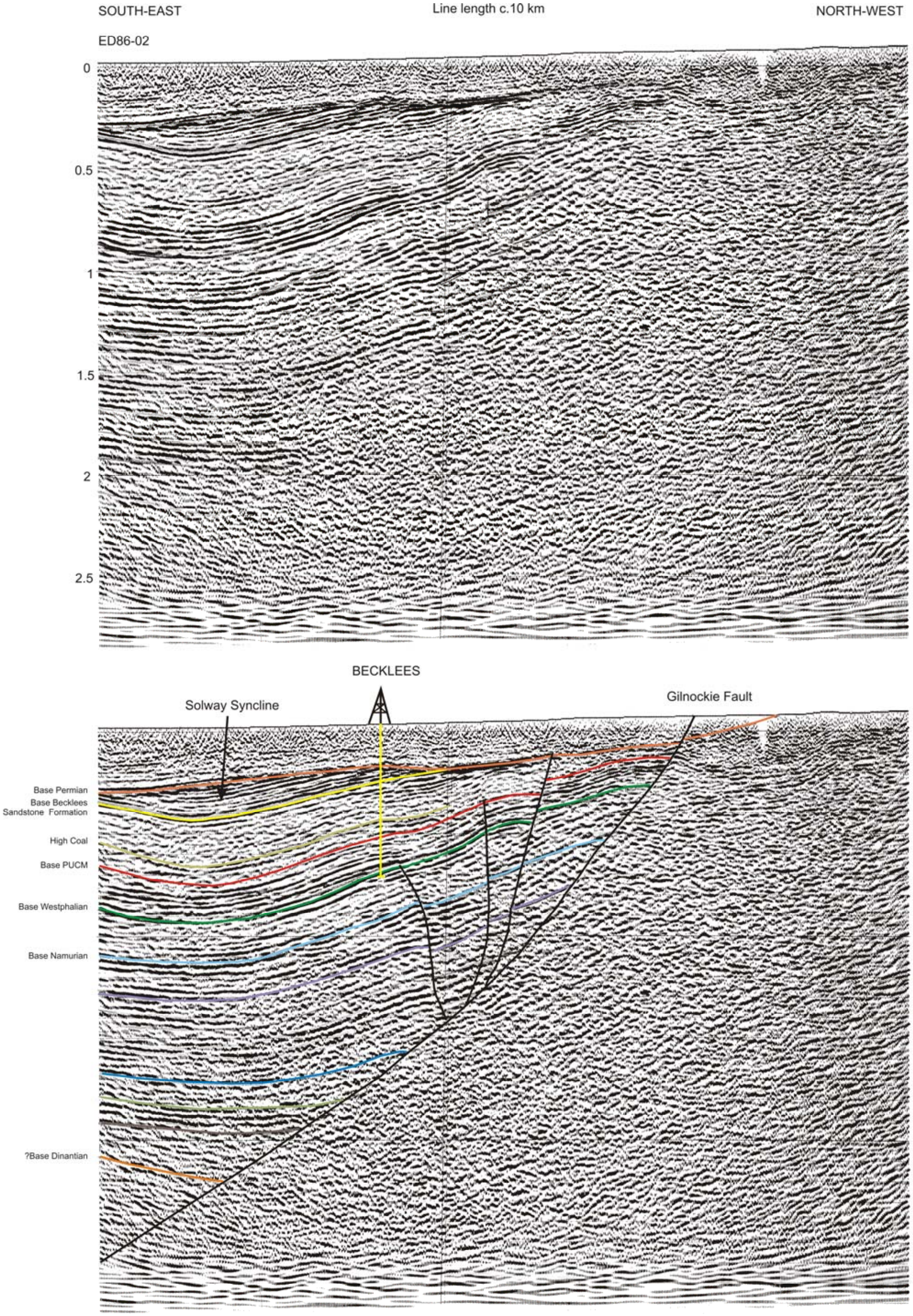

Figure 2. South-east to north-west seismic line (ED-86-02) across part of the Canonbie Coalfield. The position of this line is shown on Figure 1. Interpretation courtesy of S Holloway.

2. Tectonic and regional setting

The Silesian rocks of the Canonbie Coalfield are terminated to the north by the Gilnockie Fault (Barrett and Richey, 1945; Lumsden et al., 1967) (Figure 1). This fault is one of a set of en echelon ENE-trending structures that form the northern margin of the Northumberland-Solway Basin (Chadwick et al., 1995). Up to *c*.8000 m of Carboniferous strata were deposited in this basin. The Northumberland-Solway Basin was initiated as a rift-basin in early Dinantian, perhaps latest Devonian, times over the line of the inferred Iapetus Suture. This suture marked the closure of the Iapetus Ocean and the collision of Laurentia and Avalonia in Silurian and Early Devonian times. This collision involved the granite-cored Southern Uplands Block to the north and the Lake District-Alston blocks to the south. The main bounding faults are on the southern side of the basin, notably the Maryport-Stublick-Ninety Fathom faults, which probably follow old lines of weakness in the basement and have northerly directed dip-slip displacements of the Top Basement surface (=Caledonian unconformity surface) locally in excess of 5000 m. The Gilnockie and related southerly directed faults are interpreted as being antithetic syndepositional structures on the northern margin of the basin, and are also probably basement-related. Dip-slip displacements of the Top Basement surface on these faults are normally up to *c*.1000 m, but in the case of the Gilnockie Fault locally exceed 4000 m (Chadwick et al., 1995, map 1).

Phases of rifting continued until the end of Dinantian time, but thereafter dip-slip faulting on the major bounding faults was much subdued and basin thermal subsidence dominated. Towards the end of Carboniferous time, sedimentation ceased. The youngest rocks now preserved are Bolsovian-Westphalian D in age and form the subject of this report. In latest Carboniferous and earliest Permian times, the Carboniferous rocks of the basin were inverted and deformed within the foreland region to the Variscan Orogeny. The rocks were faulted, locally thrust, and gently folded, and the Solway Syncline and associated anticlines are among the largest folds formed at this time (Chadwick et al., 1995). The orientation of the principal stress direction at this time has been much debated. Until recently, many workers favoured E-W directed compression, with some associated strike-slip, mainly dextral, movement on easterly or ENE-directed major faults as the principal cause of the folds, many of which are directly related to reversed reactivation of Dinantian syndepositional faults (e.g. Shiells, 1964; Dunham, 1990; Chadwick et al., 1995). However, a later view now favours the deformational history to result primarily from a single kinematically partitioned phase of dextral transtension in latest Carboniferous to earliest Permian times (De Paola et al., 2005).

In several parts of northern England and in the southern North Sea, it has been suggested that deposition of the latest part of the basin-fill was contemporary with the early phases of the Variscan Orogeny and that many of the folds are in part syndepositional (e.g. Leeder and Hardman, 1990; Waters et al., 1994; Corfield et al., 1996). Within the study area, Chadwick et al. (1995, Figure 27) have demonstrated syndepositional thickening of Namurian strata into the Solway Syncline on the flanks of the Carlisle Anticline. The work presented in more detail below suggests that gentle syndepositional folding was a pervasive feature of the Canonbie Coalfield area beginning in late Dinantian times and continuing throughout Silesian times. The folding probably occurred as a response to dextral displacement on the Gilnockie Fault and other basin-bounding faults. In most other major Variscan inversion folds in northern England, the levels of Permo-Triassic and later erosion are much deeper than is generally the case in the Solway Syncline and Carlisle Anticline, and Silesian strata are totally or largely absent.

Therefore, it cannot be established whether these folds also had a similar early syndepositional history.

Erosion of Carboniferous strata began during the Variscan Orogeny and continued into Permian times. Folding had ceased by the time sedimentation began again in the area in mid-Permian times (Holliday et al., 2001, 2004), covering and preserving the Upper Carboniferous red-beds of the Solway Syncline.

3. Lithostratigraphical classification

The lithostratigraphical subdivision of Carboniferous rocks proposed by Waters et al. (in press) for onshore Great Britain is followed in this account (Figure 3). Thus, the largely grey, coal-bearing rocks above the Subcrenatum Marine Band (not certainly identified around Canonbie) are referred to the Pennine Coal Measures Group and the overlying red-beds are placed in the Warwickshire Group. In Scotland, the boundary between the Middle and Upper Coal Measures formations has conventionally been taken at a different marker bed (Aegiranum Marine Band) from that in England (Cambriense Marine Band) (Stubblefield and Trotter, 1957; MacGregor, 1960; Waters et al., in press). The new scheme does not use political boundaries to distinguish between Scottish and Pennine Coal Measures; instead it uses the distinct basins of the Midland Valley and Pennine Basin. The Canonbie area lies on the northern margin of the Pennine Basin. As in other parts of Britain, the boundary between the dominantly grey, coal-bearing Pennine Coal Measures and the largely primary red-bed Warwickshire groups is generally gradational and diachronous in the Canonbie area.

GROUP	FORMATION	MAIN MARINE BANDS	KEY MARKER BEDS IN CANONBIE AREA
Warwickshire Group	Becklees Sandstone Formation Canonbie Bridge Sandstone Formation Eskdale Wood Formation		High Coal
Pennine Coal Measures Group	Pennine Upper Coal Measures Formation Pennine Middle Coal Measures Formation Pennine Lower Coal Measures Formation	Cambriense MB Aegiranum MB Vanderbeckei MB Subcrenatum MB	=Riddings MB =Skelton MB Archerbeck Coal Nine Foot Coal =Queenslie/Solway MB Not identified
Yoredale Group	Stainmore Formation Alston Formation	C. leion MB	Catsbit (=Great) Limestone

Figure 3. Lithostratigraphical classification of Silesian strata in the Canonbie area (based on Waters et al. in press and this report).

3.1 STAINMORE AND PENNINE LOWER COAL MEASURES FORMATIONS

The Stainmore and Pennine Lower Coal Measures formations may conveniently be considered together as there are considerable uncertainties with regard to their thickness and sequence and to the position and nature of the boundary between them within the Canonbie area. They crop out over a relatively small area around Canonbie and generally are not well exposed. The lack of distinctive lithological and fauna markers, in repetitive, cyclical strata locally cut by relatively large faults, commonly makes interpretation and correlation of stream and borehole sections equivocal. Both formations dominantly comprise sandstones, siltstones and claystones with thin coals. Coarse-grained sandstones most commonly, though not exclusively, occur in the upper part of the Stainmore Formation and the lower part of the Pennine Lower Coal Measures Formation. The lower and middle portions of the Stainmore Formation also contain beds of limestone that are commonly thin and impure. The most detailed account of these strata is that given by Lumsden et al. (1967); other important sources include Peach and Horne (1903), Barrett and Richey (1945), Day (1970) and Picken (1988). Without a detailed sedimentological study, it would seem likely the two formations were formed in a vast coastal plain, with extensive lakes and marshes, which was subject to periodic marine incursion.

The lower Silesian strata in the Canonbie area are more comparable in sequence and thickness to those in the Northern Pennines and north-east England (e.g. Hull 1968; Ramsbottom et al. 1978; Dunham 1990; Mills and Holliday 1998) rather than with their equivalents in neighbouring west Cumbria (e.g. Akhurst et al. 1997), though detailed correlation of limestones with the former areas remains uncertain (Ramsbottom et al., 1978). Thus, these rocks are assigned to the Stainmore Formation of the Pennines and Northumberland rather than to the Hensingham Group of west Cumbria. Lumsden et al. (1967), Day (1970) and Ramsbottom et al. (1978) suggested that the Stainmore Formation is typically about 400 m thick around Canonbie. However, seismic reflection data indicate that this value is towards the lower end of the local thickness values, being more typical of the flanks of the Solway Syncline. Within the syncline thicknesses range up to more than 600 m (Chadwick et al., 1995, map 12). According to Lumsden et al. (1967), the Lower Coal Measures Formation is only 20-50 m thick, though Picken (1988) gave a higher general value of *c*.100 m and suggested that the greatest thicknesses of the formation are to be found in the deeper parts of the coalfield with thinning and overstep towards the flanks. This latter figure is supported here (see Figure 4).

Elsewhere in northern England, the boundary between the two formations is taken at the base of the Subcrenatum Marine Band. Unfortunately, this bed and its index fossil have yet to be recognized in the Canonbie area. In north-east England, where the presence of *Gastrioceras subcrenatum* also has yet to be confirmed, the position of the marine band can generally be inferred with some confidence from the positions of other lithological and faunal markers (Hull, 1968; Ramsbottom et al., 1978; Mills and Holliday, 1998). This is not yet possible at Canonbie, where an unconformity at or near this level has been inferred by some previous workers. The principal field evidence for this unconformity comes from an exposure at Gilnockie Bridge [NY 3857 7818] that shows a dislocation surface separating Carboniferous rocks with markedly divergent dips and strikes (Lumsden et al., 1967, p. 164, plate VIa) (Figures 1 and 4). The relatively flat-lying discordance surface separates an interbedded sandstone and mudstone succession dipping at approximately 55° from an overlying cross-bedded sandstone (Figure 5). However, an exposure in an overgrown quarry on the south-west bank of the River Esk adjacent to the bridge [3855 7815] reveals that rather than one discrete ‘unconformity’ surface there are actually a number of discordance surfaces separating inclined sedimentary blocks; these typically dip towards the east (Figure 6). Hence rather than an unconformity we believe that the character of the strata is more consistent with localized, synsedimentary channel-bank collapse. The process of channel-bank collapse is well documented from modern rivers and is one of the main mechanisms by which channels widen and migrate (Fisk, 1947, Stanley et al., 1966, Turnbull et al., 1966). Preserved channel-bank collapse structures have also been described from ancient sediments by numerous authors, including Williams et al. (1965), Laury (1971), Williams and Flint (1990), Guion et al. (1995a) and Jones et al. (1995).

Bank collapse may occur by the development of single or multiple rotational shears in cohesive near-channel sediments. This is favoured when the cut bank has been oversteepened by scouring at its base, and the bank sediment is saturated and overpressured by pore waters. Rotational failure, often involving the full height of the channel bank, can occur by slope failure, where the surface of sliding intersects the slope at or above its toe position, or by base failure where the surface of slippage passes below the toe level of the slope (Terzaghi and Peck, 1967, Laury, 1971). Base failure enables blocks of sediment to be emplaced below the maximum channel scour depth and these blocks will not generally be reworked by channel erosion.

Picken (1988, p. 68, Figure 4) also suggested an unconformity at this level based on his interpretation of the borehole data. He inferred that the Pennine Lower Coal Measures Formation gradually overstepped older strata towards a structural high to the western and north-western margins of the coalfield. The seismic reflection data provide no evidence of an unconformity elsewhere in the area of the magnitude that had been inferred from the Gilnockie Bridge outcrop. However, they are more equivocal with regard to the more subtle unconformity inferred by Picken (1988, Figure 4). Thus, although we would discount previous field evidence for an unconformity with major change in dip and strike, Picken’s (1988) suggested overstep by the Lower Coal Measures Formation cannot yet be rejected. Although such an overstep would be consistent with the observations noted above that both the Stainmore Formation and the Lower Coal Measures Formation thicken into the Solway Syncline and thin towards its margins, it is just as likely, given current uncertainties with regard to the detailed stratigraphical sequence and structure, that the apparently missing strata are in fact present but thinner. Whatever the true situation with respect to the unconformity, it seems probable from this thickness evidence, that the Solway Syncline is in part a syndepositional fold that was developing during the deposition of the Stainmore and Lower Coal Measures Formations, as suggested by Chadwick et al. (1995). Indeed, inspection of the isopach maps of Chadwick et al. (1995, map 10) suggests that syndepositional, folding may have begun during deposition of the Alston Formation (i.e. Upper Asbian-Brigantian).

3.2 PENNINE MIDDLE COAL MEASURES FORMATION

The Pennine Middle Coal Measures Formation (PMCM) is poorly exposed in its relatively small area of outcrop just north of Canonbie (Figure 1). However, because of previous coal working and the drilling of numerous cored boreholes, its sequence is well established (Barrett and Richey, 1945; Lumsden et al., 1967; Picken, 1988) and proved to be similar to other occurrences of the formation in northern England. More argillaceous in general than the Pennine Lower Coal Measures Formation, the principal lithologies are claystone, siltstone, fine-grained sandstone and a number of relatively thick, persistent coals; coarse-grained sandstone occurs locally as channel infills. The formation is also notable for the presence of some thin intervals with a marine or quasi-marine fauna, particularly at the top of the formation (Figure 4). The beds are almost everywhere grey in colour except for some local reddening, particularly to the north-west of the Solway Syncline. The formation is 200-270 m thick around Canonbie (Figure 4), with the thicker

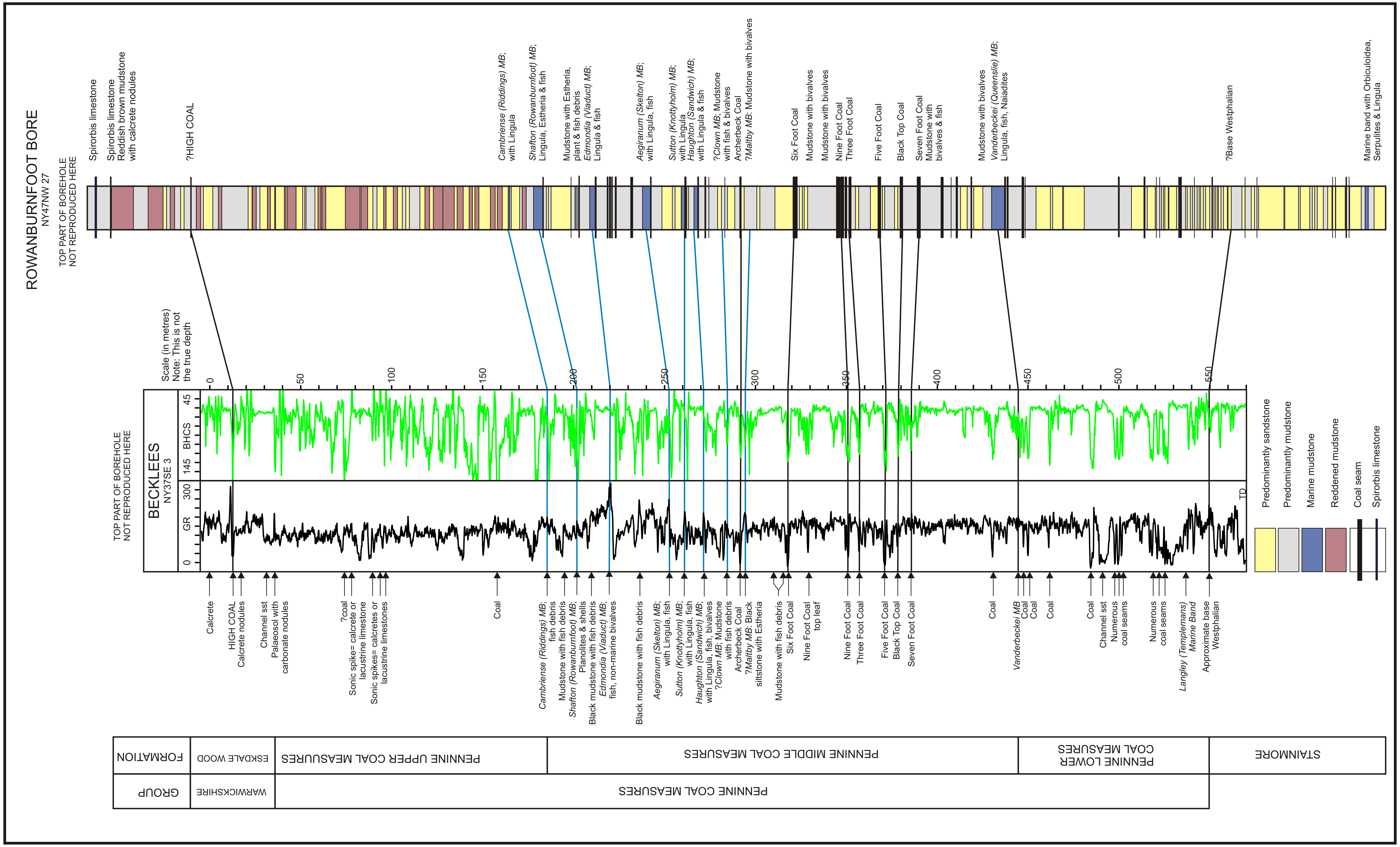

Figure 4. Composite summary log of part of the Becklees and Rowanburnfoot boreholes to show the general features of the Stainmore Formation and Pennine Coal Measures Group.

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The presence of the coal seams and, to a lesser extent, the marine mudstones (i.e. claystones and/or siltstsones) results in characteristic, highly fluctuating wireline log traces; e.g. the low gamma-ray coals contrast strongly with the high gamma-ray marine mudstones, and the coals feature prominently on both sonic and density logs (Figure 4). Though faunal evidence has not been found for the presence of every marine band in every borehole, their positions generally can be inferred by use of gamma-ray logs. Correlation of these marine intervals with the standard British marine band sequence was established by Ramsbottom et al. (1978) (Figure 7). Of note is the fact that the upper part of the PMCM contains numerous marine bands, of which 6 have previously been described. As a result of this study we believe that a further two marine bands can be recognised in the succession at Canonbie. These occur just below the level of the other 6 marine bands and it is suggested that they correspond to the Maltby and the Clown marine bands of Ramsbottom et al. (1978). The Maltby Marine Band occurs just below the Archerbeck Coal and the Clown Marine Band occurs in the interval above the Archerbeck Coal (Figure 4). Table 2 details the characteristic features of these proposed marine bands.

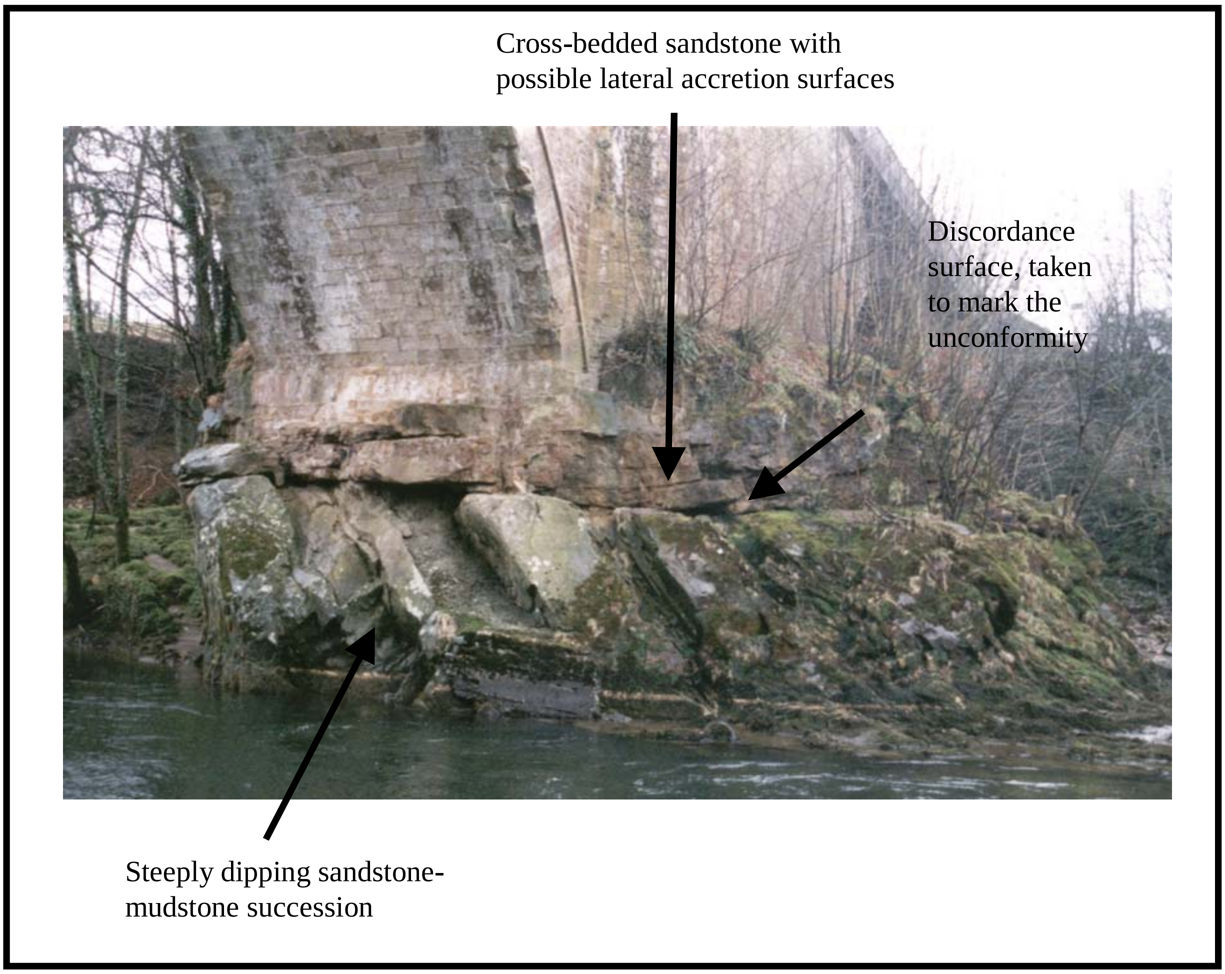

Figure 5. Photograph of the base Westphalian ‘unconformity’ at Gilnockie Bridge [3857 7818]. This is taken looking south-west; the exposure is a few metres thick, vertically.

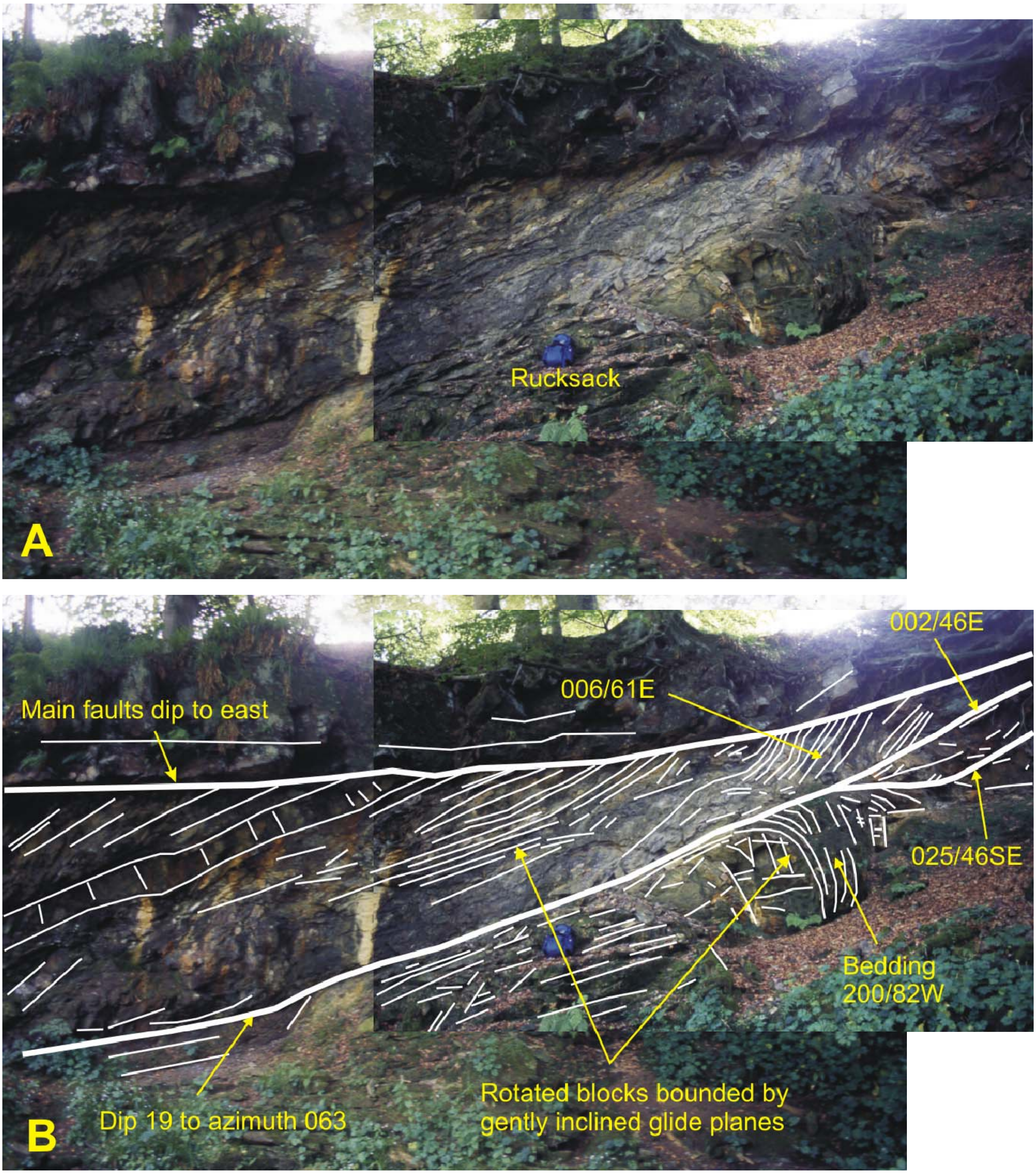

Figure 6. A. Photomontage of a quarry at Gilnockie Bridge [3858 7813]. B. Line drawing of the same quarry to show the numerous gently dipping dislocation surfaces, rather than one discrete 'unconformity' surface. These are interpreted as multiple channel bank collapse deposits.

Rucksack for scale is 0.5m in length. Photo is taken looking towards the south-east.

Sedimentary facies recognisable for the Westphalian of the UK have been documented in detail by many authors, notably Elliott (1968), Guion (1984, 1987a, b), Haszeldine (1983, 1984), Fielding (1984a, 1986), Guion and Fielding (1988) and Guion et al. (1995b). There have been no detailed sedimentological studies of the Canonbie area coal measures, although the work of Kirk (1983) from the Southern Uplands coalfields, Fielding (1982) from the Durham Coalfield and Jones (1992) from the nearby West Cumbrian Coalfield are perhaps the most geographically relevant. Sedimentation is thought to have taken place on a flat-lying, extensive upper deltaic to lower alluvial plain. Large areas of this delta plain were occupied by shallow lakes, which were infilled by sediment supplied by fluvially-dominated lacustrine deltas, channel overbank and crevasse splays. These were fed by a hierarchical network of major and minor channels. Major channels formed low sinuosity, multichannel systems whereas minor channels formed highly sinuous distributaries, characterised by frequent switching events. Following episodes of lake infilling and channel abandonment, large-scale switching of the sedimentary system resulted in areas of the delta plain being starved of siliciclastic sediment. These areas typically became vegetated leading to the development of mire complexes and to the accumulation of thick peat deposits. Analysis of controls on sedimentation indicates that regional and compactional subsidence and autocyclic sedimentary controls were dominant (Guion and Fielding, 1988). Rare glacio-eustatic sea-level rises periodically led to marine conditions. Brief analysis of the core log descriptions for numerous coal exploration boreholes in the area indicate that the PMCM of the Canonbie Coalfield appears to comprise similar sedimentary facies and hence fits in well with the depositional setting proposed for adjacent areas.

Standard Names	Canonbie
Cambriense	Riddings
Shafton	Rowanburnfoot
Edmondia	Viaduct
Aegiranum	Skelton
Sutton	Knottyholm
Haughton	Sandwich
Clown	???
Maltby	Not proved
Vanderbeckei	Queenslie
Langley	?Templeman’s

Figure 7. Correlation of marine bands in the Pennine Coal Measures Group.

3.3 PENNINE UPPER COAL MEASURES FORMATION

Lumsden et al. (1967) and Ramsbottom et al. (1978) suggested that the youngest beds in the Canonbie Coalfield contain a fauna indicating that they belong to the Tenuis Chronozone and thus span the interval between late Bolsovian and Westphalian D. The fauna includes *Anthraconaia pruvosti* and *Leaia bristolensis*, together with *Spirorbis* limestones. The Pennine Upper Coal Measures Formation (PUCM) comprises the strata between the top of the Cambriense (Riddings) Marine Band and the first development of primary red-beds of the

Warwickshire Group (Waters et al. in press) (Figures 3 and 8). The formation is mainly grey, although secondary red-beds become more common upwards. The top and bottom of the formation were not identified at outcrop but could be identified from boreholes. The upper boundary is difficult to define accurately due to the problems in distinguishing primary from secondary red-beds using mainly core descriptions and wireline logs. Where good core descriptions are available the top of the formation can be taken at the first uphole occurrence of recognisable pedogenic carbonate (calcrete) nodules. This usually occurs close to the level of the High Coal (Figures 3 and 8), which can be used as a proxy for the boundary where only geophysical logs are present over the interval of interest.

CLOWN MARINE BAND INFORMATION

Borehole	Lingula	Estheria	High gamma spike	Pyrite	Fish	Bivalves	Plants	Comments
BECKHALL	No	No	No	No	No	No	No	
BECKLEES	No	No	Moderate	Yes	Yes, abun	No	No	Black, canneloid
BOGRA	No	No	Yes	No	Yes	No	Yes	Black, canneloid
BROADMEADOWS	Yes	Yes	No		Yes, abun	Yes		Black, carbonaceous
CROOKHOLM FARM	No	No	No GR log	No	Yes	No	Yes	
EVERTOWN	No	No	Moderate	No	Yes	Yes	Yes	
GLENZIERFOOT BORE	No	No	No	No	No	No	No	Possibly faulted
KNOTTYHOLM	No	No	No GR log	Yes	Yes	No	No	Poor quality log
ROWANBURNFOOT BORE	No	No	No GR log	No	Yes	Yes	No	
STAFFLER	No	No	No		Yes	No	Yes	
TIMPANHECK	Unknown	Unknown	Yes	Unknown	Unknown	Unknown	Yes	
WOODHOUSELEES	No	No	No GR log	No	No	No	No	Faulted, or channel sst at this level

MALTBY MARINE BAND INFORMATION

Borehole	Lingula	Estheria	High gamma spike	Pyrite	Fish	Bivalves	Plants	Comments
BECKHALL	No	No	No	No	No	No	No	
BECKLEES	No	Yes	Yes	No	No	No	No	Dk grey to black
BOGRA	No	Yes	Moderate	Yes	Yes	No	Yes	
BROADMEADOWS	No	Yes	Moderate	No	No	Yes	Yes	Medium to dark grey. Graphic log records Lingula, written log does not
CROOKHOLM FARM	No	Yes	No GR log	No	No	Yes	Yes	
EVERTOWN	No	Yes	Yes	Yes	No	No	Yes	Medium grey
GLENZIERFOOT BORE	No	No	No	No	No	No	No	Possibly faulted
KNOTTYHOLM	No	No	No GR log	Yes	No	No	Yes	Poor quality log
ROWANBURNFOOT BORE	No	No	No GR log	Yes	Yes	Yes	Yes	
STAFFLER	No	No	Yes	No	Yes	Yes	Yes	
TIMPANHECK	Unknown	Unknown	moderate	Unknown	Unknown	Unknown	Unknown	
WOODHOUSELEES	No	Yes	No GR log	No	No	Yes	No	

Table 2. Characteristics of the proposed two new marine bands in the Canonbie Coalfield.

The formation is about 150 m in thickness in the Becklees and Glenzierfoot boreholes. Picken (1988) suggested that there was a major unconformity between the Pennine Middle and Upper Coal Measures in the north-west of the coalfield, with *c*.155 m of strata eroded. Further south and south-east the junction between the two formations is described as conformable (Picken 1988). The presence of an unconformity at this level is not supported here for two principal reasons. Firstly, no indication of such a major unconformity has been identified on the seismic reflection sections and, secondly, the excellent wireline log correlation between boreholes across the coalfield suggests that in fact no strata are missing in the area suggested by Picken (1988). However, a brief examination of the seismic data suggest that the strata are generally thicker along the axis of the Solway Syncline than on its flanks; also the gradation to primary red-beds may occur at lower stratigraphical levels on the flanks than in the syncline. Core-log descriptions indicate the presence of a number of thick, erosively based, medium to coarse-grained sandstones in the sequence, and it is possible that an incorrect correlation of different sandstones may have given the impression of an unconformity.

Wireline logs from boreholes that lie along the central axis of the Solway Syncline indicate that the formation largely comprises mudstones (Figure 8). Borehole logs also indicate the presence of coals, *Estheria* bands and *Spirorbis* limestones in the PUCM, but these were not exposed at surface. Sandstones, where present, are generally thin (2-5 m thick) and tend to have a serrated (‘ratty’) response on gamma ray geophysical logs (Figure 8). The exception to this occurs in the Glenzierfoot and Broadmeadows boreholes, where sandstone is present at the base of the formation, forming a single unit up to 20 m thick (Figure 3). This sandstone has a distinct blocky gamma ray form. On the north-west flank of the Solway Syncline the full thickness of the PUCM is generally not preserved due to erosion at the level of the sub-Permian unconformity. However, it would appear to contain much more sandstone than along the axis of the syncline. In the Timpanheck Borehole for example sandstone typically forms up to 50% of the succession. The major differences between this formation and the underlying PMCM formation appears to be the lack of marine facies and a marked reduction in the number and thickness of coals.

The formation was also briefly examined at outcrop along the western bank of the River Esk between GR [39053 77105] and [39000 77153], where a section up to 13 m in thickness was logged. The succession here dominantly comprises pinkish to reddish brown silty claystones, with some sandy siltstones and rare pinkish grey fine- to medium-grained micaceous sandstones. Roots are a common feature, although in places they are present only as traces due to the effects of oxidation. Ironstone nodules and thin beds are a common feature. A possible example of a coal replaced by limestone was identified along the western bank of the River Esk at GR [3904 7712]. It comprises a bed of reddened, organic rich, ferruginous limestone, 7 cm in thickness (Figure 9). The ferruginous limestone is massive, although carbonaceous laminae are present. It is underlain by a *c*.2 m thick grey to reddish-pinkish grey mudstone. This mudstone is destratified, with numerous pedogenic listric surfaces and some remnants of roots visible (Figure 10). The presence of reddening along subvertical pathways suggests a far higher root content may have been present prior to oxidation. The ferruginous limestone represents a candidate for the replacement of a coal by the process described by Mykura (1960). The underlying mudstone is interpreted as a gley palaeosol that was subsequently secondarily oxidised.

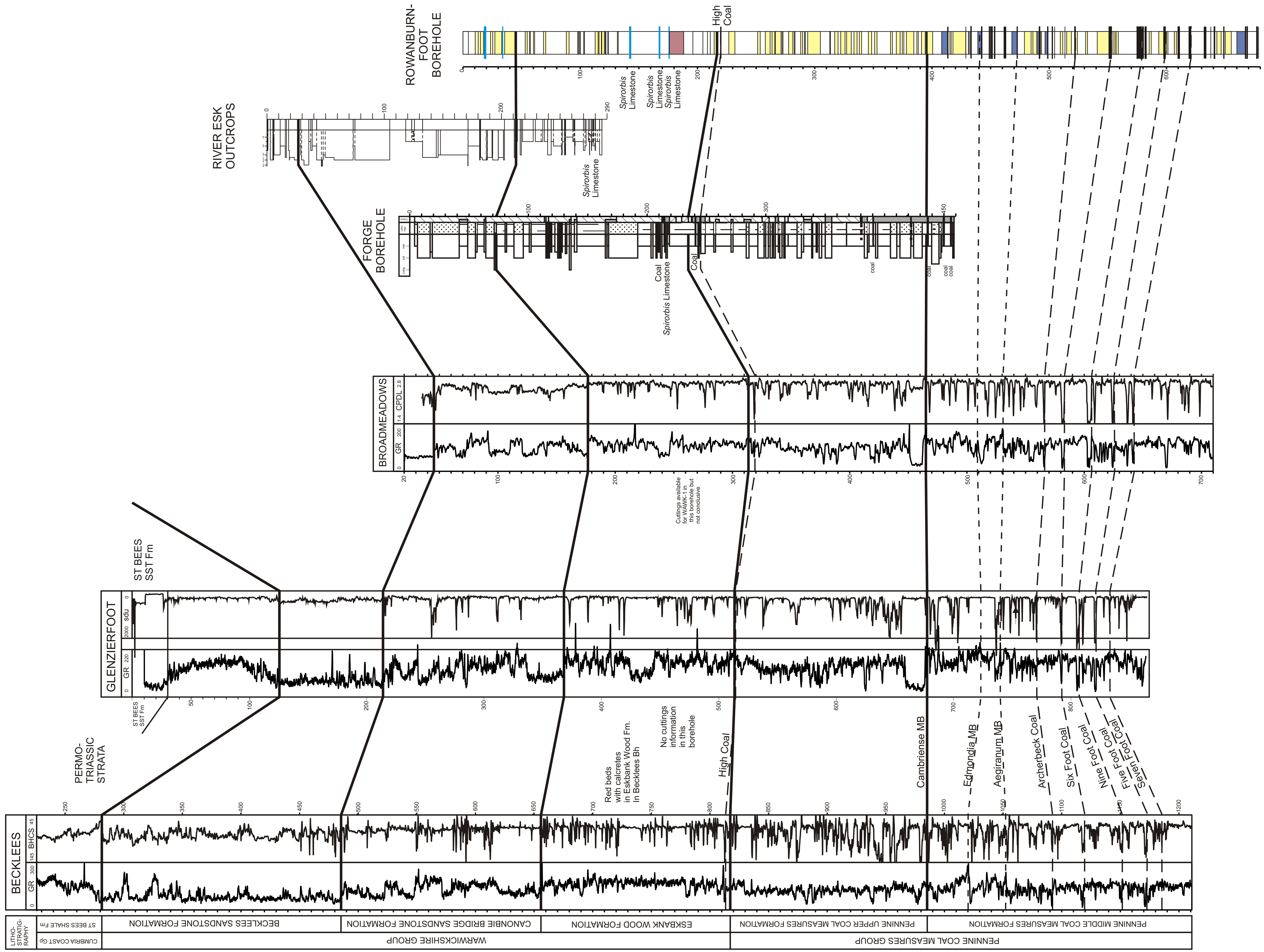

Figure 8. Correlation of the Warwickshire Group and upper part of the Pennine Coal Measures Group in the Canonbie area. See Figure 1 and Table 1 for borehole locations.

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Figure 9. Oxidised gley palaeosol (OG) overlain by remnants of oxidised coal (arrowed).

Figure 10. Close up of (secondarily) oxidised gley palaeosol: Note preservation of grey colouration in places. View looking SW [339053 577105].

3.4 WARWICKSHIRE GROUP

The term Warwickshire Group (WAWK) has been applied to the predominantly red-bed strata that typically form the upper part of the Carboniferous succession in the UK and has previously been referred to by such names as the Barren or Red Measures (Powell et al., 2000) (Figure 11). The type area of the group is the Warwickshire Coalfield in central England, where the succession attains its fullest thickness of 1225 m (Powell et al., 2000). Here the group typically comprises red mudstones and sandstones, with varying amounts of pebbly sandstone, conglomerate, grey mudstone, thin coals, lacustrine limestone (‘*Spirorbis* limestone’) and calcrete palaeosols. The group ranges in age from late Bolsovian (Westphalian C) to Autunian although, due to the effects of reddening, the degree of biostratigraphical control is reduced compared with the Pennine Coal Measures Group (Waters et al., 1995; Besly and Cleal, 1997; Powell et al., 2000).

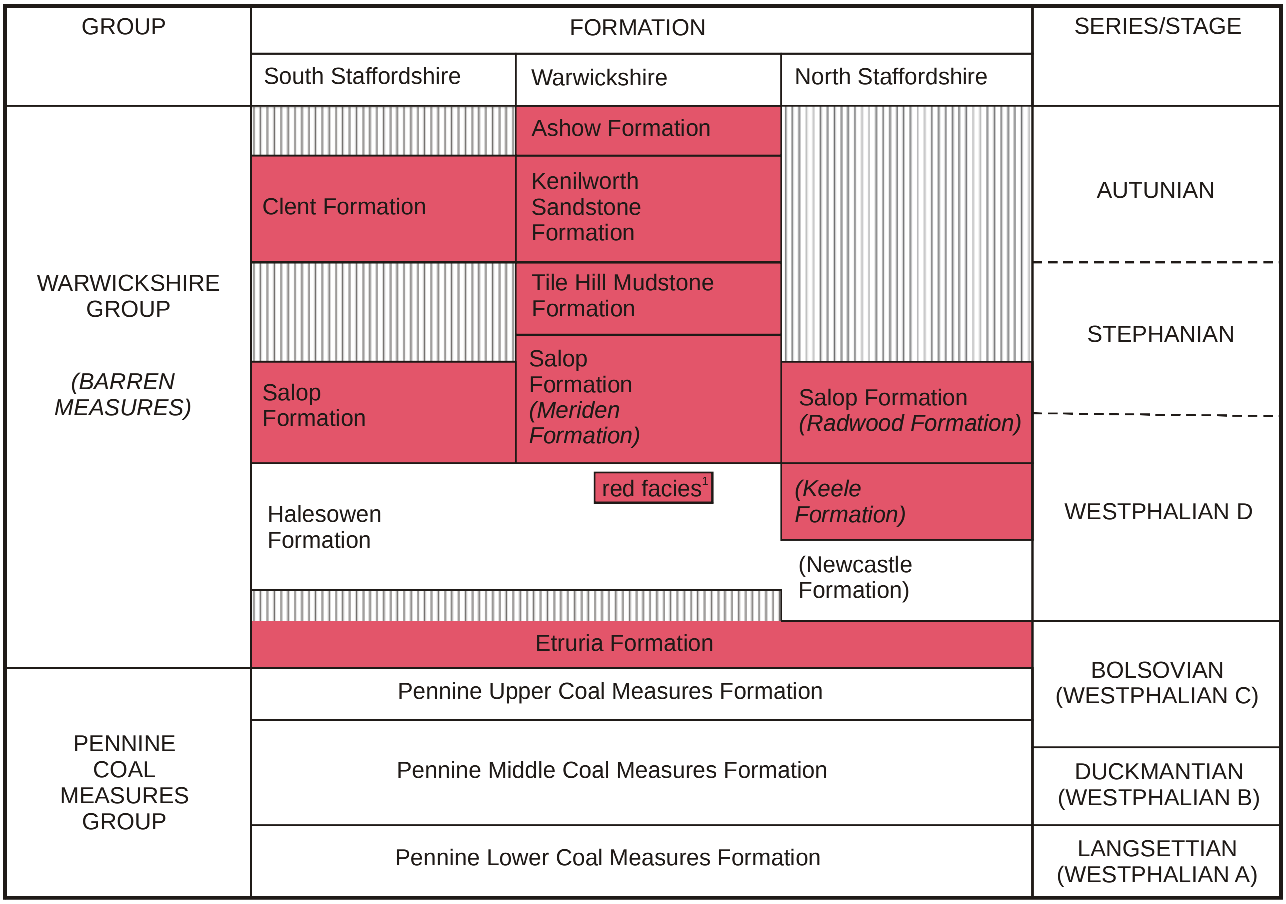

Figure 11. Stratigraphical framework for south Staffordshire, Warwickshire and north Staffordshire (modified from Powell et al., 2000). This stratigraphy has been used where possible.

The basis for the recognition of the group is that primary red-beds must be present. A large proportion of the reddening seen in Carboniferous strata is secondary in nature, i.e. it is a later reddening of original grey-beds, as described previously. However, during later Carboniferous times there was a change in climate from humid or sub-humid conditions in Bolsovian times to semi-arid conditions by Westphalian D times, brought about by the rain-shadow effect of the continuously rising Variscan mountain chain to the south (Besly, 1987). Red-beds formed during these well-drained, oxidising surface conditions are termed primary red-beds. When describing red-bed successions, Powell et al. (2000) emphasised the need to distinguish between primary and secondary red-beds, formed by later oxidative weathering. The lithologies of the Warwickshire Group formed predominantly within oxygenated surface conditions and hence represent primary red-bed facies. In the southern part of the Pennine Basin the base of the Halesowen Formation is largely unconformable onto older Pennine Coal Measures Group strata. In the Coalbrookdale Coalfield the stratigraphically older ‘Symon Unconformity’ occurs between the Etruria Formation and the Pennine Coal Measures Group (Powell et al., 2000).

The Warwickshire Group has not been recognised previously from the Canonbie area although previous work has recorded the presence of red strata in the ‘Upper Coal Measures’ of the area (Peach and Horne, 1903; Simpson and Richey, 1936; Barrett and Richey, 1945; Trotter, 1953; Lumsden et al., 1967; Day, 1970; Picken, 1988). Trotter (1953) suggested that, whilst much of the strata show evidence for secondary reddening, the uppermost *c*.120 m of strata may include primary red beds. Barrett and Richey (1945) indicated that the red strata, which they term the ‘Barren Red Coal Measures’, are up to c.460 m in thickness, although Lumsden et al. (1967) suggested a figure of c.790 m. Picken (1988) described the succession as largely comprising an interbedded succession of sandstone and mudstone, generally calcareous. Marker horizons include *Spirorbis* limestones and a persistent coal that was named the High Coal (Picken, 1988). Chadwick et al. (1995) suggested that during the Late Bolsovian to Westphalian D within the Canonbie Coalfield fluvial facies were deposited in a hot, arid environment. They also suggested that syndepositional thickening of Upper Bolsovian to Westphalian D strata into the Solway Syncline occurred and speculate as to whether the Carlisle Anticline may have supplied sediment at this time.

4. Stratigraphy of the Warwickshire Group

The definition of the Warwickshire Group is that the rocks must show evidence for primary red-bed sedimentation. This report describes for the first time the occurrence of Warwickshire Group strata in the Canonbie area. The detailed stratigraphy of the group has been determined by a study of the outcrops along the River Esk between GR [3915 7706] and [3981 7576], which forms the type section (Figure 12), together with a study of the relevant borehole information, which yields good information on the subsurface distribution of the group. As a result of this work, three subdivisions of the group have been identified. These have been given formation status and are named and defined for the first time in the following section. It is acknowledged that it would prove difficult to map these formations in the field due to the extensive coverage of till present in the area. However, these formations are readily identifiable at outcrop along the River Esk and in good quality borehole logs. A summary log of the main features of the group is illustrated in Figure 12. The formations are described in the following section, in ascending order:

4.1 ESKBANK WOOD FORMATION

4.1.2 Definition of the Eskbank Wood Formation (new name)

Derivation of name. Eskbank Wood is the name of the area of woodland that is adjacent to the main exposures of this formation along the River Esk.

Lithology description. Interbedded red mudstone (claystones and siltstones), fine- to medium-grained sandstones, calcrete palaeosols, thin beds of *Spirorbis* limestone and *Estheria*-bearing mudstones. Sparse thin coals and grey mudstones are present in the lower part of the formation; some of these coals have been oxidised and altered to limestone. One thick coal (the High Coal) may be up to about 0.5 m thick; this is known only from boreholes. Mudstones form 60-70 % of the formation, with sandstones forming the majority of the rest.

Type locality. Hush Pool, River Esk, opposite Eskbank Wood [339149 577055] to [339194 576953]. Approximately 75 m of nearly continuous outcrop of the formation is present along the eastern bank of the River Esk. This represents the middle to upper part of the formation.

Reference sections. Forge Diamond Bore (NY37NE7) cored the full thickness (*c*.163 m) of the formation, from 72.8-235.5 m downhole depth. In the Becklees borehole (NY37SE3) the formation is 164 m thick, occurring between 653-816.8 m downhole depth. The formation is cored from 744.41 m (downhole depth) to its base in the Becklees borehole and provides good modern descriptions of the strata penetrated. It is also cored in Bogra borehole (NY37NW3). The formation is also present in a number of other boreholes including Beckhall (NY37NW2), Broadmeadows (NY37NE15) and Glenzierfoot (NY37SE2).

Lower boundary. The base of the formation is only defined in boreholes; it could not be identified at outcrop. The boundary is taken at the first major red-bed strata overlying the grey mudstone dominated Pennine Upper Coal Measures Formation. It is a conformable, slightly diachronous, gradational boundary. In the Becklees borehole (NY37SE3) the base of the formation (at 816.8 m downhole depth) is defined by the last significant downhole occurrence of primary red-bed lithologies. In this instance it comprises 1.3 m of mottled reddish brown and greenish grey silty mudstone with abundant carbonate nodules. These nodules are interpreted as pedogenic calcrete glaebules and hence represent the first good evidence for the development of primary red-bed conditions. A limited number of red lithologies are known below 816.8 m (downhole depth), but it is not known whether these represent primary red-beds or could be linked to later secondary reddening processes. The lower boundary is difficult to pick in uncored boreholes, but analysis of cored boreholes shows that close to the base of the formation a distinctive coal (known as the High Coal) is typically present, and can be identified from suitable geophysical logs (e.g. sonic, density). In the Becklees borehole the High Coal occurs a few metres above the first good primary red-bed facies. The coal clearly indicates a reversion back to reducing conditions and demonstrates the gradational nature of the lower boundary. In other boreholes (e.g. Broadmeadows, Forge, Glenzierfoot and Rowanburnfoot), the High Coal occurs

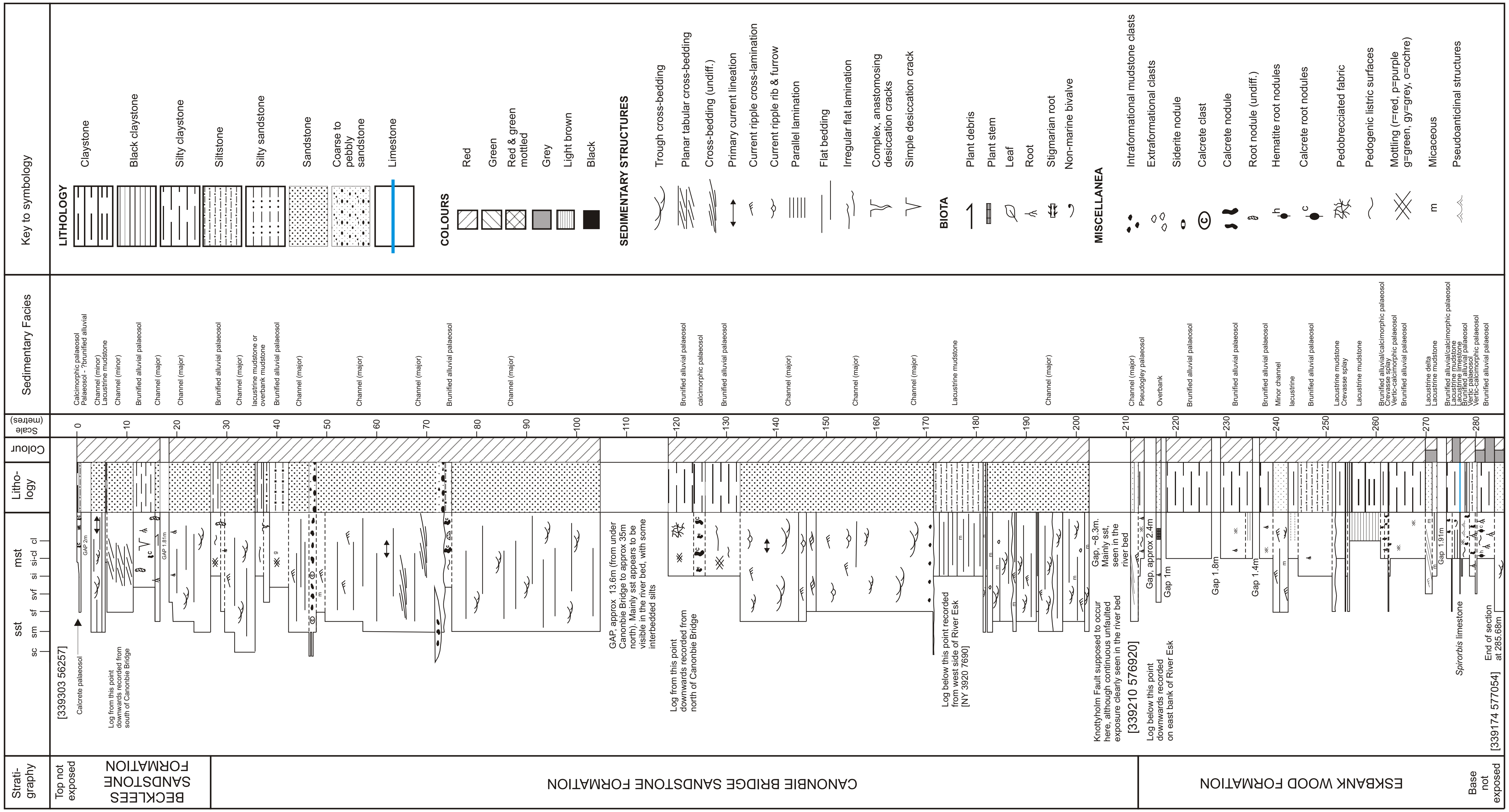

Figure 12. Composite sedimentological log of the Warwickshire Group succession exposed along the River Esk, Canonbie.

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close to the top of the Pennine Upper Coal Measures Formation, a few metres below the lowest red-bed facies.

It is suggested that in open-hole conditions the top of the High Coal is taken to mark the boundary between the PUCM and the Warwickshire Group.

Upper boundary. The top of the formation is taken at the base of the lowermost sandstone bed of the Canonbie Bridge Sandstone Formation; the boundary is abrupt. The junction can be examined at outcrop at [339194 576953] and has also been proved in numerous boreholes, including Becklees (NY37SE3) (cored depth: 653 m; geophysical log depth: 656 m; both downhole depths), Broadmeadows (NY37NE15) (geophysical log downhole depth: 176.6 m, downhole depth) and Glenzierfoot (NY37SE2) (geophysical log downhole depth: 368.2 m). On the north-western flank of the Canonbie Coalfield the full thickness of the formation is not always preserved due to erosion at the Variscan unconformity surface.

Thickness. In the Forge Diamond Bore (NY37NE 7) the formation is *c*.163 m thick. In the Becklees Borehole (NY37SE 3) the formation is 164 m thick. In Glenzierfoot (NY37SE 2) the formation is 146 m thick and in Rowanburnfoot Bore (NY47NW 27) it is 175 m.

Geographical limits. The formation is restricted to part of the Canonbie Coalfield between the Evertown [NY 3639 7594] and the Rowanburn [NY 41140 7687] areas. It is also known in its subsurface extension to the south-west, where it has been proved for a distance of at least *c*.6 km.

Age. Late Bolsovian (Westphalian C) to Westphalian D. The section along the eastern bank of the River Esk north of Canonbie Bridge comprises some mudstones that contain a non-marine fauna, particularly bivalves, at various points in the section. These have been identified as *Anthraconauta phillipsii*, *A.* aff. *Phillipsii*, *A*.cf. *tenuis*, *A*.cf. *wrightii*, possibly *Anthracomya pruvosti* and also ostracods (A.E Trueman in Barrett and Richey, 1945, p39; Lumsden et al., 1967, p.178). Trueman suggested that this indicates the *A. tenuis* or even the *A. prolifera* non-marine bivalve zone of Trueman and Weir (1946), indicative of a Westphalian D age.

Subdivisions. No formal subdivision of this formation is proposed.

4.2 CANONBIE BRIDGE SANDSTONE FORMATION

4.2.1 Definition of the Canonbie Bridge Sandstone Formation (new name)

Derivation of name. Outcrops of this formation occur along the banks of the River Esk immediately upstream and downstream of Canonbie Bridge.

Lithology description. Interbedded reddish brown to greenish grey, moderately to poorly sorted, fine- to coarse-grained sandstones (50-70 %) and reddish brown mudstones and reddish brown mudstone palaeosols including calcretes and desiccation-cracked brunified alluvial palaeosols. Sandstones are typically thick (10-30 m), forming sharp to erosively based, cross-bedded channel sandstones in multi-storey successions. Intraformational mudstone conglomerates occur scattered throughout the sandstones but are more common at channel bases. Distinct upwards-fining successions are sometimes present, as identified both in the field and from upwards increasing GR values. In hand specimen the sandstones can be micaceous and contain a noticeable component of greenish grey grains which, in thin section, can be identified as lithic clasts (Figure 13). The high lithic component gives the sandstones a characteristic gamma ray log signature, with GR values ranging from 56-120 API (mean 97.3, median 99.53 API) (Figure 14).

Type locality. Outcrops along the River Esk for *c*.250 m south of Canonbie Bridge (e.g. at [339551 576501]) and in discontinuous exposures for *c*.600 m to the north of the bridge e.g. [339502 576735 and 339317 576792]. The full thickness of the formation is present at outcrop, although there are minor breaks in exposure.

Reference sections. Forge Diamond Bore (NY37NE7), where the lower *c*.73 m of the formation was cored. In the Becklees (NY37SE3), Broadmeadows (NY37NE15) and Glenzierfoot (NY37SE2) boreholes the formation is uncored, but the full thickness is present.

Lower boundary. The base of the formation is taken at the base of the lowermost sandstone bed in a thick (20-30 m) multi-storey sandstone complex. The junction is abrupt. The junction can be examined at outcrop at [339194 576953] and has also been proved in numerous boreholes, including Becklees (NY37SE3) (cored downhole depth: 653 m; geophysical log downhole depth: 656 m), Broadmeadows (NY37NE15) (geophysical log downhole depth: 176.6 m) and Glenzierfoot (NY37SE2) (geophysical log downhole depth: 368.2 m). In the Forge Diamond Bore (NY37NE7) the base is taken at a 0.6 m thick conglomerate bed at 72.8 m (downhole depth).

Upper boundary. At outcrop at [339360 576310] and [339812 575760] the upper boundary is taken at the abrupt junction between the better cemented, reddish brown, fine- to coarse-grained, lithic sandstones of the Canonbie Bridge Sandstone Formation and the overlying Becklees Sandstone Formation which comprises softer weathering, orange brown, fine- to medium-grained sandstones that lack appreciable lithic grains (Figure 15). In uncored boreholes the boundary is marked by a shift in the gamma ray (GR) log to lower values, reflecting the change in sandstone composition from lithic rich (higher GR values) to lithic poor, ‘cleaner’ sandstones with lower GR values (Figure 8). This can be seen for example at 485.3 m (downhole depth) in Becklees Borehole (NY37SE3) and 214 m (downhole depth) in Glenzierfoot (NY37SE2). On the north-western flank of the Canonbie Coalfield the full thickness of the formation is not always preserved due to erosion at the Variscan unconformity surface.

Thickness. The formation varies in thickness from 131 m in Broadmeadows (NY37NE15) to 154 m in Glenzierfoot (NY37SE2) up to a maximum thickness of 168m in Becklees borehole (NY37SE3).

Geographical limits. The formation is restricted to part of the Canonbie Coalfield between the Evertown [NY 3639 7594] and the Rowanburn [NY 41140 7687] areas. It is also known in its subsurface extension to the south-west, where it has been proved for at least a distance of approximately 6 km.

Age. Westphalian D.

Subdivisions. No formal subdivision of this formation is proposed.

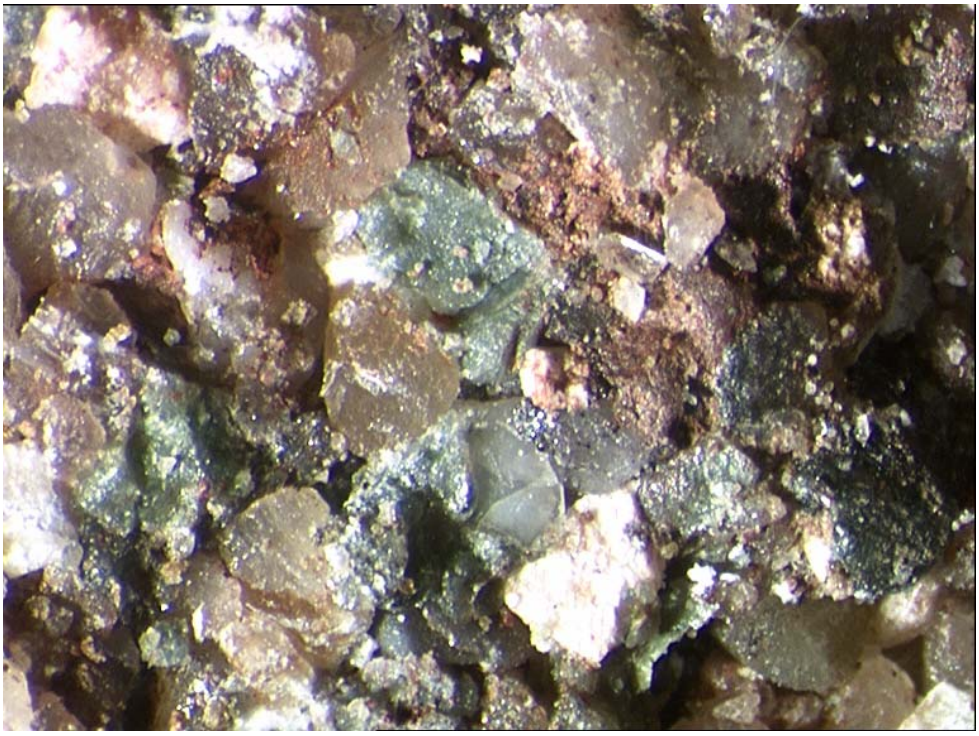

Figure 13. Close up of hand specimen of the Canonbie Bridge Sandstone Formation to show the lithic nature (light green grains). The sandstone is coarse-grained.

4.3 BECKLEES SANDSTONE FORMATION

4.3.1 Definition of the Becklees Sandstone Formation (new name)

Derivation of name: The name is derived from the Becklees borehole, which proves the greatest thickest of this formation.

Lithology description: Interbedded sandstones (70-90 %) and reddish brown mudstones and reddish brown palaeosols including calcretes. Sandstones are fine- to medium-grained, orange brown to bright reddish brown and pinkish brown, moderately to well sorted and typically lack mica. Sandstones are generally cross-bedded and occur in thick successions (10-30 m), forming sharp to erosively based channel sandstones in multi-storey units, some showing upwards-fining. In hand specimen the sandstones contain a noticeably lower proportion of lithic clasts than the underlying Canonbie Bridge Sandstone Formation (Figure 15); this is confirmed by thin section analysis. The sandstones have lower gamma ray (GR) API values compared with the underlying Canonbie Bridge Sandstone Formation, with GR values in the Becklees borehole ranging from 39-120 API (mean 77.1, median 74.02 API). Limestones and thin coals are suggested to be present from cuttings descriptions from the Becklees borehole (NY37SE 3), although these do not appear to be common and were not recorded at outcrop.

Type locality. Outcrops along the River Esk opposite Dead Neuk [339360 576310], where approximately 28 m of the lower part of the formation is present.

Reference sections. Outcrops of the lower part of the formation along the River Esk at Mason's Stream [339813 575760] and an uncored section in the Becklees borehole (NY37SE 3) from 281.7-485.3 m (downhole geophysical log depths).

Lower boundary. The base of the formation occurs at outcrop at [339360 576310] and [339812 575760]. It is taken at the abrupt junction of softer, orange brown, fine- to medium-grained sandstones that lack appreciable lithic grains that rest on the fine- to coarse-grained reddish brown lithic sandstones of the Canonbie Bridge Sandstone Formation (Figure 16). In uncored boreholes the boundary is marked by a shift in the gamma ray log to lower values, reflecting the change in composition from lithic rich (higher GR values) sandstones of the Canonbie Bridge Sandstone Formation to lithic poor, 'cleaner' sandstones with lower GR values (Becklees Sandstone Formation) (Figures. 8 and 14). This can be seen for example at 485.3 m (downhole depth) in Becklees borehole (NY37SE3) and 214 m (downhole depth) in Glenzierfoot (NY37SE2). Unusual sand-filled polygonal cracks have been recorded at the boundary between the Canonbie Bridge Sandstone Formation and the Becklees Sandstone Formation along the River Esk at [339360 576310].

Upper boundary. The top of the formation is taken at the sharp unconformable junction at the base of the Permian, which marks the Variscan unconformity. The contact is exposed in the bed of the River Esk at Mason's Stream, GR [3977 7570], where Permian breccia overlies the formation.

Thickness. The top of the formation is truncated at the Sub-Permian unconformity. Thus its full thickness is not known, but up to 203.6 m is proved in the Becklees Borehole (NY37SE3).

Geographical limits. The formation is restricted to the central parts of the Canonbie Syncline, between the Evertown (NY37NE14), Becklees (NY37SE3) and Knottyholm (NY37NE6) boreholes.

Age. Westphalian D

Subdivisions. No formal subdivision of this formation is proposed.

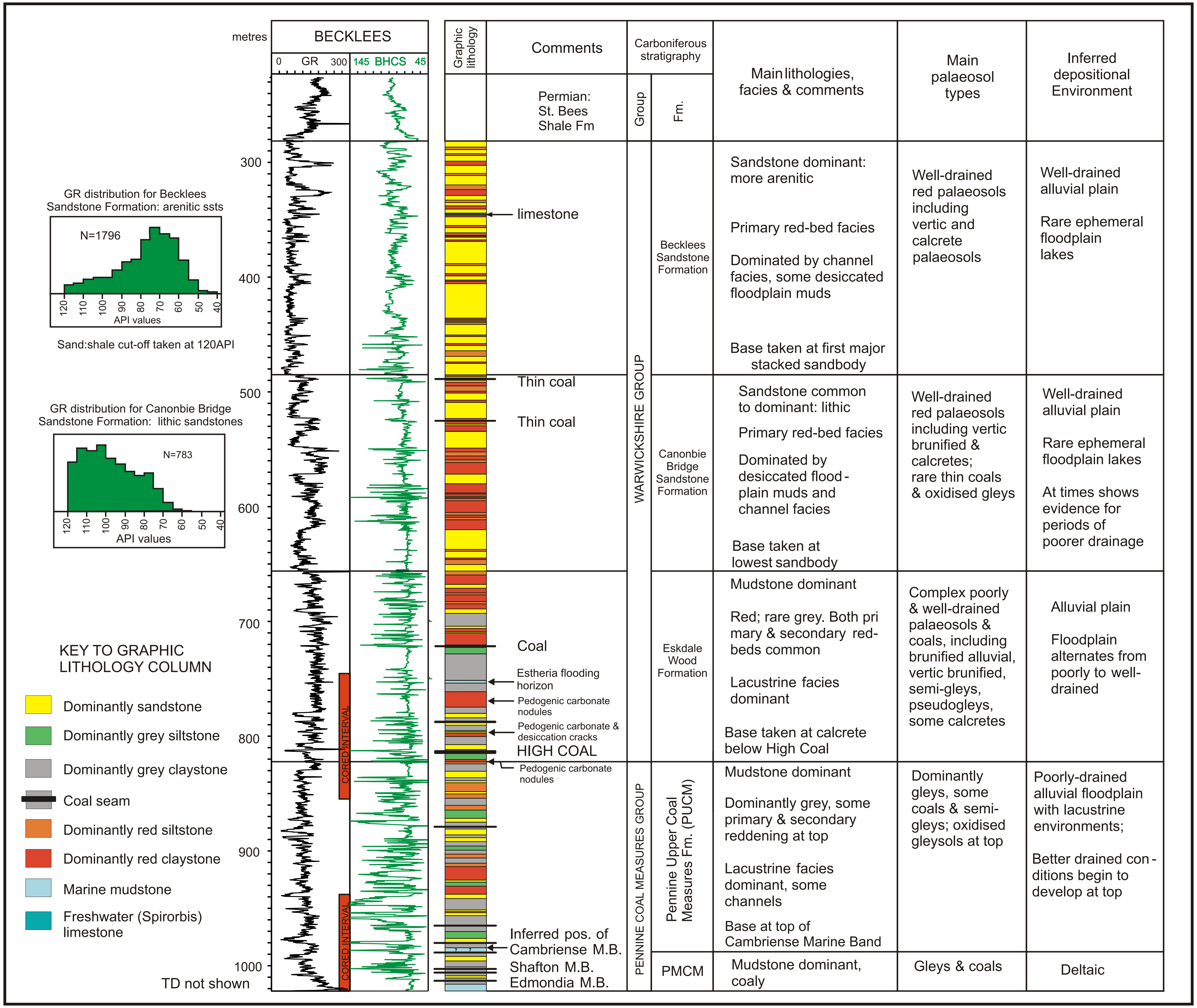

Figure 14. Summary of the main features of the Warwickshire Group (Becklees Borehole).

Figure 15. Close up of hand specimen of the Becklees Sandstone Formation. Lithology a poorly sorted, very fine- to medium-grained quartz arenitic sandstone that lacks appreciable lithic grains.

Figure 16. Junction between Canonbie Bridge Sandstone and Becklees Sandstone formations (arrowed). View looking east at Mason's Stream, River Esk [339813 575760].

5 Sedimentology of the Warwickshire Group

A number of facies associations are present in the red-bed part of the Upper Carboniferous succession at Canonbie (Table 3). Facies associations are groups of facies that are genetically or environmentally related (Reading, 1986). These facies associations are:

- Channel belt
- Overbank-floodplain
- Lacustrine
- Palaeosol

Facies Associations	Facies
Channel belt	Channel
Overbank-floodplain	Overbank Crevasse splay
Lacustrine	Lacustrine limestone Lacustrine mudstone Lacustrine delta
Palaeosol	Brunified alluvial palaeosol Vertic brunified palaeosol Calcimorphic palaeosol Semi-gley palaeosol Pseudogley palaeosol Oxidised gley palaeosol Organic hydromorphic (coals)

Table 3. Main facies associations and facies recognised from the red-bed part of the Warwickshire Group of the Canonbie area.

5.1 CHANNEL-BELT FACIES ASSOCIATIONS

There is only one facies in the channel belt association: channel.

5.1.1 Channel facies

Description: This facies comprises erosively based units of sandstone that typically vary from 2 to 10 m in thickness (Figure 17). In places sandbodies can reach a maximum of 40 to 50 m in thickness, but these clearly represent vertically stacked amalgamations of individual channels, separable by prominent erosion surfaces and conglomerate lags. They occur interbedded with the floodplain and palaeosol facies associations, described later. Sandstone typically comprises greater than 80 % of the fill, and varies from fine- to coarse-grained, commonly with scattered granules or pebbles of both intraclasts and extraclasts. Subordinate horizons of conglomerate, silty sandstone, siltstone and claystone also occur, but they typically form beds less than 0.2 m in thickness. The conglomerate dominantly comprises clasts of red mudstone, although very coarse-grained to granular rock fragments and quarztite also occur.

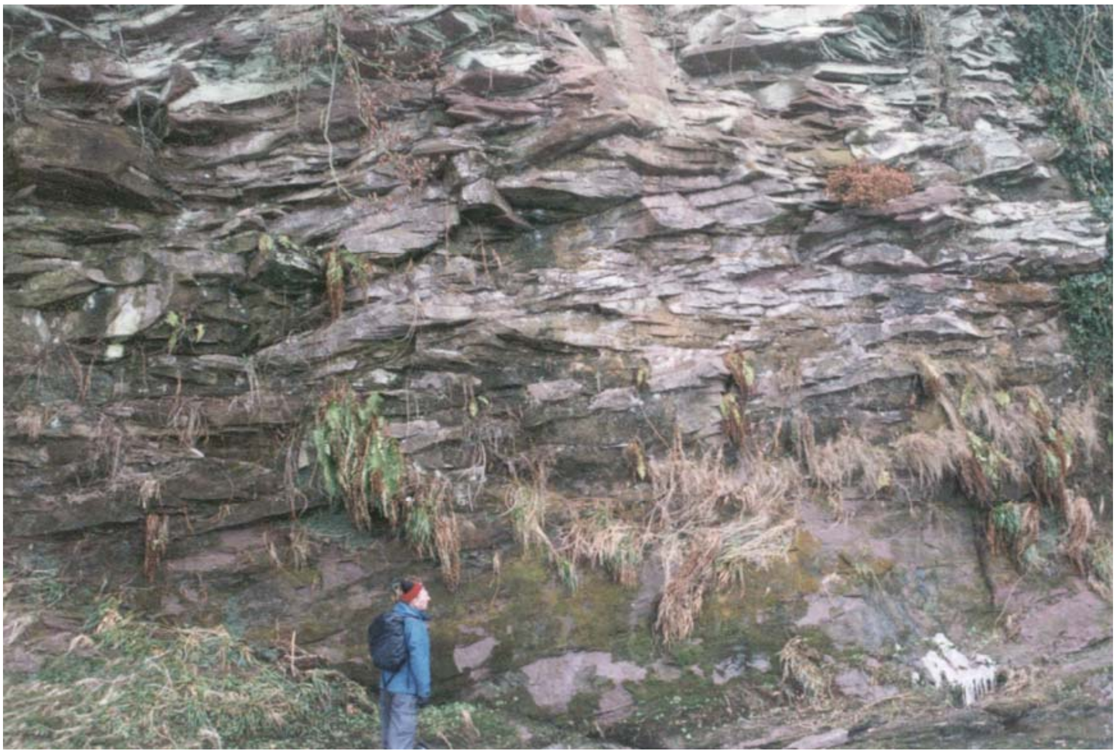

Figure 17. Example of cross-bedding within the channel facies, Canonbie Bridge Sandstone Formation, west bank of the River Esk [339180 576900]. View looking south-west.

In hand specimen, two main types of sandstones can be recognised in terms of colour and texture. The first type, which appears to be the most common, outcrops to the north and south of Canonbie Bridge (Canonbie Bridge Sandstone Formation). It varies from purple brown, pinkish brown to pinkish grey and is typically medium- to coarse-grained, poorly to moderately sorted and detailed examination shows that greenish grey grains (rock fragments) form an appreciable component. The sandstone can also be micaceous. The second type (Becklees Sandstone Formation) has a more distinctive orange brown or ‘brick red’ colour and only occurs downstream (south) of Canonbie Bridge. This sandstone is typically finer-grained (fine- to medium-grained) than the first type, is generally better sorted, has more rounded grains and has less mica; the greenish grey grains appear to be lacking. Thin sections were taken of each of these types of sandstone, the results of which are discussed later in this report.

Internal erosion surfaces are also a common feature, especially within the thicker stacked units. Trough and planar tabular cross-bedding are the dominant sedimentary structures, with high and low angle foresets recognised. Individual sets are generally fairly small (0.2 – 0.3 m in thickness), although rarely larger sets have been recorded (Figure 18). Also present, but less prevalent, are sets of current ripple cross-lamination, climbing ripples, plane beds, flat lamination and soft-sediment deformation. Sandstones are commonly micaceous and carbonaceous debris and some plant fragments (e.g. *Cordaites*) are present in places. Palaeocurrents measured in the field from these Canonbie Bridge Sandstone Formation sandbodies appear to show a flow direction towards the south-west (vector mean =250°) (Figure 19). However, when corrected for structural dip they show a distinct shift, with a dominant flow direction towards the north-north-west (vector mean=334°) (Figure 19). The removal of structural dip was carried out using proprietary dip analysis software (Table 4). To check the validity of the data produced by the software package a sample of the data (c.20%) was checked using the traditional stereonet approach to removing structural dip. It was found that there was a very good match between the two analyses. The few palaeocurrent measurements that were taken from the Becklees Sandstone Formation suggest palaeoflows directed towards the southern quadrant (Figure 19).

Figure 18. Climbing dunes at the top of a channel sandstone. Canonbie Bridge Sandstone Formation, River Esk [339540 576710].

LOCALITY DETAILS			OTHER INFORMATION			BEDDING DATA		ORIGINAL PALAEOCURRENT DATA				ROTATED PALAEOCURRENT DATA	
Location	Eastings	Northings	Facies	Sandstone type	Sedimentary structure type	Bedding azimuth	Bedding dip	Palaeocurrent azimuth	Palaeocurrennt dip	Bedding strike	Quality	software_rotated dip	software_rotated azimuth
River Esk	339200	576862	Channel	Lithic	Xb	157	27	266	14	67	av	34	313
River Esk	339149	577050	Channel	Lithic	Xb	157	27	192	38	67	p	21	232
River Esk	339243	576924	Channel	Lithic	Xb	186	20	10	10	96	P	30	7
River Esk	339177	577014	Channel	Lithic	Xb	186	20	40	20	96	P	38	24
River Esk	339570	576579	Channel	Lithic	Xb	190	23	250	10	100	g	20	344
River Esk	339528	576750	Channel	Lithic	Xb	190	23	210	38	100	g	18	233
River Esk	339528	576750	Channel	Lithic	Xb	190	23	235	33	100	av	23	276
River Esk	339528	576750	Channel	Lithic	Xb	190	23	217	39	100	g	21	243
River Esk	339528	576750	Channel	Lithic	Xb	190	23	220	44	100	g	26	242
River Esk	339528	576750	Channel	Lithic	Xb	190	23	229	38	100	g	24	261
River Esk	339528	576750	Channel	Lithic	Xb	190	23	265	30	100	av	32	304
River Esk	339528	576750	Channel	Lithic	Xb	190	23	227	38	100	g	23	259
River Esk	339487	576812	Channel	Lithic	Xb	190	23	210	26	100	av	9	269
River Esk	339478	576821	Channel	Lithic	Xb	190	23	283	22	100	g	32	325
River Esk	339200	576862	Channel	Lithic	pcl	192	20	336	20	102	g	38	353
River Esk	339200	576862	Channel	Lithic	Xb	192	20	240	10	102	g	15	342
River Esk	339200	576862	Channel	Lithic	Xb	192	20	231	10	102	g	14	345
River Esk	339548	576494	Channel	Lithic	Xb	210	48	246	18	120	av/p	35	11
River Esk	339548	576494	Channel	Lithic	Xb	210	48	254	30	120	av/g	32	349
River Esk	339326	576278	Channel	Lithic	pcl	220	5	342	5	130	g	9	11
River Esk	339326	576278	Channel	Lithic	Xb	220	5	347	10	130	Av	14	4
River Esk	339326	576278	Channel	Lithic	Xb	220	5	358	8	130	g	12	14
River Esk	339326	576278	Channel	Lithic	Xb	220	5	334	16	130	Av	19	348
River Esk	339326	576278	Channel	Lithic	Xb	220	5	350	12	130	p	16	4
River Esk	339326	576278	Channel	Lithic	Xb	220	5	50	28	130	Av	33	49
River Esk	339484	576396	Channel	Lithic	Xb	226	8	280	15	136	g	12	312
River Esk	339484	576396	Channel	Lithic	Xb	226	8	262	10	136	av/g	6	315
River Esk	339837	576028	Channel	Lithic	Xb	260	24	314	10	170	av/g	20	55
River Esk	339837	576028	Channel	Lithic	Xb	260	24	304	10	170	av/g	18	57
River Esk	339360	576310	Channel	clean	Xb	220	5	204	30	130	p	20	197
River Esk	339490	576400	Channel	clean	Xb	218	17	235	40	128	a	24	245
River Esk	339812	575760	Channel	clean	Xb	228	31	190	30	138	p	19	119
River Esk	339200	576862	Channel	Lithic	pcl	192	20	336	20	102	g	38	353
River Esk	339326	576278	Channel	Lithic	pcl	220	5	342	5	130	g	9	13
River Esk	339219	576929	Channel	Lithic	R&F	157	27	184	27	67	av	14	292
River Esk	339174	577000	Channel	Lithic	R&F	158	26	215	26	68	g	24	274
River Esk	339161	577029	Channel	Lithic	R&F	158	26	110	26	68	av	21	46
River Esk	339243	576924	Channel	Lithic	R&F	186	20	318	10	96	Av	28	350
River Esk	339243	576924	Channel	Lithic	R&F	186	20	325	10	96	G	28	352
River Esk	339177	577014	Channel	Lithic	R&F	186	20	14	10	96	G	30	9
River Esk	339177	577014	Channel	Lithic	R&F	186	20	330	10	96	Av	29	354
River Esk	339528	576750	Channel	Lithic	R&F	190	23	227	28	100	vg	16	280
River Esk	339528	576750	Channel	Lithic	R&F	190	23	206	33	100	g	12	234
River Esk	339528	576750	Channel	Lithic	R&F	190	23	194	31	100	g	8	205

Quality	
P = poor	g = good
av = average	vg = very good

Sedimentary structure type	
Xb = Cross-bedding	R&F = cross-lamination rib and furrow
Txb = trough cross-bedding	pcl = primary current lineation

Table 4. Palaeocurrent data for the Warwickshire Group along the River Esk, Canonbie.

Interpretation: The prominent basal erosion surfaces associated with this facies indicates that flow was channelised; the variation in thickness suggests deposition occurred with channels of various sizes. Its association with floodplain and palaeosol facies suggests that they predominantly represent alluvial channel systems. At times fairly high energy discharge was likely, capable of transporting a range of sediment grain sizes. Conglomerates are mainly intraformational, derived from the reworking of existing floodplain material. The sedimentary structures are all indicative of unidirectional, current generated bedforms, formed from turbulent flows. Downstream migrating sandy bedforms form the dominant fill of the channels. Channels probably flowed towards the northerly quadrant. The internal erosion surfaces present within the stacked channels represent further episodes of channel scouring and are likely to have produced channel belts many kilometres in width. It is difficult to come to any conclusions regarding channel form, but the low spread of palaeocurrent data and the lack of significant heterolithics within the channels favours a low sinuosity channel type. Mudstones represent in-channel suspension deposits, draping the existing channel morphology. The different sandstone types recognised probably represent differences in provedance, this is discussed later in the paper/report.

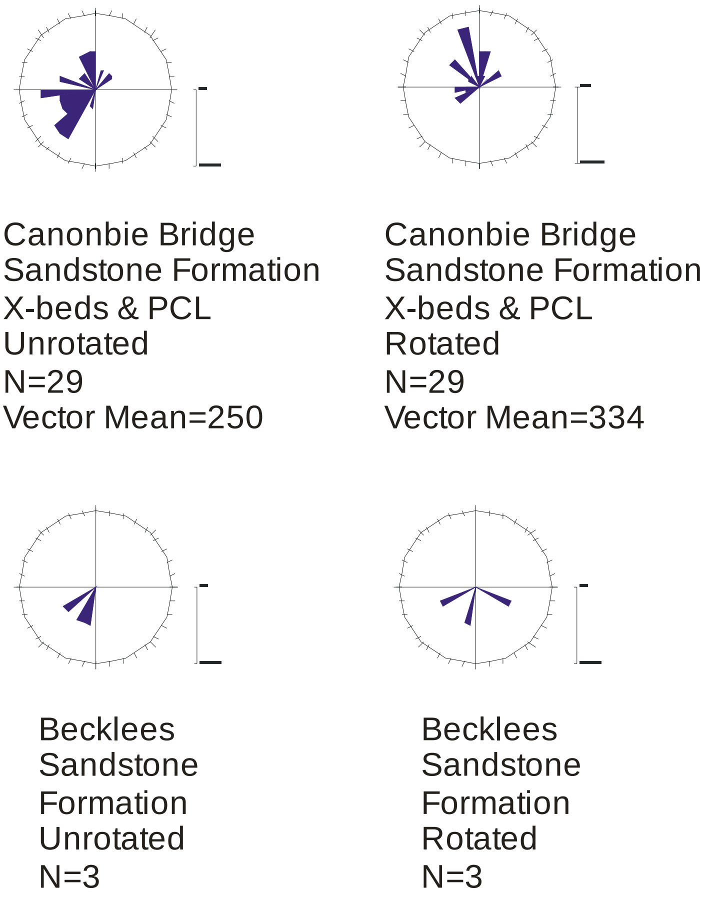

Figure 19. Palaeocurrent rose diagrams for the Warwickshire Group channel facies. Both field derived (unrotated) and restored with respect to structural dip (rotated) versions are show.

5.2 OVERBANK-FLOODPLAIN FACIES ASSOCIATIONS

This association comprises facies deposited adjacent to channel systems.

5.2.1 Overbank

Description: This facies comprises pinkish, purplish and reddish brown silty claystones, siltstones and rarely silty sandstones, in successions typically a few metres in thickness, rarely up to 23 m. The facies has been recognised at outcrop (Figure 20) and also in the Knottyholm Borehole (508-566'8"; =154.84-177.72 m). The facies is usually poorly bedded or massive and is characterised by the presence of common plant debris, stems of *Calamites, Cordaites, Sigillaria* and leaves, including *Neuropteris* (Figure 20). Reduction spots are also a common feature.

Figure 20. Overbank facies: Silty sandstone with *Cordaites* stem [339200 576950].

Interpretation: This type of facies has been recorded by a number of authors, including Elliott (1968), Guion (1984, 1987a, b), Fielding (1984a, b, 1986), Guion and Fielding (1988) and Guion et al. (1995b). Typically they have identified this facies as occurring marginal to distributary channel systems. The structureless nature of the facies probably results from rapidly deposited turbulent suspensions which flooded over the channel bank during high river stage. As the flow overtopped the channel banks, flow expanded, turbulence decreased and the suspended sediment load and abundant plant material was dumped proximal to the channel. The structureless nature suggests that suspended sediment concentrations may have been high and sedimentation rates rapid, inhibiting dynamic sorting mechanisms (Collinson and Thompson, 1989). The presence of abundant plant material is also a characteristic feature of overbank facies and resulted from the engulfment of the plant material on the channel banks, as a result of rapid deposition (Broadhurst and Loring, 1970).

5.2.2 Crevasse splay

Description: This facies comprises pinkish to reddish brown sandstone or silty sandstone in individual, sharp-based and upwards fining beds that are generally less than 0.6 m in thickness (Figure 21). In places a number of separate crevasse splays can stack vertically to form thicker sandstones, but these do not appear to form successions in excess of *c*.2 m in thickness. They are generally very fine to fine-grained, rarely medium-grained, although some can be conglomeratic. The base of the beds is usually sharp or erosive and a thin lag conglomerate can line the base. This typically comprises intraformational material, especially red mudstone clasts. The main sedimentary structures are current ripple cross-lamination and climbing ripples, although small scale sets of cross-bedding can be present. They typically occur interbedded either with lacustrine or palaeosol facies (Figure 21).

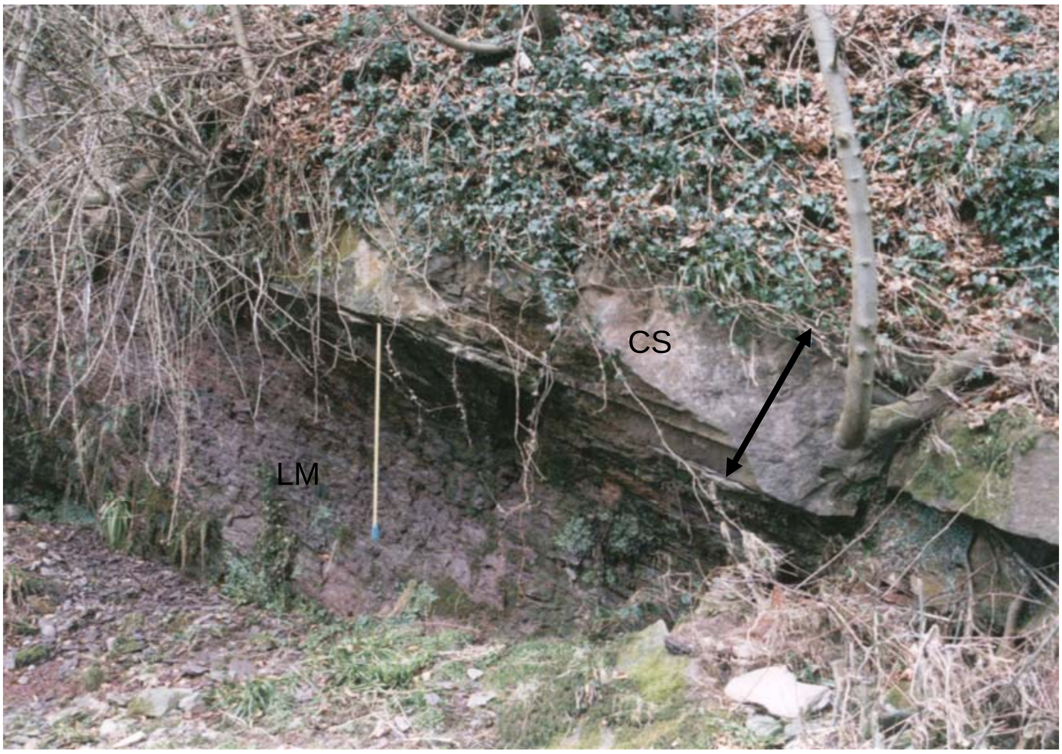

Figure 21. Example of the crevasse splay facies (arrowed and labelled CS), River Esk, Canonbie [339180 577000]. Lacustrine mudstone (LM) can be seen below the sandstone bed. View looking east. Tape measure for scale is extended for 1m.

Interpretation: These sandstones are interpreted as the deposits of sand-laden crevasse splays. These originated as a product of breaching or crevassing of a distributary channel bank, allowing floodwater from the channel to flow into the interdistributary lake as an unconfined, turbulent flow carrying a dominantly sandy bedload (Guion, 1984; Fielding, 1986). A decrease in the gradient and expansion of the flow leads to deceleration and deposition as a thin, laterally extensive sheet of sand. Their occurrence interbedded with lacustrine and palaeosol facies indicates that they represent floodplain deposits and suggests episodic deposition. High energy, turbulent flows probably carried the conglomeratic material, with mudstone clasts derived by erosion of floodplain material. Climbing ripples form during periods of bedload transportation and deposition associated with abundant fallout of suspended sediment. Cross-lamination and small-scale cross-bedding were generated by unidirectional lower flow regime currents.

5.3 LACUSTRINE FACIES ASSOCIATION

5.3.1 Lacustrine limestone

Description: This facies has been commonly recorded from cored boreholes in the area and, in the Rowanburnfoot borehole there are possibly up to 5 separate beds present. Lumsden et al. (1967, p.177) term them *Spirorbis* limestones and describe one from the Knottyholm borehole; this is greenish grey limestone, 0.1 m thick, containing *Spirorbis*, ostracods, fish scales and non-marine bivalves including *Anthraconauta*. The limestones vary from calcareous mudstones to fairly pure limestones. An example of this facies was examined on the eastern bank of the River Esk [GR 339155 577054]. It is 0.08 m thick and comprises a purple grey fine-grained, well-bedded limestone (Figure 22). There is no obvious internal structure and no obvious macrofauna. The well-bedded nature of the facies contrasts with the calcareous nodular appearance of the calcrete facies.

Interpretation: The non-marine fauna present in these limestones suggests that they represent the deposits of shallow, well-oxygenated fresh-water lakes. The calcareous nature of the deposits suggests that the water was hard and carbonate precipitation can be a common product of fresh-water lakes in humid environments (see Tucker and Wright 1990). This facies has been quite commonly described from similar stratigraphic positions in the uppermost Upper Carboniferous of the UK; see for example Brockbank (1891), Gibson (1905), Cantrill (1909), Pollard and Wiseman (1971) and Besly (1983). Although commonly termed Spirorbis limestones, Gibson (1905) and Besly (1983) prefer the term Entomostracan Limestone because *Spirorbis* tends to be uncommon and ostracods are more common. Besly (1983) has also described the presence of Euestheria in this facies elsewhere, suggesting that slightly brackish water conditions were occasionally developed. This may be related either to proximity to marine waters or, more likely, as a result of strong evaporation (Besly, 1983).

5.3.2 Lacustrine mudstone

Description: This facies comprises reddish brown, pinkish grey and greenish grey claystones, silty claystones and siltstones, in beds from 1 to 6 m thick (Figure 23). The dominant sedimentary structure is parallel lamination. In places, sandy lenses occur, and these are typically cross-laminated, with both current- and, less commonly, wave-generated structures identified. Desiccation cracks have also been recorded from this facies. Although not common, small flattened non-marine bivalves and ostracods have been recorded at outcrop and Barrett and Richey (1945) and Lumsden et al. (1967) have identified *Anthraconauta* and *Anthracomya* species in this facies. There are also rare burrows present in places and plant fragments (including stems) and comminuted plant debris also occur. There are small hematite nodules (?after siderite).

Figure 22. Lacustrine limestone facies (arrowed). B is a close up of A [339150 577050]. View looking SSE.

Figure 23. Example of a lacustrine mudstone facies, Warwickshire Group, River Esk. Note the presence of parallel lamination along which there is preferential splitting of laminae [339150 577050]. View looking SSE.

Interpretation: Low energy conditions for deposition are indicated by this facies on the basis of the fine grain size, the horizontal lamination and the presence of non-marine bivalves. These features are characteristic of deposition in a lacustrine environment (Picard and High, 1972). The fine grain size suggests that the sediment was transported into the lakes in suspension before settling onto the lake floor. The formation of lamination is related to subtle fluctuations in sediment supply, with cross-lamination indicating at least some sediment transportation by unidirectional tractional processes and some wave reworking. The presence of plant material within the lacustrine facies is related to the influx of plant material from the floodplain, carried into the lakes by channel systems and overbank flows. At times, organisms were able to colonise and burrow into the sediment leaving the visible traces of bioturbation. The presence of desiccation cracks indicates that, at times, some of these lakes dried out. However, generally they are thought to have formed perennial bodies of water, probably in excess of 2 m in depth. Reducing conditions are indicated by the presence of siderite, although later oxidation has resulted in their transformation into hematite.

5.3.3 Lacustrine delta

Description: This facies was only identified at one locality [approx. 577055 339140] and comprises an upwards-coarsening succession, 2.8 m thick. The lower part consists of laminated micaceous siltstones and sandy siltstones. The sandy siltstone contains up to 40 % sandy lenses with current and wave ripple cross-lamination, including form sets. The higher part of this facies comprises purple grey silty sandstones and very fine- to fine-grained sandstone. Current ripple cross-lamination is the dominant sedimentary structure, with some evidence for minor wave reworking; low-angle cross-bedding is also present. The top of the facies is marked by the development of brunified alluvial and calcimorphic palaeosols.

Interpretation: The lowermost, laminated siltstones probably represent deposition in a quiet water setting and a lacustrine interpretation is favoured. The overall upwards-coarsening form is indicative of the progradation of a sediment source and thought to represent the infilling of the lake by a small delta. Sediment was dominantly supplied from a feeding minor channel system. Deposition took place from bedload-transporting tractional currents that flowed down the delta front, generating ripples and small dunes. Waves were able to rework the lower parts of the delta during periods of low flow. Shallow water is suggested by the limited thickness (< 3 m) of the deltaic deposits, with lake infilling and emergence indicated by the development of palaeosols on the top of these sequences. These palaeosols are typically red and show features indicative of semi-arid conditions. The general paucity of this facies probably indicates that lake were fairly insignificant in terms of depths and extent on the floodplain, in contrast to the older, coal-bearing part of the Upper Carboniferous (Langsettian-Bolsovian).

5.4 PALAEOSOL FACIES ASSOCIATION

A palaeosol, as defined here, represents an ancient, preserved, *in situ* buried soil formed during a period of non-deposition and pedogenic (soil-forming) processes. It includes those sedimentary deposits called alluvial palaeosols, which are characterised by rapid rates of sedimentation. Palaeosols form a significant proportion of the finer-grained parts of the Upper Carboniferous succession exposed around Canonbie. Typically, their main characteristics are the partial or total destratification of the host lithology as a result of pedogenic processes (roots and burrows), the presence of distinct horizonation, varied colouration or mottling, the presence of roots, leaching or eluviation of material and precipitation of concretionary nodular material. There are two approaches to palaeosol classification. The first attempts to relate the palaeosol to modern day soils and use the same classification scheme (see Retallack, 1990) whereas the second is not concerned with naming the palaeosol but concentrates on their field appearance and an appreciation of the processes that operated during their development (see Besly and Fielding, 1989). The approach used here is a genetic one.

5.4.1 Brunified alluvial palaeosol

Description: This facies comprises reddish brown to purplish red claystones, silty claystones and siltstones in beds from 0.5 to 3 m in thickness. Within these beds the facies is typically internally structureless to weakly laminated with no obvious zonation (Figure 24); a pedobrecciated fabric can sometimes be seen on bedding surfaces and listric surfaces and desiccation cracks are a common feature (Figure 25). These are often infilled with sediment similar in grain size to the surrounding matrix which makes their identification difficult. Rooting is present but is not common and can be picked out as thin red subvertical traces up to a few centimetres in length. Plant debris also occurs but is not common. Greenish reduction mottling can be a common feature and often forms a halo around root traces. There are occasional small calcrete nodules present.

Interpretation: The facies represents the deposition of mud from weak subaqueous flows which then dried out, resulting in the development of a desiccated and often brecciated fabric. The presence of desiccation cracks indicates well-drained conditions. Listric surfaces are small-scale curved and slickensided surfaces, thought to have formed by the compactional reorientation of clay minerals associated with the presence of organic debris (Schiller, 1980). Temporary hiatuses in sedimentation were marked by plant colonisation and rooting. However, the relatively minor amounts of rooting associated with this facies indicates fairly regular sedimentation on an actively aggrading alluvial plain which reduced the amount of pedogenic modification. The presence of isolated pedogenic carbonate nodules indicates that the two depositional environments are transitional, with the calcimorphic palaeosol representing a more evolved type. The greenish grey mottling present may reflect a temporary change to poorly drained conditions, allowing minor amounts of reduction of the facies to occur. It is clear that the outer contact between the roots and the sediment formed a pathway along which reducing water could flow.

This type of palaeosol appears to have similar characteristics to those described as brunified alluvial soils (Duchaufour, 1982, pp185-188). Alluvial soils are immature and are commonly developed on modern day alluvial and deltaic plains close to rivers where they are often flooded (Duchaufour, 1982; Besly and Fielding, 1989). They represent plant colonisation of an actively aggrading sediment surface and can be poorly drained (grey alluvial soil) or freely draining (brunified alluvial soil) (Duchaufour, 1982). Brunification is a term to describe the development of brown colour in the soil, formed in part by the presence of hydrated iron oxides. Reddening is a common process associated with this type of soil formation. The process is termed rubifaction and either forms by accumulation of detrital ferric iron from lateritic source rocks or from the oxidation of iron to form hematite under free draining conditions (Fischer and Schwertmann, 1975; Besly and Turner, 1983; Besly and Fielding, 1989).

Figure 24. Brunified alluvial palaeosol, Warwickshire Group, Canonbie River Esk section. Note the red (i.e. brunified) colour, faint lamination and mottling (m) [339440 576360]. View looking south-east.

Figure 25. Close up of sand-filled desiccation cracks [339330 576290].

5.4.2 Vertic brunified palaeosol

Description: This facies is characterised by brick red to reddish brown claystones, silty claystones and siltstones in beds from 0.5 to 1 m in thickness. They are destratified and commonly have a rubbly texture; listric surfaces and desiccation cracks also occur (Figure 26). Also present in some, but not all, examples identified are concave upward planes ("slickensides" of some publications) (Figure 27). These are up to 1.1 m across and have a height 0.15 m. Calcrete nodules also form a minor part of this palaeosol type. These can occur either scattered randomly within the sediment or concentrated in the lower part of the profile. Locally reduced zones are also present.

Interpretation: This facies is interpreted as a palaeosol and has features similar to vertisols. Classic vertisols are dark coloured soils, rich in swelling clays and form through the successive shrinking and swelling of montmorillonitic clays as a result of seasonal changes in precipitation in an overall semi-arid setting. As the presence of montmorillonitic clays has not been demonstrated it is best to describe this palaeosol type as having similar features to those of a vertisol, so the term vertic brunified palaeosol is favoured here.

The presence of the rubbly texture is believed to be have formed by the sediment breaking itself up in response to repeated phases of wetting and drying. This fabric is similar to those described from modern playa lakes (Smoot, 1981; Smoot and Olsen, 1988) and is a common feature of vertisols. The concave upward planes are interpreted as pseudo-anticlines, representing the subsurface expression of a surface micro-relief known as gilgai (Wilding and Tessier, 1988). This microrelief is formed due to clay horizons shrinking and swelling with alternate wetting and drying, which forces blocks of soil material gradually upwards to form mounds. Successive wetting and drying cycles can also lead to the deposition of calcium carbonate in what is known as a calcic horizon, usually found in a lower B or upper C horizon in the soil profile. Locally reduced zones represent "drab haloes", formed by the removal of iron by dissolution.

Remobilisation is favoured along flow paths such as desiccation cracks, ped boundaries and in the presence of organics and typically reprecipitates nearby.

Figure 26. Vertic brunified palaeosol, with complex brecciated ?desiccated fabric, picked out by greenish reduced horizon [339440 576360]. Lens cap for scale is 5cm across.

5.4.3 Calcimorphic palaeosol

Description: This type of palaeosol comprises beds of structureless reddish brown mudstone up to about 0.5 m thick that are characterised by the ubiquitous presence of displacive nodules of pedogenic calcium carbonate (calcrete). The calcrete nodules, more correctly termed glaebules (Brewer 1964), are white to cream in colour, vary from sub-spherical to ellipsoidal in form and range from 0.01 to 0.13 m in size. Their proportion varies from weakly developed, isolated nodules to coalesced nodular horizons that form up to 80 % of the deposit (Figures 28 and 29). Glaebules vary from sub-spherical to ellipsoidal in form and range from 0.01 to 0.13 m in size. More ellipsoidal nodules tend to show a vertical development. Pedogenic listric surfaces are a common feature of this facies, together with desiccation cracks and rare preserved roots.

Interpretation: The muddy matrix of this facies was probably deposited by overland subaqueous flows, but later pedogenic processes have significantly modified the deposit. The presence of desiccation cracks indicates well-drained conditions were prevalent. The glaebules form by the displacive growth of calcium carbonate in the vadose zone of the soil (Wright and Tucker, 1991). This occurs by evapo-transpiration of carbonate saturated pore waters drawn to the surface by capillary forces (Scoffin, 1987, p.149). The presence of this type of palaeosol is generally taken as an indicator of formation in a semi-arid climate and the relatively low PCO_2 in arid and semi arid soils is now thought to be a significant contributory factor in the precipitation of calcium carbonate (Marion et al., 1985). The classification of calcrete maturity has been addressed by a number of workers, but the scheme of Machette (1985) is commonly used. He recognised 6 stages, with Stage 1 the most immature, marked by a few calcareous nodules and Stage 6 the most mature, marked by an indurated calcareous hardpan. The beds with more isolated calcrete glaebules represent Stage 1, aggradational calcimorphic palaeosols, whereas the more coalesced nodules represent a Stage 3 calcrete. The presence of roots and desiccation cracks also support the palaeosol interpretation and points to a period of subaerial emergence of the sediment surface.

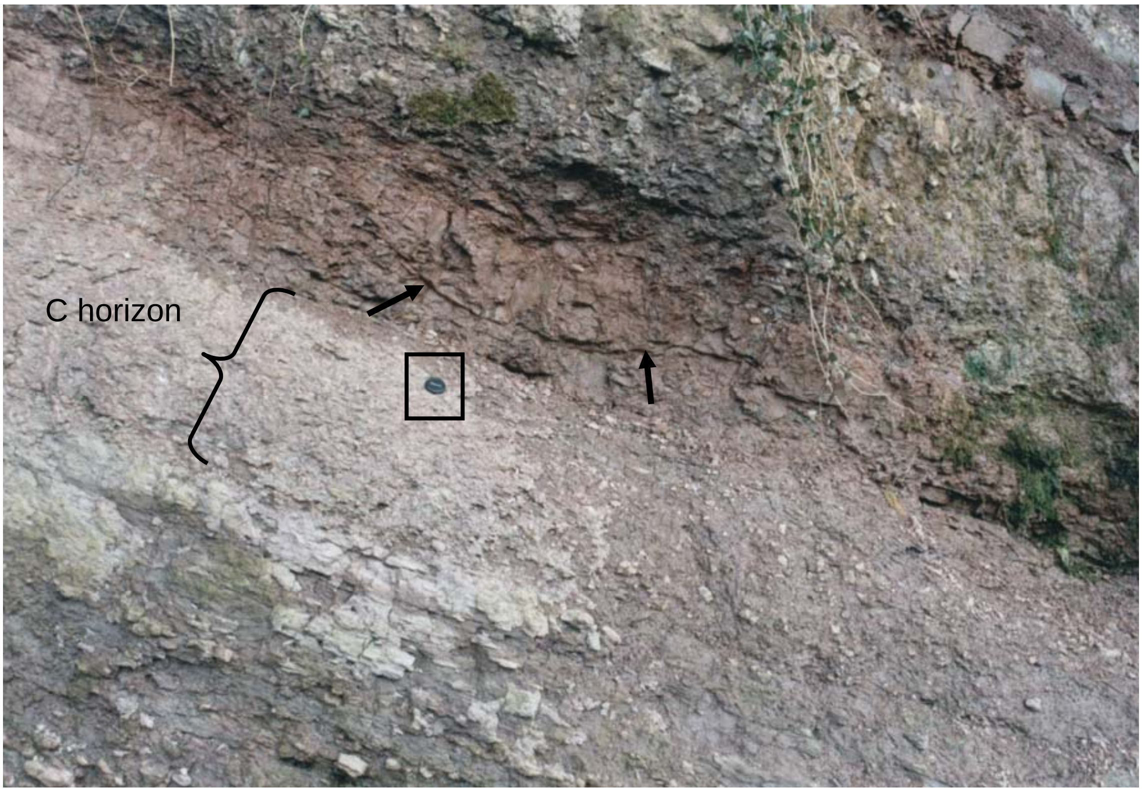

Figure 27. Vertic brunified palaeosol. Note the prominent curved 'slickensided' surfaces (wedge-shaped peds) in the B horizon (arrowed) overlying nodular accumulations of pedogenic carbonate (calcrete) in the underlying C horizon [339155 577054]. View looking NE. Lens cap for scale is 5cm across.

5.4.4 Semi-gley palaeosol

Description: This was not examined at outcrop, but core descriptions (e.g. from Becklees borehole, 834.1-835.7 m and Bogra borehole, 166.95-168.0 m) allow the facies to be described in detail. This type of palaeosol comprises a structureless claystone, silty claystone and siltstone. The main features are the colour, typically grey to brownish grey, locally reddish brown mottling, and the common occurrence of sphaerosiderite. Coaly laminae and roots are a common feature and reduction spots also occur. It can occur interbedded with better-drained palaeosols such as calcimorphic palaeosols, but typically occurs in the lower part of the red-bed succession and represents a facies present in the transition between the grey and red-beds.

Figure 28. Calcimorphic palaeosol (calcrete), with coalesced carbonate glaebules [339150 577050]. Lens cap for scale is 5cm across.

Figure 29. Calcimorphic palaeosol (calcrete), with scattered carbonate glaebules [339300 576260].

Interpretation: This facies shows mainly features of poor drainage, and formation under reducing conditions. However, the presence of sphaerosiderite indicates the mobilisation of iron by capillary action during periods of better drainage and is indicative of a temporary lowering of the water table to allow some oxygenation of the soil (Besly and Fielding, 1989). The reddish brown and brown colours also indicate slightly better drained conditions. The brown colour represents hydrated iron oxide which becomes stable in conditions where there is not enough organic matter to cause reduction and not enough time for complete oxidation to hematite (Van Wallenberg, 1973; Guion et al., 1995b). The interbedding of this facies with calcimorphic palaeosols indicates that the environment fluctuated between better-drained and hydromorphic conditions.

5.4.5 Pseudogley palaeosol

Description: This type of palaeosol is not common but has been recorded at outcrop [e.g. approx 339202 576947]. It consists of bright brick red to reddish brown silty claystone to claystone in beds up to 0.5 m in thickness. The facies is totally destratified and contain abundant listric surfaces (Figure 30). Rooting is present, sometimes these are preserved as black roots, other examples represent oxidised traces of former roots. Some grey, green and yellow-white mottling occurs, this commonly occurs as a fringe surrounding the roots (Figure 30). Rare *Stigmaria* are also present. The lithology tends to be more greyish along the horizon where *Stigmaria* are present.

Interpretation: The term pseudogley (or surface water gley) is used for a palaeosol that is usually red in colour, resulting from the presence of ferric iron, but shows evidence for periods of less well-drained conditions that lead to hydromorphic soil conditions. This is typically represented by reduction and mottling concentrated around ped boundaries and root channels (Bown and Kraus, 1987). PiPujoul and Buurman (1994) provide a review of the characteristics of pseudogleys and the processes responsible for their formation. The facies described here is believed to show similarities to pseudogleys. The red colour of the bulk of the palaeosol is thought to be a primary pedogenic feature, formed by the weathering, dehydration and recrystallisation of ferromagnesian minerals. Hence the soil profile is indicative of largely oxygenated conditions of formation. The mottling is indicative of later reduction, which occurs largely around roots. The pseudogleying forms where ponded surface water has allowed reducing conditions to penetrate down channels such as root traces and earlier formed desiccation cracks. The yellow colouration probably results from the presence of the mineral goethite. This mineral is attributed to gleying and its formation is favoured by low temperature, high organic matter content and high water activity (PiPujol and Buurman, 1994). Its concentration around roots suggests that the extensive rooting provided pathways for reducing waters to flow.

These soils are typical in regions with seasonal weather, with a long and dry summer and short wet seasons. These soils are not saturated with water during most of the year and much of the pore system is filled with air (PiPujol and Buurman, 1994). Hence dissolved ferrous iron oxidises to Fe(III) and converts to the insoluble Fe(III)-(oxy)-hydrates. Any water than penetrates the soil (rain- or ground-water) moves through larger pores and cracks and along root channels, resulting in iron reduction being concentrated along these zones (PiPujol and Buurman, 1994). The formation of a pseudogley is favoured where there is a temporary high water table and an impermeable layer close to the surface (Duchafour, 1982, p.341).

Figure 30. Pseudogley palaeosol with common pedogenic listric surfaces and goethitic mottling (arrowed) along former roots [339220 576930]. View looking north-east. Lens cap for scale is 5cm across.

5.4.6 Oxidised gley palaeosol

Description: This facies is characterised by pinkish grey to reddish grey brown claystones, silty claystones and siltstones in beds up to about 2 m in thickness. These contain abundant listric surfaces, which are typically characteristic of poorly drained soils (Guion et al., 1995b) (Figure 31). Other features include partially or completed oxidised siderite concretions. The presence of rooting, including *Stigmaria*, is a common feature of this facies, although many have clearly undergone some oxidation and are present only as traces. Red, yellow and green mottling is common as haloes along former roots and reduction spots also occur. One example of the facies at outcrop [approx 339053 577105] was overlain by a 0.07 m thick fine-grained red limestone with coaly-carbonaceous stringers (Figure 9).

Interpretation: This type of palaeosol is interpreted as an alluvial hydromorphic soil (gleysols) that originally accumulated under poorly drained, reducing conditions and was later oxidised during early burial. The main lines of evidence to support this include the patchy reddening which indicates incomplete oxidation of the sediment, the common occurrence of listric surfaces and *Stigmaria*, the presence of which indicate waterlogged conditions. Listric surfaces typically form in organic rich sediments during early compaction (Schiller, 1980; Besly, 1983; Besly and Fielding, 1988). The presence of relict siderite nodules partially replaced by hematite indicates a formation originally under reducing conditions and later replacement as a result of oxidation during early burial (Besly and Fielding, 1989).

Figure 31. Oxidised gley palaeosol. Note the common occurrence of polished pedogenic listric surfaces. Lens cap for scale is 5cm across.

The fine-grained red limestone with abundant coaly material is interpreted to represent the former position of an oxidised coal. This is suggested by its position immediately above an oxidised gley palaeosol, together with the presence of degraded coaly material that represent remnants of the former coal. The transformation from coal to limestone is a well known phenomenon associated with secondary oxidation and reddening of the Coal Measures and has been described in detail from the Ayrshire Coalfield by Mykura (1960). Alteration appears to have taken place at a low temperature with the coals first replaced by calcite that may in turn have been replaced by dolomite or siderite (Mykura, 1960). Alteration of coals to limestone has taken place within a vertically restricted belt in the lower part of the zone of reddening and it is assumed that the process of oxidation played an important role in such replacement. The lateral passage into limestone appears to be dependant on the presence of calcium- and magnesium-rich fluids which, in the case of the examples described by Mykura (1960), were supplied from surface decomposition of Permian olivine-basalts. The passage of coal into limestone is usually associated with an overall reduction in thickness of the bed and the reddening of the adjacent strata. These changes can occur over relatively short distances. Indeed Mykura (1960, p.79) described the lateral passage from a normal coal, 1.4m thick, into a 0.05m bed of siderite over a distance of 1.22m, although this rapid lateral transformation is quite unusual and changes over distances of a few hundred metres seems to be more common (Mykura, 1960).

5.4.7 Organic hydromorphic (coals)

Description: No examples of this facies were seen at outcrop, however, records from boreholes suggest that this facies is present in the Warwickshire Group, although coals are not common. They have been greatly affected by oxidation so that typically they are present as “thin bands of irony rubble or, more often, have been replaced to some extent by dolomite…..” (Lumsden et al., 1967). Where coals are present they are typically associated with a return to grey-bed deposition

(Barrett and Richey, 1945). The thickest known coal in the Warwickshire Group is the High Coal, which is up to a maximum of 1.2 m. In the Forge Borehole three coal seams are known in close proximity to each other (0.18 m thick coal at 214 m, 0.36 m thick coal at 241 m and 0.41 m thick coal at 245 m), the lowest two are interpreted as part of the High Coal at the base of the group (Figure 8). Where present higher in the Warwickshire Group they typically form thin beds, noted as ‘traces’ in borehole logs. Picken (1988) suggested that all coals at Canonbie are bituminous and are generally good coking coals, with ash contents 9-12% and sulphur contents up to 2%. However, it is not known whether the Warwickshire Group coals were sampled.

Interpretation: This type of palaeosol is interpreted as the autochthonous deposition, burial and coalification of organic material. This organic material formed in shallow, submerged peat-forming mires (Gore, 1983), which developed on abandoned channels and on infilled lake surfaces. As this facies was not examined during this study they will not be treated in detail. However, their formation clearly indicates a return to poorly-drained, waterlogged conditions on the floodplain. The oxidation of coals is discussed in Section 5.4.6.

5.5 DEPOSITIONAL ENVIRONMENT

The lower part of the Warwickshire Group (Eskdale Wood Formation) shows a marked change in the sedimentary style from the typical poorly-drained, coal-bearing delta or alluvial plain conditions that typified the Pennine Coal Measure Group to one in which a complex fluctuation of depositional environments occurs, with the common establishment of emergent conditions leading to red-bed formation. Mudstone deposition was dominant and points to the importance of lacustrine conditions at this time. Reducing conditions characterised the lakes within the PUCM, leading to the deposition of grey muds. However, during the deposition of the Warwickshire Group there was an increasing tendency for the lakes to dry out, leading to emergent conditions. This was probably linked to water table lowering, which led to the formation of desiccation cracks and better-drained palaeosols. Initially these were typically semi-gley, pseudogley and brunified alluvial palaeosols, characterised by red and green mottling of the soil profiles. Incipient calcimorphic palaeosols also occur, characterised by isolated carbonate nodules in the brunified alluvial palaeosols.

These better-drained periods alternated with a return to poorly-drained conditions in which coals were able to form from the accumulation of peat. The thickest of these is the High Coal, present close to the base of the Eskdale Wood Formation. Also known are grey lacustrine mudstones containing a variety of different fauna including *Estheria* and non-marine bivalves (e.g. *Anthraconauta*, *Modiolaris* and *Naiadites*). Thin freshwater limestones have also been recorded from this formation, suggesting the development of shallow, well-oxygenated fresh-water lakes at various times, possibly characterised by high rates of surface water evaporation. Into these lake small lacustrine deltas formed, fed from river systems. The presence of thick sandstones with blocky gamma ray characters and thin bedded crevasse splays suggests that, at times, the environment developed into something more akin to an alluvial plain rather than a wetland.

Towards the top of the Eskdale Wood Formation there is an increasing tendency towards better-drained continental conditions and red-bed development, with brunified alluvial and calcimorphic palaeosols becoming dominant, some of which can be locally quite well developed. Also present, but less common than lower in the formation, are lacustrine facies. These are generally red but lack features indicative of well-drained conditions (e.g. desiccation cracks) suggesting periods of subaqueous deposition, possibly in reducing conditions. These were later oxidised and reddened, probably early in the diagenetic process. Channels are also known, but they are typically minor and do not form a significant percentage of the formation.

The Canonbie Bridge Sandstone Formation shows a marked change in sedimentation patterns, with the establishment of large fluvial systems in the area. Sandstone comprises up to 60-70% of the formation, forming large, erosively based channel systems that generally form multi-storey sandbodies. Such fluvial systems record the delicate interplay between subsidence, base-level change and sediment supply, with a high sediment load combined with increasing rates of accommodation space generation suggested for this period, allowing significant reworking on the floodplain. Typically these channels carried a coarse sediment load marked by presence of common lithic detritus, recycled from an earlier metasedimentary terrain. Palaeocurrent analysis suggests that these channel systems flowed from south to north; low sinuosity channel systems are proposed. Locally channel overbank and palaeosol facies are known. These typically comprise well-drained red facies, with brunified alluvial and calcimorphic palaeosols dominant. This indicates that the floodplain was generally well-drained, although a thin coal is reported from cuttings from high in the Canonbie Bridge Sandstone Formation in the Becklees borehole, which may represent a temporary reversal to poorly drained conditions.

Hence it is proposed that the environment during the deposition of the Canonbie Bridge Sandstone Formation comprised an alluvial plain crossed by large, northerly flowing braided channel systems that drained a terrain rich in lithic material. In the Midlands, Southern North Sea and South Wales similar large, northerly flowing river systems carrying abundant lithic material, deposited as the Pennant Sandstone and Halesowen formations, are indicative of a source from the rising Variscan mountains to the south, although it is unknown whether the channels from the Canonbie area are correlatable with these. Heavy mineral data does, however, suggest that Upper Carboniferous, Variscan sourced sandstones are known from West Cumbria (Hallsworth, 2001).

Finally, the last preserved unit within the Warwickshire Group is the Becklees Sandstone Formation. This again comprises a high proportion of sandstone (80-90%), and a distinct provedance change is suggested for this formation. These sandstones comprise sharp-based, cross-bedded sandbodies that contain considerable fewer lithic grains to that of the Canonbie Bridge Sandstone Formation. Deposition in channel systems is again indicated. There were too few palaeocurrent measurements taken to be confident of channel trends, although flow towards the southerly quadrant is suggested by the data. The unusual sand-filled polygonal cracks recorded at the boundary between the Canonbie Bridge Sandstone Formation and the Becklees Sandstone Formation may represent joints which, if this is the case, would point to a time gap between the two formations, marked by lithification of the Canonbie Bridge Sandstone.

In summary, the Warwickshire Group shows good evidence for increased sediment flux and for climatic controls on sedimentation. The presence of more evolved, red palaeosols and reddening in general is indicative of a gradual change to a more arid climate combined with local uplift. The climate change has been related to a rain shadow effect as a result of the growth of the Variscan mountain chain (Rowley et al., 1985). Large volumes of coarse sediment were supplied into the basin at times, with channels consistently flowing to the north. Major rejuvenation of the source area must be responsible for the abrupt increase in grain size, although the cannabilism of earlier metasedimentary terrains also occurred.

6 Petrography

Field analysis indicated that the Canonbie Bridge Sandstone Formation contained considerably more lithic grains than the Becklees Sandstone Formation. Hence five thin sections were prepared in order to describe and quantify briefly the main petrographic characteristics of the sandstones from these two formations (Table 5). There are clear differences shown by the two formations, with the Canonbie Bridge Sandstone Formation characterised by the presence of abundant lithic grains; these are much less common in the overlying Becklees Sandstone Formation. Brief petrographic descriptions are given in the following section.

Collectors prefix	Collectors number	Locality name	QS	Eastings	Northings	Location Information	RCS name or code (field identification)	Stratigraphy	Comments
NJN	98	River Esk	NY37NE	339360	576310	Natural outcrop, approx 300m downstream (SW) of Canonbie Bridge, on SE bank	Calcareous silicate-sandstone	Upper Carboniferous; Warwickshire Group: Becklees Sandstone Formation	Brick red sandstone. Very friable; very fine- to medium-grained, poorly sorted
NJN	99	River Esk	NY37NE	339813	575760	Natural outcrop, approx 1.3km downstream of Canonbie Bridge, on east bank. River Esk marked as Mason's Stream on 10k sheet close to this locality	Calcareous silicate-sandstone	Upper Carboniferous; Warwickshire Group: Becklees Sandstone Formation	Moderately sorted, brick red sandstone; fine-grained
NJN	100	River Esk	NY37NE	339789	576088	Approx 600m ESE from Dead Neuk. Close to where track from Park House joins River Esk. Outcrop set back from river.	Calcareous silicate-sandstone	Upper Carboniferous; Warwickshire Group: Canonbie Bridge Sandstone Formation	Medium-grained lithic sandstone
NJN	101	River Esk	NY37NE	339838	576005	Approx 600m ESE from Dead Neuk. Close to where track from Park House joins River Esk. Outcrop along back of river.	Calcareous silicate-sandstone	Upper Carboniferous; Warwickshire Group: Canonbie Bridge Sandstone Formation	Medium- to coarse-grained lithic sandstone
NJN	102	River Esk	NY37NE	339551	576501	Natural outcrop, approx 20m downstream (SSW) of Canonbie Bridge, on SE bank	Calcareous silicate-sandstone	Upper Carboniferous; Warwickshire Group: Canonbie Bridge Sandstone Formation	Medium-grained lithic sandstone

Table 5. Metadata for the thin sections prepared from the Canonbie Bridge and Becklees Sandstone formations. RCS = Rock Classification Scheme.

6.1 CANONBIE BRIDGE SANDSTONE FORMATION

Three thin sections were prepared of sandstones from this formation (NJN100-102). Sandstones are all lithic-arenites (Figure 32) and vary in grain size from medium- to medium- to coarse-grained. Representative photomicrographs of these sandstones are illustrated in figures 33-35. Sandstones are poorly to moderately sorted with subangular to subrounded grains. The dominant framework grain is quartz (45-52%); this is generally monocrystalline quartz, although polycrystalline quartz is a common component. Also present as a major constituent (36-42%) are rock fragments. The majority are typically fine foliated or schistose low grade metasedimentary clasts that show aligned micas and stretched quartz. Brown intraformational mudstone clasts and some igneous rock fragments also occur. Also present are common potassium feldspar grains and, in lesser quantities, elongate mica grains and sodium feldspar. Tourmaline is present as a trace mineral.

The main authigenic components are quartz overgrowths, present on detrital quartz and feldspar grains (Figure 33). Authigenic illite occurs in places as a grain replacive and pore filling cement; pore-filling kaolinite (as 'books') is also present in some samples. Clay/iron oxide 'dust' rims are typically present and iron oxide also occurs as pore filling cement in places. Compactional textures are quite common, particularly indented micas and rock fragments (Figure 34). Porosity is usually quite high, and is usually secondary, as a result of both grain and cement dissolution (Figure 34).

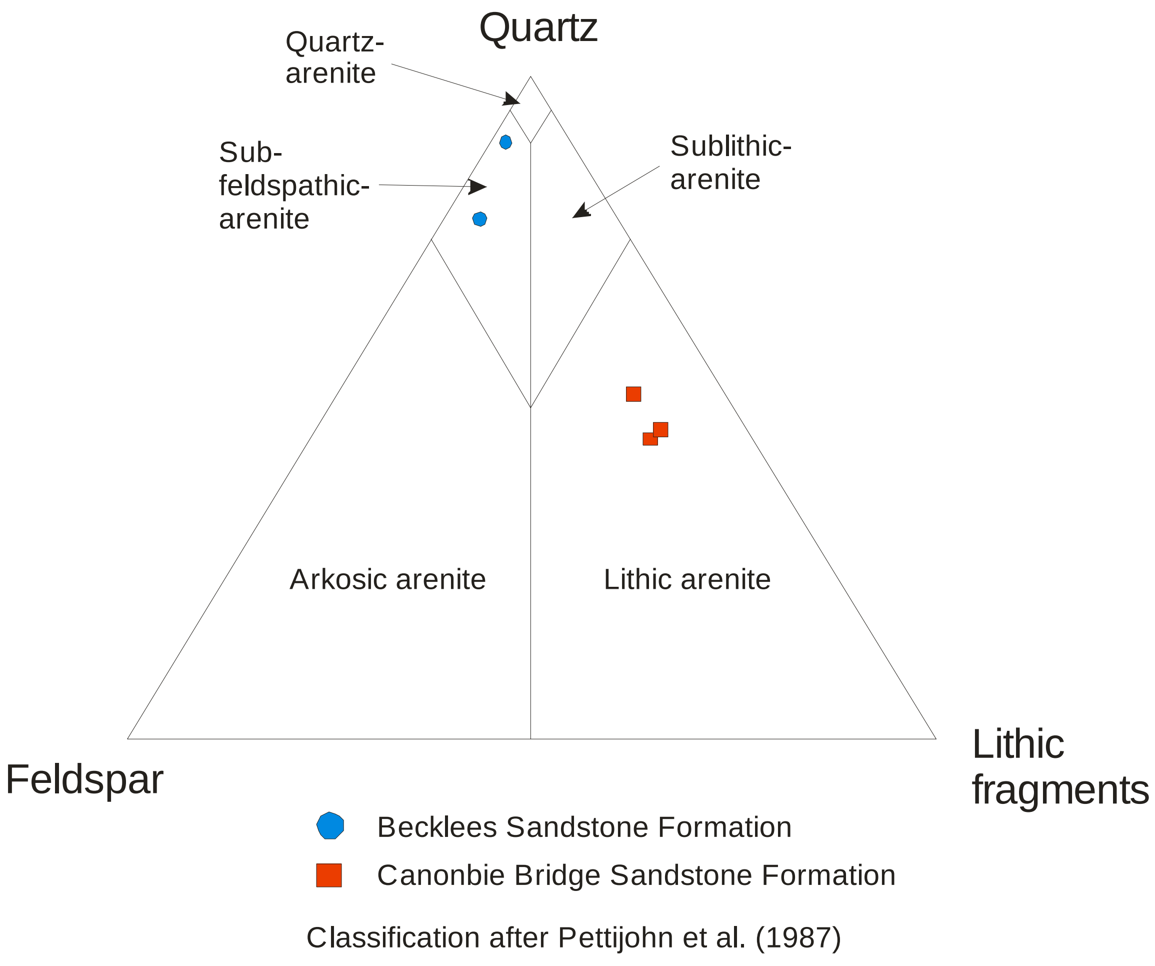

Figure 32. Ternary diagram (modified after Pettijohn et al., 1987) to show the classification of the Warwickshire Group sandstones.

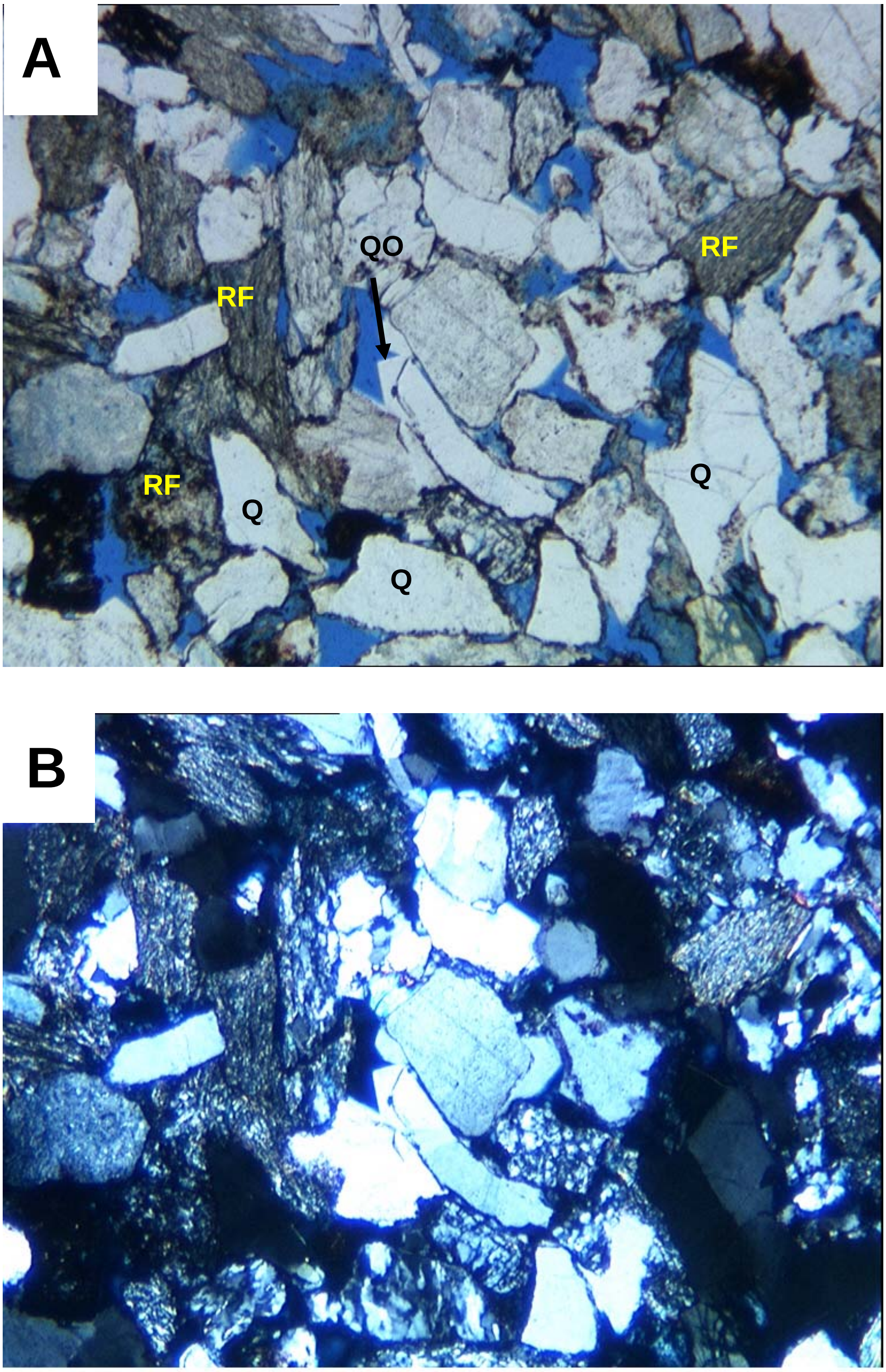

Figure 33. Thin section photomicrograph of the Canonbie Bridge Sandstone Formation (Sample NJN102). This is a medium-grained lithic sandstone; grains typically range from 0.25-0.5mm across (RF=rock fragments, Q=quartz, QO=quartz overgrowths). A. PPL and B. XP. In PPL any porosity present is indicated by blue-dyed resin impregnation of the thin section.

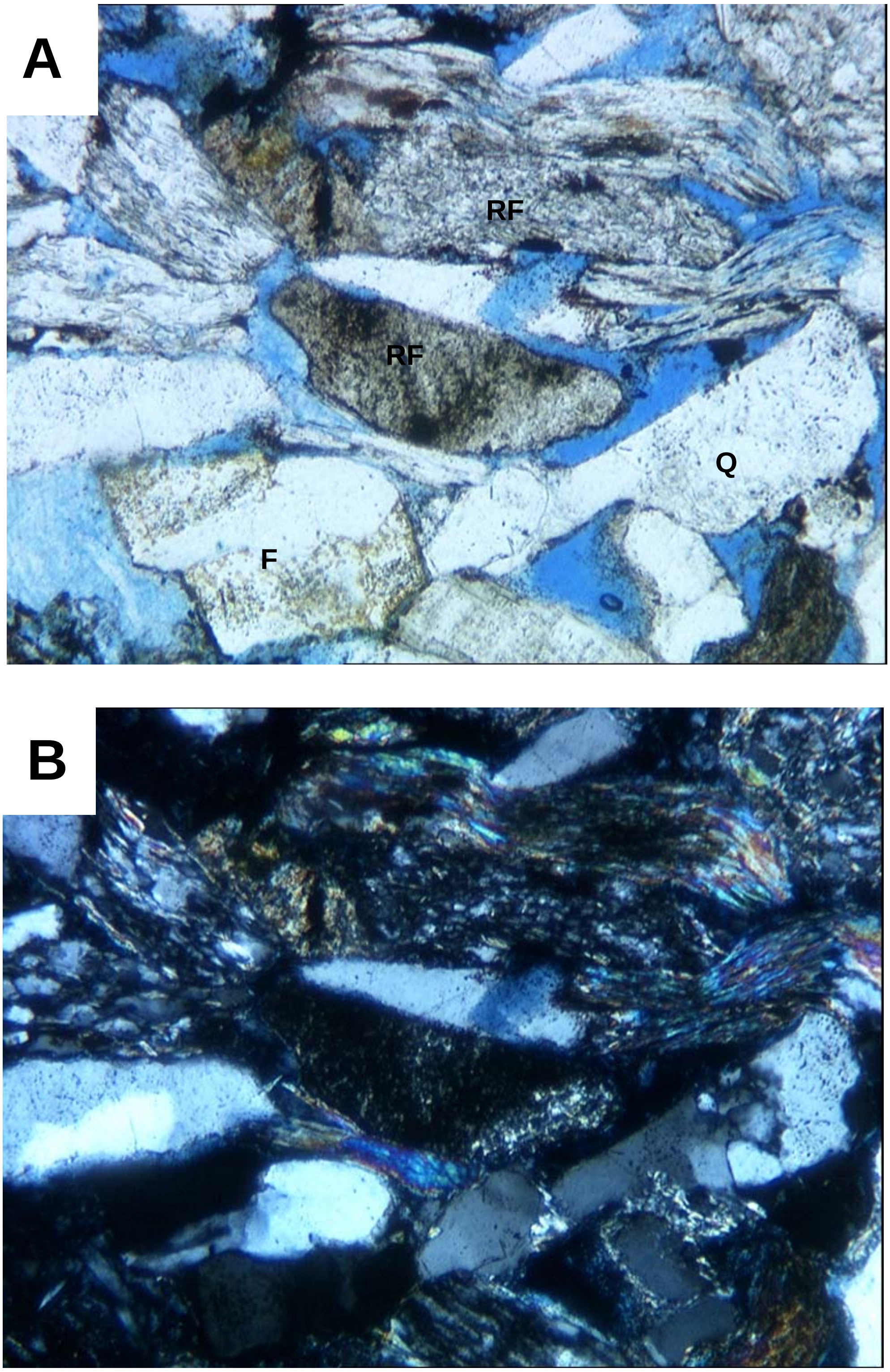

Figure 34. Thin section photomicrograph of the Canonbie Bridge Sandstone Formation (Sample NJN100). This is a medium-grained lithic sandstone; grains typically range from 0.25-0.5mm across (RF=rock fragments, Q=quartz, F=feldspar). A. PPL and B. XP. In PPL any porosity present is indicated by blue-dyed resin impregnation of the thin section.

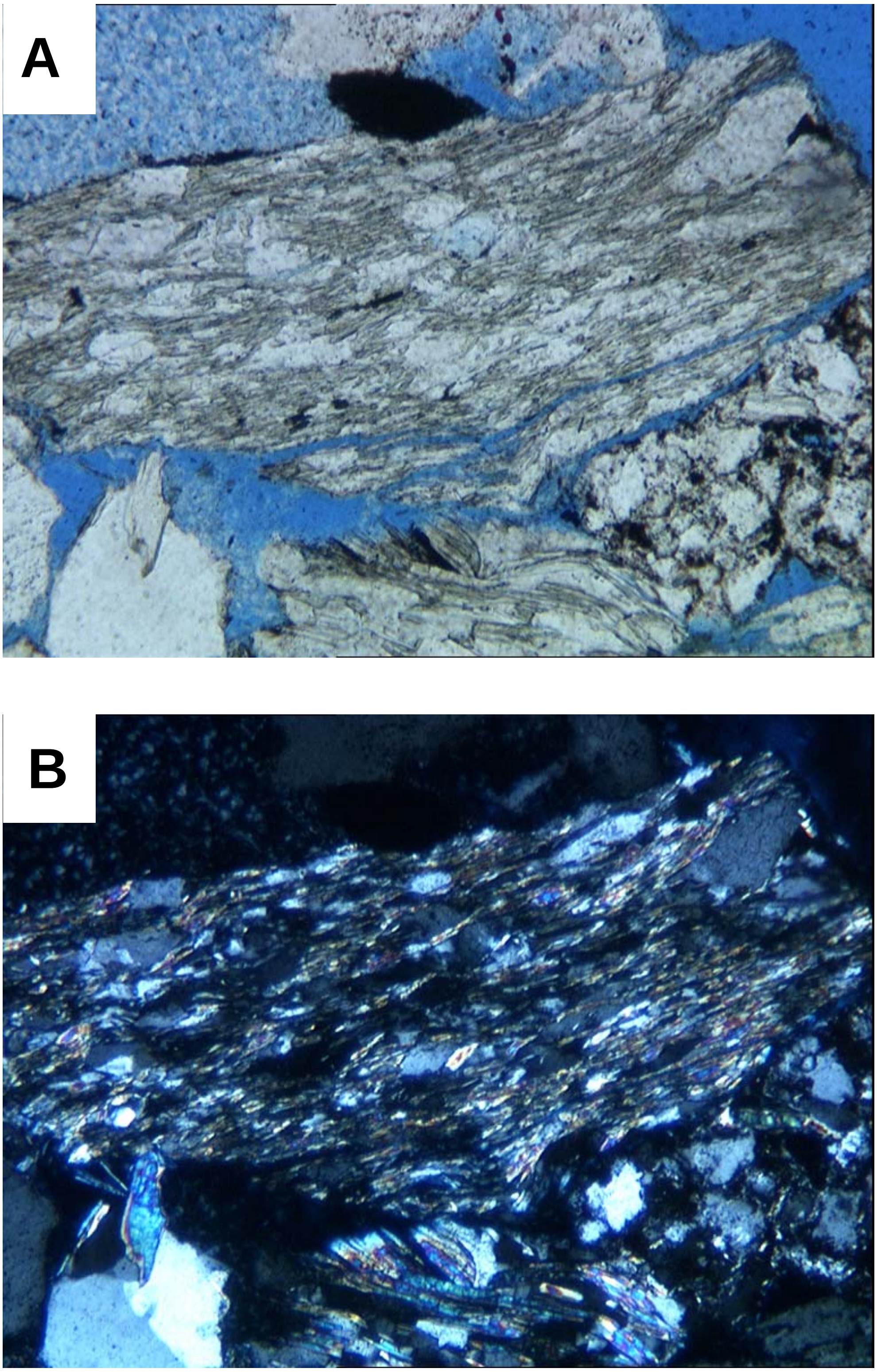

Figure 35. Thin section photomicrograph of the Canonbie Bridge Sandstone Formation (Sample NJN101) to show the common lithic grains. This is a medium- to coarse-grained sandstone, so grains typically range from 0.25-1 mm across. A. PPL and B. XP. The grain occupying the main part of the field of view is a metamorphic rock fragment. In PPL any porosity present is indicated by blue-dyed resin impregnation of the thin section.

6.2 BECKLEES SANDSTONE FORMATION

Two thin sections were prepared of sandstones from this formation (NJN98 and NJN99); these can both be classified as subfeldspathic-arenites (Figure 32). Representative photomicrographs of these sandstones are illustrated in figures 36-38. The sandstones are fine-grained and poorly to moderately sorted, although a distinctly bimodal texture is present locally (Figures 36 and 37); grains are typically subangular to subrounded, with one or two of the larger grains being rounded or well rounded. The dominant framework grain is quartz (78-90%); this is generally monocrystalline quartz, with less common polycrystalline quartz and chert. Inclusion 'bubbles' are seen in some quartz grains. Also present as a significant constituent is potassium feldspar (8-16%). Rock fragments are less common (2-5%) but appear to be similar to those described from the Canonbie Bridge Sandstone Formation, i.e. low grade metasedimentary clasts, intraformational mudstone clasts and some igneous rock fragments. Also present in lesser amounts are sodium feldspar and rare mica grains.

The sandstones are typically poorly cemented with a highly porous, open framework form, with common oversized pores (Figures 36-38). It would appear that extensive grain and cement dissolution has caused this texture. The main authigenic component is blocky pore filling dolomite. Quartz overgrowths and authigenic illite are also present in places. Clay/iron oxide 'dust' rims are typically present and iron oxide also occurs as pore filling cement in places.

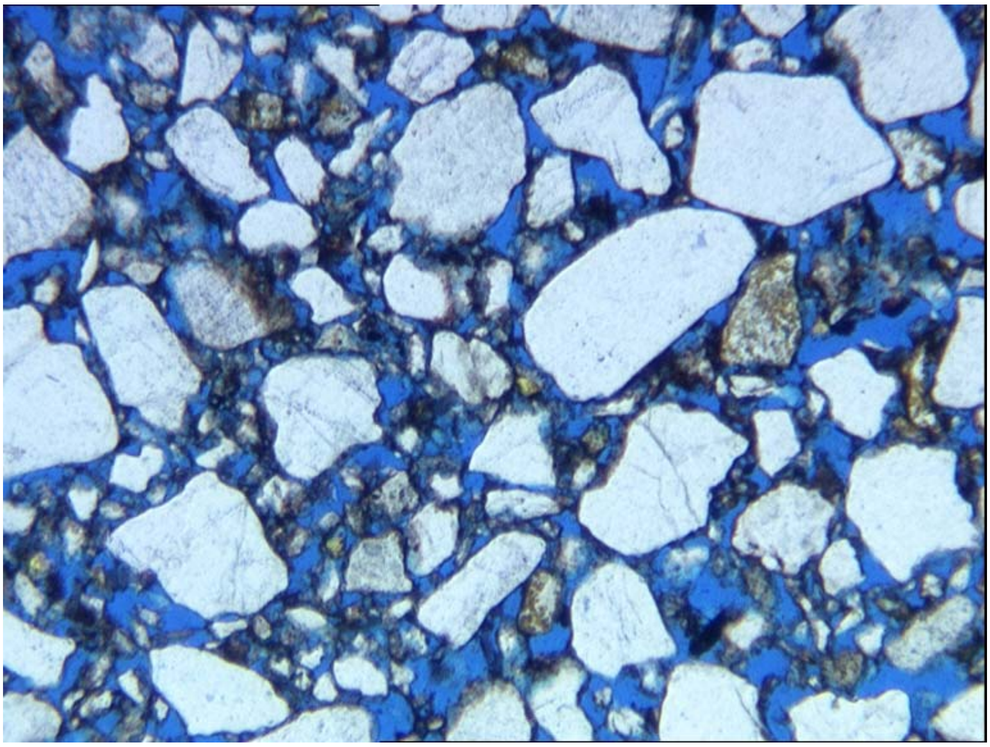

Figure 36. Thin section photomicrograph of the Becklees Sandstone Formation (Sample NJN98). This is a poorly sorted very fine- to medium-grained sandstone. Larger grains are typically from 0.25-0.5 m across; these are dominantly quartz grains. Porosity is indicated by blue-dyed resin impregnation of the thin section.

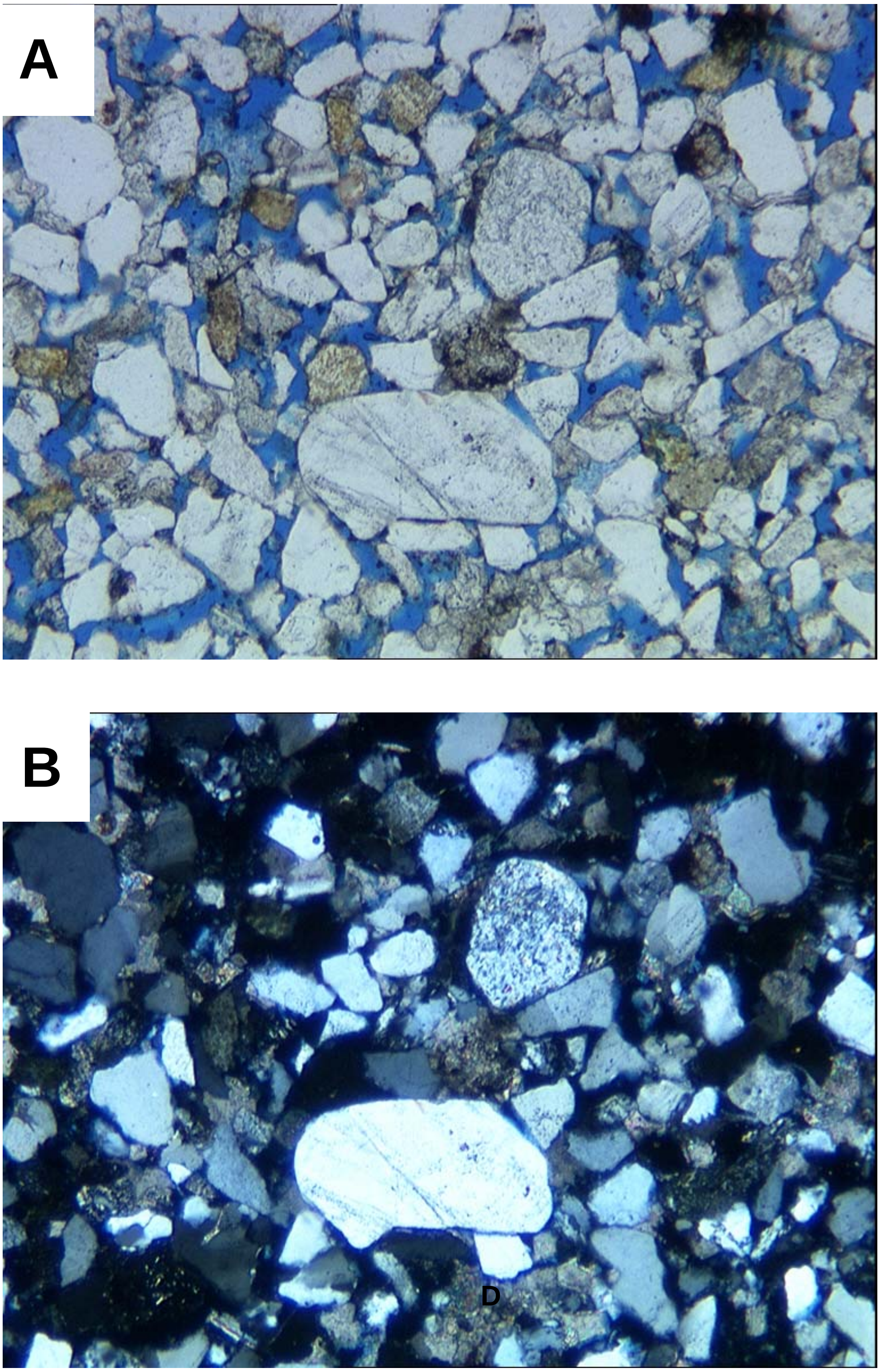

Figure 37. Thin section photomicrograph of the Becklees Sandstone Formation (Sample NJN99). This is a fine-grained sandstone so grains are typically 0.125-0.25 mm across. A. PPL and B. XP. In PPL any porosity present is indicated by blue-dyed resin impregnation of the thin section. The yellow grains in PPL are feldspars and quartz forms the majority of the grey grains; dolomite cement (D) can also be seen in XP.

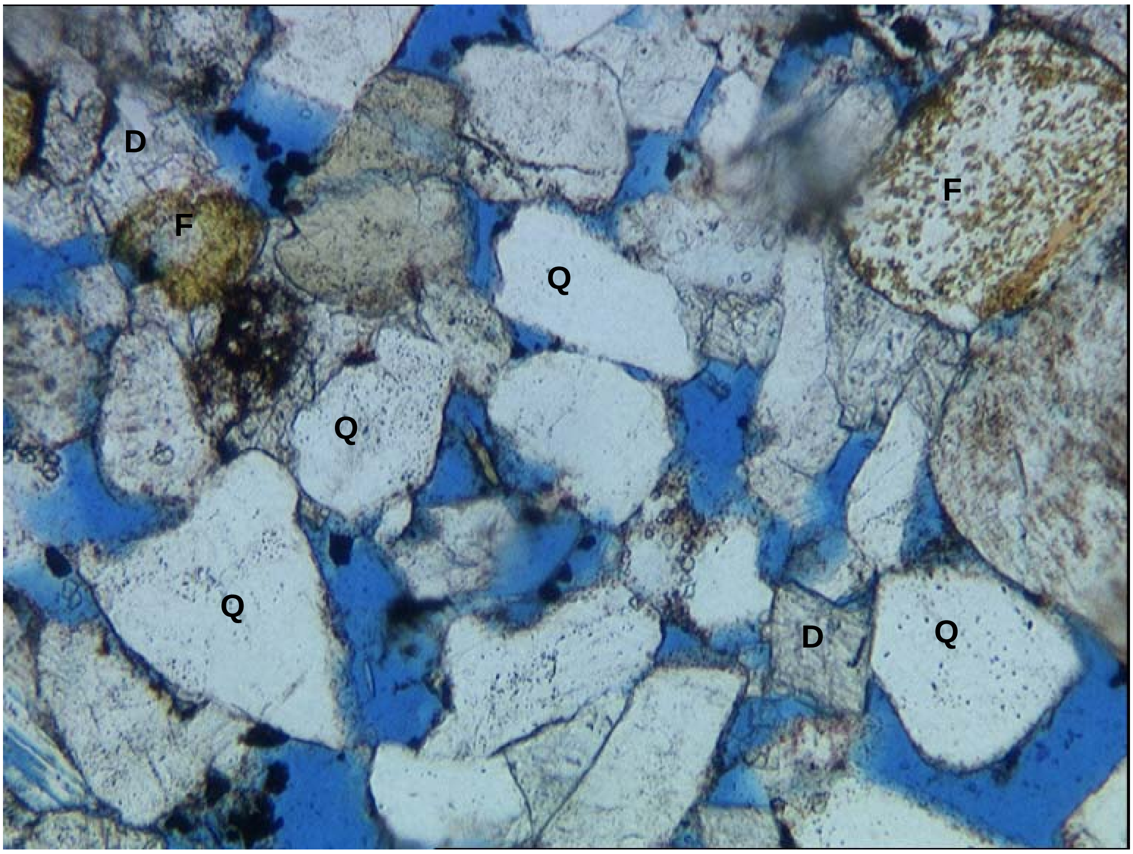

Figure 38. Thin section photomicrograph of the Becklees Sandstone Formation (Sample NJN99). This is a fine-grained sandstone so grains are typically 0.125-0.25 mm across. In PPL any porosity present is indicated by blue-dyed resin impregnation of the thin section. Q=quartz, F=feldspar, D=dolomite.

7 Comparisons with other UK areas

There are a number of other areas in the UK that preserve equivalent strata to that present at Canonbie, specifically West Cumbria, Lancashire, Southern Scotland, the English Midlands, the Irish Sea and the southern North Sea.

7.1 NORTHERN ENGLAND AND SOUTHERN SCOTLAND

7.1.1 West Cumbria

Geographically the West Cumbrian Coalfield area is closest to Canonbie, connected in the subsurface via the Solway Syncline (Chadwick et al., 1995). The Warwickshire Group is considered to extend to West Cumbria where Akhurst et al. (1997) assigned the youngest Carboniferous strata, of Phillipsii to Tenuis Chronozone (Late Bolsovian to Westphalian D) to the Whitehaven Sandstone Formation, divisible into the Bransty Cliff Sandstone Member and the overlying Millyeat Beds Member. The nature of the base of the formation is still subject to some debate, centred on whether it is unconformable or not. Detailed borehole correlations by Taylor (1961) for example established that the base was conformable and that perceived unconformity was merely the effects of secondary reddening penetrating into older strata. The most recent publication to deal with this issue, that of Akhurst et al. (1997), concluded that the base was unconformable. On the coast south of Whitehaven the Bransty Cliff Sandstone Member occurs approximately 30 m above the Unnamed H coal and the associated overlying Cambriense Marine Band (Jones, 1993).

The Bransty Cliff Sandstone Member comprises a thick (c.100 m) succession largely comprising sandstone, which can be locally coarse-grained (Jones, 1993; Akhurst et al., 1997) (Figure 39). The Bransty Cliff Sandstone Member is thought to represent the deposit of large braided fluvial river systems that flowed from north-east to south-west (Jones 1993). Petrographically, sandstones from the Bransty Cliff Sandstone Member are quartz dominant. Feldspar and mica occur and angular grains can be common in some samples and hematite is present as grain rims, overgrown by later quartz (Figures. 40 and 41). They typically lack the high percentage of lithic grains seen in the sandstones from Canonbie. Some of the grains have been described as having an ‘ashy’ appearance, as a result of kaolinization of feldspars (Eastwood et al., 1931). Hallsworth (2001) has described the heavy mineral assemblages of the Bolsovian to Westphalian D succession in west Cumbria. Sandstones are characterised by moderate monazite to zircon ratios (2.4 – 6.6) and higher amounts of chrome spinel (mostly 1.5 – 8.3). Garnet is generally absent but, where present, are generally of the spessartine-rich, low pyrope and low grossular type. This is typical of the southerly-derived ‘Mexborough-type’ garnets recorded in the Yorkshire area (Hallsworth, 2001).

Figure 39. Bransty Cliff Sandstone Member of the Whitehaven Sandstone Formation. Section at Bransty, north of Whitehaven harbour [297370 519270].

The overlying Millyeat Beds Member of the Whitehaven Sandstone Formation comprises a red-bed succession of mudstone, less common sandstone, thin coals, locally present mottled palaeosols and lacustrine *Spirorbis*-bearing limestones (Akhurst et al., 1997). The Millyeat Beds Member contains a greater proportion of lacustrine facies compared with the Bransty Cliff Sandstone Member and represents deposition in interdistributary bay or lacustrine environments with minor river channels (Akhurst et al., 1997).

Correlating the Cumbrian succession with that of Canonbie is made difficult because the stratigraphy of the succession in Cumbria is still uncertain. The Bransty Cliff Sandstone Member occurs approximately 30 m above the Unnamed H coal and the associated overlying Cambriense Marine Band near Whitehaven (Jones, 1993). One possibility is that the Bransty Cliff Sandstone Member belongs to the Pennine Upper Coal Measures Formation and that the sandstones in the PUCM on the north-west flank of the Solway Syncline may be possible correlatives. No calcrete palaeosols are known from the member, although evidence for incipient primary reddening and desiccation cracks do occur, suggesting that it could be included in the Warwickshire Group (e.g. Waters et al. in press). The Millyeat Beds Member, on the other hand, has definite Warwickshire Group characteristics, e.g. thin coals, *Spirorbis* limestones and gley palaeosols that show some incipient reddening, and is a probable correlative of the Eskbank Wood Formation of Canonbie. If this is the case then this would suggest that the Bransty Cliff Sandstone Member is older than anything seen at Canonbie. It is notable that there appear to be no equivalents of the higher Canonbie Bridge Sandstone and Becklees Sandstone formations in west Cumbria.

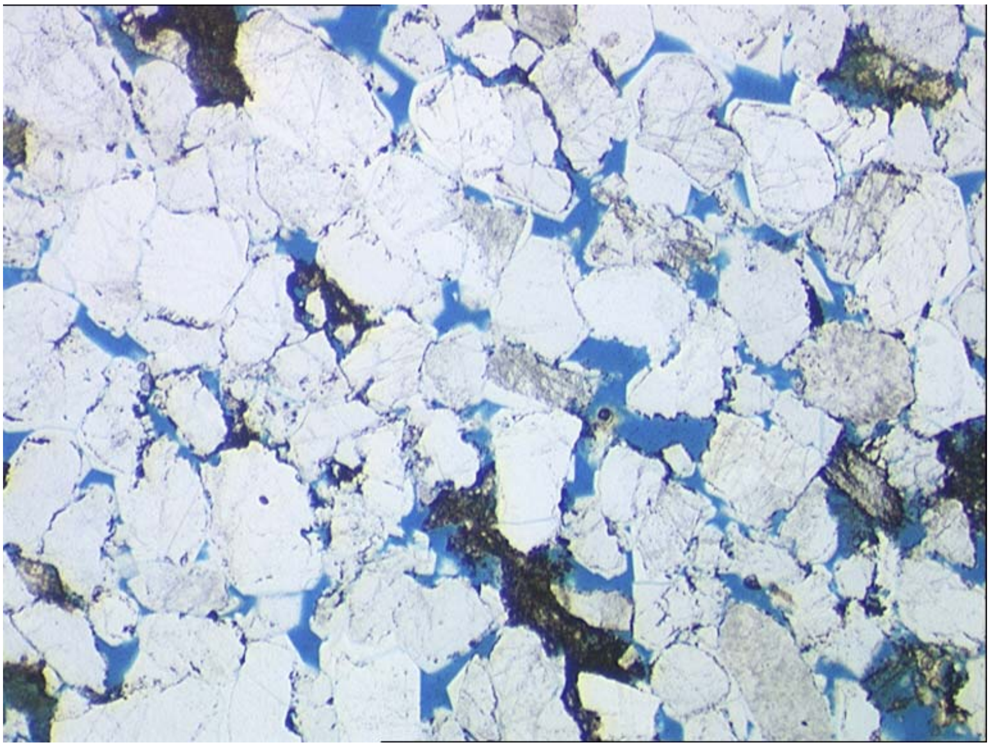

Figure 40. Thin section (in PPL) of a coarse-grained sandstone from the Whitehaven Sandstone Formation, Bransty Cliff Sandstone Member, west Cumbria [296600 517900]. Note the sandstone is dominated by quartz. ‘Dirtier’ grey grains are feldspars. The sandstone lacks the appreciable lithic grains seen in the sandstones from Canonbie. This thin section forms part of the PhD collection by one of the authors (NSJ).

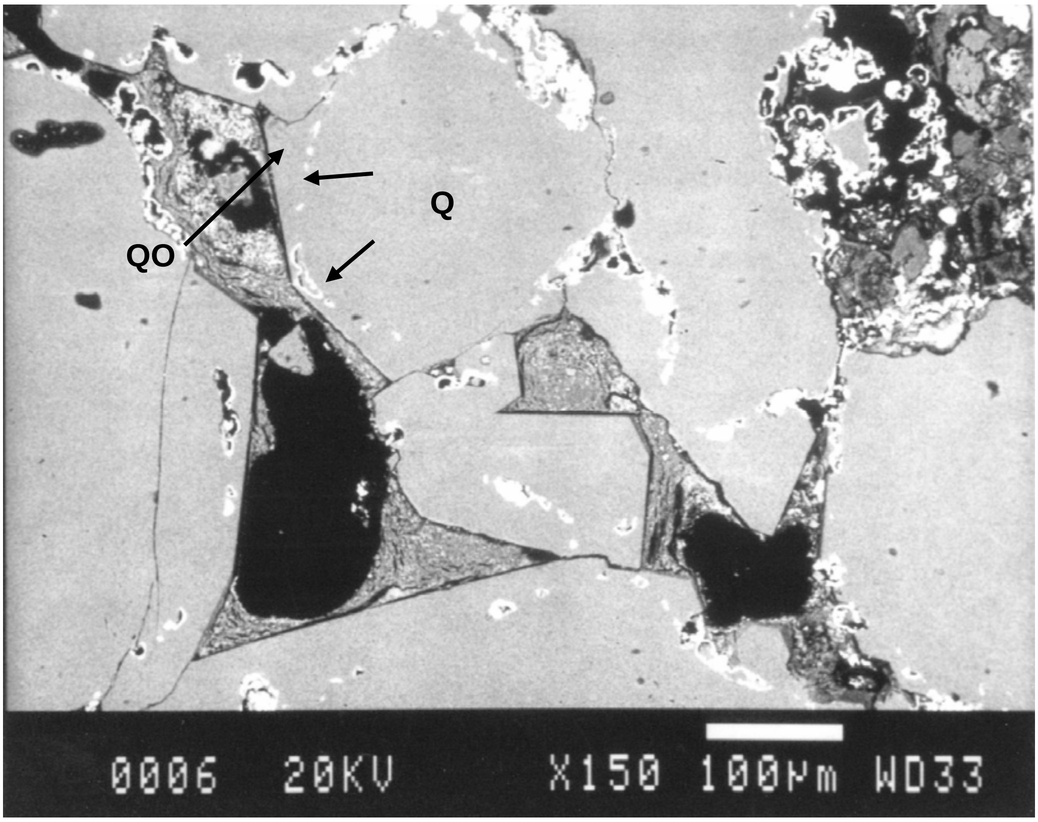

Figure 41. SEM image of a sandstone from the Whitehaven Sandstone Formation, Bransty Cliff Sandstone Member [296600 517900]. Note the early hematite (arrowed) (probably after a clay rim), surrounding an original quartz grain (Q), with a later authigenic quartz overgrowth (QO). Porosity is black. This thin section forms part of the PhD collection by one of the authors (NSJ).

7.1.2 Northumberland

The Northumberland/Durham Coalfield preserves a thick sequence of Bolsovian sediments, up to 300 m, with Pennine Upper Coal Measures Formation strata known locally e.g. in the Boldon Syncline (Smith, 1994). These are typically grey measures with numerous, thin coal seams (Smith, 1994), thus cannot be equivalent to the Canonbie succession. Nearby coalfields such as the Midgeholme and Stainmore Coalfields can be excluded from this discussion because only strata up to the lowermost Duckmantian (Westphalian B) are preserved (Taylor et al., 1971; Ramsbottom et al., 1978).

7.1.3 Southern Scotland

In southern and mid Scotland the Upper Carboniferous successions (i.e. those above the Aegiranum (Skipsey's) Marine Band) are assigned to the Scottish Upper Coal Measures Formation, where they are known from Sanquhar, central Ayrshire, along the Central Coalfield Syncline (at Airdrie and Alloa), Douglas and the East Fife areas (Ramsbottom et al. 1978). Faunal evidence suggests the presence of Upper Similis-Pulchra, Phillipsii and Tenuis chronozones in these coalfields (Ramsbottom et al., 1978). At Airdrie there are up to 270 m of Scottish Upper Coal Measures strata. These are mainly red but the presence of numerous rooted horizons, remnants of root traces, as well as coal replaced by limestone indicates later secondary reddening was an important process (Forsyth et al., 1996). The borehole Hallside (IGS Bore Hallside [266930 659740]) contains a few hundred metres of Scottish Upper Coal Measures strata, comprising interbedded red sandstone, mottled mudstones and micaceous siltstones, with some purple and red seatearths and rare coals replaced by limestone. Interestingly, desiccation cracks have been recorded in the core (e.g. at 58, 86, 121 and 132 m), indicating the start of better drained conditions. To the north of Alloa, approximately 200 m of youngest Westphalian strata, above the Aegiranum Marine Band, are estimated to occur along the northern margin of the Central Coalfield Syncline, along the River Devon, although no details are known (Francis et al., 1970, p.221). In the Sanquhar Coalfield Simpson and Richey (1936) described Barren Red Coal Measures strata occurring to at least 180 m above Aegiranum (Skipsey's) Marine Band. However, whilst these are reddened, the descriptions include coals and siderite nodules, indicating that reducing conditions occurred during deposition.

The most compelling evidence for the presence of Warwickshire Group equivalent strata comes from south-west Ayrshire. Plant fossils found in Ayrshire have been suggested to be either Westphalian D or even Stephanian in age (Wagner, 1966). Mykura (1967) records up to 450 m of strata above the Aegiranum (Skipsey's) Marine Band) in a number of boreholes in this area. The lowermost c.180 m or so of strata above the Aegiranum Marine Band is particularly arenaceous (Mykura, 1967). The uppermost c.120 m of strata are predominantly red-beds, and include *Spirorbis* limestones, desiccation cracked mudstones, mud-clast breccias and beds with calcareous concretions, which are likely to be calcretes (Mykura, 1967). This succession may be equivalent to the lower part of the succession (Eskbank Wood Formation) proved at Canonbie.

7.1.4 Ingleton

There are few detailed descriptions of the Westphalian succession in the Canonbie Coalfield, with the work of Ford (1954) representing the seminal account. Ford recognised a lower grey, coal-bearing unit (Pennine Lower and Middle Coal Measures formations) and an upper dominantly red-bed succession, approximately 580 m thick, which unconformably overlies the older grey strata. It is believed that the unconformity is quite pronounced, with most of the Duckmantian Pennine Lower and Middle Coal Measures Formations truncated by the unconformity and overlain by strata from the Phillipsii Chronozone (Ford, 1954; Ramsbottom et al., 1978). The boundary is marked by up to 12 m of conglomerate in the River Greta [approx 367180 471900] (Ford, 1954). The overlying 'Red Measures' have been divided into lower and upper units, with the 'Lower Red Measures' comprising up to 275 m of strata in the Holden House Borehole (SD67SE/1) [365790 473970]. The lower succession generally comprises red conglomerates and sandstones (forming up to 30% of the succession), mudstones and silty mudstones, locally with variegated and mottled mudstones, calcareous mudstones (marls) and seatearth palaeosols. The conglomerates and sandstones contain rounded pebbles of mudstone and siderite and have been described as 'gritty'. This is here taken to indicate that the coarser fraction largely comprises quartz grains. A 0.1 m thick coal has been recorded near Leck Mill [364500 477100]. Ironstone nodules and plant remains are commonly described in the succession, with a bivalve fauna indicating the basal part of the Phillipsii Chronozone (Late Bolsovian age).

The overlying succession, the 'Upper Red Measures' are separated from the 'Lower Red Measures' by a series of faults. This upper succession is best exposed at outcrop along the River Greta between the two road bridges at Ingleton, from [368910 472760] to [369420 473250], where they are about 240 m thick and are described as generally redder than the underlying red-beds (Ford, 1954). The succession dominantly comprises sandstone, with several beds of breccia present. Also described are rooted horizons, seatearths and three limestones, two of which are dolomitized (Ford, 1954). Within the succession a mudstone has been recorded with a non-marine bivalve fauna that includes *Anthraconauta phillipsii* (Williamson) and *Anthraconauta tenuis* (Davies and Trueman), indicative of a late Bolsovian, or even possibly early Westphalian D age.

A field visit to Ingleton was carried out by the authors, accompanied by M. McCormac, in October 2006. The intention was to examine the Lower and Upper Red Measures and compare them with the Upper Carboniferous successions at Canonbie. A number of localities along the River Greta were visited, from the Viaduct at Ingleton village centre [369330 473130] downstream to caravan park at Park Foot [367190 471930]. Unfortunately the river section outcrops are much degraded compared with those described by Ford in 1954 and it was not possible to examine any outcrops in the 'Upper Red Measures'. Poor quality exposures of the 'Lower Red Measures' are available at Park Foot, where fine-grained red sandstones occur in the stream bed and banks on both sides of the river. Little could be concluded about the stratigraphy and correlation based on this visit and reliance must be put on the outcrop and borehole descriptions given by Ford (1954).

The description of the 'Lower Red Measures' suggests that it largely comprises secondarily reddened Upper Carboniferous strata. Original reducing conditions at the time of deposition are indicated by the common occurrence of plant remains and ironstone nodules. Its late Bolsovian, or even possibly early Westphalian D age, together with the coarseness of some of the sandstones, may indicate equivalence perhaps to the Whitehaven Sandstone Formation from West Cumbria, although this is extremely speculative. The 'Upper Red Measures' are tentatively assigned to the Warwickshire Group and, on the basis of the presence of the beds of limestone, the general lack of features such as calcrete palaeosols, and a similar stratigraphical age as determined from non-marine bivalves, it is suggested that it may be equivalent to the Eskbank Wood Formation.

7.2 ENGLISH MIDLANDS AND CENTRAL PENNINE BASIN

The English Midlands saw the diachronous spread of red-beds northwards during the late Duckmantian (Westphalian B) onwards (Besly, 1998; Powell et al., 2000) and represents the 'type area' for the Warwickshire Group. The earliest unit within the Warwickshire Group, the Etruria Formation (Figure 11), comprises a mottled red mudstone-dominated succession with rare lenticular coarse sandstones ('espleys'), sometimes with volcanic and lithic clasts (Besly, 1983; Glover et al., 1993; Powell et al., 2000). The formation is up to 330 m in thickness and is known from central and northern England and North Wales (Powell et al., 2000). In North Wales it was formerly referred to as the Ruabon Marls and in Lancashire it was termed the Ardwick Marls (Tonks et al., 1931; Magraw, 1960; Smith and George, 1961; Davies et al., 2004). The Etruria Formation typically lacks calcrete palaeosols, although well-drained palaeosols such as brunified alluvial and ferruginous palaeosols are known, as well as post-depositionally oxidised and hydromorphic gleys (Besly, 1983; Besly and Fielding, 1989; Glover et al., 1993; Besly and Cleal, 1997).

The Halesowen Formation occurs above the Etruria Formation in central and northern England and North Wales (Figure 11). The formation was formerly referred to as the Coed-yr-allt Beds in

North Wales and the Ardwick Limestones in Lancashire (Tonks et al., 1931; Magraw, 1960; Smith and George, 1961; Davies et al., 2004). The formation typically comprises grey-green or red micaceous sandstones (litharenite) and mudstone with thin coals, beds of *Spirorbis* limestone and calcrete (Powell et al., 2000). Glover and Powell (1996) and Besly and Cleal (1997) described sandstones from the Halesowen Formation as metasediment-dominated litharenite (Association B of Besly and Cleal, 1997). These sandstones contain up to 60 % of low-grade metasedimentary grains, mainly foliated psammite and pelite rich in muscovite, chlorite and biotite. This gives unweathered (‘fresh’) sandstones a distinctive green colour (Glover and Powell, 1996). There are petrological similarities between the Halesowen Formation and the Pennant Sandstone Formation of South Wales (Besly, 1988). The Halesowen Formation sandstones are rich in garnet and a source rich in chrome spinel and chloritoid is suggested (Hallsworth, 1992). This metasedimentary detritus is thought to be largely recycled, derived from the Rheno-Hercynian Zone of the Variscan Orogenic belt (Besly and Cleal, 1997; Besly, 1998).

Spanning the interval between the Late Westphalian D and Early Stephanian is the Salop Formation (=Erbistock Beds of North Wales) (Figure 11). This comprises an interbedded succession of red and red-brown mudstones and sandstones, some pebbly, with thin *Spirorbis* limestones and calcrete in the lower part (Powell et al., 2000). Sandstones are mostly sublitharenite (Association C of Besly and Cleal, 1997), largely comprising monocrystalline and polycrystalline quartz and minor potassium feldspar. These sandstones also typically contain detrital carbonate grains, formed either through reworking of calcrete or representing detrital reworked Carboniferous Limestone grains (Glover and Powell, 1996; Besly and Cleal, 1997). According to Besly and Cleal (1997), sandstones of the Salop Formation (Association C) are identifiable in the field by their distinctive orange-brown colour. The Salop Formation consists of recycled Carboniferous and perhaps Devonian lithic material. The Salop Formation also contains calcrete.

The Upper Stephanian Tile Hill Mudstone Formation is only known from the southern part of the Warwickshire Coalfield area and comprises reddish brown mudstone, with subordinate thin red-brown and green sandstones and some conglomerate lenses (Powell et al., 2000). The Clent Formation, of Autunian age, comprises subangular breccia with a red-brown mudstone matrix and some sandstone (Powell et al., 2000). There is a distinctive suite of local clasts, derived largely from Uriconian (Precambrian) volcanic and volcaniclastic rocks that crop out in the Welsh Borderlands (Glover and Powell, 1996; Powell et al., 2000). The Kenilworth Sandstone Formation is a distinctive unit, known only from the Kenilworth area of Warwickshire. It is formed from locally derived Precambrian and Lower Palaeozoic rocks of the Lickey Ridge (Powell et al., 2000). The last unit with in the Warwickshire Group of the Midlands area is the Ashow Formation, of Autunian age. This comprises red-brown mudstone with subordinate, but locally thick fine- to medium-grained sandstone (Powell et al., 2000). It typically occurs in the southern part of the Warwickshire Coalfield.

It is difficult to be confident of the correlation between Canonbie and the Midlands area, due to the large distances involved and the likelihood of lateral facies changes. It is possible that the Eskbank Wood Formation is equivalent to the Etruria Formation. However, whilst they are of similar age, there are marked lithological differences between the Etruria and Eskbank Wood formations. These include the presence of calcretes in the Eskbank Wood Formation, which are not present in the Etruria Formation and the presence of ferruginous palaeosols in the Etruria Formation, which are absent from the Eskbank Wood Formation. Hence it is more likely that the two units are not the same and that the Eskbank Wood Formation has no equivalent unit in the Midlands.

The Halesowen Formation forms the chronostratigraphic equivalent to the Canonbie Bridge Sandstone Formation and the litharentitic composition of the sandstones described from the Halesowen Formation has some similarities with the sandstones from the Canonbie Bridge Sandstone Formation. One significant difference is that the Halesowen Formation was deposited in a humid climate. However, it is known that the lithic sands show a marked diachroneity northwards and hence would have arrived in Canonbie at a later time than in the English Midlands, by which time there had been an extensive change from a humid to a semi-arid climate.

The overlying Salop Formation also appears to have some features in common with the Becklees Sandstone Formation, particularly in terms of its distinctive orange-brown colour and lower proportion of lithic material. However, the Salop Formation represents a switch from the distally travelled sands of the Halesowen Formation to a local source from the Wales Brabant High. This locally reworked material includes for example Carboniferous Limestone grains. Hence the Salop Formation is not likely to be the same as the Becklees Sandstone Formation and there be no stratigraphic equivalence for this unit in the Midlands. Palaeocurrent data for the Becklees Sandstone Formation indicate a northerly derivation, making it unlikely that there is a Midlands equivalent.

7.3 OFFSHORE EAST IRISH SEA AND SOUTHERN NORTH SEA

Little is known of the uppermost parts of the Westphalian succession in the East Irish Sea (Chadwick et al., 2001). In the Eubonia Basin Bolsovian to Westphalian D strata are suggested to be present and Westphalian D to Stephanian strata may occur in the central parts of Quadrant 109 Syncline (Jackson and Mulholland, 1993). The upper part of the Carboniferous succession in Well 33/22-1 in the Kish Bank Basin comprises approximately 144 m of interbedded red and grey mudstones and sandstones, thought to be of Westphalian D age (see Jackson et al., 1995). Details tend to be lacking due to the absence of core data across these stratigraphic intervals.

Offshore in the southern North Sea chronostratigraphically equivalent successions are present to that of Canonbie (Besly, 1998). The Bolsovian (Westphalian C) aged Cleaver Formation is a grey-bed succession, suggested to have been derived from an interfingering of detritus sourced from the Rinkøbing Fyn High to the north-east and from the Variscan orogenic belt to the south (Morton et al., 2005). The overlying red-bed facies were assigned to the Schooner Formation, divisible into lower and upper Ketch members (Cameron, 1993). More recently it has been suggested that the name Schooner Formation be dropped and the Lower Ketch Member be termed the Ketch Formation and the Upper Ketch Member be termed the Boulton Formation (Moscariello, 2003; Besly, 2005); this more recent terminology is used here. These red-bed formations range from Bolsovian (Westphalian C) to Westphalian D in age. Leeder and Hardman (1990) proposed that Bolsovian-Westphalian D 'Barren Red Measures' in the southern North Sea (SNS) represent the diachronous spread of well-drained alluvium sourced from adjacent developing growth anticlines (e.g. Murdoch and Ravenspurn anticlines). The formation of these anticlines resulted from Late Carboniferous regional compressional tectonics (Leeder and Hardman, 1990).

The Ketch Formation largely comprises fluvial single and multi-storey braided channel deposits, with rooted overbank deposits and ferruginous palaeosols (Besly et al., 1993). Although the base of the Ketch Formation is defined as the lowest horizon of primary red-bed facies (Cameron 1993, p.22), an angular unconformity is present at the base of the Ketch Formation (Besly, 1998; Moscariello, 2003; Jones et al., 2005). Besly et al. (1993) suggested that the Ketch Formation formed contemporaneously with the evolving Variscan foreland basin, with sediment derived as a result of Variscan uplift. More recent work by Morton et al., (2005), on the heavy mineral assemblages, suggested that the Ketch Formation comprises a single source area draining two distinct lithologies, one ultramafic and the other Al-poor metasedimentary rocks. The Rinkøbing Fyn High is favoured as the likely source area (Morton et al., 2005). Besly (1998, p.123) suggested that the Bolsovian (Westphalian C) Ketch Formation is equivalent to that of the Canonbie succession.

The Westphalian D Boulton Formation comprises finer-grained channel facies, as well as non-marine limestones, calcrete palaeosols and some grey, coal-bearing facies (Besly, 1998, 2005). The formation is less feldspathic and richer in metamorphic lithic material than the Ketch Fomation and a Variscan source is suggested for this unit (Besly, 1998; Morton et al., 2005). Jones et al. (2005, p.186) also described the presence of low-grade metasedimentary rock fragments in sandstones of the Boulton Formation, which they believe are indicative of a southerly derivation. Besly (1998) suggested that the Boulton Formation is equivalent to the Halesowen Formation.

In terms of relating the onshore Canonbie succession with that of the southern North Sea, it is suggested that the Eskbank Wood Formation is chronostratigraphically of similar age to the Ketch Formation, but lithologically the Ketch Formation has some similarities with the Whitehaven Sandstone Formation of west Cumbria. The lithic- rich Boulton Formation has much in common with the Canonbie Bridge Sandstone Formation. If this were the case then there would appear to be no equivalent to the overlying Becklees Sandstone Formation in the southern North Sea.

These correlations are extremely tentative and are much more work would be needed on the petrography and provedance indicators of the Canonbie succession in order to determine a relationship. No heavy mineral analysis has yet been carried out on the Canonbie Coalfield Warwickshire Group sandstones and it is suggested that this would be an interesting development of this study.

8 Conclusions

Our understanding of the youngest Carboniferous rocks (Bolsovian-Westphalian D) in the UK is often hampered by their limited preservation and the common occurrence of reddening of the strata. One such Upper Carboniferous succession is present at outcrop and in boreholes around the Canonbie area of south-west Scotland, preserved along the NNE-trending Solway Syncline. This is one of the few areas in the UK outside of the English Midlands where such strata can be directly examined at outcrop and hence represents an important scientific site. Early workers place these reddened Upper Carboniferous strata at Canonbie into the Upper Coal Measures and were uncertain as to its origin. From the work presented here it is clear that these strata can be assigned to the Warwickshire Group on the basis that red-bed facies occur within it that show evidence for early oxidation (primary reddening) of the strata. At outcrop about 290 m of the Warwickshire Group are almost continuously exposed along the banks of the River Esk. In boreholes the fullest thickness of the group is known from the Becklees Borehole, close to the central axis of the Solway Syncline, where up to about 530 m of Warwickshire Group are indicated from wireline logs. Seismic reflection data indicate that the group could be up to *c*. 700 m in the centre of the Solway Syncline.

The Solway Syncline and associated Carlisle Anticline appear to be long-lived structural features in the area, probably linked to dextral displacement on the Gilnockie Fault and other basin-bounding faults. Fold development was probably initiated in Late Visean (Asbian) times and was marked by syndepositional thickening of strata into the Solway Syncline and thinning onto the adjacent Carlisle Anticline until-end Carboniferous times when more intense folding took place.

Three formations have been recognised within the group, from base upwards, the Eskbank Wood, Canonbie Bridge Sandstone and Becklees Sandstone formations. These three formations have distinctive geophysical log signatures and hence are readily correlatable in the subsurface around Canonbie. The Eskbank Wood Formation ranges in thickness between 145 and 175 m. The base of the formation is diachronous, marked by the repeated alternations of grey and primary red-bed strata. Where no core or core descriptions exist it is difficult to determine the position of this change and it is suggested that the base is taken at position of the High Coal, which forms a prominent marker horizon. The formation is generally comprises red mudstones, with some fine- to medium-grained sandstones, calcrete palaeosols, thin beds of *Spirorbis* limestone and *Estheria*-bearing mudstones. The overlying Canonbie Bridge Sandstone Formation ranges in thickness from 131 to 154 m. The base of the formation is sharp, marked by the incoming of thick units of medium- and coarse-grained cross-bedded channel sandstones. A noticeable feature of these sandstones is their greenish grey colouration, which can be related to the presence of abundant lithic grains. The Becklees Sandstone Formation is the final unit recognised from the Warwickshire Group of Canonbie, overlain unconformably by Permian strata. Its full thickness is not known, but up to 200 m is proved in the Becklees Borehole. This sandstone is finer grained, has a distinct orange brown colouration and contains a significantly lower proportion of lithic components.

Warwickshire Group sedimentation in the Canonbie area largely took place on a well-drained alluvial plain, characterised by an early, primary oxidation of the strata. Large braided river systems were common features on this alluvial plain, with palaeocurrent data from the Canonbie Bridge Sandstone showing channels flowed towards the north. Overbank and floodplain fines were commonly deposited lateral to channels and soils were able to form during intervals of low sediment aggradation.

Comparisons with other areas suggest that these are the lateral equivalents of some of the formations recognised in Scotland, the English Midlands and in the Southern North Sea. The published descriptions of the red-beds in Ayrshire are similar to those of the Eskbank Wood Formation. The Eskbank Wood Formation may be the chronostratigraphic equivalent of the Etruria Formation, but there appears to be significant lithological differences between the two formations. The other important difference is that the Etruria Formation is likely to have been deposited under a largely humid climate, whereas in Canonbie the environment showed fluctuations between humid (coal-forming, grey bed deposition) to a more semi-arid climate (red-beds with calcretes) for the Canonbie succession. The Eskbank Wood Formation is also chronostratigraphically equivalent to the Ketch Formation of the southern North Sea, which is believed to have been derived from the Rinkøbing Fyn High.

Metasediment-dominated litharenites from the Halesowen Formation and the Pennant Sandstone Formation of South Wales appear to be similar in description to that of the Canonbie Bridge Sandstone Formation. Again, one major difference is that the Halesowen and Pennant Sandstone formations were deposited in a humid climate, whereas there are many features in the Canonbie Bridge Sandstone indicating a drier climate prevailed in this area. The Halesowen and Pennant Sandstone formations are largely thought to have been derived from the Rheno-Hercynian Zone of the Variscan Orogenic belt. Offshore, the Boulton Formation also shows a lithic rich character to the sandstones and hence could be equivalent to the Canonbie Bridge Sandstone Formation. This is also believed to have a Variscan derivation.

Finally the Becklees Sandstone Formation has much in common with the Salop Formation of the English Midlands, particularly in terms of its distinctive orange-brown colour and lower proportion of lithic material. However, the local (Wales Brabant High) derivation indicated for the Salop Formation, combined with the southerly flow direction indicated for the Becklees Sandstone Formation make it unlikely that these are equivalent stratigraphic units. It would appear that there is no equivalent to the Becklees Sandstone Formation in the southern North Sea.

If these assumptions about the lateral equivalents of the Canonbie succession are correct then it is clear that the southerly derived Variscan detritus was transported considerable distances across the southern North Sea and UK areas, to a position at least a few hundred kilometres north of what has previously been recognised. The Canonbie succession preserves some of the youngest Carboniferous known from onshore UK and is younger than that of the southern North Sea succession. However, further work is needed to confirm these conclusions and there is much still to learn about the provenance of these units, which is beyond the remit of this study.

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

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