REGIONAL EVOLUTION OF A FLUVIODELTAIC CYCLIC SUCCESSION IN THE MARSDENIAN (LATE NAMURIAN STAGE, PENNSYLVANIAN) OF THE CENTRAL PENNINE BASIN, UK.

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SUMMARY: Basinwide analysis of sedimentary facies, isopachytes and palaeocurrents for two late Marsdenian (Pennsylvanian) sedimentary cycles within part of the Millstone Grit Group, has led to a new sequence-stratigraphic interpretation for the relationships between its constituent sandstone units (currently named Huddersfield White Rock, Chatsworth Grit, Brooksbottoms Grit, Holcombe Brook Grit, Brown Edge Flags and Redmires Flags). The *Bilinguites superbilinguis* ($R_{2c}1$) and *Verneulites sigma* ($R_{2c}2$) marine bands related to fourth-order marine highstands show faunal variations possibly reflecting fifth-order sea-level fluctuations. The lower $R_{2c}1$ cycle consists entirely of deep water mudstone. The overlying $R_{2c}2$ cycle shows an upward regressive passage through pro-delta and delta-slope deposits to mouthbar and channel sandstones. The latter comprises an 'eastern inflow' of northerly provenance, the distribution of which was not influenced by the underlying basement configuration, and a 'southern inflow' sourced from the Wales-Brabant High. Falling sea-levels resulted in progressive narrowing of the fluvial pathway within the main sandstone body of the 'eastern inflow', with a concomitant increase in flow velocities and grainsize. At lowstand, this culminated in the Chatsworth palaeovalley, 25 km wide, the basal surface of which can be correlated into the interfluve areas as a leached palaeosol. Higher sandstone bodies, where developed, are of two kinds: an earlier set present outside of the palaeovalley was formed during regression, and a later set within the palaeovalley was formed as sea level rose. As part of this transgressive systems tract, a *Lingula* band developed across the flooded Chatsworth palaeovalley and its interfluve margin. The transgression culminated in the highstand of the *Cancelloceras cancellatum* ($G_{1a}1$) Marine Band.

This study describes a fluviodeltaic succession within the upper part of the Millstone Grit Group, which outcrops across the central and southern Pennines, around the margins of the Peak District and in the Rossendale inlier (Fig. 1). It is based primarily on observations from surface exposures, supported by information from boreholes (Fig. 2), of the succession deposited within the *Bilinguites superbilinguis* ($R_{2c}1$) and *Verneulites sigma* ($R_{2c}2$) sub-biozones of the late Marsdenian Substage (Namurian Regional Stage of the Pennsylvanian) (Fig. 3). The initial aim of the study was to determine the relationships of a number of sandstone units, namely the Huddersfield White Rock, Chatsworth Grit, Brooksbottoms Grit, Holcombe Brook Grit, Brown Edge Flags and Redmires Flags, the stratigraphical relationships of which are shown in Figure 3. Current nomenclatures for these sandstones are confusing and a simplified scheme is presented. This has led, for the first time, to an understanding of the order in which these sandstones were deposited, and in turn, to a new interpretation of the sequence stratigraphy of this classic cyclic succession.

Benfield (1969) carried out the first detailed sedimentological study of the Huddersfield White Rock, covering its outcrop around the north, north-west and west of the Yorkshire Coalfield. He considered it to be deposited within a deltaic distributary complex prograding towards the north-west and west, flanked to the north by lagoons and beach barriers. Lateral variations in the Holcombe Brook Grit and the Brooksbottoms Grit were summarized by Wright *et al*. (1927, fig. 9), but there has been no recent sedimentological interpretation. The Chatsworth Grit has been the subject of sedimentological studies by Mayhew (1966) in north-east Derbyshire, Kerey (1978) in Staffordshire and O'Beirne (1996) in a broad area of the East Midlands and South Yorkshire. Cross-bedding measurements recorded in these studies indicate that the main delta progradation was towards the WSW. O’Beirne (1996) was the first to recognise the existence of an incised fluvial channel within the Chatsworth Grit outcrops, and attributed it to a drop in sea-level, thereby applying a sequence-stratigraphic model to the succession.

It is worth noting the historical significance to sedimentology of this succession, in that the earliest use of cross-bedding as an indicator of current direction and sediment provenance was applied to the Chatsworth Grit around Sheffield by Sorby (1859).

1. BASINAL SETTING

The study area is located within the Central Pennine Basin, a broad depositional area extending from the Craven Fault System in the north to the Wales-Brabant High in the south (Fig. 1, Inset A). The basin is thought to have developed in response to a phase of north-south extension during late Devonian and early Carboniferous times (Leeder 1982; 1988). The rifting produced a series of grabens and half-grabens, separated by platforms and tilt-block highs (Fig. 1). The down-faulted areas formed a system of connected sub-basins that were subject to relatively high subsidence rates, creating a province dominated by basin-floor facies. Over the intervening platforms, early Carboniferous (Tournaisian and Visean) deposition was thinner (or absent). The Wales-Brabant High was a persistent topographical feature throughout the Carboniferous, providing limited amounts of sediment to the southern part of the basin (Trewin & Holdsworth 1973; Aitkenhead 1977; Chisholm & Hallsworth 2005).

By late Visean time the magnitude of regional north-south extension had greatly reduced and thermal relaxation subsidence became the dominant structural control on basin evolution (Leeder 1988), so that during Namurian and Westphalian times the basin subsided regionally, with a depocentre extending from south Lancashire to north Staffordshire (Calver 1968; Ramsbottom 1969; Collinson *et al.* 1977). However, compaction of the earlier sediments continued, and differential compactional subsidence was superimposed on the regional subsidence, causing the Tournaisian-Visean pattern of thickness variations to be replicated in the Namurian succession, though with diminished amplitude (Aitkenhead *et al.* 2002, fig. 16).

The Namurian infill of the Central Pennine Basin is dominated by the Millstone Grit Group (Fig. 1), a fluviodeltaic succession of siliciclastic sediments that were derived mainly from distant source areas in Laurentia-Baltica to the north-east (Gilligan 1920; Hallsworth *et al*. 2000; Evans et al. 2001) (Fig. 1, Inset B). Eustatically driven sea-level fluctuations exerted a major control on the cyclic sedimentation characteristic of the group (Holdsworth & Collinson, 1988). The major sea-level rises within the basin (numbering 50 to 60 through the Namurian) resulted in the deposition of marine mudstones with acme pelagic faunas dominated by thick-shelled ammonoids. These mudstones are commonly referred to as marine bands, of which eight are recognized within the Marsdenian (Fig. 3). Overlying non-marine mudstones show a broad coarsening upwards into siltstones and sandstones deposited in delta-slope or delta-top environments as deltas advanced. “Non-marine” is understood to include freshwater dilution of sea-water. The top of each cycle is marked by emergence, with the development of palaeosols (seatearths) and coal seams.

During the early Namurian, the presence of deep water (up to a few hundred metres deep) in the widespread underfilled basins remaining from Tournaisian-Visean times caused the deltaic systems to prograde only a short distance southward (up to 20 km in a basin in excess of 100 km wide), with argillaceous basinal sediments (the Craven Group) deposited widely elsewhere (Waters & Davies 2006; Waters *et al*. 2007). This initial phase of deltaic sedimentation included thick bodies of comparatively deep-water turbidites, fed by channels that by-passed the delta-slopes to be deposited in delta-front aprons (Walker 1966; Collinson 1969; McCabe 1978; Jones 1980). These turbidite-fronted deltas prograded southwards with time, as accommodation space became filled.

Following infill of the inherited deep basin, sedimentation rates began to broadly match subsidence rates and shallow-water, sheet-like deltas were deposited, commonly in cycles tens of metres thick. Mudstones dominate the lower part of each cycle and are overlain by generally sheet-like and laterally extensive sandstones deposited by fluvio-deltaic systems. During periods of base-level fall, rivers incised into their deltas and palaeosols developed on interfluves. The Marsdenian deposits, which include the $R_{2c}1$ and $R_{2c}2$ cycles of the present study, belong to this phase of the basin’s development.

The Namurian deltas were river-dominated, with subordinate wave influence. Tidal features are rare, but have been recognized within

Kinderscoutian and Marsdenian deposits in Yorkshire (Aitkenhead & Riley 1996; Brettle *et al*. 2002). The rarity of tidal features has been attributed to a small tidal range (less than 1 m) in the Central Pennine Basin (Wells et. al. 2005), due to its relative isolation from the oceans (Collinson 1988).

2. LATE MARSDENIAN STRATIGRAPHY

The Millstone Grit Group extends across most of the Central Pennine Basin (Fig. 1). The base of the group is taken at the base of the first thick quartzo-feldspathic sandstone, of Namurian age, typically present above the Bowland Shale Formation of the Craven Group (Waters *et al*. 2007). The base is markedly diachronous, ranging from Pendleian along the northern margin of the Central Pennine Basin to Marsdenian in the East Midlands and Staffordshire.

This study concentrates on strata deposited during the later part of the Marsdenian Substage, in the *Bilinguites superbilinguis* (R_{2c}) biozone. This includes two sedimentary cycles defined by their bounding marine bands: the $R_{2c}1$ cycle, between the *Bilinguites superbilinguis* Marine Band and the *Verneulites sigma* Marine Band, and the $R_{2c}2$ cycle, between the *Verneulites sigma* Marine Band and the *Cancelloceras cancellatum* Marine Band. The bottom of the last-named marks the base of strata of Yeadonian age (Fig. 3). However, the *Verneulites sigma* Marine Band is not recorded everywhere across the basin, and is apparently absent from the north-east of the basin, north of Huddersfield.

The sandstones described in this study occur entirely within the $R_{2c}2$ cycle. The sandstone names, shown in stratigraphical context in Figure 3, have evolved over a long period of time and are of local applicability: they do not relate consistently to separate sandbodies, so are of limited use for the purpose of this study. Some notes on the traditional nomenclature are given here to allow connection with existing literature.

The *Huddersfield White Rock* is the name given to the sandstones in West Yorkshire (Wray *et al*. 1930; Bromehead *et al*. 1933; Stephens *et al.* 1953; Cooper & Burgess 1993), though it was sometimes abbreviated to

White Rock (Edwards *et al*. 1950). Locally, Warley Rock was used north of Huddersfield (Wray *et al*. 1930). In Lancashire the *Holcombe Brook Grit* overlies the *Brooksbottoms Grit* (Wright *et al*. 1927; Price *et al*. 1963; Taylor *et al*. 1963). The *Chatsworth Grit* is the name used across the southern part of the basin, in South Yorkshire, Derbyshire and Staffordshire. The term Rivelin Grit, formerly used in South Yorkshire (Davies 1941; Eden *et al*. 1957), is obsolete. Brown Edge Flags and Redmires Flags are thin sandstones present above the Chatsworth Grit in the northern part of the Peak District. Stevenson & Gaunt (1971, p.183) acknowledge the unsuitability of the term Brown Edge Flags, as at Brown Edge, 10 km west of Sheffield, the sandstone seen is in fact the Redmires Flags. However, the term is widely used and is retained in this study.

A simpler system based on informal terms is preferred for the main part of this paper (Fig. 4). The major fluviodeltaic sandstones are grouped together as the *main sandstone body.* Localized turbiditic sandstones found below the main sandstone body are called *lower sandstone bodies* and thin, discontinuous fluviodeltaic sandstones developed above are referred to as *higher sandstone bodies.*

Coals thick enough to have been worked in the past are a feature of the higher parts of the $R_{2c}2$ cycle, and have been given names (Figs. 3, 5 & 6). These are of strictly local validity, however, and attempts to correlate them beyond their type areas are probably misplaced, as discussed in section 6.5. The Upper Meltham Coal (Wray *et al*. 1930; Bromehead *et al*. 1933) typically overlies the Huddersfield White Rock and can be found as far north as Bradford (Waters 2000). In Lancashire, the Brooksbottoms Coal rests upon (or locally within) the Brooksbottoms Grit (Wright *et al*. 1927, fig 9). Above the Chatsworth Grit, a coal is variously recognized as the Baslow Coal in Derbyshire (Smith *et al*. 1967), the Ringinglow Coal around Sheffield (Eden *et al*. 1957) and the Feather Edge Coal north of Leek (Aitkenhead *et al*. 1985). Coals among the *higher sandstone bodies* include the Simmondley Coal, south of Glossop (Stevenson & Gaunt 1971) and the Holcombe Brook coals of Lancashire (Wright *et al*. 1927, fig 9).

3. DEPOSITIONAL ENVIRONMENTS

Detailed facies analysis of sedimentary rocks in the $R_{2c}1$ and $R_{2c}2$ cycles has been carried out on the outcrops east of the Pennine Axis by Benfield (1969) in the north, and by O'Beirne (1996) farther south. These studies recognized a series of sedimentary environments within the broad context of deltaic deposition established for the Millstone Grit Group as a whole. The outcrops west of the Pennine Axis have also been studied for the present work, but in much less detail, so facies analysis has not been attempted beyond that required to assign exposures to the depositional environments recognized in the eastern outcrops.

Deposition took place as deltas advanced into a body of water that was linked to the open oceans by long and probably tortuous routes (Holdsworth & Collinson 1988; Wells *et al.* 2005). The salinity of the water body varied from fully marine, during marine highstands, to non-marine during lowstands. Sedimentary structures, maximum grainsize, and context in the depositional succession all play a part in the recognition of environments. Six lithofacies associations, corresponding to the main depositional environments, have been recognized in this study and are summarized below. Detailed descriptions of the component facies are provided in Table 1.

3.1 Basin-floor deposits

These include dark grey and black laminated or massive mudstones and siltstones, largely unfossiliferous but with marine faunas concentrated in thin beds ('marine bands'). Salinities ranged from fully marine to non-marine, and deposition was mainly from suspension. Basin-floor deposits commonly grade up into delta-slope deposits.

The marine bands comprise laterally extensive dark grey and black, fissile or massive mudstone. Lamination, when visible, is on a sub-millimetre scale. The mudstones may contain compressed thick- and thin-shelled ammonoids, or pectinoid bivalves including *Dunbarella*, or the brachiopod *Lingula*, or combinations of all three. The ammonoid-bearing beds typically have sharp bases and tops and range from 0.05-0.3 m thickness. They may be interbedded with *Lingula*-bearing, typically structureless mudstones associated with serpulid worm tubes and *Planolites* burrows (O'Beirne 1996).

The marine bands are commonly interbedded with, and overlain by, dark grey and black mudstone and dark grey siltstone that lack marine fauna. This facies may be structureless or show planar lamination. The distinctive features of marine bands indicate that bottom conditions were anoxic. The absence of strong tidal flows within the basin (Wells *et al.* 2005) would have resulted in a stratified water column, which would have favoured such stagnant bottom conditions.

3.2 Delta-slope deposits

These are predominantly well-laminated, micaceous and carbonaceous siltstones, with mudstone and sandstone interbeds, deposited on the slope beyond the distributary mouthbars of the advancing river deltas. Suspended fine-grained material was carried as turbulent plumes far beyond the mouthbars by hypopycnal (buoyant) outflow. Fine to medium sand-grade material was also transported on to the lower delta-slopes by density-currents carried through the mouthbars during river floods (hyperpycnal flow). These occur both as massive erosively-based sandstones deposited in feeder channels, and as lobes of sheet-like turbiditic sandstones deposited by unconfined flow. Delta-slope deposits are commonly overlain by mouthbar deposits, either gradationally or with erosive contact.

3.3 Mouthbar deposits

These are predominantly fine- to medium-grained sandstones deposited by traction currents. Current-ripple laminated fine-grained sandstones, commonly bioturbated by *Lockeia* (*Pelecypodichnus*), are typical of a distal mouthbar environment. Interbeds of the delta-slope, parallel laminated mudstones and siltstones are common, whilst in some places this facies association includes sharp-based massive or parallel laminated fine-grained sandstones deposited by density-currents. Trough and tabular cross-bedded fine- to medium-grained sandstones are more typical of the proximal mouthbar environment.

Medium-grained distributary channel deposits have been recognized by O'Beirne (1996) but these have proved difficult to distinguish from cross-bedded mouthbar sandstones. Mouthbar deposits may be overlain by coarser-grained river channel deposits, or by finer-grained delta-top deposits, including palaeosols.

3.4 Distributary and fluvial channel deposits

These are mainly cross-bedded sandstones deposited by traction currents. The grain size is coarser than that of the mouthbar deposits. These deposits occupy channels of varying width, from kilometres to tens of kilometres scale. Typically, the smaller channels, which may represent distributary channels, are filled by coarse- to very coarse-grained sandstone with metre-scale tabular and trough cross-bedding. Sandstones in the largest channel, which may represent a major fluvial channel, range up to granule grade and may include rounded quartz pebbles up to 3 cm across. Cross-bed sets are up to 4 m thick. All channel bases are erosive on mouthbar or underlying deposits, and overlying deposits include delta-top deposits with palaeosols. The continuum of grainsize and bedform within the channel fill has made the distinction between true fluvial channels and distributary channels developed on the delta plain impossible to draw.

3.5 Delta-top deposits

These are a variable series of mudstones, siltstones and sandstones, sometimes forming upward-coarsening units capped by thin coals, locally with palaeosol successions of variable thickness. Sandstone grainsize is variable, typically very fine- to fine-grained, locally ranging up to coarse-grained, with the main sedimentary structures comprising ripple cross-lamination, cross-bedding and parallel lamination. Deposition from traction currents in crevasse channels and crevasse splays into backswamp areas is envisaged. Elsewhere, wave-ripple lamination, symmetrical wave-ripple marks and parallel lamination indicate deposition in shallow water environments within interdistributary bays (Benfield, 1969) and suggest gradation to delta flank deposits.

3.6 Delta-flank deposits

Delta-flank deposits were described by Benfield (1969; Facies H) in the north-east of our study area. They consist of a variable series of very fine- to fine-grained sandstones, siltstones and mudstones, with wave-ripple marks and subordinate parallel lamination, and intercalations of clayey siltstone with brackish to marine fauna. Deposition in beach barriers and lagoons is inferred (Benfield 1969). The facies is underlain by thin basin-floor mudstones and is in places overlain by river channel deposits.

4. DESCRIPTION OF $R_{2c}1$ CYCLE

The $R_{2c}1$ cycle consists entirely of argillaceous basin-floor deposits, the basal *Bilinguites superbilinguis* Marine Band being overlain by non-marine mudstones. The marine band may occur in up to four distinct ammonoid-bearing beds, separated by Lingula-bearing or barren mudstones (O'Beirne 1996). Carbonaceous material, mainly drifted plant debris, is common, with thin allochthonous coal locally developed, e.g. at Ramsden Clough (Bromehead *et al*. 1933, p. 62 and 152) and Meltham Moor (O'Beirne 1996).

The $R_{2c}1$ cycle lacks the widespread sandstones typical of many of the Marsdenian cycles (Figs. 3, 5 & 6) and as a consequence the cycle is generally only a few metres thick within the study area. Localized areas of greater thickness are shown in Figure 7. Those close to basin margins probably mark the position of clastic supply routes to the basin from surrounding upland areas, namely the Wales-Brabant High and Central Lancashire High. Those in more central locations, as in the Alport Basin and Edale Gulf, may be related to areas of deeper water positioned above basement lows (as suggested by the way the isopachs have been drawn), or they may alternatively be related to the major eastern supply route that dominated deposition in the $R_{2c}2$ cycle.

5. DESCRIPTION OF $R_{2c}2$ CYCLE

The lowest part of the $R_{2c}2$ cycle typically comprises an argillaceous succession, commonly with the *Verneulites sigma* Marine Band at its base. This marine band, like the $R_{2c}1$ band, may occur in up to four distinct leaves (O'Beirne 1996). It is present in the Huddersfield to Blackburn areas but has not been proved farther north (Fig. 7). This may be because the $R_{2c}2$ marine band lies immediately above the $R_{2c}1$ marine band, as seen at Barkisland [SE 070 201] (Wray *et al*. 1930) and previous mapping has been unable to differentiate between them. However, in the Bradford area, where *Verneulites sigma* has not been found, it was suggested by Stephens *et al*. (1953) that the $R_{2c}2$ band is represented by a *Lingula* band. If so, this might imply the existence of freshwater effluent along the northern margin of the Central Pennine Basin.

The *Verneulites sigma* Marine Band is overlain by a variable thickness of barren mudstones, up to about 25 m thick (Figs. 5 & 6). These mudstones may be structureless or show planar lamination (e.g. beds similar to Fig. 8, units A & B). These in turn pass upwards, either gradationally to delta-slope siltstones, with interbedded mudstones and sandstones, or sharply into localized turbiditic sandstones (Fig. 8, units C & D), here referred to as the *lower sandstone bodies* (Fig. 4). Delta slope siltstones range up to 50 m in the Newton Bank Borehole (Fig. 5).

The upper part of the cycle is dominated by the major fluviodeltaic sandstones, grouped together as the *main sandstone body,* which are overlain by thinner, discontinuous fluviodeltaic sandstones developed locally and referred to as the *higher sandstone bodies.* The three types of sandstone bodies are described in detail below.

5.1 Lower sandstone bodies

The *lower sandstone bodies* locally underlie the *main sandstone body*, separated from it by siltstone and mudstone, up to 30 m thick at Mouselow Quarry, near Glossop [SK 0249 9519 to 0258 9503]. Grain-size in these sandstones ranges up to medium-grained. The location of the largest sandstone bodies of this type is shown in Fig. 9A. The more north-westerly of these is well exposed at Mouselow Quarry. Here, south-westward-directed palaeocurrents, inferred from primary current lineation, and from cross-lamination in the overlying waning-flow sands (Fig. 8), suggest sediment supply from the Huddersfield delta-lobe. To the south-east around Chatsworth, the other large lower sandstone body is considered to be an early deposit from a distributary located farther south, presumably the Brooksbottoms delta lobe.

The section at Mouselow Quarry is illustrated in Fig. 8, with beds displaying either sheet-like or channelized geometries. The lowermost, planar-bedded part of the sandbody (Fig. 8, unit C), up to 5 m thick, includes upwards-thinning beds towards the top. The bases and tops of the sandstone beds are typically sharp and sub-planar, with common small flute and tool marks on the bases. The sandstone beds are between 0.1 and 0.5 metres thick and are internally structureless, or planar laminated towards bed tops. The overlying channelized sandstone (Fig. 8, unit D), up to 10 m thick, is ungraded, massive to very thick-bedded with beds internally structureless or weakly laminated. Floating mudstone clasts are common, especially above erosive surfaces. The massive sandstones include discontinuous internal erosion surfaces. At the base there is up to 4 m erosional relief, with steep and step-like erosional surfaces and a complex of fractures associated with possible bank-collapse (Fig. 8, detail). The massive sandstones at Mouselow Quarry are overlain by a thin development of rhythmic laminites, together with planar and cross-laminated sandstones.

The *lower sandstone bodies* are interpreted as deposits on the delta-slope formed in front of distributary mouths. The sharp bases of the sandstone beds (units C & D, Fig. 8), associated with the presence of flute and tool marks, suggest that the sandstones were deposited from density-currents. The sheet geometry of beds and subordinate development of channels in unit C (Fig. 8) indicates unconfined flow of the density-currents. These turbidity currents could have been generated from sediment-laden flood discharges into basinal water of reduced salinity, with the upward thinning succession in the sheet-like structureless sandstone facies (unit C, Fig. 8) indicating a systematic waning of flow. Alternatively, they may have been the result of down-slope mobilization of sediment, which had been rapidly deposited on the upper slope of a distributary mouthbar.

The channelized massive sandstones (unit D) were deposited from high-density turbidity currents generated by hyperpycnal flows (O’Beirne 1996). Comparable facies have been described in Namurian strata of the Pennine Basin from the Grindslow Shales (Kinderscoutian) of the Peak District (Collinson 1970) and the Scar House Beds (Arnsbergian) of North Yorkshire (Martinsen 1990). The absence of mudstone partings within the channelized massive sandstones suggests that beds were either deposited in rapid succession, with insufficient time for thicknesses of mud to accumulate from suspension, or that the argillaceous deposits were removed by scouring associated with the passage of the turbidity currents. The absence of palaeosols indicates that the channels were entirely submerged. The steep, step-like nature of the erosive bases of some massive beds emphasizes the rapidity and near-contemporaneity of the erosional and depositional processes.

The rhythmic laminites with planar and cross-laminated sandstones present above the massive turbidite sandstones at Mouselow Quarry (unit E, Fig. 8) reflect an apparently rapid cessation of density-currents. This may have been due to a decrease in river discharge or to the infill of the turbidite feeder channels resulting in a broader dispersion of these currents, followed by transition, firstly to lower flow regime tractional current deposition and then to argillaceous deposition from suspension.

5.2 Main sandstone body

The *main sandstone body* comprises sandstones showing evidence of deposition in mouthbars and distributary channels during delta advance and in fluvial channels during aggradation within incised valleys. The succession contains erosion surfaces, but generally coarsens upwards. The base of the *main sandstone body* overlies delta-slope deposits, gradationally or erosively, and the top is defined by the first palaeosol in the local succession. The names applied in different parts of the area are Huddersfield White Rock, Chatsworth Grit, Brooksbottoms Grit and (very locally) Holcombe Brook Grit (Fig. 4).

5.2.1 Grainsize

Maximum grainsize in the *main sandstone body* shows significant geographical variations (Fig. 9A). A central zone where quartz pebbles are common, and range up to 3 cm in size, is flanked to north and south by areas where pebbles are less common and rarely exceed 1 cm. Farther away from the central zone, in the north-east and south-east of the study area, are regions where sandstones are mainly fine- to medium-grained. Outside of these zones, sandstones of mouthbar or distributary channel facies are thin, or absent and the very fine- to fine-grained sandstones of delta-flank origin, recognized by Benfield (1969), are present.

Within this broad regional pattern, localized grainsize variations occur: for example, in the area of fine- to medium-grained sandstones, between Mixenden and Wainstalls, north-west of Halifax, and around Golcar, west of Huddersfield, fluvial channels up to 2.5 km wide, of W–E and SW–NE orientation, respectively, are filled with coarse to granular sandstone, which lacks extra-basinal pebbles (Benfield, 1969).

5.2.2 Palaeocurrents

Cross-bedding in the *main sandstone body* measured during the present work (shown in Fig. 9B) confirms that the broadly westward palaeoflow, noted in many of the eastern outcrops by Mayhew (1966), Benfield (1969) and O'Beirne (1996), extends to the western outcrops, but with some divergence into south-westward and north-westward flows. In the north-east lobe of finer grade sandstones, palaeocurrents are principally to the north-west, but bifurcate to the west in the more westerly outcrops. South-westward flows are evident in the south of this lobe. A similar dominance of south-westward to southward palaeocurrents is identified in the south-eastern outcrop of the *main sandstone body*. Palaeoflow directions in both the lower and the *higher sandstone bodies* have not been measured on a regional basis and are omitted from Figure 9B.

5.2.3 Thickness variations

Isopachs for the *main sandstone body* are shown in Figure 9C. A general westward thickening, up to a maximum of 88 m, reflects the overall configuration of the Central Pennine Basin. Marsdenian strata, as a whole, show a similar thickening to the west of the Pennines, with deltaic successions infilling inherited accommodation space located to the west and south of the underlying Kinderscoutian deltas (Collinson *et al*. 1977). The area also coincides with the greatest regional (thermal) subsidence during the Namurian (Ramsbottom 1969; Collinson *et al*. 1977). A prominent zone of thickening in the south-east of the study area, up to 48 m, corresponds with the north-west to south-east–trending Widmerpool Gulf.

*5.2.4 Heavy mineral*s

Two sources of sediment have been distinguished on the basis of heavy minerals in the sandstones. In the outcrop area north of the Widmerpool Gulf, samples containing amounts of monazite appropriate to the main Millstone Grit river system have been obtained from the Chatsworth Grit of the outcrop area (Chisholm & Hallsworth 2005), whereas samples from the Melbourne Borehole (Fig. 6), south of the Widmerpool Gulf, contain less monazite (Hallsworth *et al*. 2000, table 2). The latter are interpreted to belong to a separate minor supply system that brought sediment from the Wales-Brabant High (Fig. 9D).

5.2.5 Subdivisions of main sandstone body

The information summarized above leads to a subdivision of the *main sandstone body* into several units, as shown in Figures 9A, 9B, 9C & 9D. Three of these units appear to have a common inflow from the east of the study area, which is presumed to be a branch of the northern river that supplied sediment for the rest of the Millstone Grit Group. This is referred to here as the *'eastern inflow'*. A fourth unit, identified in borehole logs in the south-east of the study area, has been included in the *main sandstone body* on account of its thickness. Its heavy mineral content and position adjacent to the Wales-Brabant High suggests that it may have been supplied directly from there, either as a separate entity or via tributaries to a southern branch of the Millstone Grit river. The direction of palaeoflow in this region is conjectural, as are the shape of the sandbody and its relationship with the sandstones of the eastern inflow (Figs. 9A, 9B, 9C & 9D). Church & Gawthorpe (1994) interpreted this unit as a succession of mouthbar and channel sandstones formed at a time of high sea-level, and found no evidence for incision within it.

Among the deposits related to the eastern inflow, at any one place the *main sandstone body* commonly coarsens upwards. The maximum grainsize recorded (Fig. 9A) thus indicate the youngest unit present at each locality. On this basis, the three units of the *main sandstone body* (see below, *Phases 1–3*), which are recognized primarily on their grainsize, appear to form a time sequence that records increasing current power as the fluvio-deltaic system advanced across the basin. It is evident that the configuration of the underlying basement (Fig. 9D) had no influence on the palaeoflow pattern or the distribution of the different grades of sand deposited.

Phase 1 The main outcrop of the Huddersfield White Rock around Huddersfield comprises dominantly fine- to medium-grained sandstone (Fig. 9A) showing a broadly fan-shaped arrangement of palaeocurrents in a lobe of mainly mouthbar sandstones, referred to here as the Huddersfield delta-lobe (Figs. 9B & 9D). The main axis of fluvial palaeoflow appears to have been towards the north-west, with divergence occurring at the distributary mouth as mouthbar sands built out to form a sub-delta some 40 km long by 20 km wide. Underlying delta slope deposits, represented by parallel-laminated, mudstone, siltstone and silty sandstone, were deposited mainly from suspension. The succession shows a progradational transition to overlying distributary mouthbar deposits comprising ripple cross-laminated sandstone and ultimately cross-bedded sandstone, displayed at Deer Stones, Holme Moss (Fig. 10). Here, the ripple cross-laminated sandstones, which were deposited as traction loads transported by episodic, unconfined, weak bottom currents, are interbedded with erosively-based sheet-like structureless sandstones, indicative of more energetic density-currents (to form Facies A of Benfield 1969). The presence of density-current deposits in the *lower sandstone bodies* of the delta-slope, as at Mouselow Quarry, Glossop (Fig. 8) and in the mouthbar deposits of the *main sandstone body*, as at Deer Stones (Fig. 10), suggests that the two environments show a continuum of deposition and are genetically related.

The main distributary channel that fed the Huddersfield delta-lobe is not proved at outcrop, and its location in the subcrop is problematical. To the east, within the northern part of the Gainsborough Trough, the interval is marked by deposition of fine-grained lacustrine/bay sediments (Steele 1988) and no equivalent of the Huddersfield White Rock can be recognized. A position to the south-east, in the area later occupied by the Chatsworth palaeovalley, is provisionally indicated (Fig. 9).

Locally, coarse-and very coarse-grained sandstones, in channels up to 2.5 km wide (Fig. 9A) and up to 11 m deep, are eroded into the fine- to medium-grained sandstones between Mixenden and Wainstalls, north-east of

Halifax, and around Golcar, west of Huddersfield (Facies F of Benfield 1969). These channels could be regarded as parts of the contemporary (Phase 1) distributary network in the delta lobe. However, the channels are orientated almost perpendicular to the north-westward palaeocurrents within the adjacent mouthbar facies (Figs. 9A, 9B) and show westward palaeoflow (not shown in Fig. 9B), suggesting that the channels are not linked directly to the underlying mouthbar deposits. A possible link to Phase 2 deposition is suggested by the coarse grainsize.

To the west of the Pennine axis, quarries at Summit [SD 947 180; SD 945 181; SD 950 189] (Fig. 2) prove a succession of fine- to medium-grained cross-bedded mouthbar and distributary channel sandstones at least 30 m thick. These display variable foreset orientations with a mean towards the north, broadly consistent with palaeocurrents seen in the Huddersfield White Rock to the north of Huddersfield (Fig. 9B). Coarser-grained sandstones with scattered quartz granules occur towards the top of the succession here, however, suggesting the possible presence of a fluvial channel. This locality is thought to lie close to the western limit of the Huddersfield delta-lobe described above, although it has been named, historically, as Holcombe Brook Grit (e.g. Wright *et al*. 1927, fig. 15).

Phase 2 Farther west in Lancashire, the Brooksbottoms Grit (Figs. 3 & 4) consists of fine-, medium- and coarse-grained mouthbar, distributary and fluvial channel sandstones with cross-bedding showing palaeocurrents directed mainly towards the north and west (Fig. 9B). Rare quartz pebbles range up to 2 cm in size. The overall grainsize and the maximum grainsize of the fluvial sandstones is greater than that of the Huddersfield White Rock (Fig. 9A), suggesting that the main sand supply was not from the Huddersfield delta-lobe to the east, but from a region farther south (Fig. 9D). The apparent eastward pinch-out of the Brooksbottoms Grit in Lancashire (Wright *et al*. 1927) supports this interpretation.

In the western outcrops to the south of Glossop, there exists a zone where the maximum grainsize is greater than that of the Huddersfield lobe but smaller than that of the Chatsworth palaeovalley. Similar zones can be recognized on both sides of the Chatsworth palaeovalley in the eastern outcrops (Figs. 6 and 9A). These are provisionally regarded as deposits of Phase 2, forming the upstream part of the Brooksbottoms delta-lobe. At Birch Vale, 7 km south of Glossop (Fig. 5) coarse-grained fluvial channel-facies sandstones, partly cross-bedded, with a granule conglomerate containing scattered quartz pebbles up to 8 mm in size, rest sharply on fine- to medium-grained sandstones with low-angle planar lamination that suggest deposition on a mouthbar. The section illustrates that the lower part of the Brooksbottoms Grit includes a mouthbar facies comparable with that of the Huddersfield delta-lobe.

In the eastern outcrop, a set of sandstones inferred to be part of the Brooksbottoms delta lobe is seen at Callow Bank [SK 253 823] near Hathersage, where medium-grained massive sheet sandstones, 5 m and 3 m thick, occur in association with coarsening-upwards (siltstone to fine-grained sandstone) bioturbated shallow water deposits. The section was interpreted by O'Beirne (1996, facies 5.2) as a mouthbar facies. These beds lie beneath well-developed coarser-grained sandstones belonging to Phase 3, the Chatsworth palaeovalley. The presence of sheet-like massive sandstones within a shallow water mouthbar setting is comparable to the association seen at Deer Stones in the *main sandstone body* of the Huddersfield delta-lobe (Fig. 10).

Regionally, there is a lack of evidence of significant incision at the base of the Brooksbottoms delta lobe. It is inferred that the lobe filled the accommodation space between the Huddersfield and Widmerpool delta lobes. Chronologically, Phase 2 may have overlapped with Phase 1.

Phase 3 In the eastern outcrops there is a zone (Figs. 6 and 9A) where very coarse-grained cross-bedded sandstones, with quartz pebbles up to 3 cm, make up the highest parts of the *main sandstone body*. These coarse sediments commonly exhibit large-scale cross-stratification and may be assigned to the cross-bedded fluvial facies of the River Channel Association (Table 1). The zone includes the original type area of the Chatsworth Grit and these beds comprise the fill of the feature we refer to as the Chatsworth palaeovalley. However, it should be noted that the palaeovalley occupies only part of the wider area over which the term Chatsworth Grit has been applied (see Fig. 4).

O'Beirne (1996) recognized four main types of large-scale tabular cross-stratification within the palaeovalley fill. The first type, cosets of large planar foresets, probably developed near the crests of downcurrent accreting in-channel barforms, with erosive coset surfaces indicating renewed periods of sedimentation down the slip-face. The maximum thickness of 5.6 m marks the minimum barform height, with erosional truncation of the barform having occurred during a subsequent flood event. The second type, single large cross-bed sets at least 4.2 m thick, developed from single duneforms. The third type, cosets of downcurrent-dipping cross-bed sets (0.2 to greater than 1 m thick) indicate a coalesced dunefield in which smaller dunes migrated over large dunes. The fourth type, flat-lying sets of planar tabular cross-beds typically 1 m, but up to 2 m thick (e.g. Fig. 11B) were produced by straight-crested dunes, which developed between bars during waning flow. The absence of evidence of lateral accretion surfaces, a paucity of abandonment deposits and the unidirectional transport direction suggest the system was dominated by braided channels. These braided channel systems probably reflect high fluvial discharge rates, steeper river gradients and the coarse grainsize of the bedload (Orton & Reading 1993). In these eastern outcrops, extensive (100s – 1000s metres) horizontal erosion surfaces separate the very coarse-grained sandstone into as many as three stacked river channel bodies (O'Beirne 1996).

The margin of the Chatsworth palaeovalley is well marked on its north side at The Naze, near Chinley (Fig. 11A), and at Moscar [SK 228 877], but its south side is not well defined. Within the fluvial channel facies, mean palaeocurrents are generally directed towards the west, but range between north-west and south-west. They are similar to those in the adjacent exposures of the Brooksbottoms lobe, but are significantly different from those of the Huddersfield lobe (Fig. 9B). Palaeocurrent directions and grainsize in these western outcrops are consistent with a south-westward continuation of the Chatsworth palaeovalley towards Stoke-on-Trent. In the subsurface beyond the eastern outcrop, a similar major fluvial channel sandstone has been identified as far east as Gainsborough (Steele 1988).

As with the Brooksbottoms lobe, a succession of depositional environments can be recognized in the western outcrop, where exposures allow. For example, at Cumberland Cottage, near Buxton (Fig. 5), the highest part of the *main sandstone body* is a very coarse-grained, cross-bedded granular channel deposit, with quartz pebbles up to 2 cm. Underlying beds are fine- to medium-grained sandstones with interbedded siltstones. The sandstones are partly ripple cross-laminated and partly cross-bedded, with massive beds towards the base. This combination of features indicates deposition on mouthbars like those of the Huddersfield lobe.

5.3 Higher sandstone bodies

In much of the study area, the succession above the *main sandstone body* is dominated by mudstone and siltstone with lenticular sandstones, typically in one or two upward-coarsening cycles between 1 and 30 m thick (Figs. 5, 6 & 12). This succession is well developed above the Chatsworth Grit at outcrop west of Sheffield and Chesterfield and here includes two named sandstones, the Brown Edge Flags and the Redmires Flags. It is also present in the subsurface to the east, where up to four cycles have been identified from borehole gamma-ray wireline logs (O'Beirne 1996). The succession also occurs in the north-west of the study area where, as the 'Holcombe Brook Series' (Wright *et al*. 1927, fig. 9), it overlies the Brooksbottoms Grit. The succession here is very variable, with one or more lenticular sandstones referred to as Holcombe Brook Grit.

The sandstones above the *main sandstone body* west of Sheffield are generally fine- to medium-grained, with wave- and current-ripple lamination. Bioturbation is common, including *Chondrites*, *Lockeia* (*Pelecypodichnus)*, *Conostichnus*, *Cochlichnus* and *Planolites* (O'Beirne 1996). The presence of *Chondrites* and *Planolites* suggests deposition in brackish to marine water, whereas *Lockeia* (*Pelecypodichnus)* is indicative of deposition in freshwater (Eagar *et al*. 1985). This facies represents minor shallow-water deltaic and shoreline sediments deposited within a delta-top environment. Correlations between the cycles developed in different parts of the area are difficult, for reasons discussed in the section on sequence stratigraphy (see below).

The pattern of thickness variations within the interval above the *main sandstone body* is shown in Fig. 13. A localized maximum of just under 40 m in the central part of the area could be related to its position above the Chatsworth palaeovalley, which may have been underfilled during the period of rising sea-level that followed incision (O'Beirne 1996). However, the location this maximum thickness within the Edale Gulf, and the existence of another in the Alport Basin (Fig. 13), might alternatively imply a control by differential subsidence. A more marked maximum in the Rossendale Basin may be explained by either control, or both. However, the presence of an area of increased thickness here, above the Brooksbottoms lobe of the *main sandstone body*, has implications for the sequence-stratigraphic interpretation of the $R_{2c}2$ cycle (see below).

Palaeocurrent directions determined in scattered localities are consistent with a continuation of the transport system seen in the *main sandstone body*, but are too few to be definitive. The heavy mineral content of samples from the Redmires Flags and the Brown Edge Flags gives evidence of some dilution of the typical Millstone Grit sand by material from another source, suggested by Chisholm & Hallsworth (2005) to be the Wales-Brabant High. If this is true, the diluting material must have been added to the sediment flux of the eastern distributary somewhere to the east of the study area.

Palaeosols, some with thin coals, are widespread within the *higher sandstone bodies*, though commonly immature. These palaeosols are indicated by common rootlets. The presence of carbonaceous material associated with the rootlets suggests the palaeosols formed in a poorly drained environment, typical of formation on a shallowly submerged lacustrine delta. A prominent leached palaeosol at the top of the minor lacustrine delta cycles at Winscar Reservoir, near Dunford Bridge (Fig. 12) is a potentially significant correlation surface. Its strongly leached nature implies that the palaeosol developed over a long period.

The coal seams formed from the autochthonous accumulation of peat within an organic-rich mire environment. These coals are typically sediment-starved, although thin dirt bands may indicate minor input of sediment in periods of overbank flooding. The peats developed in swamp (rheotrophic mire) environments on abandoned or sediment-starved parts of the delta-top.

A significant correlation surface within this highest part of the $R_{2c}2$ cycle is associated with an unnamed *Lingula* band, present above the Brown Edge Flags of the Sheffield area (Eden *et al*. 1957). In the Rod Moor No. 2 Borehole, the *Lingula* band comprises five distinct fossil bands within a 4 m-thick interval (O'Beirne 1996). A *Lingula* band has also been proved in a number of other boreholes, suggesting that it may extend as far north as the Colne Road Mills Borehole, Huddersfield (Fig. 6), where a *Lingula* band rests directly upon what is mapped as a local upper leaf of the Huddersfield White Rock.

The highest part of the succession normally comprises basin-floor mudstones (Figs. 5, 6 & 12), which extend up to the base of the *Cancelloceras cancellatum* Marine Band.

6. SEQUENCE STRATIGRAPHY

Repeated fluctuation of sea-level is a well-established feature of Namurian sedimentation in the Central Pennine Basin (Wright *et al*. 1927, fig. 4; Holdsworth & Collinson 1988), and the principles of sequence stratigraphy can therefore be applied to the succession. A general context for sequence-stratigraphic interpretation of this succession has been provided by Martinsen *et al*. (1995), and is accepted here. These authors argue that due to the lengthy and sinuous nature of connections between the open sea and the basin, the condensed section represented by each of the ammonoid-bearing marine bands is likely to coincide with a maximum of the sea-level curve, rather than with the 'R inflexion point' of the rising sea-level curve predicted by the Exxon sequence-stratigraphic model (Posamentier *et al.* 1988). This has implications for the timing of entry of fluvial sand into the basin, suggesting that the major influx of sand began during the falling stage of the sea-level curve, and not at its maximum, so that the major sandbodies should be regarded as falling-stage systems tracts, rather than highstand systems tracts.

Sequence-stratigraphic interpretations that deal with Marsdenian rocks include studies by Brettle (2001); Wignall & Maynard (1996); O'Beirne (1996) and Jones & Chisholm (1997), based on outcrop sections, and by Church & Gawthorpe (1994), using subsurface well data. The time interval represented by each sedimentary cycle – the interval between successive marine-band highstands – has been estimated at between 65,000 (Davies *et al*. 1999) and 180,000 years (Martinsen *et al*. 1995); Collinson (2005) has used a figure of 90,000 years. These values are consistent with the fourth-order cyclicity of Mitchum & Van Wagoner (1991). The amplitude of sea-level variation has been estimated at about 42 m (Maynard & Leeder 1992). The existence of a superimposed higher-frequency cyclicity (fifth-order) of lesser amplitude has been proposed (e.g. by Jones & Chisholm 1997; Brettle 2001).

Comprehensive sequence-stratigraphic analyses of the $R_{2c}1$ and $R_{2c}2$ cycles are not attempted here; instead, we try to identify different elements of sequence-stratigraphic models and assess their significance, accepting that each cycle was deposited between two marine flooding surfaces, with an intervening lowstand implied (Fig. 14). In the upper cycle, evidence is provided for the presence of a sequence boundary and its correlative interfluve palaeosol. We also examine whether lower-amplitude fluctuations may have been superimposed on the major variation of sea-level.

6.1 Marine bands

The ammonoid-bearing marine bands indicate development of fully marine conditions in response to basinwide maximum marine flooding events. The acme faunal phase, typically the thick-shelled ammonoids, is here taken to represent the maximum flooding surface developed at maximum sea-level, as argued for the early Namurian marine bands by Martinsen *et al.* (1995).

The *Bilinguites superbilinguis* and *Verneulites sigma* marine bands are probably indicative of fourth-order sea-level maxima (Fig. 14). The *Bilinguites superbilinguis* Marine Band was associated with a relative sea-level rise sufficient to drown the underlying Guiseley Grit – Ashover Grit deltaic system (Fig. 3) and the establishment of relatively deeper water conditions across the basin. The *Verneulites sigma* Marine Band has a lower density ammonoid fauna and is not as laterally extensive as the underlying *Bilinguites superbilinguis* Marine Band, being absent in the northern parts of the Central Pennine Basin (Fig. 7). This suggests that the sea-level rise associated with the *Verneulites sigma* Marine Band was comparatively small. It is possible that the relative magnitude of the two marine bands could relate to their position on a third-order cycle, the *Bilinguites superbilinguis* Marine Band occurring closer to the maximum third-order sea-level curve.

Internally, both marine bands consist of distinct leaves of ammonoid- and *Lingula*-bearing mudstone and faunally-barren mudstone. Within the ammonoid-bearing beds, the high density of nektonic (free-swimming) fauna, and lack of significant terrestrial sediment influx, suggest low sedimentation rates. These events coincided with periods of relative sediment starvation resulting from drowning of the hinterland. The concentration of nektonic fauna and the absence of benthic species or evidence of bioturbation indicate deposition in fully marine waters with anoxic bottom conditions. The *Lingula* band faunas are interpreted as displaying tolerance of a wide range from brackish to marine conditions (Calver 1968). The benthic nature of the fauna and the lack of lamination within the mudstones suggest oxic conditions, perhaps in shallow waters. The common presence of a *Lingula* band below the ammonoid-bearing mudstones suggests development of brackish-marine conditions in advance of the marine transgressive acme. The *Lingula* bands also develop to the exclusion of ammonoid-bearing mudstones along the more marginal, shallower water, lower salinity parts of the Central Pennine Basin in the case of both the *Bilinguites superbilinguis* and the *Verneulites sigma* marine bands.

In the barren mudstones, anoxic conditions are implied by the absence of fauna and high concentrations of organic carbon. Where this facies intercalates with marine faunas, it is possible that the barren intervals represent pulses of fresh water into the basin, introduced via deltas and supplying fine detrital material, including comminuted plant debris. Locally high concentrations of carbonaceous material and thin coals are probably derived from drifted plant material sourced from fluvial discharges.

In summary, the *Bilinguites superbilinguis* and *Verneulites sigma* marine bands show evidence of periodic fluctuations of salinity and reduction/oxidation conditions, which may reflect relative sea-level changes attributed to fifth-order (high frequency–low magnitude) sea-level fluctuations superimposed upon the fourth-order flooding events (Fig. 14).

6.2 Basin-floor non-marine deposits

The highstand associated with the *Bilinguites superbilinguis* Marine Band was of sufficient magnitude and/or limited duration to prevent development of a deltaic or fluvial system during the $R_{2c}1$ cycle within the entire Central Pennine Basin. The top of the $R_{2c}1$ cycle is marked only by an upward transition from barren mudstone to marine mudstone at the base of the *Verneulites sigma* Marine Band. There is no evidence of an unconformity or palaeosol, and the sequence boundary inferred to exist between the two highstands must be represented by a correlative conformity within the barren mudstone interval (Fig. 14).

Within the $R_{2c}2$ cycle, the barren mudstone succession above the *Verneulites sigma* Marine Band coarsens upward into parallel-laminated siltstones and mudstones. This facies represents suspension deposits from hypopycnal or homopycnal flows that accumulated in a pro-delta environment (Benfield 1969; O’Beirne 1996). The coarsening-upward successions are indicative of increasing proximity to the distributary mouth in a prograding delta during the transition from sea-level highstand to early falling-stage.

6.3 Lower sandstone bodies

The *lower sandstone bodies* were deposited by density-currents in a delta-slope environment within the deeper parts of the Alport Basin and the Edale Gulf, where the $R_{2c}1$ cycle is thickest (compare Figs. 7 & 9A). Subsidence rates and gradients would have been greater here, and hyperpycnal (density) underflows may have been more common, generating the greater abundance of the erosively-based massive sandstones (O’Beirne 1996).

The sequence-stratigraphic significance of the *lower sandstone bodies* is uncertain. Erosive surfaces within the *lower sandstone body* at Mouselow

Quarry (Fig. 8) might be taken to indicate one or more periods of relative sea-level fall, and the overlying 30 m thick succession from basin-floor mudstone to delta-slope siltstone above the *lower sandstone body* could be inferred to represent sea-level rise. However, the similarity of the sheet-like structureless sandstones at Mouselow Quarry (Fig. 8) to those within the lower part of the mouthbar deposits of the Huddersfield delta-lobe at Deer Stones (Fig. 10), located directly up palaeocurrent, suggests that the two depositional areas were genetically related and show a continuum of deposition. This would suggest that the prominent, but only locally developed, erosive surfaces within the deposits are not indicative of base-level falls, but reflect channel erosion and infill during flood events. The reversion to mudstone above the *lower sandstone body* may reflect out-building of the delta in a north-north-westward direction (Fig. 15A).

Although it is recognized that sea-level changes may be an important control on river incision and aggradation, sequence stratigraphical models may often overlook the importance of tectonic and climatic factors (Salter 1993). Repeated aggradation and incision may reflect a response to a highly fluctuating discharge within a basin (Salter 1993) and this process is envisaged as the most likely explanation of the *lower sandstone body* architecture.

6.4 Main sandstone body

The regressive upward coarsening passage through delta-slope deposits to mouthbar, distributary channel and fluvial sands of the *main sandstone body* was accompanied by a narrowing of the regional fluvial pathway (Figs. 15A & 15B), with a concomitant increase in flow velocities resulting in an increase in grainsize. This culminated in the markedly erosive base of the Chatsworth palaeovalley (Fig. 15C). Mayhew (1966) regarded this zone as the main fluvial distributary channel. However, O'Beirne (1996) suggested that the channel had been incised into earlier sediments during a fall in sea-level, and was therefore a palaeovalley, the fill of which formed the coarsest and youngest part of the *main sandstone body*. This view, the evidence for which is presented in Section 5.2.5, is accepted here.

Incised palaeovalleys can be generated through base-level fall (potential incision) or discharge-controlled incision (kinematic incision) (Leeder & Stewart 1996). The increasing grainsize within successive phases of narrowing of the fluvial pathway would be expected during either process of incision. In the study area, the unconformable surface is regionally extensive and deeply erosive, the Chatsworth palaeovalley being some 25 km wide, with at least 55 m of erosional relief (Figs. 5 & 6). It cuts down into the underlying part of the *main sandstone body*, but incision is insufficient to remove either the *Bilinguites superbilinguis* or *Verneulites sigma* marine bands. The erosive surface associated with the Chatsworth palaeovalley can be correlated into the interfluve areas as a leached palaeosol (Figs. 6 & 15C). As for the underlying part of the *main sandstone body* – the Huddersfield and Brooksbottoms delta-lobes – the sequence-stratigraphic interpretation, summarized in Figure 14, suggests their formation occurred during the earlier stages of falling sea-level. The *main sandstone body*, as a whole, may thus be interpreted as the deposit of a forced regression (Posamentier *et al*. 1992).

Sequence-stratigraphic models predict that incised palaeovalleys are filled by aggradational deposits of a lowstand systems tract that develop during sea-level lowstand and early sea-level rise (Miall 1991). The deposits within the incised valley of the Chatsworth palaeovalley thus relate partly to the lowstand but mainly to aggradation during the following rise of sea-level (Figs. 14 & 15D). All the deposits overlying the channel sands must also have been formed during the transgression that culminated in the highstand of the *Cancelloceras cancellatum* ($G_{1a}1$) Marine Band (Figs. 5 & 6).

6.5 Deposits above the main sandstone body

Deposits above the *main sandstone body* are in two parts: immediately above the *main sandstone body* are upward-coarsening thin sedimentary cycles, generally with palaeosols, and above these are basin-floor mudstones passing up to the *Cancelloceras cancellatum* Marine Band. The minor cycles could have been deposited under the influence either of falling or of rising sea-level, and their interpretation involves a consideration of their position relative to the incised Chatsworth palaeovalley, together with some assessment of their contained palaeosols.

Away from the Chatsworth palaeovalley, at Winscar, for example (Fig. 12), the section above the Huddersfield lobe of the *main sandstone body* includes a thick leached palaeosol between a minor cycle and the overlying basin-floor mudstones. A lower palaeosol, at the base of the minor cycle, is not leached. This implies that the higher palaeosol owes its origin to prolonged exposure on an interfluve area, and must have been formed as the sea-level fell to its lowest position (Fig. 15C), probably equating with incision of the Chatsworth palaeovalley. The thin cycle under the palaeosol must, like the Huddersfield lobe below, be part of the regressive systems tract. It is an open question whether the minor cycle owes its origin to a minor fluctuation of sea-level superimposed on the regression, or if it resulted from an autocyclic shift of delta-top environments. The hinterland shift in facies from leached palaeosol to overlying non-marine mudstones seen at Winscar (Fig. 12) is interpreted as an initial flooding surface above which the abrupt decrease in grainsize reflects a diminution of sediment supply during retrogression of the supply system. These overlying basin-floor mudstones locally contain *Lingula*, as at the nearby Oxspring No. 1 Borehole (Fig. 6), indicative of the establishment of brackish salinities, consequent upon a base level rise (Fig. 14). The *Lingula* band associated with this transgressive flooding surface is seen widely within and beyond the margins of the Chatsworth incised valley (Fig. 15D).

In areas underlain by the Chatsworth palaeovalley the situation is markedly different. Here, as noted above, the minor cycles, as well as the overlying basin-floor mudstones, must all belong to the transgressive systems tract. A section above the Chatsworth palaeovalley near Errwood Hall in the Goyt Valley [SK 0045 7506], exposes mudstone passing up into fine-grained sandstone followed by a coal and then basin-floor mudstones with the *Cancelloceras cancellatum* Marine Band. The lack of any palaeosol beneath the coal is a notable feature of the section and suggests that the coal is allochthonous. Another example is Rod Moor No. 3 Borehole (Fig. 6) (Eden *et al*. 1957, p. 212), where two cycles occur above the Chatsworth palaeovalley. The lower cycle, which includes the Brown Edge Flags, is capped by a thin coal lacking any palaeosol development. This cycle is overlain by a *Lingula* band, which can be traced across the Chatsworth incised valley (Fig. 15D). The upper cycle, which includes the Redmires Flags, shows a single poorly developed palaeosol at the top, overlain by basin-floor mudstones with the *Cancelloceras cancellatum* Marine Band. A similar section is recorded at Rod Moor No. 2 Borehole (O'Beirne 1996). The absence of a mature leached palaeosol within the deposits above the *main sandstone body* within the Chatsworth palaeovalley is consistent with the sequence-stratigraphical interpretation of deposition within a transgressive systems tract.

Sections through the beds above the *main sandstone body* are few, however, so the reliability of palaeosol development (ranging from absent to mature leached palaeosol) as a discriminator between falling-stage and rising-stage systems tracts cannot be tested thoroughly. Nevertheless, it seems likely that the deposits of the thin cycles, lying immediately above the *main sandstone body* infilling the Chatsworth palaeovalley are not genetically related to those occurring outside of this channel, and may be appreciably younger.

The presence of a *Lingula* band within the fluviodeltaic clastic deposits both above the incised channel and within the interfluve areas above the Brooksbottoms and Widmerpool delta lobes (Figs. 5, 6, 15D), may provide a correlatable and time-equivalent surface, which may be an index of position within the transgressive systems tract. However, with limited sections available, it is difficult to test this relationship on a regional basis. An ammonoid-bearing marine band has only been recorded at this level within the Central Pennine Basin at Smeekley Wood No. 3 Borehole [SK 2968 7653] near Chesterfield, suggesting that the *Lingula* band resulted from a comparatively minor sea-level rise. The *Lingula* band may, therefore, reflect a fifth-order sea-level rise imposed upon the broadly rising sea-level that culminated in the maximum flooding surface at the base of the *Cancelloceras cancellatum* Marine Band (Fig. 14).

The succession above the Brooksbottoms lobe of the *main sandstone body* in the north-west of the study area is unusually thick, and contains numerous palaeosols (Fig. 5). The lower palaeosols may represent an interfluve developed during the Chatsworth palaeovalley incision, and the higher palaeosols may be backswamp deposits that kept pace with increasing accommodation space created as sea-level rose. The highest part, as elsewhere, comprises basin-floor mudstones deposited during progressive flooding as sea-level rose towards the *Cancelloceras cancellatum* Marine Band highstand.

To summarize, individual sandstones and coal seams in the succession above the *main sandstone body* should not be readily correlated, because they may be of widely different ages; some formed during the regression and others during the transgression.

7. CONCLUSIONS

The *Bilinguites superbilinguis* and *Verneulites sigma* marine bands mark highstands of sea-level, and define the bases of the $R_{2c}1$ and $R_{2c}2$ cycles, respectively. Both marine bands relate to fourth-order sea-level changes, of which the frequency is in the order of 100,000 years. However, the *Bilinguites superbilinguis* Marine Band appears to be associated with a higher magnitude sea-level rise. Internally, both marine bands show evidence of periodic fluctuations of salinity and reduction/oxidation conditions, which may reflect relative sea-level change attributed to fifth-order fluctuations superimposed on the fourth-order sea-level curve. Both marine bands are overlain by non-marine mudstones that mark a reduction in basinal salinity, brought about by the effects of falling sea-level on a restricted basin, possibly enhanced by climatically controlled increases in fluvial discharge rates.

The $R_{2c}1$ cycle and lower part of the $R_{2c}2$ cycle are affected by differential compactional subsidence inherited from the early Carboniferous structural architecture. This resulted in thicker $R_{2c}1$ cycle successions, and in the *lower sandstone bodies* of the $R_{2c}2$ cycle being mainly confined to the under-filled parts of the Alport Basin and the Edale Gulf. The *lower sandstone bodies* are dominated by deposits from density-currents on a delta-slope. Erosive surfaces within the delta-slope deposits are seen as indicative of erosion in response to periodic increases in fluvial discharge, rather than to base-level falls.

The sandstones of the $R_{2c}2$ cycle are typical of the Millstone Grit Group, having been deposited in fluvial and deltaic environments under the influence of cyclic sea-level changes. The bulk of the sediment, which was transported from a region between Scandinavia and Baltica, entered the Central Pennine Basin at its eastern side. There was a subsidiary influx from a local source area to the south.

The *main sandstone body* of the $R_{2c}2$ cycle shows evidence of narrowing of the main transport path, with concomitant increase in current strength. This is consistent with a progressive fall of sea-level, and a forced regression of the deltaic shoreline. The coarsest deposits occupy an incised valley cut during the period of lowest sea-level, but filled by aggradation during the subsequent rise of sea-level. It is noticeable that structural elements in the Late Devonian to early Carboniferous basement appear to have had no influence on the course of the main sediment path.

Deposits overlying the *main sandstone body* are of two types, which differ in age. Those above the incised palaeovalley record the continuing rise of sea-level towards the highstand of the *Cancelloceras cancellatum* Marine Band, which defines the top of the cycle, but those lateral to the main channel can have two components. The lower records events prior to the lowstand, and is separated by a significant leached palaeosol from an upper component that relates to the rising sea-level.

Minor palaeosol beds within these higher deposits may point to minor oscillations of sea-level, but could also be of autocyclic origin, resulting from processes inherent to deltaic development such as switching between delta-lobes.

Finally, we have shown that the present nomenclature for the sandstones of the $R_{2c}2$ cycle are at best confusing and in places erroneous. We have presented a simplified scheme that places the sandbodies in a time-dependent sequence stratigraphic framework.

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CAPTIONS

Fig. 1 Summary geological map showing the distribution of the Millstone Grit Group and main structural elements (named in italics) within the study area.

Inset A - the regional setting; Inset B – the plate tectonic configuration derived from Waters & Davies (2006).

Fig. 2 Distribution of key boreholes (normal text) and field localities (in italics) used to produce isopachyte maps and correlation panels. Those shown in bold are described in more detail within the text or figures. The outcrop of the combined $R_{2c}1$ and $R_{2c}2$ cycles is derived from BGS DigMap50k data.

Fig. 3 Comparison of the Marsdenian lithostratigraphical successions for the Rossendale (Lancashire), Huddersfield (Yorkshire) and Chatsworth (Derbyshire) areas. The inset shows the position of the Marsdenian regional substage within the international and regional chronostratigraphy of the Carboniferous.

Fig. 4 Simplified stratigraphy of the $R_{2c}2$ cycle, showing relationship between informal terminology of sandstone units used in this paper and local lithostratigraphical names.

Fig. 5 Correlation of key boreholes and surface sections from west of the Pennine Axis; see Figure 2 for their location.

Fig. 6 Correlation of key boreholes from east of the Pennine Axis; see Figure 2 for their location.

Fig. 7 $R_{2c}1$ cycle: recorded thicknesses in metres (black figures) with isopachs drawn to emphasize local thickness maxima (purple dashed lines). Green line shows where the overlying $R_{2c}2$ marine band passes from ammonoid facies, with *Verneulites sigma*, into a *Lingula* band. Late Devonian to early Carboniferous structural elements based on Kirby *et al*. (2000) and Smith *et al*. (2005).

Fig. 8 Composite graphic log and photograph for the section at Mouselow Quarry, near Glossop [SK 0249 9519 to 0258 9503], which includes one of the *lower sandstone bodies* (lower leaf of the Huddersfield White Rock). The section shows a sharp transition from basin-floor deposits (units A and B) to overlying delta-slope deposits, with sheet-like internally structureless sandstone beds (unit C) incised by a marked channel, infilled by mainly massive sandstone (Unit D). The lower photograph shows details of the marked incised surface associated with complex erosive and bank collapse structures.

Fig. 9 Summary of information on the *main sandstone body*, with inferred phases of deposition. **9A,** Geographical distribution of maximum grainsize. Location of the turbiditic *lower sandstone bodies* also shown. **9B,** Cross-bedding measurements at selected localities, to indicate the regional palaeocurrent pattern. **9C,** Thickness in boreholes and surface sections. Data points correspond to those shown on Figure 2. **9D,** Location and architecture of the *main sandstone body* related to Late Devonian to early Carboniferous structure. Structural elements as for Figure 7.

Fig. 10 Graphic log and photograph of the section in the *main sandstone body* (Huddersfield lobe) at Deer Stones, Holme Moss [SE 097 033]. The section comprises beds (units A, B, C, E, G and I) of structureless, fine- to medium-grained sandstone, locally planar laminated towards bed tops, with bed bases locally show scouring to a depth of up to 2 m. These are interbedded with ripple cross-laminated, fine-grained sandstone (units D, F and H). The top of the section is dominated by trough cross-bedded, fine- to medium-grained sandstone (unit J and L).

Fig. 11A View of Chinley Churn from Chinley Head, near Hayfield [SK 049 847] showing the northern margin of the Chatsworth palaeovalley, incising a much thinner and finer-grained sandbody of the Brooksbottoms lobe.

Fig. 11B Planar cross-bedding exposed in the crag at The Naze, indicating palaeocurrents towards the west-south-west, consistent with the regional trend within the Chatsworth palaeovalley (see Figure 9B).

Fig. 12 Graphic log and photographs of the section at Winscar Reservoir, near Dunford Bridge [SE 1521 0303], showing the top of the *main sandstone body* (unit A - Huddersfield lobe) and *higher sandstone bodies* (units D and E). The *higher sandstone bodies* are capped by a leached palaeosol (unit F) and ganister (unit G), the top of which is marked by a flooding surface, shown in detail in the inset photograph.

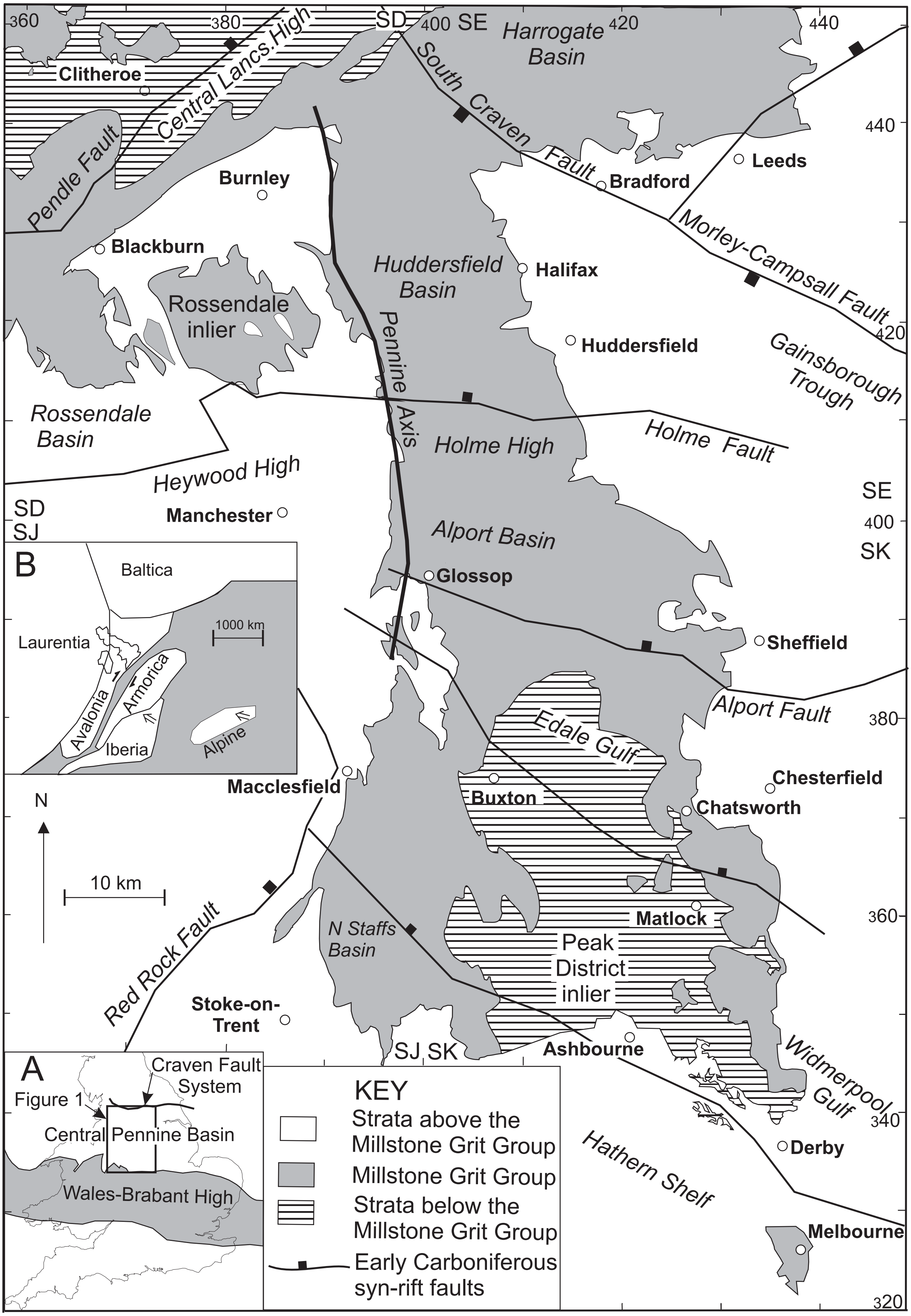
Fig. 13 Deposits above the *main sandstone body*: thickness in boreholes and surface sections (metres). Data points correspond to those shown on Figure 2, with some additional details; yellow lines and figures are isopachs. Structural elements as for Figure 7.

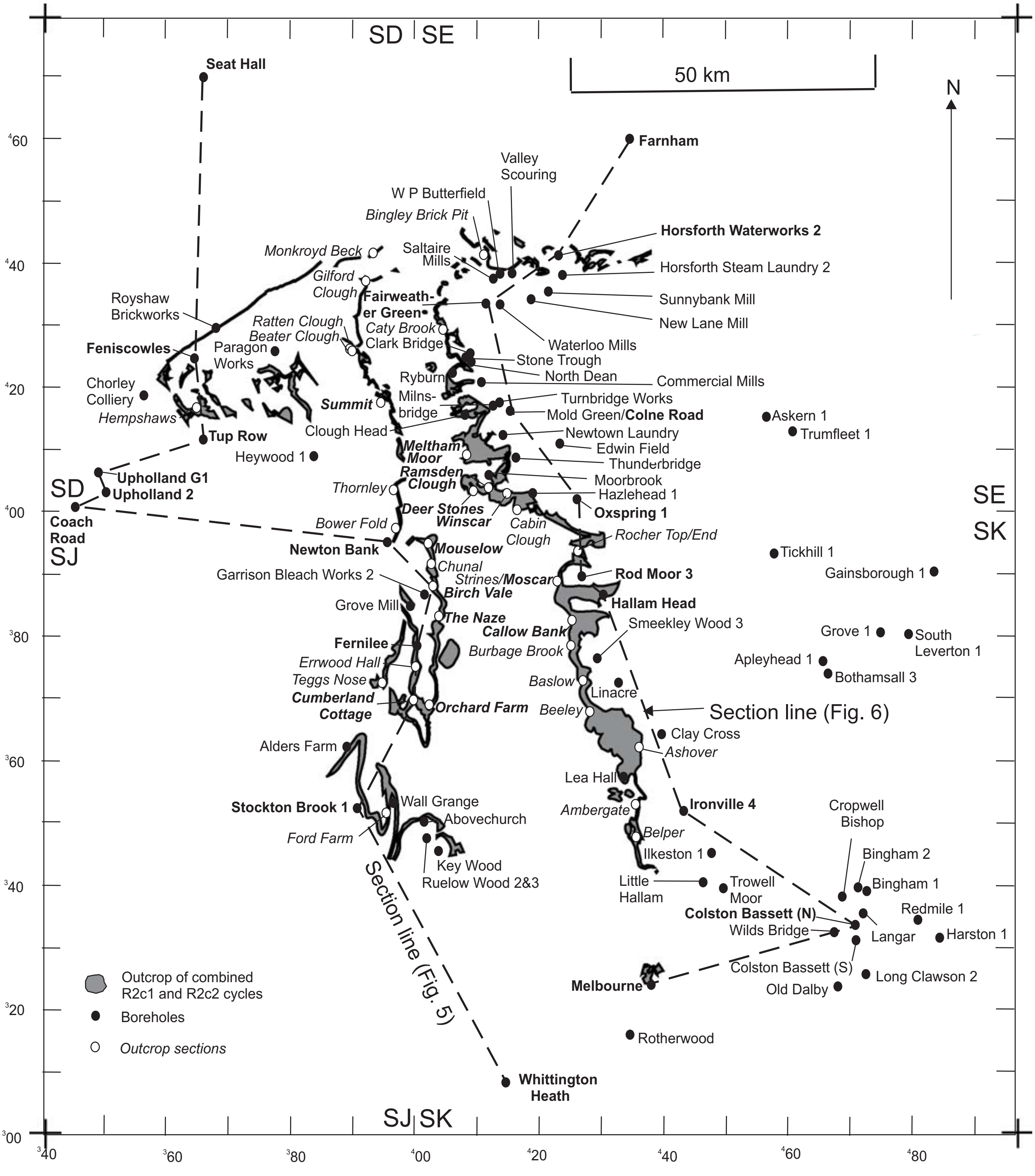
Fig. 14 Sequence stratigraphic interpretation of the $R_{2c}1$ and $R_{2c}2$ cycles presented on a schematic sea-level curve.

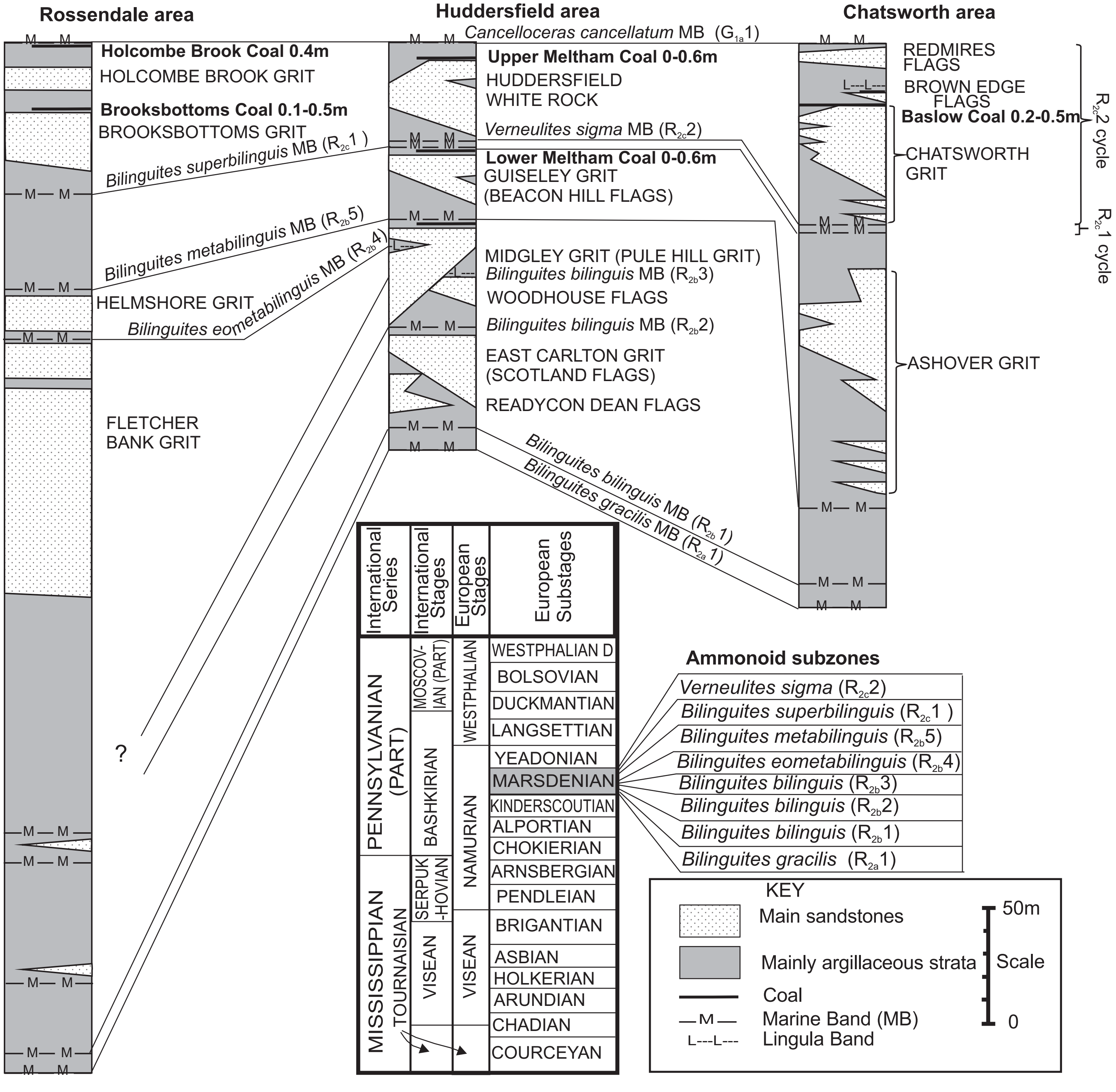
Fig. 15 Palaeogeographic maps for the $R_{2c}2$ cycle, showing the key depositional features in response to variations in relative sea-level. A-Highstand Systems Tract: deposition of the Huddersfield and Widmerpool lobes. B- Early Forced Regressive Systems Tract: deposition of the

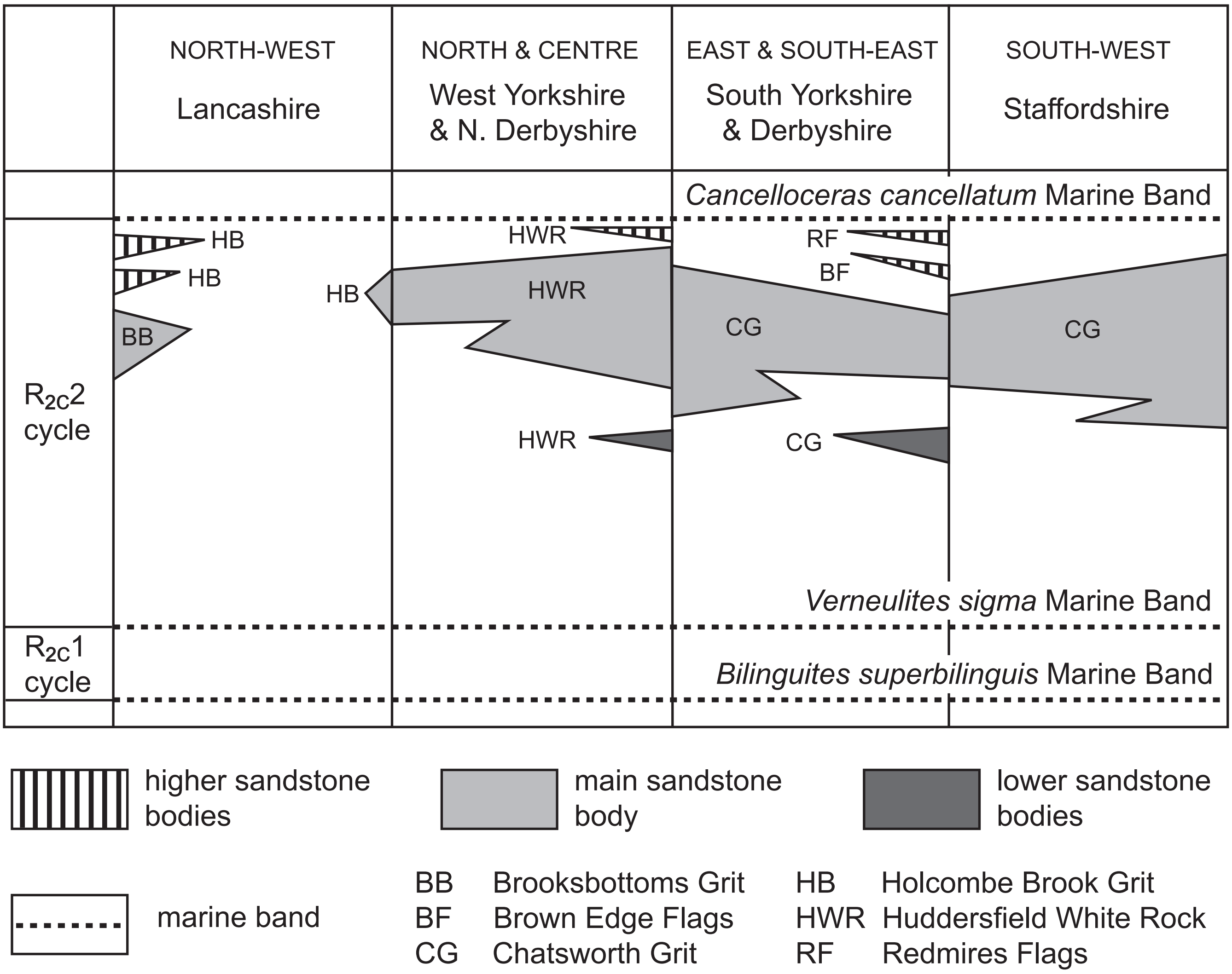
Brooksbottoms lobe and incision of the Huddersfield lobe delta-top. C- Late Forced Regressive Systems Tract: fluvial incision to produce the Chatsworth palaeovalley and emergence of the interfluve areas. D- Late Lowstand to Transgressive Systems Tract: flooding and infilling of the incised valley, and flooding extending over the interfluve areas. Arrows indicate generalized palaeocurrents.

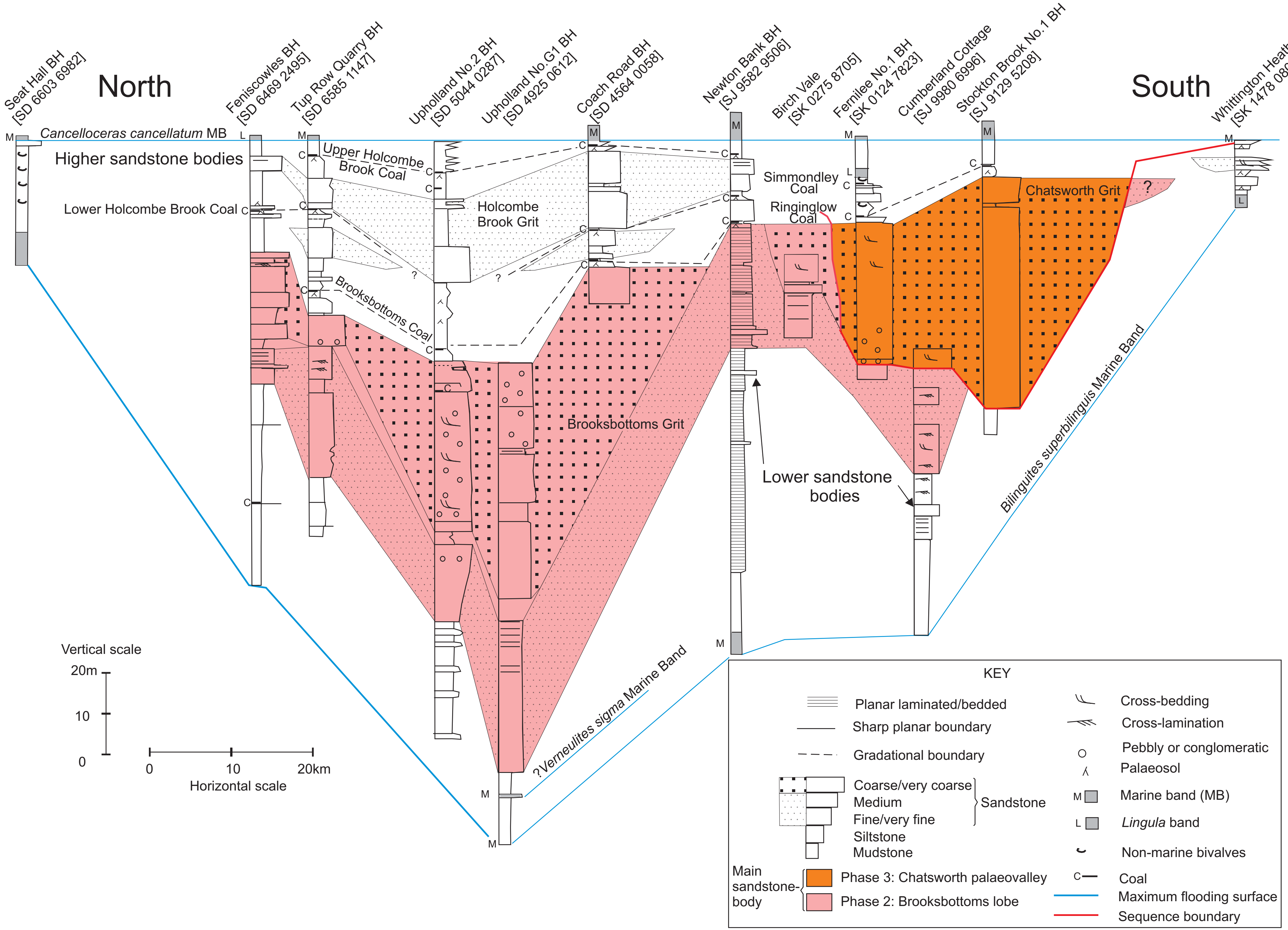
Table 1 Description of the main lithofacies and facies associations present within the $R_{2c}1$ and $R_{2c}2$ cycles. Partly based upon studies of Benfield (1969) and O'Beirne (1996).

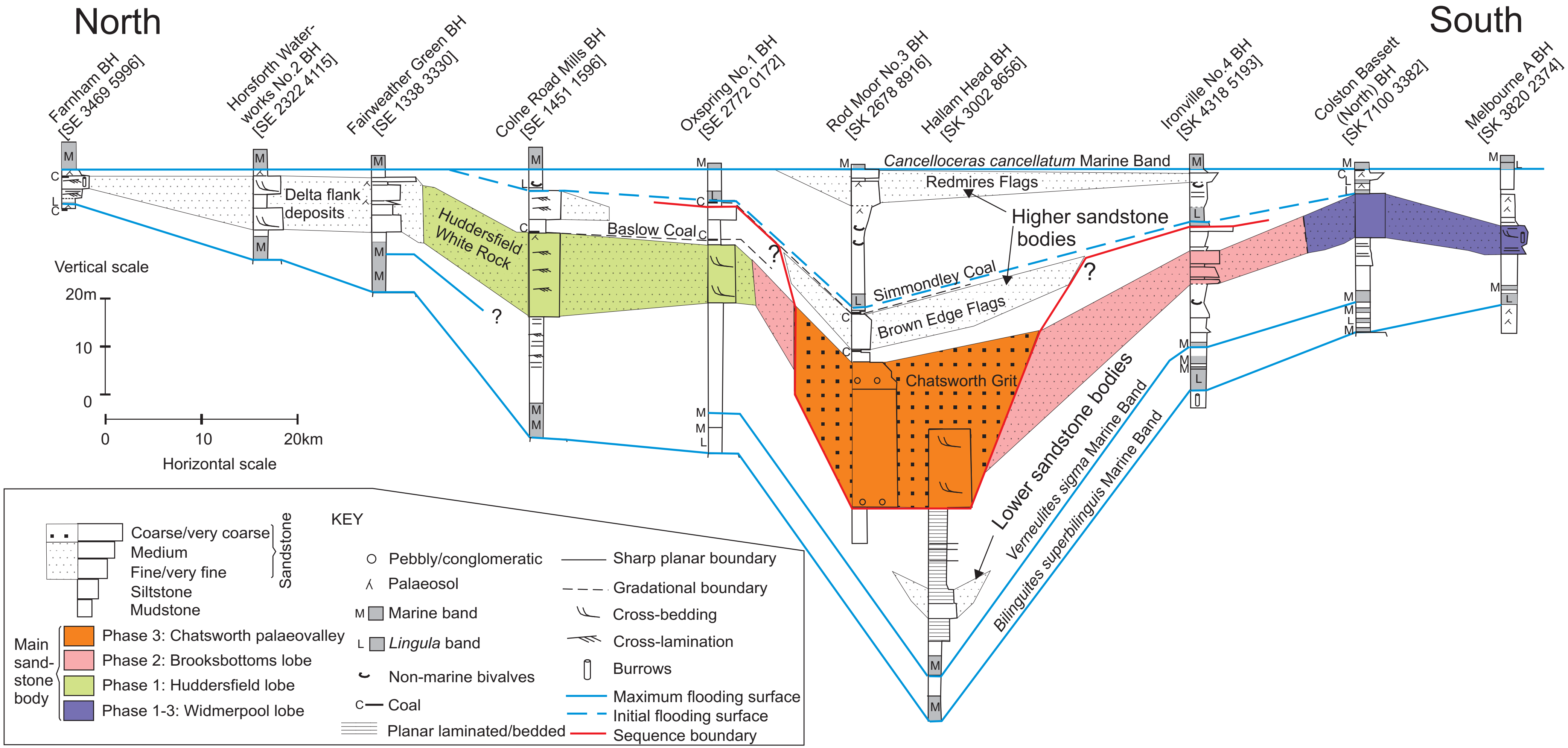

360
380
SD
400
SE
420
440
Harrogate Basin
Clitheroe
Central Lancs.High
South Craven Fault
Pendle Fault
Burnley
Bradford
Leeds
Blackburn
Huddersfield Basin
Halifax
Morley-Campsall Fault
Rossendale inlier
Pennine Axis
Huddersfield
Gainsborough Trough
Rossendale Basin
Holme High
Holme Fault
Heywood High
SD
SJ
Manchester
Alport Basin
SE
400
SK
B
Baltica
Laurentia
1000 km
Avalonia
Armorica
Iberia
Alpine
Glossop
Sheffield
Alport Fault
380
Edale Gulf
Macclesfield
Buxton
Chesterfield
Chatsworth
N
10 km
Red Rock Fault
N Staffs Basin
Matlock
360
Peak District inlier
Stoke-on-Trent
Ashbourne
SJ SK
Widmerpool Gulf
A
Craven Fault System
Figure 1
Central Pennine Basin
Wales-Brabant High
KEY
Strata above the Millstone Grit Group
Millstone Grit Group
Strata below the Millstone Grit Group
Early Carboniferous syn-rift faults
340
Derby
Hathern Shelf
Melbourne
320

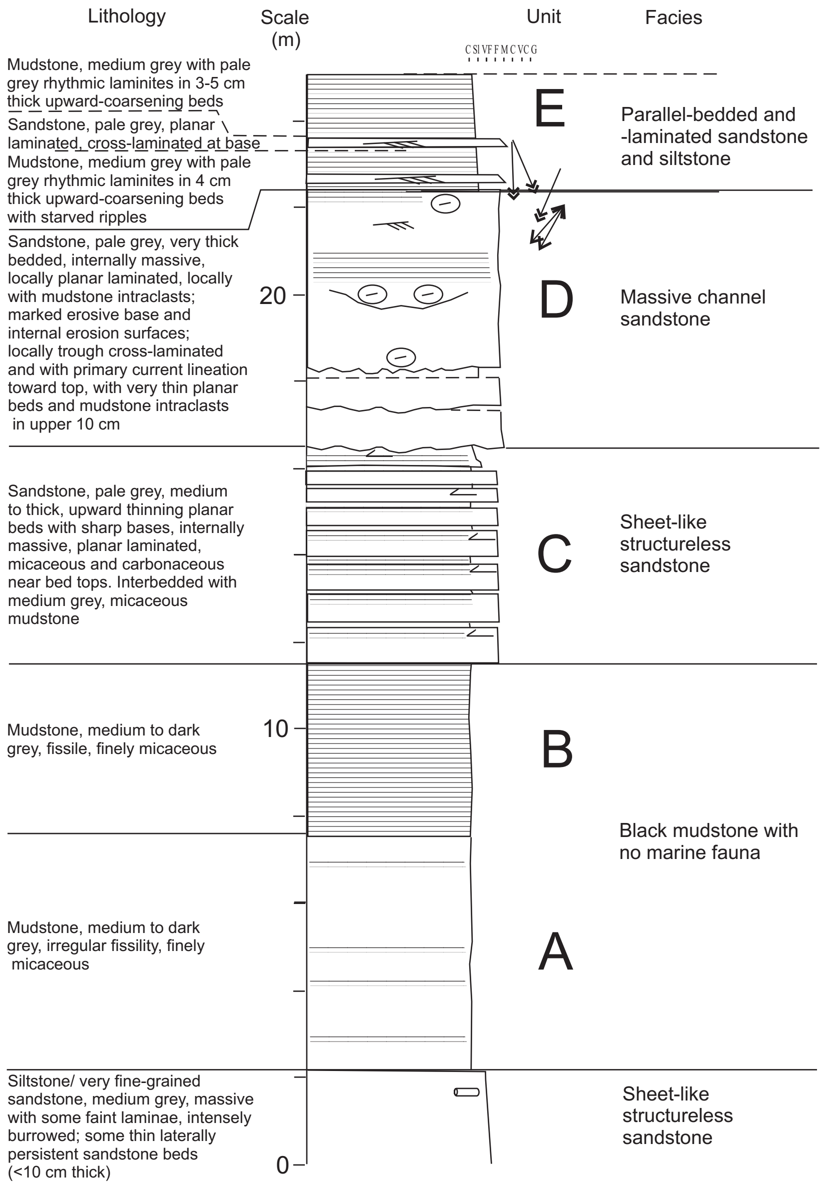

SD SE
50 km
N
Seat Hall
Farnham
Valley Scouring
W P Butterfield
Bingley Brick Pit
Horsforth Waterworks 2
Monkroyd Beck
Saltaire Mills
Horsforth Steam Laundry 2
Gilford Clough
Royshaw Brickworks
Fairweather Green
Sunnybank Mill
New Lane Mill
Ratten Clough
Beater Clough
Caty Brook
Clark Bridge
Feniscowles
Paragon Works
Waterloo Mills
Stone Trough
North Dean
Chorley Colliery
Ryburn
Commercial Mills
Summit
Milnsbridge
Turnbridge Works
Hempshaws
Mold Green/Colne Road
Askern 1
Clough Head
Trumfleet 1
Tup Row
Newtown Laundry
Edwin Field
Heywood 1
Meltham Moor
Thunderbridge
Upholland G1
Ramsden Clough
Moorbrook
SD
Upholland 2
Thornley
Hazlehead 1
Coach Road
Deer Stones
Winscar
Oxspring 1
SE
SJ
Bower Fold
Cabin Clough
SK
Rocher Top/End
Newton Bank
Mouselow
Tickhill 1
Chunal
Garrison Bleach Works 2
Strines/Moscar
Rod Moor 3
Gainsborough 1
Birch Vale
Grove Mill
Hallam Head
The Naze
Smeekley Wood 3
Callow Bank
Grove 1
South Leverton 1
Fernilee
Burbage Brook
Errwood Hall
Apleyhead 1
Bothamsall 3
Teggs Nose
Baslow
Linacre
Cumberland Cottage
Orchard Farm
Beeley
Section line (Fig. 6)
Clay Cross
Alders Farm
Ashover
Lea Hall
Wall Grange
Stockton Brook 1
Ironville 4
Cropwell Bishop
Abovechurch
Ambergate
Ford Farm
Belper
Ilkeston 1
Bingham 2
Key Wood
Ruelow Wood 2&3
Little Hallam
Trowell Moor
Bingham 1
Section line (Fig. 5)
Redmile 1
Colston Bassett (N)
Wilds Bridge
Langar
Harston 1
Outcrop of combined R2c1 and R2c2 cycles
Boreholes
Outcrop sections
Colston Bassett (S)
Long Clawson 2
Melbourne
Old Dalby
Rotherwood
Whittington Heath
SJ SK
⁴60
⁴40
⁴20
⁴00
³80
³60
³40
³20
³00
³40
³60
³80
⁴00
⁴20
⁴40
⁴60
⁴80

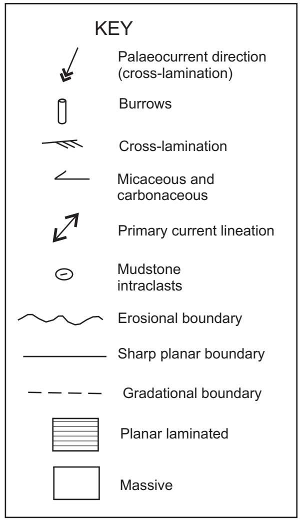

Rossendale area
Huddersfield area
Chatsworth area
Cancelloceras cancellatum MB ($G_{1a}1$)
Holcombe Brook Coal 0.4m
HOLCOMBE BROOK GRIT
Brooksbottoms Coal 0.1-0.5m
BROOKSBOTTOMS GRIT
Bilinguites superbilinguis MB ($R_{2c}1$)
Bilinguites metabilinguis MB ($R_{2b}5$)
Bilinguites eometabilinguis MB ($R_{2b}4$)
HELMSHORE GRIT
FLETCHER BANK GRIT
?
Upper Meltham Coal 0-0.6m
HUDDERSFIELD WHITE ROCK
Verneulites sigma MB ($R_{2c}2$)
Lower Meltham Coal 0-0.6m
GUISELEY GRIT (BEACON HILL FLAGS)
MIDGLEY GRIT (PULE HILL GRIT)
Bilinguites bilinguis MB ($R_{2b}3$)
WOODHOUSE FLAGS
Bilinguites bilinguis MB ($R_{2b}2$)
EAST CARLTON GRIT (SCOTLAND FLAGS)
READYCON DEAN FLAGS
Bilinguites bilinguis MB ($R_{2b}1$)
Bilinguites gracilis MB ($R_{2a}1$)
REDMIRES FLAGS
BROWN EDGE FLAGS
Baslow Coal 0.2-0.5m
CHATSWORTH GRIT
ASHOVER GRIT
$R_{2c}2$ cycle
$R_{2c}1$ cycle
M M
L---L---
International Series
International Stages
European Stages
European Substages
MISSISSIPPIAN
PENNSYLVANIAN (PART)
TOURNAISIAN
VISEAN
SERPUKHOVIAN
BASHKIRIAN
MOSCOVIAN (PART)
VISEAN
NAMURIAN
WESTPHALIAN
WESTPHALIAN D
BOLSOVIAN
DUCKMANTIAN
LANGSETTIAN
YEADONIAN
MARSDENIAN
KINDERSCOUTIAN
ALPORTIAN
CHOKIERIAN
ARNSBERGIAN
PENDLEIAN
BRIGANTIAN
ASBIAN
HOLKERIAN
ARUNDIAN
CHADIAN
COURCEYAN
Ammonoid subzones
Verneulites sigma ($R_{2c}2$)
Bilinguites superbilinguis ($R_{2c}1$)
Bilinguites metabilinguis ($R_{2b}5$)
Bilinguites eometabilinguis ($R_{2b}4$)
Bilinguites bilinguis ($R_{2b}3$)
Bilinguites bilinguis ($R_{2b}2$)
Bilinguites bilinguis ($R_{2b}1$)
Bilinguites gracilis ($R_{2a}1$)
KEY
Main sandstones
Mainly argillaceous strata
Coal
Marine Band (MB)
Lingula Band
50m
Scale
0

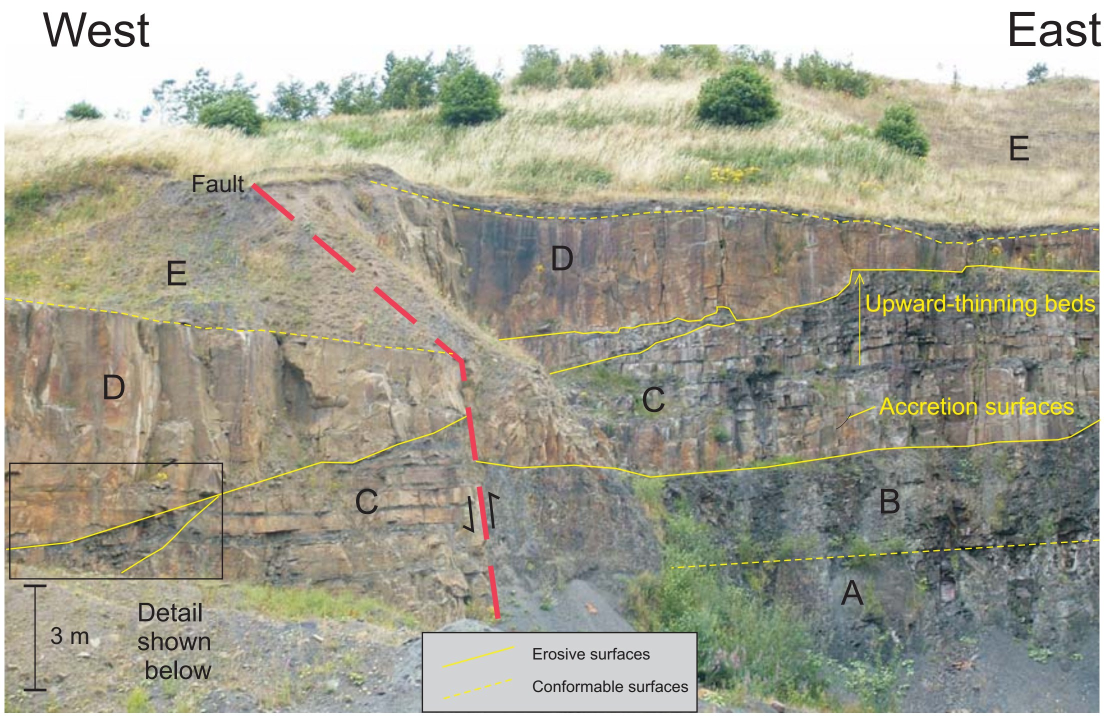

NORTH-WEST
Lancashire
NORTH & CENTRE
West Yorkshire & N. Derbyshire
EAST & SOUTH-EAST
South Yorkshire & Derbyshire
SOUTH-WEST
Staffordshire
Cancelloceras cancellatum Marine Band
HB
HB
BB
HB
HWR
HWR
HWR
RF
BF
CG
CG
CG
$R_{2C}2$ cycle
Verneulites sigma Marine Band
$R_{2C}1$ cycle
Bilinguites superbilinguis Marine Band
higher sandstone bodies
main sandstone body
lower sandstone bodies
marine band
BB Brooksbottoms Grit
BF Brown Edge Flags
CG Chatsworth Grit
HB Holcombe Brook Grit
HWR Huddersfield White Rock
RF Redmires Flags

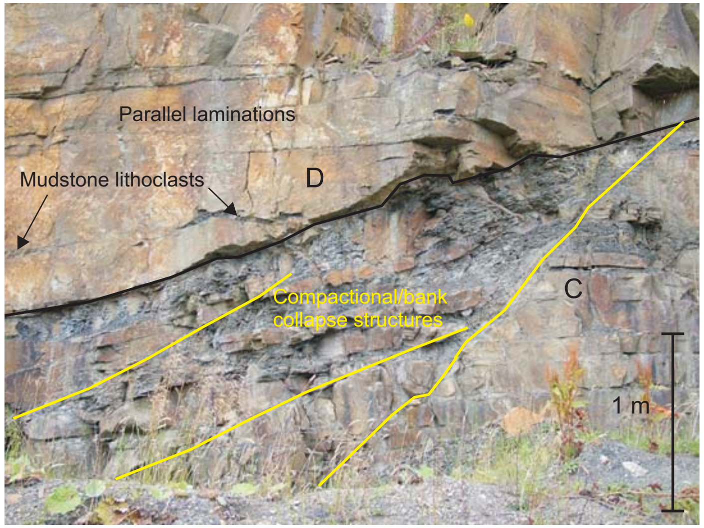

North
South
Seat Hall BH [SD 6603 6982]
Feniscowles BH [SD 6469 2495]
Tup Row Quarry BH [SD 6585 1147]
Upholland No.2 BH [SD 5044 0287]
Upholland No.G1 BH [SD 4925 0612]
Coach Road BH [SD 4564 0058]
Newton Bank BH [SJ 9582 9506]
Birch Vale [SK 0275 8705]
Fernilee No.1 BH [SK 0124 7823]
Cumberland Cottage [SJ 9980 6996]
Stockton Brook No.1 BH [SJ 9129 5208]
Whittington Heath BH [SK 1478 0800]
Cancelloceras cancellatum MB
Higher sandstone bodies
Upper Holcombe Brook Coal
Lower Holcombe Brook Coal
Holcombe Brook Grit
Brooksbottoms Coal
Brooksbottoms Grit
Simmondley Coal
Ringinglow Coal
Chatsworth Grit
Lower sandstone bodies
Billinguites superbilinguis Marine Band
?*Verneulites sigma* Marine Band
M
L
C
?
Vertical scale
20m
10
0
0
10
20km
Horizontal scale
KEY
Planar laminated/bedded
Sharp planar boundary
Gradational boundary
Coarse/very coarse
Medium
Fine/very fine
Sandstone
Siltstone
Mudstone
Main sandstone-body
Phase 3: Chatsworth palaeovalley
Phase 2: Brooksbottoms lobe
Cross-bedding
Cross-lamination
Pebbly or conglomeratic
Palaeosol
Marine band (MB)
Lingula band
Non-marine bivalves
Coal
Maximum flooding surface
Sequence boundary

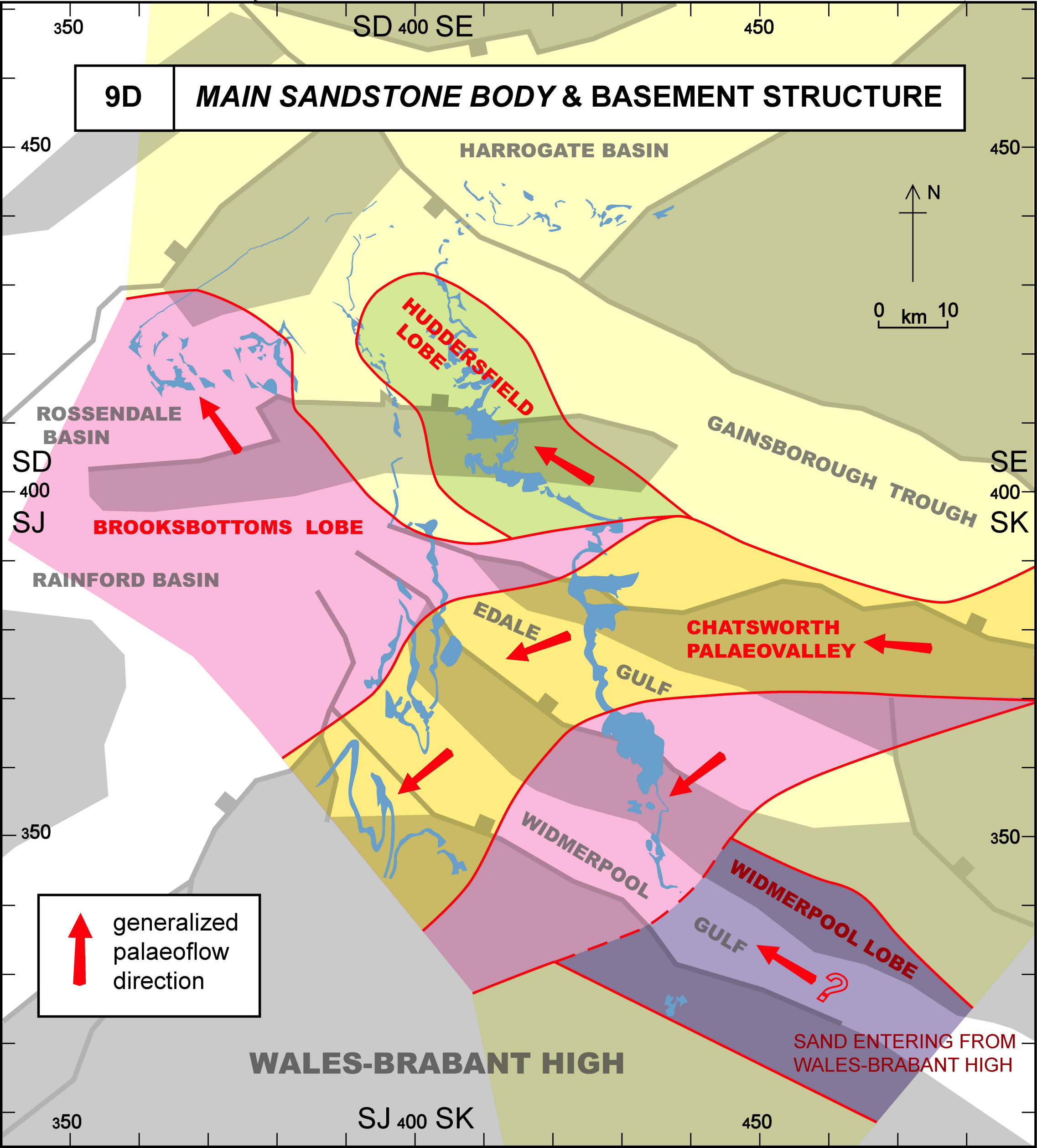

North
South
Farnham BH [SE 3469 5996]
Horsforth Water-works No.2 BH [SE 2322 4115]
Fairweather Green BH [SE 1338 3330]
Colne Road Mills BH [SE 1451 1596]
Oxspring No.1 BH [SE 2772 0172]
Rod Moor No.3 BH [SK 2678 8916]
Hallam Head BH [SK 3002 8656]
Ironville No.4 BH [SK 4318 5193]
Colston Bassett (North) BH [SK 7100 3382]
Melbourne A BH [SK 3820 2374]
Cancelloceras cancellatum Marine Band
Redmires Flags
Higher sandstone bodies
Delta flank deposits
Huddersfield White Rock
Baslow Coal
Simmondley Coal
Brown Edge Flags
Chatsworth Grit
Lower sandstone bodies
Verneulites sigma Marine Band
Bilinguites superbilinguis Marine Band
M
L
C
?
Vertical scale
20m
10
0
0
10
20km
Horizontal scale
KEY
Coarse/very coarse
Medium
Fine/very fine
Siltstone
Mudstone
Sandstone
Main sand-stone body
Phase 3: Chatsworth palaeovalley
Phase 2: Brooksbottoms lobe
Phase 1: Huddersfield lobe
Phase 1-3: Widmerpool lobe
Pebbly/conglomeratic
Palaeosol
Marine band
Lingula band
Non-marine bivalves
Coal
Planar laminated/bedded
Sharp planar boundary
Gradational boundary
Cross-bedding
Cross-lamination
Burrows
Maximum flooding surface
Initial flooding surface
Sequence boundary


Lithology
Scale (m)
Unit
Facies
C Sl VF F M C VC G
Mudstone, medium grey with pale grey rhythmic laminites in 3-5 cm thick upward-coarsening beds
Sandstone, pale grey, planar laminated, cross-laminated at base
Mudstone, medium grey with pale grey rhythmic laminites in 4 cm thick upward-coarsening beds with starved ripples
E
Parallel-bedded and -laminated sandstone and siltstone
Sandstone, pale grey, very thick bedded, internally massive, locally planar laminated, locally with mudstone intraclasts; marked erosive base and internal erosion surfaces; locally trough cross-laminated and with primary current lineation toward top, with very thin planar beds and mudstone intraclasts in upper 10 cm
20
D
Massive channel sandstone
Sandstone, pale grey, medium to thick, upward thinning planar beds with sharp bases, internally massive, planar laminated, micaceous and carbonaceous near bed tops. Interbedded with medium grey, micaceous mudstone
C
Sheet-like structureless sandstone
Mudstone, medium to dark grey, fissile, finely micaceous
10
B
Black mudstone with no marine fauna
Mudstone, medium to dark grey, irregular fissility, finely micaceous
A
Siltstone/ very fine-grained sandstone, medium grey, massive with some faint laminae, intensely burrowed; some thin laterally persistent sandstone beds (<10 cm thick)
0
Sheet-like structureless sandstone

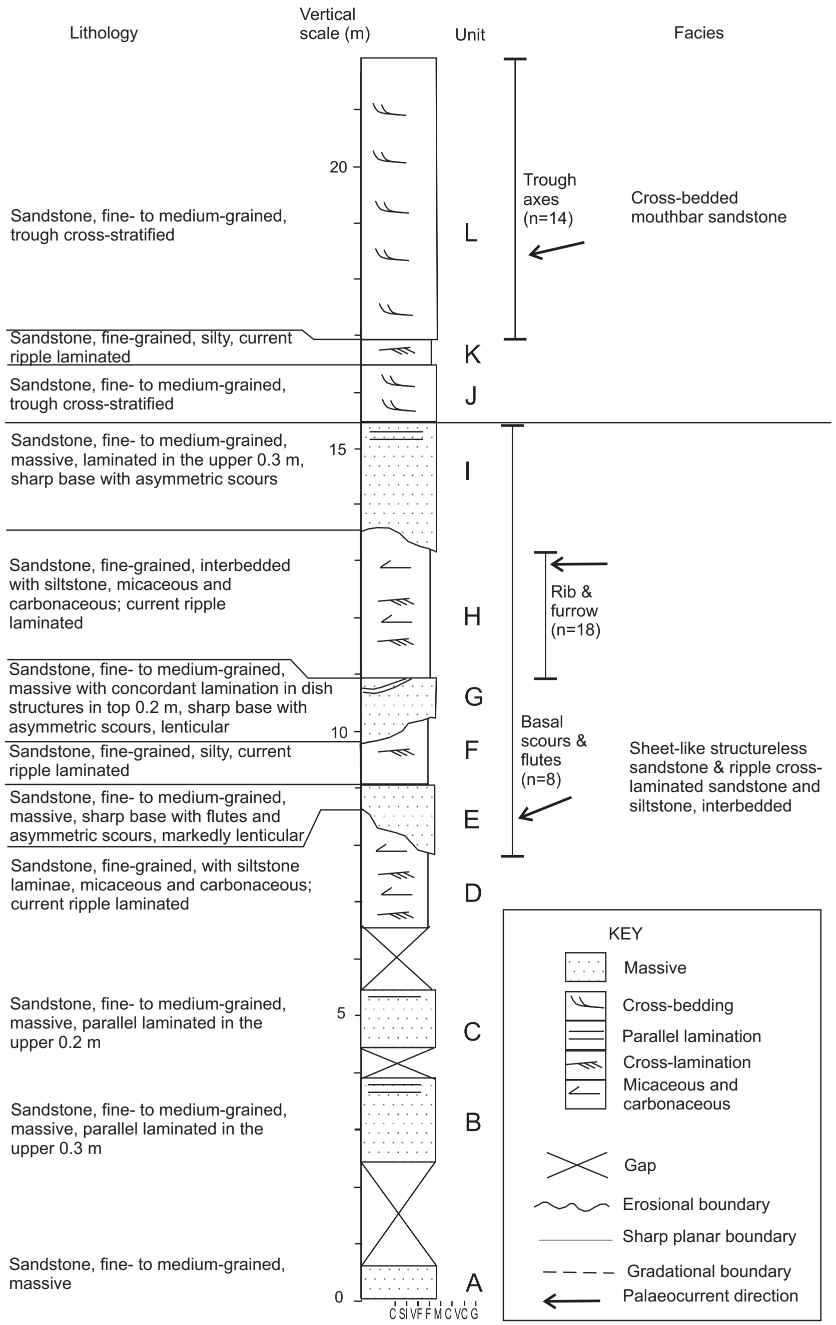

KEY
Palaeocurrent direction (cross-lamination)
Burrows
Cross-lamination
Micaceous and carbonaceous
Primary current lineation
Mudstone intraclasts
Erosional boundary
Sharp planar boundary
Gradational boundary
Planar laminated
Massive

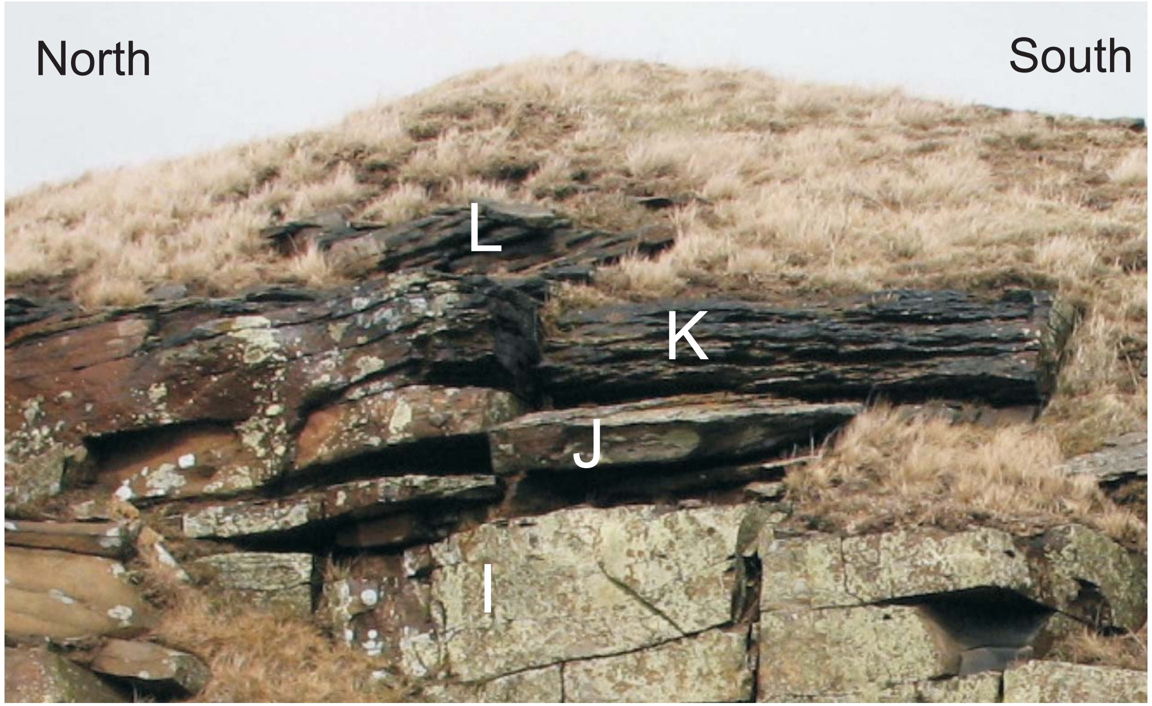

West
East
Fault
E
D
E
D
C
C
Upward-thinning beds
Accretion surfaces
B
A
3 m
Detail shown below
Erosive surfaces
Conformable surfaces


Parallel laminations
Mudstone lithoclasts
D
Compactional/bank collapse structures
C
1 m

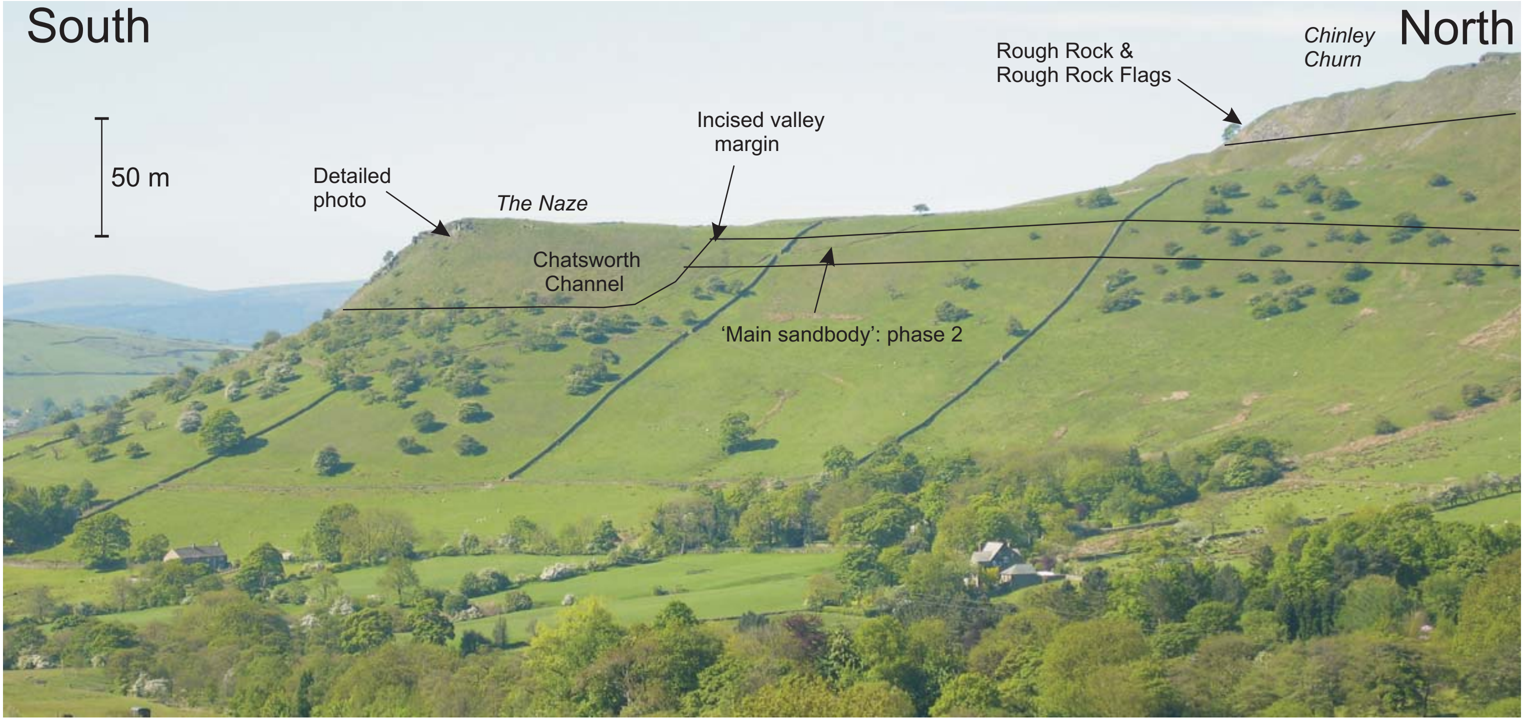


9D *MAIN SANDSTONE BODY* & BASEMENT STRUCTURE

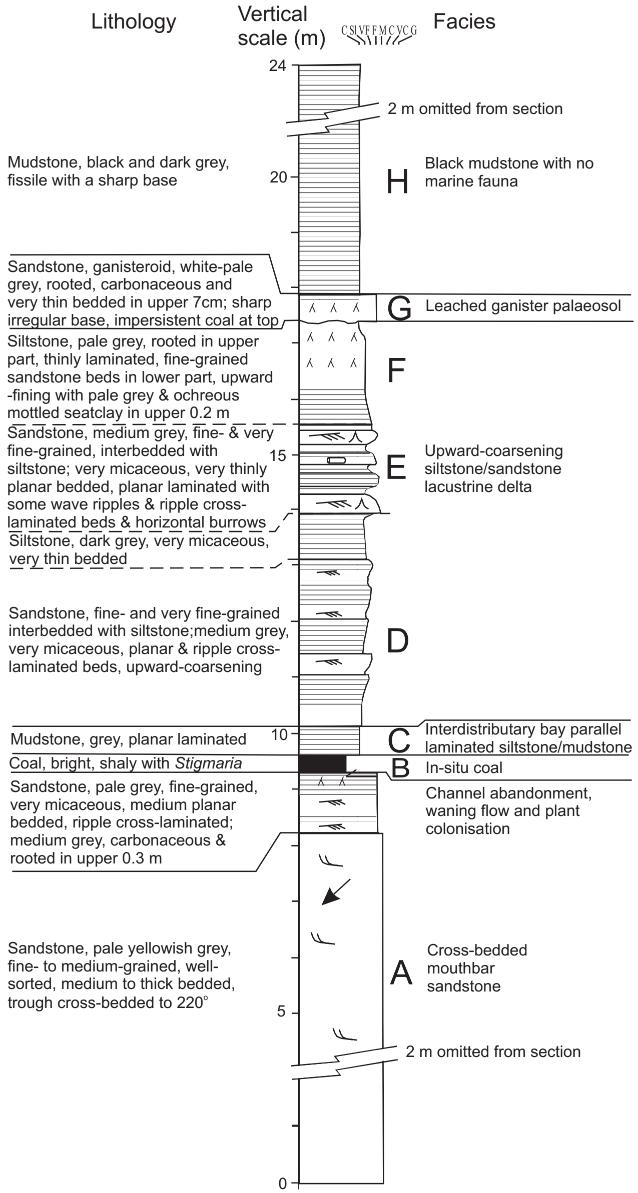

Lithology
Vertical scale (m)
Unit
Facies
Sandstone, fine- to medium-grained, trough cross-stratified
Sandstone, fine-grained, silty, current ripple laminated
Sandstone, fine- to medium-grained, trough cross-stratified
Sandstone, fine- to medium-grained, massive, laminated in the upper 0.3 m, sharp base with asymmetric scours
Sandstone, fine-grained, interbedded with siltstone, micaceous and carbonaceous; current ripple laminated
Sandstone, fine- to medium-grained, massive with concordant lamination in dish structures in top 0.2 m, sharp base with asymmetric scours, lenticular
Sandstone, fine-grained, silty, current ripple laminated
Sandstone, fine- to medium-grained, massive, sharp base with flutes and asymmetric scours, markedly lenticular
Sandstone, fine-grained, with siltstone laminae, micaceous and carbonaceous; current ripple laminated
Sandstone, fine- to medium-grained, massive, parallel laminated in the upper 0.2 m
Sandstone, fine- to medium-grained, massive, parallel laminated in the upper 0.3 m
Sandstone, fine- to medium-grained, massive
20
15
10
5
0
C Sl VF F M C VC G
L
K
J
I
H
G
F
E
D
C
B
A
Trough axes (n=14)
Rib & furrow (n=18)
Basal scours & flutes (n=8)
Cross-bedded mouthbar sandstone
Sheet-like structureless sandstone & ripple cross-laminated sandstone and siltstone, interbedded
KEY
Massive
Cross-bedding
Parallel lamination
Cross-lamination
Micaceous and carbonaceous
Gap
Erosional boundary
Sharp planar boundary
Gradational boundary
Palaeocurrent direction

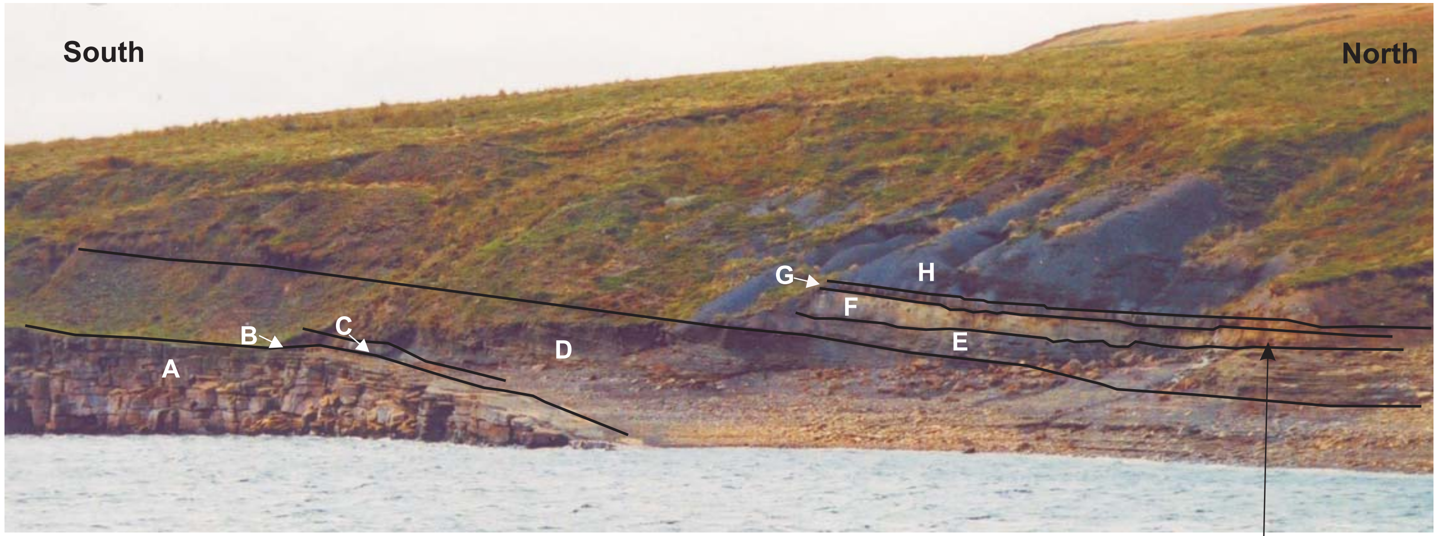

North
South
L
K
J
I

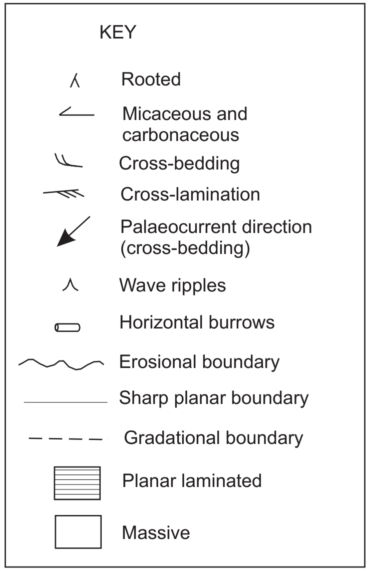

North
South
H
I
G
H
D
E
F
G
E
D

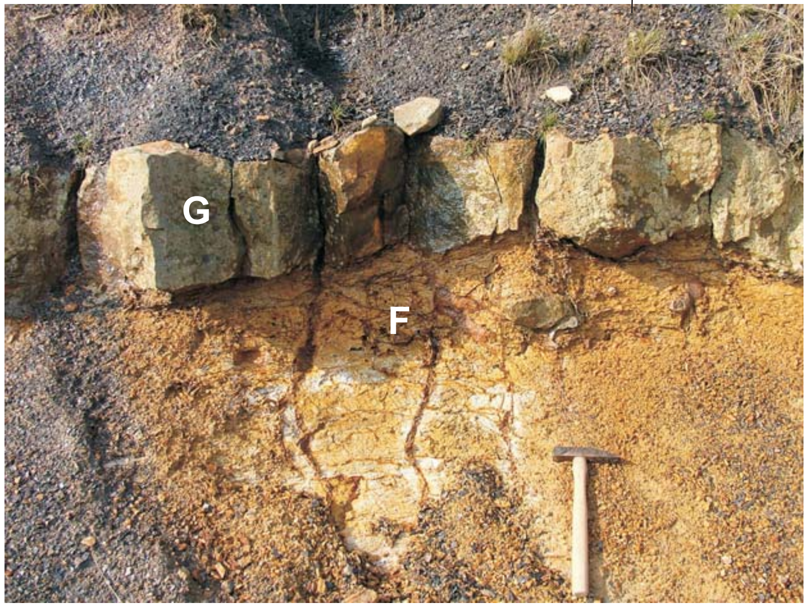

South
North
50 m
Detailed photo
The Naze
Incised valley margin
Chatsworth Channel
'Main sandbody': phase 2
Rough Rock & Rough Rock Flags
Chinley Churn

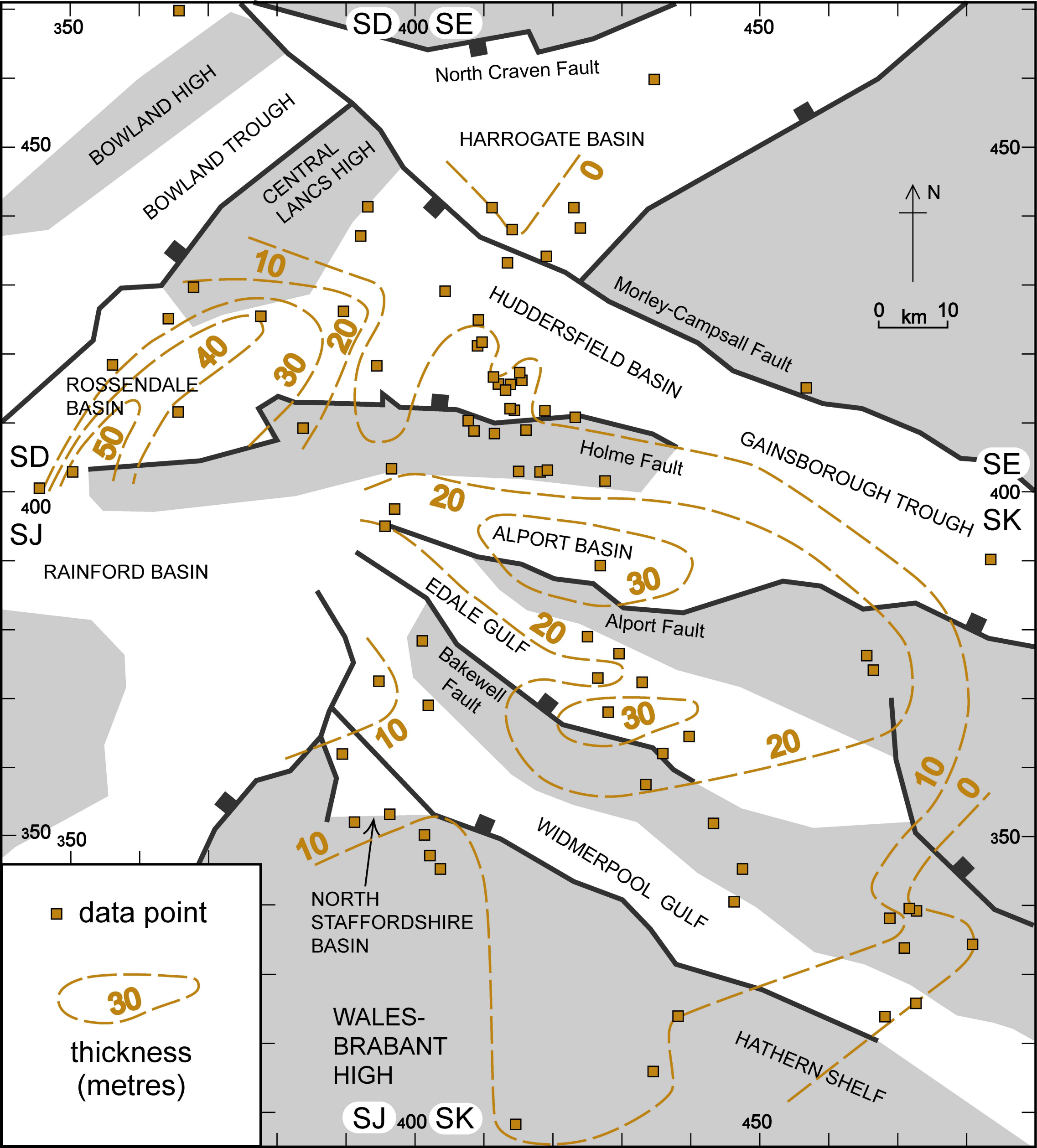

West
East
1 m

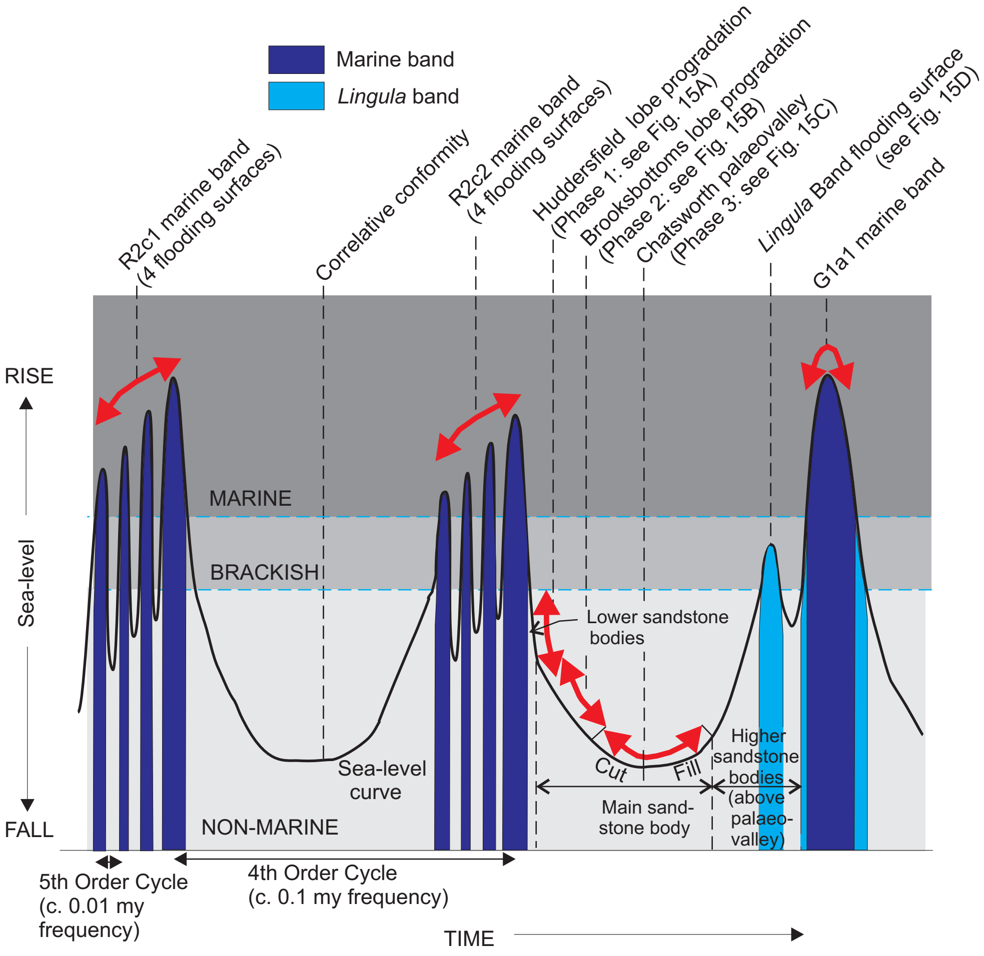

Lithology
Vertical scale (m)
C Sl VF F M C VC G
Facies
24
2 m omitted from section
20
Mudstone, black and dark grey, fissile with a sharp base
H
Black mudstone with no marine fauna
Sandstone, ganisteroid, white-pale grey, rooted, carbonaceous and very thin bedded in upper 7cm; sharp irregular base, impersistent coal at top
G
Leached ganister palaeosol
Siltstone, pale grey, rooted in upper part, thinly laminated, fine-grained sandstone beds in lower part, upward -fining with pale grey & ochreous mottled seatclay in upper 0.2 m
F
Sandstone, medium grey, fine- & very fine-grained, interbedded with siltstone; very micaceous, very thinly planar bedded, planar laminated with some wave ripples & ripple cross-laminated beds & horizontal burrows
15
E
Upward-coarsening siltstone/sandstone lacustrine delta
Siltstone, dark grey, very micaceous, very thin bedded
Sandstone, fine- and very fine-grained interbedded with siltstone;medium grey, very micaceous, planar & ripple cross-laminated beds, upward-coarsening
D
Mudstone, grey, planar laminated
10
C
Interdistributary bay parallel laminated siltstone/mudstone
Coal, bright, shaly with *Stigmaria*
B
In-situ coal
Sandstone, pale grey, fine-grained, very micaceous, medium planar bedded, ripple cross-laminated; medium grey, carbonaceous & rooted in upper 0.3 m
Channel abandonment, waning flow and plant colonisation
Sandstone, pale yellowish grey, fine- to medium-grained, well-sorted, medium to thick bedded, trough cross-bedded to 220°
A
Cross-bedded mouthbar sandstone
5
2 m omitted from section
0

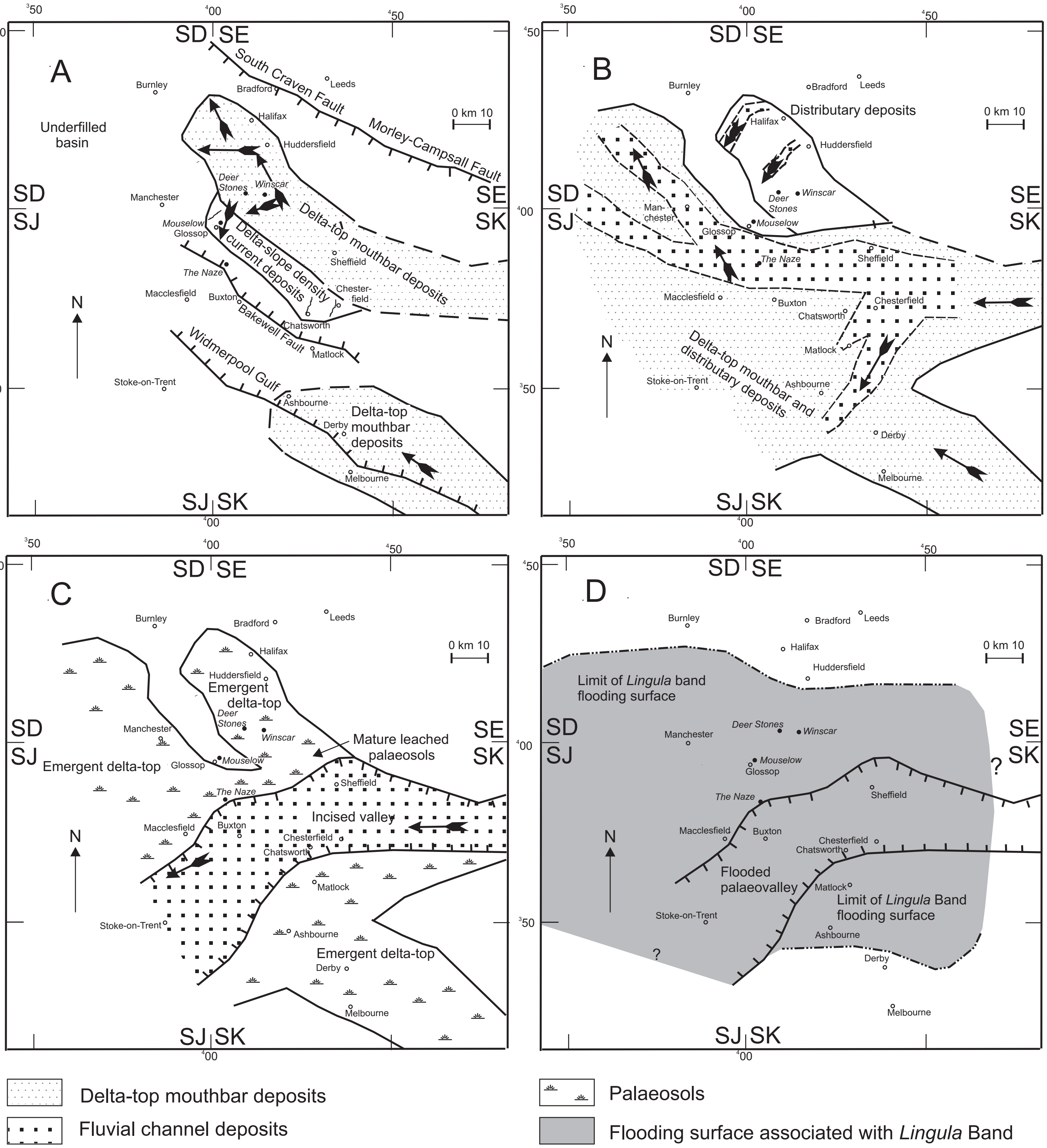

South
North
A
B
C
D
E
F
G
H


KEY
Rooted
Micaceous and carbonaceous
Cross-bedding
Cross-lamination
Palaeocurrent direction (cross-bedding)
Wave ripples
Horizontal burrows
Erosional boundary
Sharp planar boundary
Gradational boundary
Planar laminated
Massive


G
F


350
SD 400 SE
450
North Craven Fault
450
450
BOWLAND HIGH
BOWLAND TROUGH
CENTRAL LANCS HIGH
HARROGATE BASIN
0
N
0 km 10
10
20
40
30
HUDDERSFIELD BASIN
Morley-Campsall Fault
ROSSENDALE BASIN
50
SD
400
SJ
Holme Fault
GAINSBOROUGH TROUGH
SE
400
SK
20
ALPORT BASIN
30
RAINFORD BASIN
EDALE GULF
20
Alport Fault
Bakewell Fault
30
10
20
10
0
350
350
350
10
WIDMERPOOL GULF
NORTH STAFFORDSHIRE BASIN
data point
30
thickness (metres)
WALES-BRABANT HIGH
HATHERN SHELF
SJ 400 SK
450


Marine band
Lingula band
R2c1 marine band (4 flooding surfaces)
Correlative conformity
R2c2 marine band (4 flooding surfaces)
Huddersfield lobe progradation (Phase 1: see Fig. 15A)
Brooksbottoms lobe progradation (Phase 2: see Fig. 15B)
Chatsworth palaeovalley (Phase 3: see Fig. 15C)
Lingula Band flooding surface (see Fig. 15D)
G1a1 marine band
RISE
Sea-level
FALL
MARINE
BRACKISH
NON-MARINE
Sea-level curve
Lower sandstone bodies
Cut
Fill
Main sand-stone body
Higher sandstone bodies (above palaeo-valley)
5th Order Cycle (c. 0.01 my frequency)
4th Order Cycle (c. 0.1 my frequency)
TIME


A
SD SE
SD SJ
SE SK
SJ SK
350
400
450
South Craven Fault
Morley-Campsall Fault
Underfilled basin
Burnley
Bradford
Leeds
Halifax
Huddersfield
Deer Stones
Winscar
Manchester
Mouselow
Glossop
Delta-slope density current deposits
Delta-top mouthbar deposits
Sheffield
Chesterfield
The Naze
Macclesfield
Buxton
Bakewell Fault
Chatsworth
Matlock
Widmerpool Gulf
Stoke-on-Trent
Ashbourne
Derby
Melbourne
0 km 10
N
B
Distributary deposits
Delta-top mouthbar and distributary deposits
C
Emergent delta-top
Mature leached palaeosols
Incised valley
D
Limit of Lingula band flooding surface
Flooded palaeovalley
Limit of Lingula Band flooding surface
?
Delta-top mouthbar deposits
Fluvial channel deposits
Palaeosols
Flooding surface associated with Lingula Band

MAIN SANDSTONE BODY

Sand entering the basin from the east - 'eastern inflow'

🟩	*Phase 1:* delta deposits grading up from delta slope deposits; generally up to medium-grained, rarely coarser. Exposed as the Huddersfield delta lobe in the north-east; may overlap chronologically with Phase 2
🟥	*Phase 2:* delta deposits generally up to coarse-grained, with quartz pebbles up to 1 cm. Overlain axially by deposits of Phase 3, but exposed in Lancashire as the Brooksbottoms delta lobe, and in areas south of the Chatsworth palaeovalley
🟨	*Phase 3:* deposits include quartz pebbles up to 3 cm. Chatsworth palaeovalley, incised into deposits of Phases 1 & 2

Sand derived from the Wales-Brabant High - 'southern inflow'

🟪	*Phases 1-3 not distinguished;* relationship with deposits from eastern inflow obscure

Sand thin, or absent, or not distinguished from *higher sandstone bodies* in $R_{2c}2$ cycle

🟨

No information on $R_{2c}2$ cycle

⬜

Combined outcrop of $R_{2c}1$ & $R_{2c}2$ cycles

🟦

Association	Facies	Thickness	Lithology	Relationship	Facies interpretation
Basin-floor deposits	**Black mudstone with marine/ brackish fauna**	Up to 8 m, typically less than 1 m	Dark grey and black, fissile or massive mudstone which may contain thick- and thin-shelled ammonoids, *Dunbarella* or *Lingula*	*B. superbilinguis* & *C. cancellatum* MBs present across entire region; *V. sigma* MB absent from basin margins; *Lingula* Band above *main sandstone body*. Typically underlain and overlain by *Black mudstone with no marine fauna facies*.	Marine flooding events and deposition in anoxic bottom conditions
	Black mudstone with no marine fauna	Typically 10m, ranging 1-15 m	Structureless or planar lamination, dark grey and black mudstone and dark grey siltstone that lack marine fauna	Overlies or intercalates with *Black mudstone with marine/brackish fauna facies*; Typically overlain by *Pro-delta parallel-laminated siltstone and mudstone facies*.	Suspension deposits in anoxic bottom conditions, water column non-marine or stratified
Delta-slope deposits	**Pro-delta parallel-laminated siltstone and mudstone**	Up to 5 m	Parallel laminated, medium grey siltstone and dark grey mudstone, typically upward coarsening	Overlies *Black mudstone with no marine fauna facies;* Overlain by other delta slope deposits, or Mouthbar deposits.	Suspension deposits from hypopycnal or homopycnal flows
	Sheet-like structureless sandstone (Facies A- subfacies 2 of Benfield 1969)	Up to 16 m	Fine- to medium-grained, moderately to thickly bedded sandstone. The bases of the sandstone beds are typically sharp and sub-planar with common small flute- and tool marks. The sandstones are structureless, planar laminated towards sharp bed tops.	Forms *lower sandstone bodies*, commonly interbedded with and underlain by *Pro-delta parallel-laminated siltstone and mudstone facies* in a distal delta slope setting. Locally interbedded with *Current ripple cross-laminated sandstone and siltstone facies* within a proximal delta slope to distal mouthbar setting; overlain by, or laterally equivalent to, *Massive channel sandstone facies*	Deposition from unconfined density currents (hyperpycnal flows) mainly in distal delta slope setting
	Massive channel sandstone	Up to 10 m	Fine- to medium-grained, ungraded, micaceous and carbonaceous sandstone, with beds internally structureless or weakly laminated, with occasional floating mudstone clasts. Beds display either a sheet-like or channelised geometry bound by sharp or erosive basal surfaces and can include flute and load casts.	Forms *lower sandstone bodies*, typically underlain by *Sheet-like structureless sandstone facies*; overlain by *Pro-delta parallel-laminated siltstone and mudstone facies*.	High-density turbidity currents generated by hyperpycnal flows
Mouthbar deposits	**Parallel-bedded and parallel-laminated sandstone**	Up to 10 m	Micaceous and carbonaceous, very fine- to medium-grained, commonly normal-graded, parallel-bedded and parallel-laminated sandstone beds up to 0.1 m thick, with subordinate mudstone and siltstone interlaminations and rare cross-lamination	Occurs in association with *Current ripple cross-laminated sandstone and siltstone facies*	Deposited predominantly from suspension, with subordinate tractional transport
	Current ripple cross-laminated sandstone & siltstone (Facies A-Subfacies 1 of Benfield 1969)	Up to 16 m	Current ripple laminated, thinly bedded, very fine- to medium-grained sandstone and siltstone with *Lockeia (Pelecypodichnus)*, *Cochlichnus* and *Arenicolites*	Lowest part of *main sandstone body*, underlain by *Pro-delta parallel-laminated siltstone and mudstone facies*; overlain by *Cross-bedded mouthbar sandstone facies*, or *Upward-coarsening siltstone/sandstone facies*	Traction loads transported by episodic, unconfined currents in distal mouthbar setting
	Cross-bedded mouthbar sandstone (Facies C of Benfield 1969)	Up to 20 m	Trough and tabular cross-bedded, fine- to medium-grained sandstone	Upper part of the *main sandstone body* of Huddersfield delta lobe, present above *Current ripple cross-laminated sandstone and siltstone facies* and *Sheet-like structureless sandstone facies*	Proximal mouthbar; may also include distributary channel deposits
	Current ripple cross-laminated, possibly tidally influenced sandstone (Facies D of Benfield 1969)	Up to 4 m	Current ripple laminated, fine-grained sandstone with unidirectional and locally bidirectional palaeocurrents	Overlies C*ross-bedded mouthbar sandstone facies.*	Possible intertidal environment
River channel and distributary deposits	**Cross-bedded fluvial sandstone** (Facies F of Benfield 1969)	Up to 60 m in Chatsworth palaeovalley; Up to 11 m in Huddersfield delta lobe.	Coarse- to very coarse-grained sandstone, which also includes granules and small pebbles. The sandstone includes massive beds, giant planar foresets, planar cross-beds and trough cross-beds.	Typical for *main sandstone body* of the Chatsworth palaeovalley and upper part of Brooksbottoms delta lobe, locally developed at top of the Huddersfield delta lobe. Erosive base can incise *Basin-floor* and *Mouthbar sandstone facies* associations; overlain by *Leached palaeosol facies*.	Deposited within an active distributary channel with both straight- and sinuous-crested dune bedforms.and large-scale bar forms

Assoc-iation	Facies	Thickness	Lithology	Relationship	Facies interpretation
Delta top deposits	**Interdistributary Bay parallel laminated siltstone/mudstone** (lower part of Facies B of Benfield 1969)		Grey micaceous siltstone and dark grey mudstone with isolated beds of very fine-grained sharp-based sandstone (c. 0.01 m thick). Faint cross-lamination or rare symmetrical ripples are locally present. *Planolites* bioturbation and rare *Lingula* may be evident.	Underlain by *Black mudstone with no marine fauna facies*; Overlain by *Upward-coarsening siltstone/sandstone facies*	Deposited predominantly from suspension, the presence of current- and wave-ripple lamination indicating relatively shallow deposition.
	Upward-coarsening siltstone/sandstone (upper part of Facies B of Benfield 1969)	Up to 30 m cycles	Clayey siltstone upwards-coarsening to very fine-grained sandstone, with wave and current ripple lamination. The sandstone top may be marked by a ganister. *Chondrites*, *Lockeia (Pelecypodichnus)*, *Conostichnus* and *Planolites* common to pervasive.	Typical of the *higher sandstone bodies*, including Redmires Flags. Occurs above the *Current ripple cross-laminated sandstone and siltstone.*	Minor delta fills of shallow lakes or shoreline deposits of inter-distributary bays. Cycles with upward transition from suspension to bedload traction deposits.
	Wave and current ripple laminated sandstone (Facies E of Benfield 1969)		Wave and current ripple laminated, very fine- to fine-grained sandstone.	Underlain by *Pro-delta parallel-laminated siltstone & mudstone facies.*	Moderate wave energy and lower flow regime unidirectional currents on a delta flank, marginal to distributary mouthbar (crevasse channels).
	Levee and backswamp siltstone and sandstone (Facies G of Benfield 1969)	Up to 7 m	Interbedded current ripple laminated, fine-grained sheet-like sandstone with rootlets and clayey micaceous siltstone.	Present above thin development of *Cross-bedded fluvial sandstone facies*	Channel levee and backswamp
	Waterlogged muddy palaeosol	Less than 1 m	Pale grey to cream mudstone with orange-red staining. Rootlets are abundant and associated carbonaceous debris common. The mudstone commonly forms aggregates with slickenside surfaces common.	Underlain by proximal mouthbar deposits and overlain by thin coals	Poorly drained environment close to sea or lake level
	Leached palaeosol	0.5 to 1.0 m	Ranging from hard, white quartz-rich, fine- to coarse-grained ganister to buff, micacaeous, variably rooted fine-grained sandstone with relict parallel and cross-lamination.	Present above the *Levee and backswamp sandstone and siltstone facies, Cross-bedded sandstone facies* or *Fluvial channel sandstone facies asociation*; Overlain by *In-situ coal*, *Black mudstone with marine/brackish fauna* or *Black mudstone with no marine fauna*	Leached palaeosols developed on a well-drained substrate
	In-situ coal	Up to 2 m	Laminae of fusain and vitric coal may be present and plant debris is abundant; may include silty/muddy partings	Present above the *Waterlogged muddy palaeosol* and *Leached palaeosol facies*	Autochthonous accumulation of peat within a rheotrophic mire environment
	Mudstone and allochthonous coal	?Up to 3 m	Black to dark grey mudstone, typically parallel-laminated with abundant plant debris and thin coal laminae. Silty and micaceous laminae are locally present.	Commonly underlain gradationally by the *Waterlogged muddy palaeosol facies*.	Deposited from suspension with plant debris, within an environment of high water-table.
Delta flank deposits	**Wave influenced sandstone and brackish-marine siltstone** (Facies H of Benfield 1969)	Up to 15 m	Very fine- to fine-grained, well-sorted, wave ripple laminated sandstone with intercalations of clayey siltstone with brackish to marine fauna.	Underlain by *Pro-delta parallel-laminated siltstone and mudstone facies*; Locally overlain by *Cross-bedded fluvial sandstone facies*	Beach barrier with lagoons