Carboniferous geology of northern England

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Abstract
The British Geological Survey (BGS) has produced a wholesale rationalisation of Carboniferous lithostratigraphical nomenclature. This presentation describes the Carboniferous stratigraphy of northern England, illustrated with research carried out as part of recent BGS mapping projects.
During the Tournaisian and Visean a phase of north–south rifting resulted in the development of grabens and half-grabens, separated by platforms and tilt-block highs. Visean marine transgressions resulted in the establishment of platform carbonates, which gradually onlapped raised horst and tilt-block highs. The evolution of one such tilt-block high, the Askrigg block, and associated Great Scar Limestone Group, is described in detail. During late Visean times a cyclic succession of fluvio-deltaic clastics, marine reworked sandstones and shallow-shelf marine carbonates (Yoredale Group) dominated across northern England, terminating deposition of the platform carbonates. To the south of the Craven fault system, which defines the southern margin of the Askrigg Block, the block and basin structures persisted, though generally the high subsidence rates created a province dominated by hemipelagic mudstones and carbonate/siliciclastic turbidites (Craven Group).
Cessation of rifting during the late Visean in the area between the Southern Uplands and the Wales–Brabant High resulted in a period dominated by thermally induced regional subsidence during Namurian and Westphalian times, with formation of the Pennine Basin. During early Namurian times fluvio-deltaic systems started to feed siliciclastic sediment into the northern margin of the basin (Millstone Grit Group). Initial deposition in the basinal areas is marked by the formation of thick turbidity-fronted delta successions. By late Namurian times, the southern part of the basin began to be infilled by fluvio-deltaic systems entering the basin from the east and south-east, but ultimately still sourced from the north. Three case studies are described in detail: the Kinderscout Grit, Ashover Grit and Chatsworth Grit. The development of these sand bodies occurred within a regime of regular and marked sea level changes. Evidence will be provided for the duration of this cyclicity.
From early in the Westphalian, a coal-forming delta-top environment, associated with formation of the Pennine Coal Measures Group became established across the Pennine Basin. There was gradual waning of the influence of marine flooding events in the basin. The sediment influx into the Pennine Basin progressively changed from a dominantly northern provenance, comparable to the Millstone Grit Group, to initially a western source and subsequently to a southern one, later in the Westphalian.

Introduction
The Carboniferous, arguably more than any other system, is emblematic of the geology of northern England, and of Yorkshire in particular. The mineral resources present within Carboniferous strata were of paramount importance in the development of the Industrial Revolution in Britain and controlled the location and growth of some of our northern cities, including Leeds, the home of this year's OUGS Symposium. If one considers the archetypal landscape of northern England it is likely to include the wild moors of the Pennines, or the grand scenery of the Yorkshire Dales. These areas have been the focus of much research over the decades and still offers new discoveries, some of which will be described in this paper.
This paper describes: recent changes to the chronostratigraphical nomenclature used to subdivide the Carboniferous Period; the plate tectonic setting relevant to the story of the sedimentary evolution of the Carboniferous of northern England; a new lithostratigraphical scheme, developed recently by the BGS to rationalise the multitude of local terminologies and to better reflect the evolution of depositional environments with time; a systematic description of the Carboniferous succession of northern England.

Chronostratigraphy
The international chronostratigraphical nomenclature for the Carboniferous comprises two subsystems, the Mississippian and Pennsylvanian (Fig. 1), with the familiar Dinantian and Silesian – now obsolete terms. The International Committee on Stratigraphy has introduced six unnamed series, which are largely one-to-one matches with the new international stages. The early Carboniferous stages of Tournaisian and Visean have been used in the UK for several decades. Younger international stage names are less familiar, mostly derived from key Russian sections. However, in the UK we have long-established terms that are still acceptable to use, though now downgraded. The Namurian, Westphalian and Stephanian have become regional stages, where they used to be series, and stages such as Courceyan, Chadian etc. have been downgraded to regional substages.

Because Figure 1 is scaled with reference to time, it shows how short the durations of some of these substages were within the Pennsylvanian, which is ultimately why they cannot be considered as international stages.

Tectonic evolution

During the Carboniferous, northern England was located on the southern margin of the Laurussian plate (Fig. 2). In the late Devonian to early Carboniferous, there was a northward subduction of the oceanic plate attached to Gondwana below the Laurussian plate. This resulted in a regime of back-arc extension, causing the reactivation of earlier basement lineaments in northern England to produce a series of tectonic blocks and basins. By late Mississippian times, consumption of the oceanic plate resulted in collision of the Gondwana and Laurussia plates. Crustal thickening and foreland basin development was evident, particularly in southern Britain, by the end of the Visean. However, in northern England the influences of the deformation are not evident until the end of the Carboniferous.

The main tectonic influence on northern England during the Mississippian was the north–south extension and thinning of the lithosphere. This was not a simple effect, because of the complexity of pre-existing basement lineaments that reactivated during this phase of extension. Structural highs, such as the Alston and Askrigg blocks of northern England (Fig. 3) are associated with slow subsidence rates, development of shallow seas and the formation of platform carbonates. The main subsidence was taken up in grabens and half-grabens, such as the Craven Basin, Gainsborough Trough and Widmerpool Gulf, which tend to be associated with deeper basinal successions typified by sedimentation from suspension or turbidity currents. This linked series of small sub-basins eventually evolved during the Pennsylvanian into the larger Pennine Basin. The Southern Uplands and the Wales–Brabant High formed persistent upland areas during the Carboniferous, defining the northern and southern boundaries of the Pennine Basin, respectively.

Climate and sea level influences upon sedimentation

A significant factor in the evolution of sedimentary successions during the Carboniferous is climatic change. This, in part, reflects a northward movement of Britain across the Equator, and the global change from greenhouse to icehouse conditions, with resultant instigation of dramatic sea level fluctuations.

During the early Tournaisian there was a broad marine transgression (Fig. 4), probably reflecting subsidence associated with the phase of back-arc extension rather than a sea level rise. The Tournaisian and the early Visean were characterised by relatively small and infrequent sea level fluctuations and a stable climate, typically semi-arid with short wetter intervals.

By Asbian and Brigantian times, there was a change to sea level fluctuations with both a higher frequency (Fig. 4), about 50 cycles, and higher amplitude, between 10–50m. At the same time there were higher-frequency fluctuations between semi-arid and humid climatic conditions. This suggests that glacio-eustatic controls of both sea level and climate started to dominate at this time. Intense glaciations may have brought about short-term seasonally drier climates, whereas ice melting resulted in sea level rises and a potentially wetter equatorial climate. However, research suggests that at this time there are no major ice sheets forming across Gondwana, with glaciation restricted to sub-alpine upland environments (Fielding *et al.* 2008).

The main phase of glacial eustacy occurred during Namurian times, with high frequency sea level variations, up to 60 cycles, and amplitudes of up to *c.* 60m. High-amplitude sea level changes persisted into the Westphalian, though with a lower frequency; 19 or 20 Coal Measures cycles are associated with marine flooding events. There was, however, consistency in a humid climate during the Namurian and Westphalian as a result of the equatorial location. However, toward the end of the Westphalian and into the Stephanian, there is no evidence of any further marine invasion in Britain and there was a change towards a semi-arid to arid climate. This may, in part, be due to the northward migration of Laurussia at the time, but also could be related to a rain-shadow effect, as Britain was located north of the growing Variscan mountain belt.

Lithostratigraphy

The BGS has over recent years been involved in the simplification of Carboniferous lithostratigraphy, with the results published by Waters *et al.* (2007; 2009), which can be freely downloaded from the BGS website (http://www.bgs.ac.uk/downloads/browse.cfm?sec=1&cat=2). The scheme was designed to rationalise the plethora of formation names found in the Carboniferous of northern Britain. It also aimed to develop a group nomenclature more representative of the sedimentological evolution during the Carboniferous by subdividing the succession into broad sedimentary facies associations (Fig. 5):

1. the Continental and peri-tidal facies is well developed in the Stainmore Trough between the Askrigg and

Alston blocks, represented by the Ravenstonedale Group. The facies is limited in age to the Tournaisian and early Visean;
2. the heterolithic clastic and non-marine carbonate facies is restricted within northern England to the Northumberland Trough–Solway Basin as part of the Border Group and is of early Visean age;
3. the platform carbonate facies, with distinct group names for the different highs. In northern England the facies is largely represented by the Great Scar Limestone Group; other platforms are associated with deposition of the Bowland High and Peak Limestone groups. These platform carbonates are largely Tournaisian to Visean in age;
4. the hemipelagic facies comprises mainly suspension deposit mudstones with some turbidite deposits, represented by the Craven Group. They accumulated in part at the same time as the platform carbonates, but within the deeper water basins, ranging from Visean to Namurian age;
5. the Yoredale,
6. Millstone Grit and
7. Coal Measures facies comprise markedly cyclic successions. They were deposited at a time of marked glacial eustacy, major sea level changes inducing the cyclicity, but with each facies having different characteristics, permitting differentiation between the three groups;
8. the Barren Measures represent a return to almost the same semi-arid environment conditions that existed at the beginning of the Carboniferous. Red-beds dominate, coal seams are minor or absent. This facies, of late Westphalian to Stephanian, of very limited extent in northern England, includes parts of the Ingleton Coalfield.

Tournaisian: early basin evolution
During the Tournaisian there was a regime of marine transgression, particularly well developed in southern Britain and southern Ireland, with formation of a widespread platform carbonate succession (Fig. 6a). These carbonates did not extend far into northern England, where areas of emergent land were extensive. Between these uplands, alluvial plains are shown extending across much of northern and central England; realistically, the alluvial deposits are based on a small number of exposures and deep boreholes, so the full extent of these plains is uncertain. The Ravenstonedale Group of the Stainmore Trough is representative of these alluvial plain deposits. Pebbly sandstones dominate, typically red owing to deposition within an oxidising environment and with dominant calcrete palaeosols, suggesting a semi-arid environment. This facies locally passes into marginal marine flats where there is development of ferroan dolostones and evaporates, such as gypsum and anhydrite, again indicating a semi-arid environment.

Visean: block and basin controls upon sedimentation
By early Visean times prominent upland areas were developed along the Wales–Brabant High and Alston Block–Lake District High. The dominant lithofacies are platform carbonates. However, incipient development of the Craven Basin, with formation of deeper-water hemipelagic mudstones represents drowning of earlier Tournaisian platform carbonates (Fig. 6b).
In Yorkshire, the classic development of platform carbonates is associated with the Great Scar Limestone Group of the Askrigg Block. This is a tilt-block high that passes northwards to the half-graben of the Stainmore Trough (Fig.7). The continental and peri-tidal facies of the Ravonstonedale Group was prevalent in the deeper part of the basin. The marine carbonates gradually onlapped the tilt-block high so that by Arundian and Holkerian times the marine carbonates extended across the tilt-block high. From late Holkerian to early Brigantian times the southern flank of the shelf, close to the Mid Craven fault system was marked by Cracoean buildups of knoll reefs and shelf-edge tracts. This formed an abrupt margin between the platform carbonates and the deep-water hemipelagic shales, which form the Craven Group.
There is broadly a transition across all of the UK Carboniferous platform carbonate successions from thinner darker grey Arundian-Holkerian limestones to thicker-bedded pale grey Asbian-Brigantian cyclic limestones, and it is the latter that form the classic limestone pavements of the Yorkshire Dales. During the early Visean the platform carbonates are interpreted as being deposited in a gently sloping carbonate ramp with varying water depths. A significant feature was the formation of mud-mounds, also known as knoll reefs and Waulsortian reefs, mainly formed from microbial framework lime muds. The mud-mounds were formed in water depths up to *c.* 280m, with different communities prevalent depending on the location of the mounds. One of the characteristics is the presence of algae, not of corals, as the main framework builders. The mud-mounds tended not to be present at very shallow depths, where a high siliciclastic influx and mobile carbonate shoals occur. During the late Visean the reefs built upwards and outwards to form apron (or Cracoean) reefs separating a distinct shallow shelf from reef slope deposits. The apron reefs limited resedimentation of deposits through

storm or wave activity, promoting an increase in relative height, and increasing the slope angle and marking the break between shelf and basin deposition. The transition between the two platform types broadly coincides with the possible Asbian–Brigantian glacio-eustatic event, suggesting that rapid sea level fluctuations may drive the formation of apron reef flanked shelves. A distinctive feature of these late Visean carbonates is the presence of up to eight pot-holed bedding surfaces, overlain by thin mudstones. These palaeokarstic surfaces are inferred to indicate periodic emergence, possibly in response to glacio-eustatically driven sea level falls. The marginal Cracoean reef limestones are well developed along the southern flank of the Askrigg Block. They can have a knoll-like geometry or as laterally broader shelf-edge apron reef. Up to 100m of succession are dominated by massive wackestones with abundant crinoids and productid brachiopods; corals, although common, did not have the framework-building characteristics of modern reefs, that role being largely occupied by algae.

By Brigantian (late Visean) times, the platform carbonates were most extensively developed on the flanks of the Wales–Brabant High, such as the Peak District (Fig. 6c). The Askrigg and Alston blocks were covered extensively by the Yoredale lithofacies, characterised by upward-coarsening cycles. The basal, comparatively thin marine carbonates, represent the maximum flooding surfaces. They are laterally extensive and are used to help correlate successions regionally. Marine shales pass up into commonly thin tabular quartzititic sandstones, mainly fine- to medium-grained. The sandstones typically represent shallow lobate deltas affected by marine reworking following abandonment. Locally, fluvial channel sandstones are present. Cycles are commonly capped by seatearth palaeosols and thin coals. Tucker *et al.* (2009) have presented evidence for the main cycles to represent short orbital eccentricity cycles of *c.* 112kyr. Studying the Great Limestone, they recognised limestone-mudstone couplets representing millennial-scale environmental changes, suggesting that the muds represented high-frequency sea level rises.

To the south, within the Craven Basin, the hemipelagic lithofacies of the Craven Group were being deposited at the same time as the Yoredale Group on the Askrigg Block. The Craven Group is represented by dark carbonaceous mudstones, formed by the slow accumulation of suspended terrigenous fine sediments below storm wave bases and probably at water depths in the order of >100m. The late Visean succession was deposited marginal to a carbonate platform and hence includes carbonate turbidites, with sharp bases and gradational tops. Carbonate breccias and slump structures are common within slope deposits. Namurian parts of the succession would more typically contain siliciclastic turbidites developed in the prodelta setting, signalling the advance of the main deltaic systems.

Namurian: deltaic deposition

By the early Namurian there was an extensive, linked basin, part-filled by hemipelagic shales of the Craven Group, bounded to the north by fluvio-deltaic sandstones of the Millstone Grit Group (Fig. 6d). Those sandstones present on the southern flank of the Pennine Basin are quartzitic and sourced from the Wales–Brabant High. Sandstones on the northern flank are quartz-feldpathic and are sourced far from the north.

The Millstone Grit and Yoredale groups differ in respect of their relative ‘marineness’: the Yoredale Group was associated with comparatively small-scale sea level rises, the maximum flooding surface being represented by limestone with shallow-water benthic communities; by contrast, in the Millstone Grit Group the main flooding events were associated with marine bands commonly containing ammonoids (goniatites); these fully marine pelagic feeders accumulated on an anoxic basin floor free of benthic fauna and, because of the high sea level stand, minimal sediment input. Because the ammonoids evolved so rapidly, the majority of marine bands are associated with a new diagnostic species. During the Namurian, of 13myr duration, there are some 60 marine bands, so, on average, the cycles are *c.* 200,000 years each in duration.

In the south, delta slope and turbidite fans of the Morridge Formation represent strata of Millstone Grit lithofacies with protoquartzitic sandstones sourced from the south (Fig. 8). The main development of quartz-feldspathic fluvio-deltaic sandstones prograded gradually southwards into the Central Pennine Basin. Consequently, in the central part of the basin, the Bowland Shale Formation (Craven Group) extended up into the Kinderscoutian. The first phase of basin infill was associated with deposition of deep-water turbidite-fronted deltas. During the Pendleian and Arnsbergian the focus of deposition was in the northern flank of the basin. By late Arnsbergian times this part of the basin had been largely infilled and sedimentation rates broadly matched subsidence rates, such that much thinner cycles of shallow-water sheet-like deltas dominated and turbidite deposits were absent. During the Kinderscoutian there was a prominent increase in fluvial discharge that resulted in the southward progradation of the focus of deposition of turbidite-fronted deltas (including the Mam Tor Sandstones), which again rapidly infilled that part of the basin. The process repeated itself with the migration of turbidite-fronted deltas to the southern margin of the basin during Marsdenian times. By the end of the Marsdenian, the early Carboniferous block and basin topography had been entirely buried beneath fluvio-

deltaic sediments and basinal topography was subdued.
Three examples of typical Millstone Grit Group depositional features are illustrated:

1. At the time of deposition of the Kinderscout Grits in Yorkshire, farther to the south in Derbyshire, there was deposition of a thick succession (up to 135m) of thin interbeds of siltstone and sandstone, known as the Mam Tor Sandstone. This is interpreted as a distal turbidite apron, developed on a delta slope, basin-ward of the Kinderscout Grit fluvial system. The beds are overlain by thick-bedded coarse-grained lenticular sandstones of the Shale Grit, representing proximal turbidite lobes. The overlying Grindslow Shales comprise thin-bedded siltstones interpreted as delta slope deposits, with coarse- to very coarse-grained internally massive sandstones representing turbidite feeder channels.
2. Current work on revision of the Derby Sheet is concentrating on looking at another turbidite-fronted delta system, the Ashover Grit, of Marsdenian age. The turbiditic sandstones developed in advance of, and were subsequently overridden by, the fluvial Ashover Grit and show large-scale, syn-sedimentary slumping. The large rotational blocks developed on the delta front were displaced towards the north-north-west on listric failures. There is also an earlier phase of syn-sedimentary deformation comprising low-angle shear planes associated with both extensional and compressional deformation, interpreted as slide sheets.
3. Above the Ashover Grit, one cycle contains a thick sandstone succession variously known as the Huddersfield White Rock in Yorkshire, Chatsworth Grit in the East Midlands and Brooksbottoms Grit in Lancashire (Fig. 9). There was an assumption that these sandstones were laterally equivalent. By analysing both maximum grain size and palaeocurrent directions throughout the Central Pennine Bain it was possible to recognise four distinct sand bodies (Waters *et al.* 2008). The Huddersfield lobe is charaterised by sandstones typically fine- to medium-grained, with local development of delta-top channels of coarse-grained sandstone, with a fanning of palaeocurrent direction from north-west to south-west. The Huddersfield lobe entered the basin from the east, perhaps controlled by a depositional low associated with the Gainsborough Trough. The Widmerpool lobe, mainly known from subsurface data, is of similar grain size and may be coeval with the Huddersfield lobe, but is associated with sedimentation in a separate system building along the Widmerpool Gulf. No palaeocurrent data is available for this area, but it is assumed that it entered from the south-est along the Widmerpool Gulf. The Brooksbottoms lobe has variable grain size, but the average is coarse-grained to granular. A similar fanning of palaeocurrent direction from north-west to south-west is evident. Progressively falling sea level resulted in the basin-ward stepping of the depositional system, a regressive systems tract, forming the Brooksbottoms lobe. The falling base level culminated in a fluvial sand body occupying an incised valley (the Chatsworth palaeovalley) *c.* 25km across and *c.* 50m deep. The sand body is typified by quartz pebbles in excess of 5mm. Palaeocurrents are consistently towards the west. The abrupt northern margin of the Chatsworth Grit incised valley is evident at Chinley Churn, south of Glossop. The Chatsworth palaeovalley can be compared with the modern Brahmaputra River, both representing low-sinuousity fluvial systems. During seasonal floods the entire Brahmaputra braid-plain, *c.* 8km wide, becomes flooded and the lozenge-shaped bars actively migrate downriver. During low-flow regime the water retreats to distinct channels, with erosion of the bar form producing reactivation surfaces. Relict braid-plain deposits flank the active system, with the entire fluvial succession being *c.* 20km wide, similar in scale to the Chatsworth palaeovalley.

To summarise, the Namurian sand bodies show a systematic relationship to sea level change. Because of the lengthy and sinuous nature of connections between the open sea and the Central Pennine Basin, the Maximum Flooding Surfaces (marine bands) are likely to coincide with a maximum of the sea level curve (Waters *et al.* 2008). During the early phase of the falling stage, deltas built out into the basin, as evident during deposition of the Huddersfield White Rock. During the late falling stage, there was basin-ward migration of the centre of deltaic deposition, evident with the Brooksbottoms Grit and ultimately with marked incision formed a broad palaeovalley that during the earliest rising stage part filled with fluvial sediments: the Chatsworth Grit.
A similar explanation has been proposed for the geometry of the Kinderscout Grits. Typically, downstream of the channel, sediments were transported by submarine feeder channels, bypassing the upper part of the delta slope, to accumulate as a delta-front apron of coalescing turbidite lobes. The distal to proximal transition of these turbidite lobes is seen as the Mam Tor Sandstone and Shale Grit. Sands bypassed the delta slope within feeder channels, leaving the slope starved of sands, forming the Grindslow Shales. During the rising stage the incised valley filled with thin upwards-coarsening cycles associated with deposition of fine-grained Brown Edge Flags and Redmires Flag, representing the Transgressive Systems Tract. These sandstones cannot be traced outside the incised valley, where a thick leached palaeosol equates with much of this interval.

Westphalian: coal-forming mires

The Westphalian is associated with deposition of the Coal Measures facies, which extended across the Pennine Basin (Figure 6e). The extensional tectonics of the early Carboniferous had been superseded by a phase of thermal subsidence, caused by the cooling of the asthenosphere beneath tectonically thinned lithosphere. Isopachytes for combined Pennine Lower and Middle Coal Measures formed a broad bulls eye pattern, with their thinnest development at basin margins and greatest thickness (about 1.5km thick) in the basin depocentre around south Lancashire (Fig. 10). Anomalous thicknesses occur across parts of northern England. It appears that the granite-rooted highs of the Askrigg and Alston blocks were isostatically buoyant during the Carboniferous, with little subsidence occurring during the Westphalian. The current distribution of Coal Measures strata, at outcrop and in the subsurface, represents subsequent tectonic isolation of what was a laterally continuous succession.

There are three formations within the Pennine Coal Measures Group: the Pennine Lower, Middle and Upper Coal Measures, the bases defined by prominent marine bands — the Subcrenatum, Vanderbeckei and Cambriense bands, respectively. Broad lithological changes are recognised, the lower part of the Pennine Lower Coal Measures is dominated by a number of flooding events, hence several marine bands, whereas the coal seams are generally much thinner and of poor quality. The main coal resource is within the upper part of the Lower Coal Measures and the lower part of the Pennine Middle Coal Measures. Here, there are few marine flooding events and coals are thickly developed. In the upper part of the Pennine Middle Coal Measures, there is a reversion to an environment with a large number of marine bands, with the coals generally thinner and poorer quality. Within the Pennine Upper Coal Measures there are no more flooding events, the coals are generally thin, with significant distributary channels present in the upper part of the formation.

The Coal Measures lithofacies comprises cyclic successions of mudstone, siltstone, sandstone and coal, commonly known as cyclothems. A typical cycle is upwards coarsening, passing from lacustrine mudstone, through lacustrine deltas, locally capped by delta-top distributary channels of varying scale (Fig. 11). Ultimately, emergence is evidenced by the formation of a palaeosol and coal. Duff and Walton (1962) showed that in the East Pennine Coalfield, on average, there is a greater cyclothem thickness for cycles with the presence of a thin, basal, marine shale (12m), as opposed to a lacustrine shale (8m). It is possible that the accommodation space for many of the lacustrine cycles reflects a combination of regional thermal subsidence and compaction-related subsidence following distributary avulsion, producing the space for a new cycle to develop. In the case of marine cycles, a rise in sea level is likely to have enhanced the accommodation space formed by regional and compactional subsidence.

A typical Coal Measures swamp environment was associated with large tree-like clubmosses and tree ferns, growing on a floodplain with a permanently high water table, much like the modern day Amazon Basin. The trees and associated vegetable matter collected within anoxic conditions, in which the organic material did not oxidise and consequently accumulated to form the peat, which in turn was buried, compressed and heated to form coal.

In the East and West Midlands, many coal seams repeatedly split towards the north, away from the Wales–Brabant High, reflecting increasing subsidence rates towards the Pennine Basin depocentre. At the margins, where subsidence rates were low, peats had a long time to accumulate, forming few, but much thicker seams. The Staffordshire Thick Coal is up to 17m thick, which would equate with 170m thickness of peat formation. Some coals, particularly those below and above the marine flooding events, occur as single extensive coal seams.

Coal splits can also be seen on a much smaller scale in association with major distributary channels. East of Sheffield the Threequarters coal splits and increases in ash content towards the Silkstone Rock (Aitkenhead *et al.* 2002). On the north side this coal fails toward the channel and on the south has been removed by erosion by one of the multiply stacked channel sand bodies.

The majority of sand bodies within the Pennine Coal Measures Group are associated with minor lacustrine deltas or meandering channel systems (Fig. 11), with relatively sluggish flow velocities and a low gradient profile. The delta-top floodplain within interdistributary areas may have been occupied by shallow freshwater lakes up to 10m deep, for at least part of the year. Breaches of levees marginal to the channels resulted in sheet-like, sharp-based crevasse splay deposits. The migrating channels generated laterally accreting point bar deposits. Abandoned meander loops formed ox-bow lakes, the abandoned channels commonly filling with peat rather than with channel sands, resulting in local development of swilley coals. In contrast to the topographical lows associated with ox-bow lakes, channel sand bodies compacted to a lesser degree and formed relative topographical highs, associated with thinner coal development.

Pioneering work using heavy minerals suites (mainly Monazite:Zircon, Chrome Spinel:Zircon and

Garnet:Zircon ratios) combined with palaeocurrent data to distinguish sandstone provinces has provided the greatest resolution of the interplay of distinct fluvial systems within the Pennine Basin (e.g. Chisholm and Hallsworth 2005). They recognise four source regions (Fig. 2):

1. during the late Namurian and early Langsettian (the lower part of the Pennine Lower Coal Measures) the source region was from the north, but with sediments entering the basin from both the north and east. The sandstones are typically quartz-feldspathic and micaceous and locally can be medium- to coarse-grained and even pebbly. The source area is inferred to be from the margins of the Laurentia and Baltica plates in Norway or Greenland based upon the mixed ages of zircons and monazites of Archaean granultes, mid-Proterozoic sediments and Silurian granites;
2. during the deposition of the upper part of the Pennine Lower Coal Measures and lower part of the Pennine Middle Coal Measures the source region was from the west. Initially there is some recurrence of the northern influence with deposition of the Grenoside Sandstone. These western-sourced sandstones are typically finer-grained and more clay-rich and include chrome spinels, indicative of an ophiolitic source. The most likely candidate is Appalachia–Labrador–Newfoundland, which at the time was much closer to Britain than it is today;
3. during deposition of the upper part of the Pennine Middle Coal Measures and Pennine Upper Coal Measures the source region was from the Variscan orogen, located to the south-east. The sandstones are typically cleaner and quartz-felspathic, and locally can be coarse-grained and pebbly. A source from central Europe is inferred, with river systems bypassing around the east of the Wales–Brabant High and entering the eastern part of the basin;
4. a final source represents an influence of a local southern source, possibly associated with the Wales–Brabant High. This influence is not observed farther to the north in the Yorkshire Coalfield.

By the Late Westphalian and Stephanian sedimentation was dominated by deposition of typically red-bed alluvial successions (Fig. 6f). These are particularly evident along the southern margin of the Pennine Basin, and have recently been described along the northern margins at Canonbie and West Cumbria. However, over the Yorkshire area they are mostly absent, removed by the end Carboniferous Variscan deformation. Uplift associated with this deformation event is largely concentrated in the basin depocentre, with up to 4km uplift estimated, with about 1km to 2km of uplift in Yorkshire. Limited expression of these red-beds, forming what has become known as the Warwickshire Group, are evident in small outliers such as the Ingleton Coalfield.

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Figure captions

Figure 1 Carboniferous chronostratigraphical nomenclature (redrawn extract from Waters 2008).

*Figure 2 Plate tectonic reconstruction for Mississippian times (*c*. 340Ma). Northern Britain was located just south of the Equator, with northward migration of the Laurussian Plate resulting in a location just north of the Equator by the end of the Carboniferous. The arrows illustrate the provenance or source areas of the deltaic systems evident during Namurian and Westphalian times. There are four main source areas: (1) the old Caledonian Mountain belt located between Greenland and Scandinavia, with major rivers flowing southward across Britain from this highland area; (2) a source from the west, between Newfoundland and the eastern seaboard of Canada, which because there was no Atlantic Ocean at that time, was close to the west of Ireland. (3) and (4) the other two sources are linked in that they are part of the newly formed Variscan highlands, with a source from the south-east (central Europe) and a source from the south (France and Iberia), respectively. Also, note that northern England was located at the end of a long arm of sea, which extends several thousand kilometres. The nearest open ocean is out towards southern USA. (Palaeogeographical reconstruction adapted from model produced by Ron Blakey, NAU Geology:* www.jan.ucc.nau.edu/~rcb7/index.html).

Figure 3 Tectonic framework during the Mississippian showing the main structural highs, evident as upland areas or shallow shelf seas, and deeper water basinal areas. BH- Bowland High; BT- Bowland Trough; CLH- Central Lancashire High; DH- Derbyshire High; GT- Gainsborough Trough; HB- Humber Basin; HdB- Huddersfield Basin; LDH- Lake District High; WG- Widmerpool Gulf (redrawn from Waters and Davies 2006).

Figure 4 Carboniferous sea level and climatic record. The coastal onlap curve provides an impression of relative sea level rise, with highest levels towards the left. The climate curve attempts to show variations of apparent aridity to humidity, based upon sedimentological features (from Waters and Davies 2006).

Figure 5 Carboniferous lithostratigraphy of northern England (from Waters and Davies 2006; Waters et al. *2007).*

Figure 6 Palaeogeographical reconstructions showing the distribution of the main facies associations shown in Figure 5. (a) Mid Tournaisian, (b) Arundian (early Visean), (c) Brigantian (late Visean), (d) Arnsbergian (early Namurian), (e) Langsettian (early Westphalian) and (f) Asturian (late Westphalian) (from Waters and Davies 2006; Waters et al. *2007).*

Figure 7 A schematic N–S section showing the correlation of Tournaisian and Visean across the Craven Basin–Askrigg Block–Stainmore Trough (from Waters and Davies 2006).

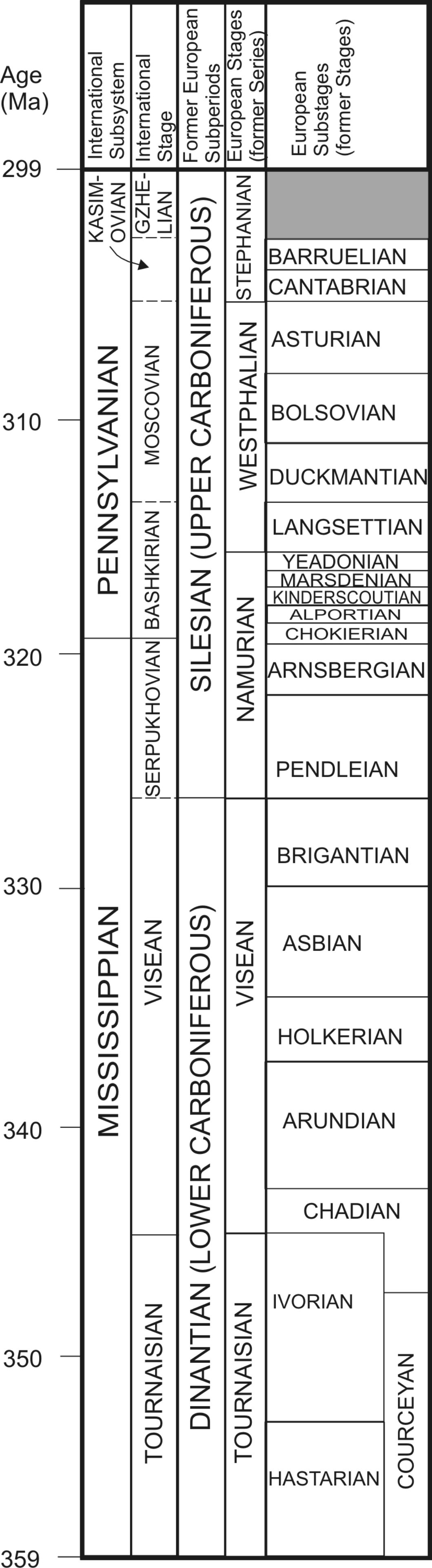
Figure 8 Distribution and lithofacies of the main sandstones of the Millstone Grit Group of the Central Pennine Basin. AsG- Ashover Grit; BB- Brooksbottom Grit; BrG- Brennand Grit; BS- Bowland Shale Formation; CG-

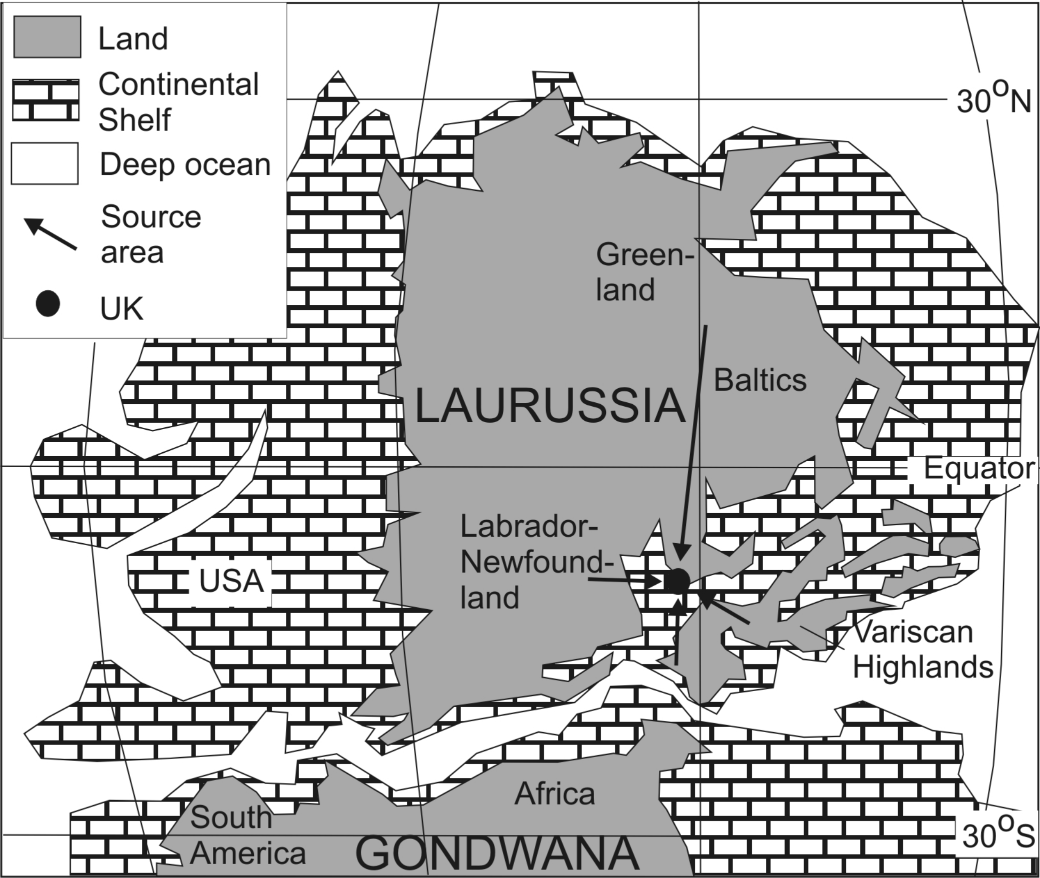
Chatsworth Grit; CoSS- Cocklett Scar Sandstones; DuCS- Dure Clough Sandstones;EdG- Eldroth Grit; ElCr- Ellel Crag Sandstone; FB- Fletcher Bank Grit; FCS- Five Clouds Sandstones; GG- Grassington Grit; GGt- Gorpley Grit; GtG- Greta Grits; HB- Holcombe Brook Grit; HG- Hazel Greave Grit; HHb- Heysham Harbour Sandstone; HM- Helmshore Grit; HR- Huddersfield White Rock; KG- Kinderscout Grit; LFG- Lower Follifoot Grit; LH- Lower Haslingden Flags; LoS- Longnor Sandstones; LvS- Laverton Sandstone; ML- Main Limestone; Mp- Marchup Grit; MT- Mam Tor Sandstones; Not- Nottage Crag Grit; PG- Pendle Grit; PS- Parsonage Sandstone; PH- Pule Hill Grit; R- Rough Rock; RoG- Roaches Grit; RSG- Red Scar Grit; SG- Shale Grit; SlvS- Silver Hills Sandstone; SnS- Sheen Sandstones; ToD- Todmorden Grit; WrSt- Ward's Stone Sandstone; WWG- Warley Wise Grit. The dashed lines represent the time-lines of sub-stage boundaries; the thick lines are the boundaries between the new formations defined within the Millstone Grit Group (from Waters and Davies 2006; Waters et al. *2009).*

Figure 9 Distribution of the main sand bodies of the Huddersfield White Rock/Chatsworth Grit/ Brooksbottoms Grit (from Waters et al. *2008).*

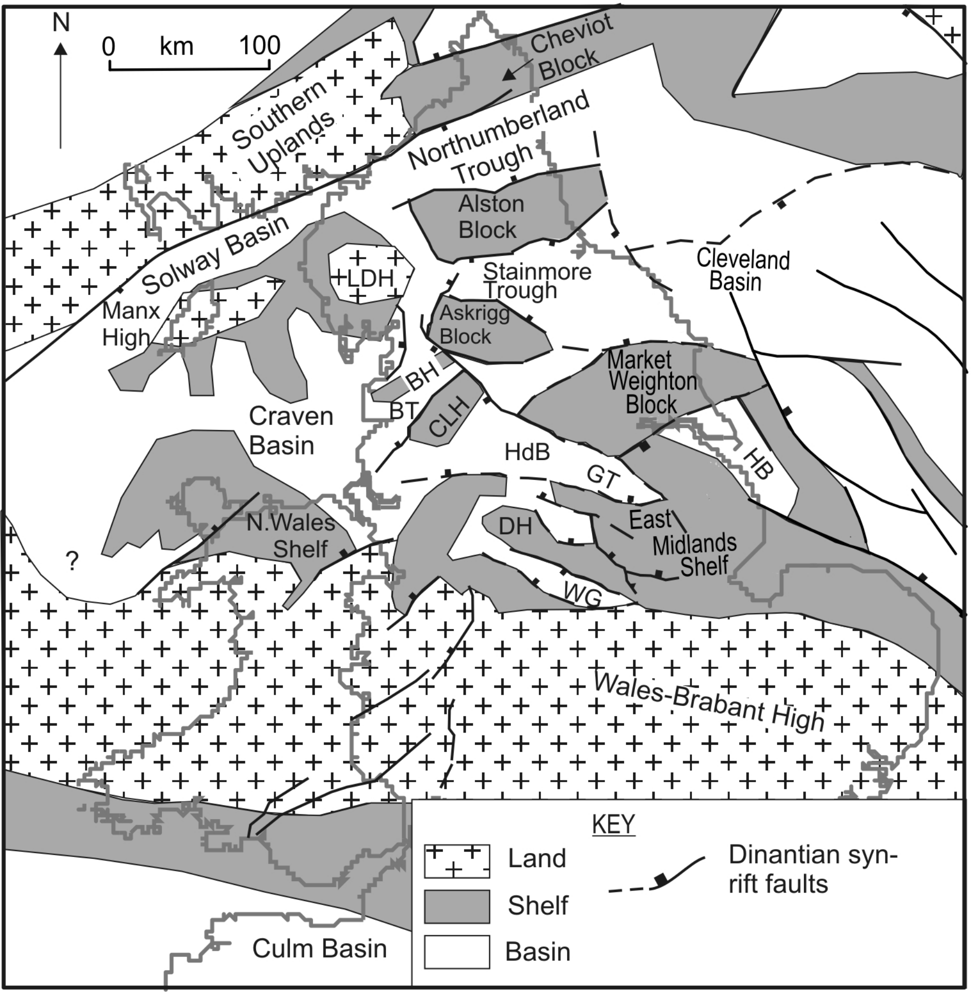
Figure 10 Distribution of Westphalian coalfields in England and Wales and generalised thickness of the combined Pennine Lower and Middle Coal Measures (from Waters and Davies 2006; Waters et al. *2009).*

Figure 11 Typical Coal Measures cycle (adapted from Guion et al. *1995).*

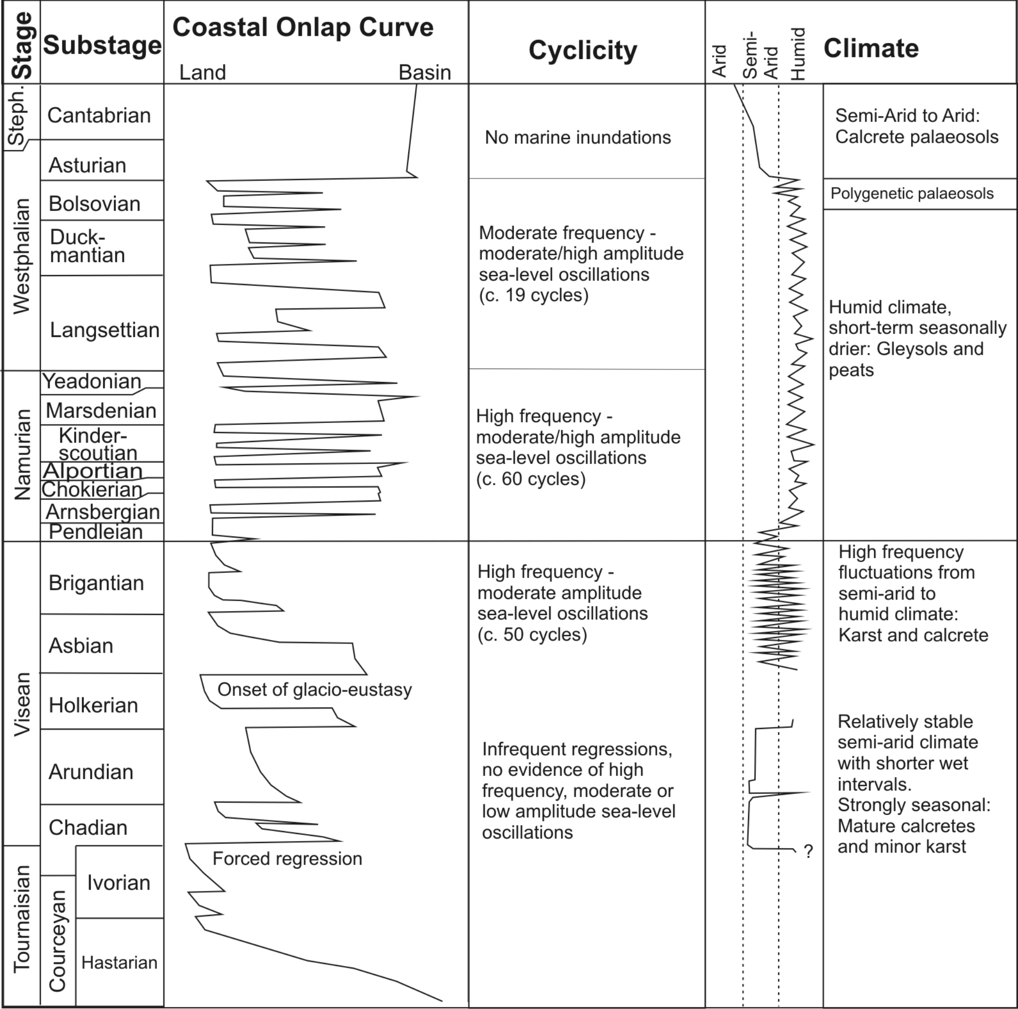

Age (Ma)
International Subsystem
International Stage
Former European Subperiods
European Stages (former Series)
European Substages (former Stages)
299
310
320
330
340
350
359
PENNSYLVANIAN
MISSISSIPPIAN
KASIM-OVIAN
GZHE-LIAN
MOSCOVIAN
BASHKIRIAN
SERPUKHOVIAN
VISEAN
TOURNAISIAN
SILESIAN (UPPER CARBONIFEROUS)
DINANTIAN (LOWER CARBONIFEROUS)
STEPHANIAN
WESTPHALIAN
NAMURIAN
VISEAN
TOURNAISIAN
BARRUELIAN
CANTABRIAN
ASTURIAN
BOLSOVIAN
DUCKMANTIAN
LANGSETTIAN
YEADONIAN
MARSDENIAN
KINDERSCOUTIAN
ALPORTIAN
CHOKIERIAN
ARNSBERGIAN
PENDLEIAN
BRIGANTIAN
ASBIAN
HOLKERIAN
ARUNDIAN
CHADIAN
IVORIAN
HASTARIAN
COURCEYAN

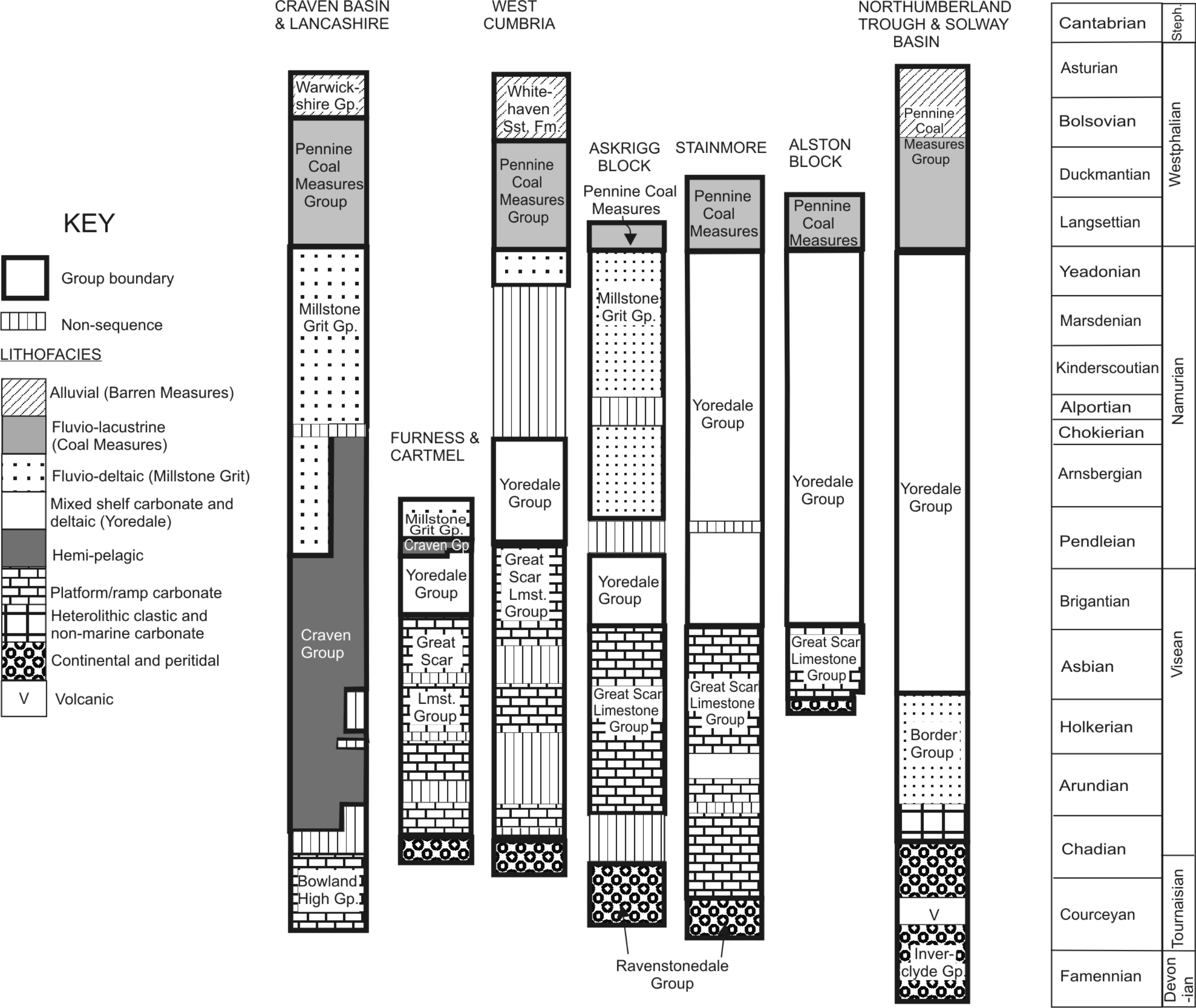


Land
Continental Shelf
Deep ocean
Source area
UK
30°N
Equator
30°S
Green-land
Baltics
LAURUSSIA
Labrador-Newfound-land
USA
Variscan Highlands
Africa
South America
GONDWANA

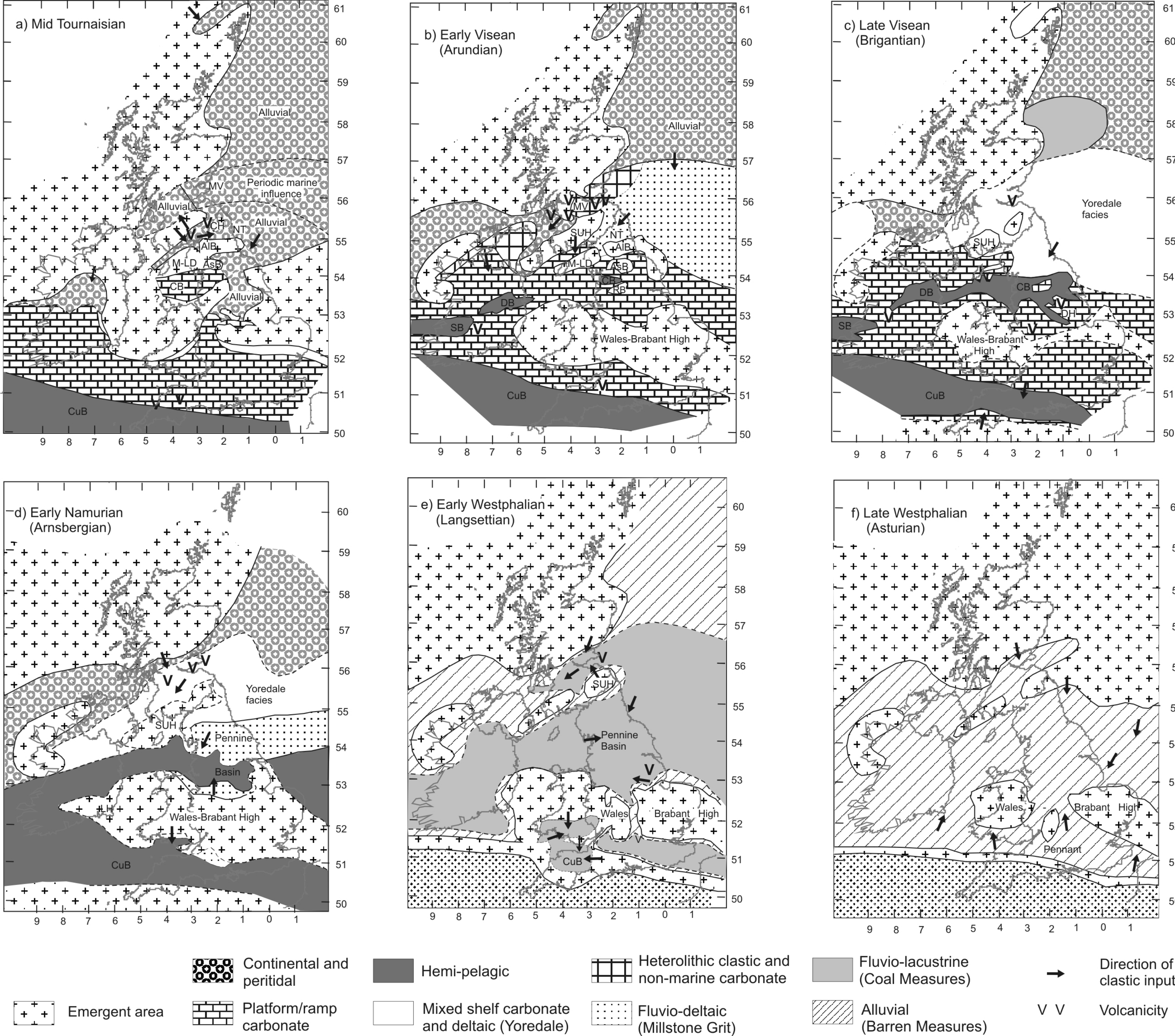


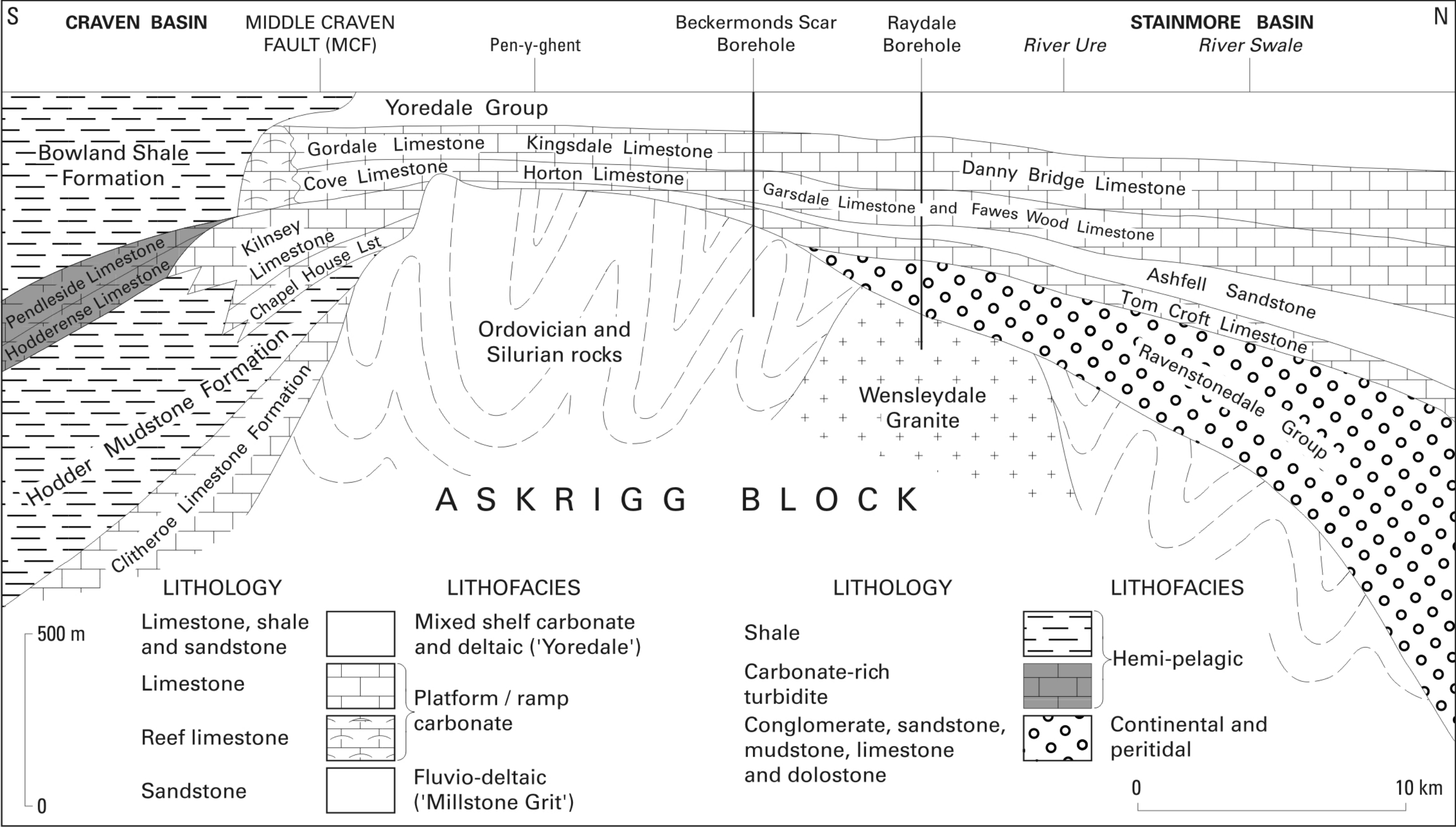
N
0 km 100
Southern Uplands
Cheviot Block
Northumberland Trough
Solway Basin
Alston Block
Manx High
LDH
Stainmore Trough
Askrigg Block
Cleveland Basin
BH
BT
CLH
Market Weighton Block
Craven Basin
HdB
GT
HB
N.Wales Shelf
DH
East Midlands Shelf
?
WG
Wales-Brabant High
Culm Basin
KEY
Land
Shelf
Basin
Dinantian syn-rift faults

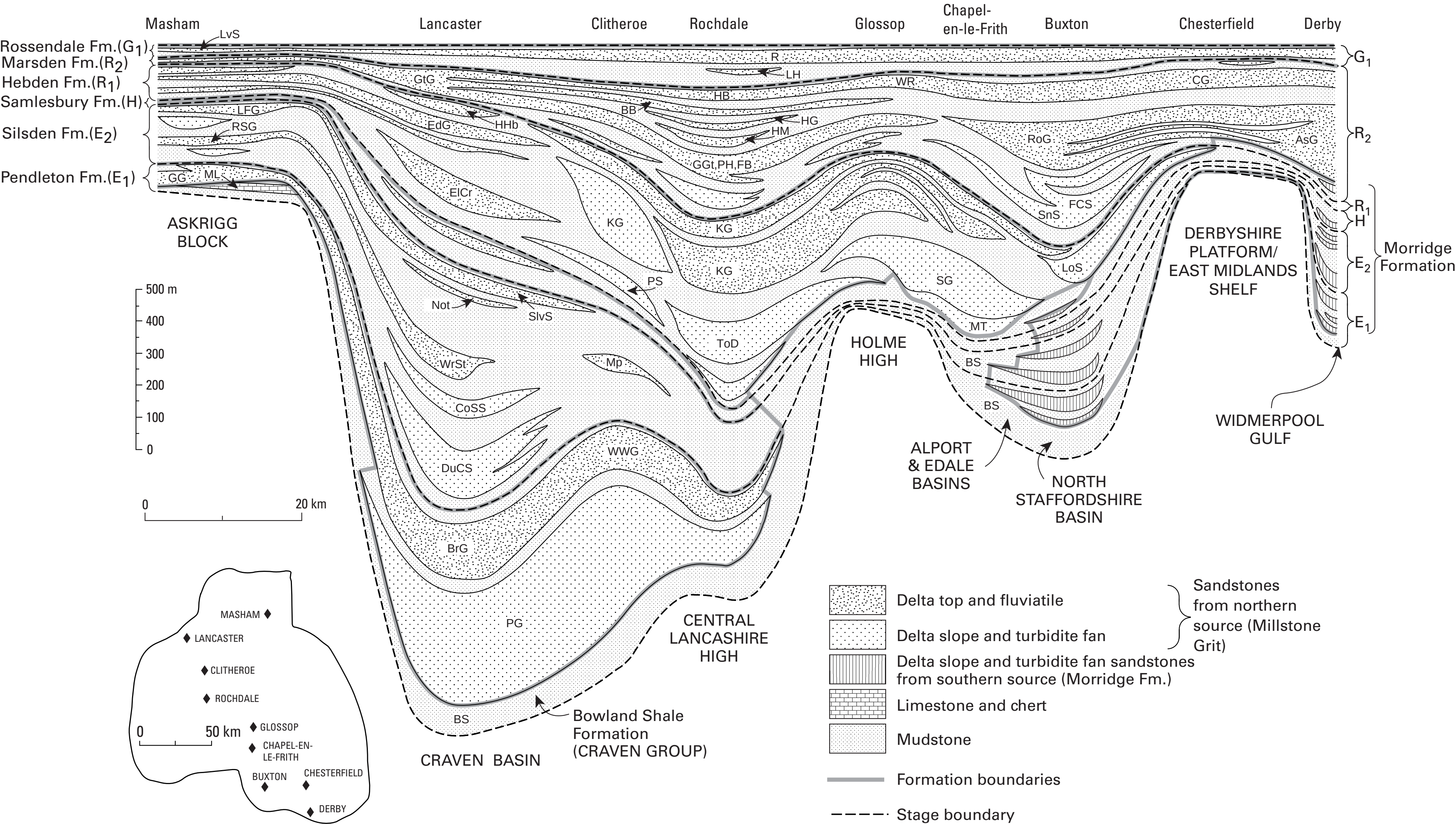

Stage
Substage
Coastal Onlap Curve
Land
Basin
Cyclicity
Arid
Semi-Arid
Humid
Climate
Steph.
Cantabrian
Asturian
Westphalian
Bolsovian
Duck-mantian
Langsettian
Namurian
Yeadonian
Marsdenian
Kinder-scoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Visean
Brigantian
Asbian
Holkerian
Arundian
Chadian
Tournaisian
Courceyan
Ivorian
Hastarian
Onset of glacio-eustasy
Forced regression
No marine inundations
Moderate frequency - moderate/high amplitude sea-level oscillations (c. 19 cycles)
High frequency - moderate/high amplitude sea-level oscillations (c. 60 cycles)
High frequency - moderate amplitude sea-level oscillations (c. 50 cycles)
Infrequent regressions, no evidence of high frequency, moderate or low amplitude sea-level oscillations
?
Semi-Arid to Arid: Calcrete palaeosols
Polygenetic palaeosols
Humid climate, short-term seasonally drier: Gleysols and peats
High frequency fluctuations from semi-arid to humid climate: Karst and calcrete
Relatively stable semi-arid climate with shorter wet intervals. Strongly seasonal: Mature calcretes and minor karst

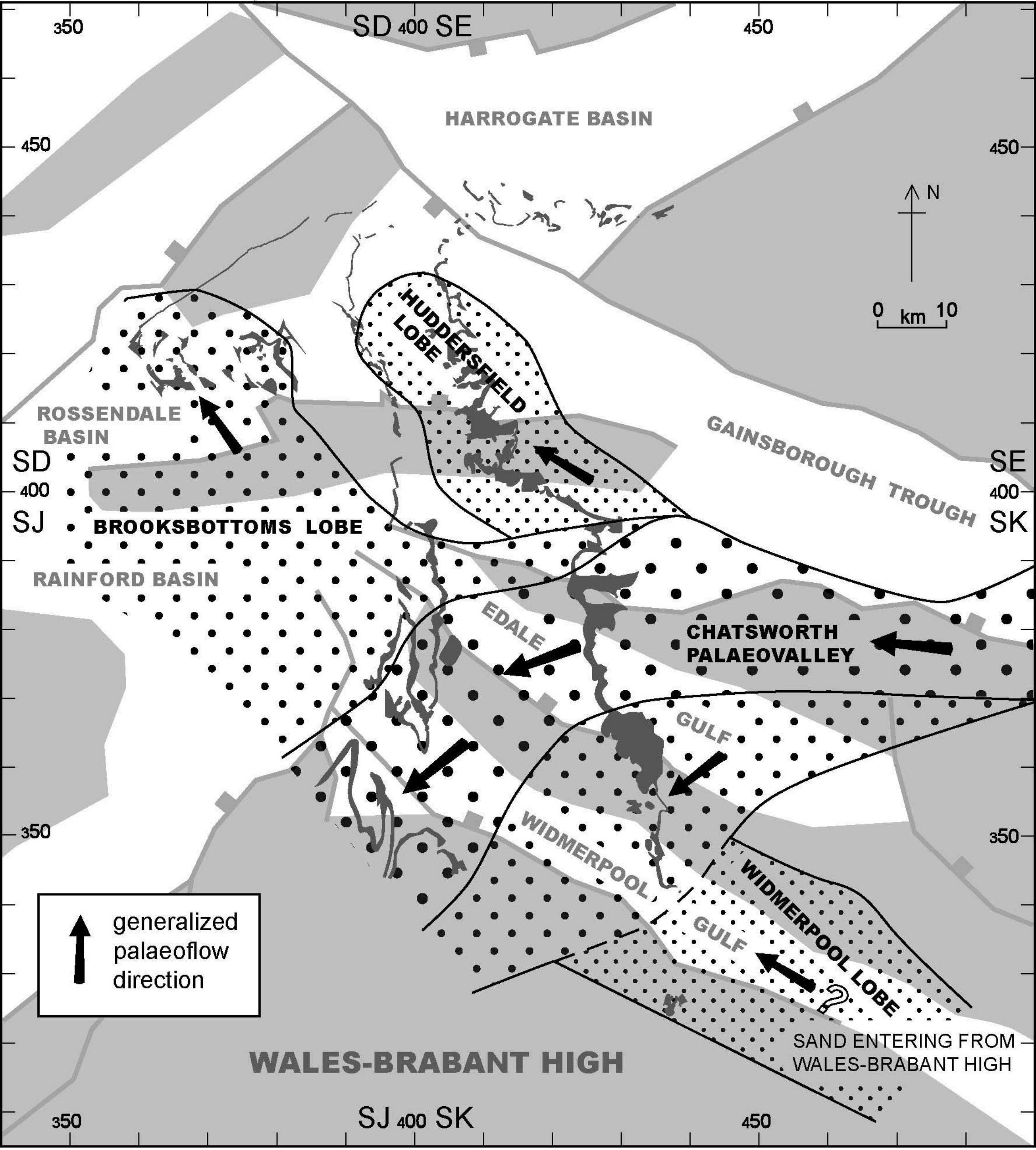


KEY
Group boundary
Non-sequence
LITHOFACIES
Alluvial (Barren Measures)
Fluvio-lacustrine (Coal Measures)
Fluvio-deltaic (Millstone Grit)
Mixed shelf carbonate and deltaic (Yoredale)
Hemi-pelagic
Platform/ramp carbonate
Heterolithic clastic and non-marine carbonate
Continental and peritidal
V
Volcanic
CRAVEN BASIN & LANCASHIRE
Warwick-shire Gp.
Pennine Coal Measures Group
Millstone Grit Gp.
Craven Group
Bowland High Gp.
FURNESS & CARTMEL
Millstone Grit Gp.
Craven Gp
Yoredale Group
Great Scar Lmst. Group
WEST CUMBRIA
White-haven Sst. Fm.
Pennine Coal Measures Group
Yoredale Group
Great Scar Lmst. Group
ASKRIGG BLOCK
Pennine Coal Measures
Millstone Grit Gp.
Yoredale Group
Great Scar Limestone Group
STAINMORE
Pennine Coal Measures
Yoredale Group
Great Scar Limestone Group
Ravenstonedale Group
ALSTON BLOCK
Pennine Coal Measures
Yoredale Group
Great Scar Limestone Group
NORTHUMBERLAND TROUGH & SOLWAY BASIN
Pennine Coal Measures Group
Yoredale Group
Border Group
V
Inver-clyde Gp.
Cantabrian
Steph.
Asturian
Bolsovian
Duckmantian
Langsettian
Westphalian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Namurian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Visean
Courceyan
Tournaisian
Famennian
Devon-ian

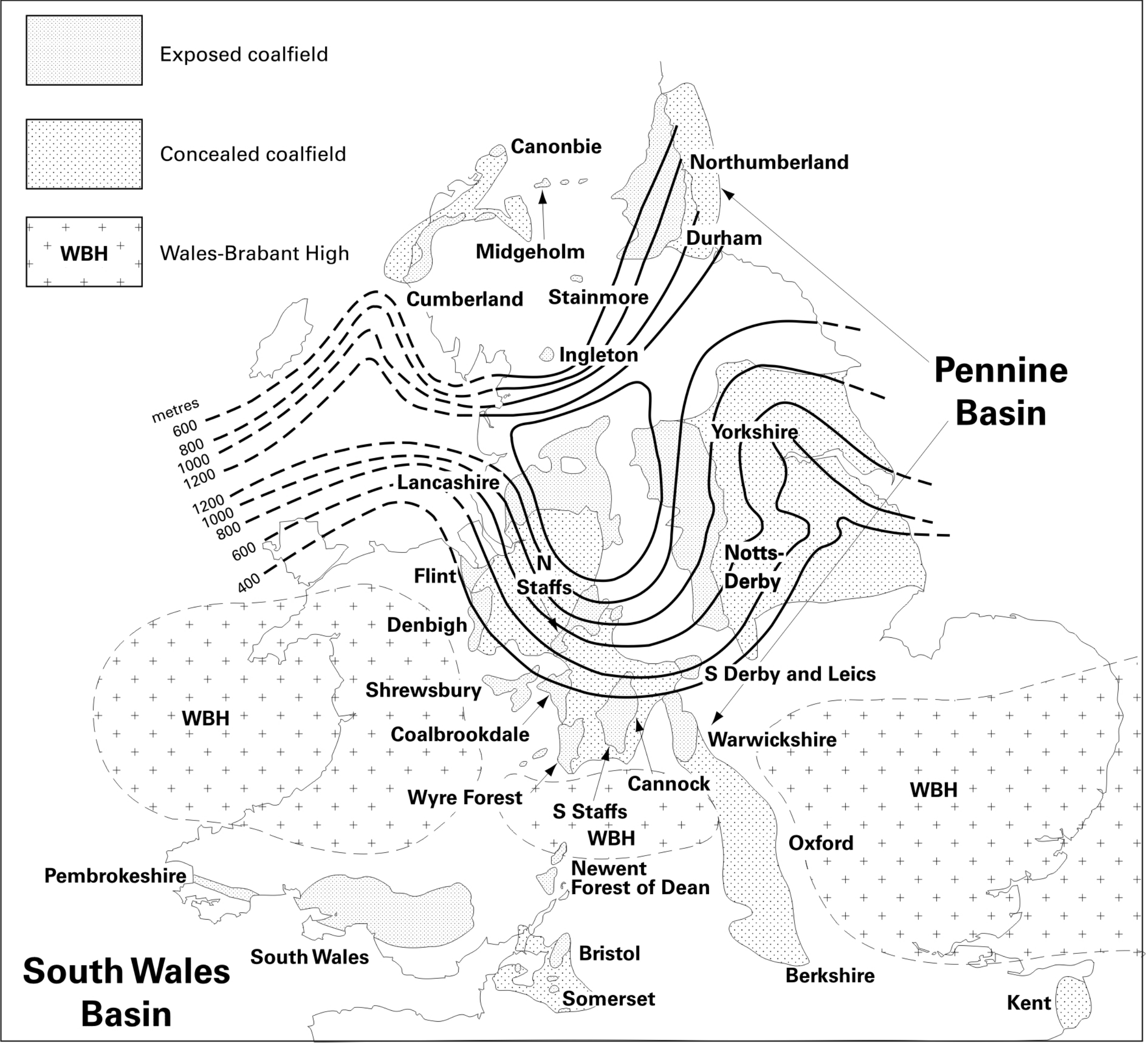

a) Mid Tournaisian
Alluvial
Periodic marine influence
MV
Alluvial
CH
NT
Alluvial
AlB
M-LD
AsB
CB
Alluvial
CuB
b) Early Visean (Arundian)
Alluvial
MV
SUH
NT
AlB
M-LD
AsB
CB
RB
DB
SB
Wales-Brabant High
CuB
c) Late Visean (Brigantian)
Yoredale facies
SUH
CB
DB
DH
SB
Wales-Brabant High
CuB
d) Early Namurian (Arnsbergian)
Yoredale facies
SUH
Pennine
Basin
Wales-Brabant High
CuB
e) Early Westphalian (Langsettian)
SUH
Pennine Basin
Wales
Brabant High
CuB
f) Late Westphalian (Asturian)
Wales
Brabant High
Pennant
Continental and peritidal
Emergent area
Platform/ramp carbonate
Hemi-pelagic
Mixed shelf carbonate and deltaic (Yoredale)
Heterolithic clastic and non-marine carbonate
Fluvio-deltaic (Millstone Grit)
Fluvio-lacustrine (Coal Measures)
Alluvial (Barren Measures)
Direction of clastic input
V V
Volcanicity


S
CRAVEN BASIN
MIDDLE CRAVEN FAULT (MCF)
Pen-y-ghent
Beckermonds Scar Borehole
Raydale Borehole
River Ure
STAINMORE BASIN
River Swale
N
Yoredale Group
Bowland Shale Formation
Gordale Limestone
Kingsdale Limestone
Cove Limestone
Horton Limestone
Danny Bridge Limestone
Garsdale Limestone and Fawes Wood Limestone
Kilnsey Limestone
Chapel House Lst
Pendleside Limestone
Hodderense Limestone
Hodder Mudstone Formation
Clitheroe Limestone Formation
Ordovician and Silurian rocks
Wensleydale Granite
Ashfell Sandstone
Tom Croft Limestone
Ravenstonedale Group
ASKRIGG BLOCK
500 m
0
LITHOLOGY
LITHOFACIES
Limestone, shale and sandstone
Mixed shelf carbonate and deltaic ('Yoredale')
Limestone
Platform / ramp carbonate
Reef limestone
Sandstone
Fluvio-deltaic ('Millstone Grit')
LITHOLOGY
LITHOFACIES
Shale
Carbonate-rich turbidite
Hemi-pelagic
Conglomerate, sandstone, mudstone, limestone and dolostone
Continental and peritidal
0
10 km

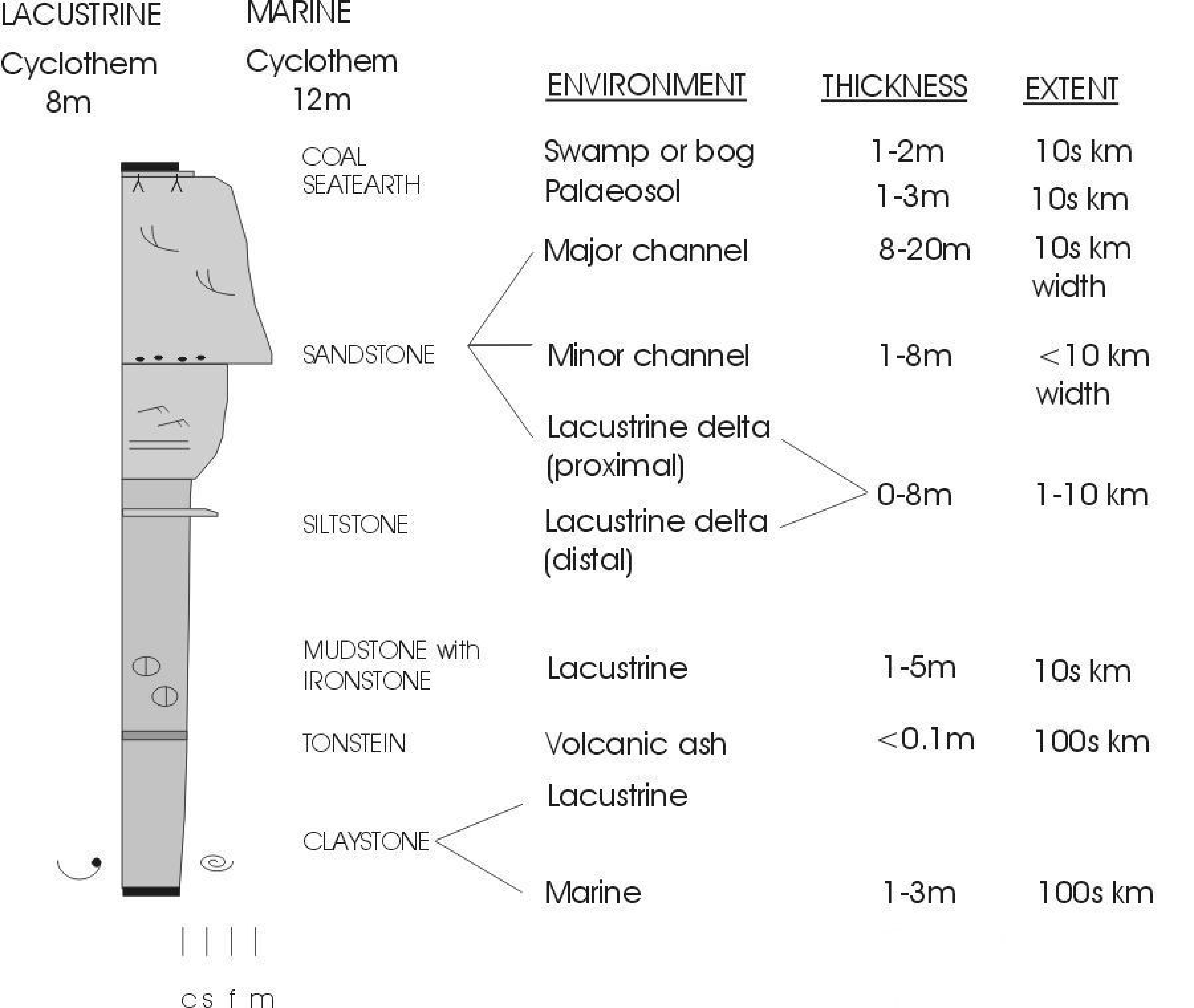

Masham
Lancaster
Clitheroe
Rochdale
Glossop
Chapel-en-le-Frith
Buxton
Chesterfield
Derby
Rossendale Fm.(G1)
Marsden Fm.(R2)
Hebden Fm.(R1)
Samlesbury Fm.(H)
Silsden Fm.(E2)
Pendleton Fm.(E1)
LvS
R
LH
GtG
WR
CG
HB
LFG
RSG
EdG
HHb
BB
HG
HM
RoG
AsG
GGt,PH,FB
GG
ML
ElCr
KG
FCS
SnS
LoS
SG
PS
ToD
MT
Not
SlvS
WrSt
Mp
CoSS
WWG
DuCS
BrG
PG
BS
ASKRIGG BLOCK
HOLME HIGH
DERBYSHIRE PLATFORM/ EAST MIDLANDS SHELF
G1
R2
R1
H
E2
E1
Morridge Formation
500 m
400
300
200
100
0
0
20 km
ALPORT & EDALE BASINS
NORTH STAFFORDSHIRE BASIN
WIDMERPOOL GULF
CENTRAL LANCASHIRE HIGH
Bowland Shale Formation (CRAVEN GROUP)
CRAVEN BASIN
MASHAM
LANCASTER
CLITHEROE
ROCHDALE
GLOSSOP
CHAPEL-EN-LE-FRITH
BUXTON
CHESTERFIELD
DERBY
0
50 km
Delta top and fluviatile
Delta slope and turbidite fan
Sandstones from northern source (Millstone Grit)
Delta slope and turbidite fan sandstones from southern source (Morridge Fm.)
Limestone and chert
Mudstone
Formation boundaries
Stage boundary



‘MAIN SANDSTONE BODY’ & BASEMENT STRUCTURE



Exposed coalfield
Concealed coalfield
WBH
Wales-Brabant High
Canonbie
Northumberland
Midgeholm
Durham
Cumberland
Stainmore
Ingleton
Pennine
Basin
metres
600
800
1000
1200
1200
1000
800
600
400
Yorkshire
Lancashire
Notts-
Derby
N
Staffs
Flint
Denbigh
S Derby and Leics
Shrewsbury
Coalbrookdale
Warwickshire
WBH
WBH
Wyre Forest
Cannock
S Staffs
WBH
Oxford
Newent
Forest of Dean
Pembrokeshire
South Wales
Bristol
Berkshire
South Wales
Basin
Somerset
Kent


LACUSTRINE
Cyclothem
8m
MARINE
Cyclothem
12m
ENVIRONMENT
THICKNESS
EXTENT
COAL
SEATEARTH
Swamp or bog
1-2m
10s km
Palaeosol
1-3m
10s km
SANDSTONE
Major channel
8-20m
10s km width
Minor channel
1-8m
<10 km width
Lacustrine delta (proximal)
SILTSTONE
Lacustrine delta (distal)
0-8m
1-10 km
MUDSTONE with IRONSTONE
Lacustrine
1-5m
10s km
TONSTEIN
Volcanic ash
<0.1m
100s km
CLAYSTONE
Lacustrine
Marine
1-3m
100s km
c s f m