Westphalian mid-A to mid-C depositional controls, UK Pennine Basin: regional analyses and their relevance to southern North Sea interpretations

From Earthwise

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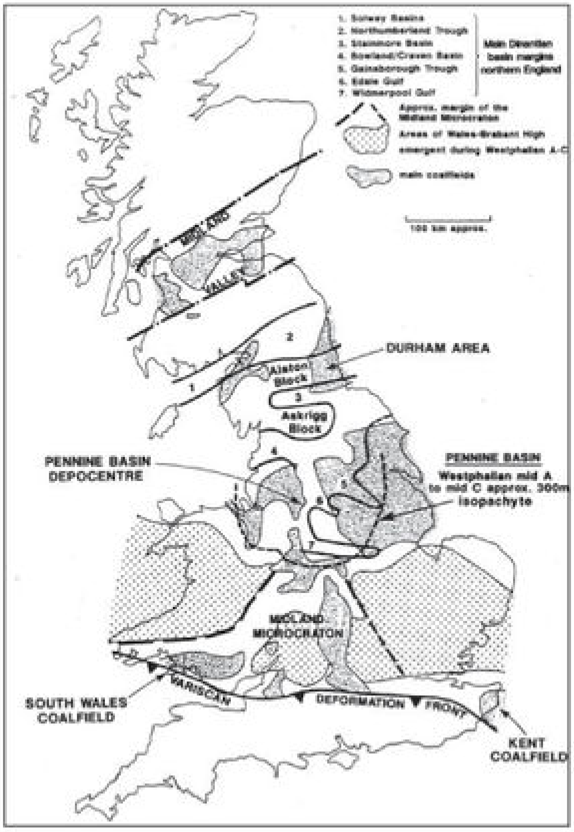
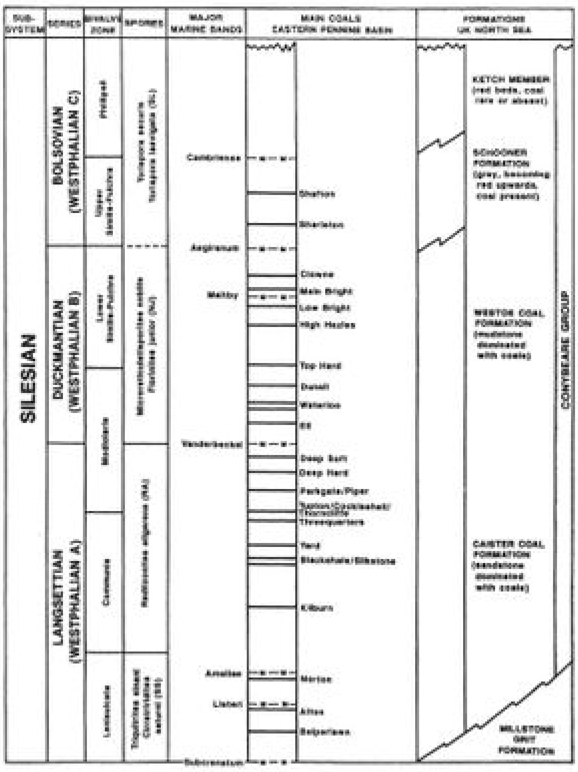


Figure 1 Tectonic framework of the main UK onshore Upper Carboniferous coalfields (based on Rippon 1997).



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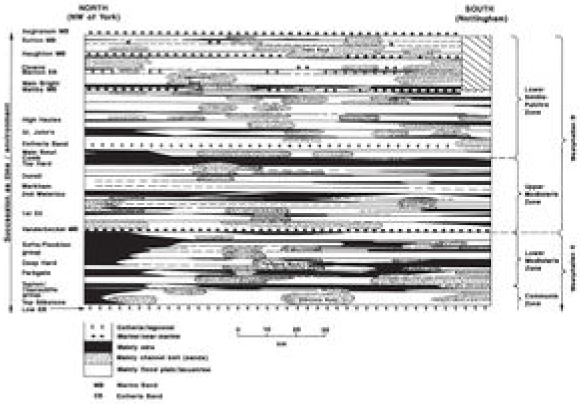

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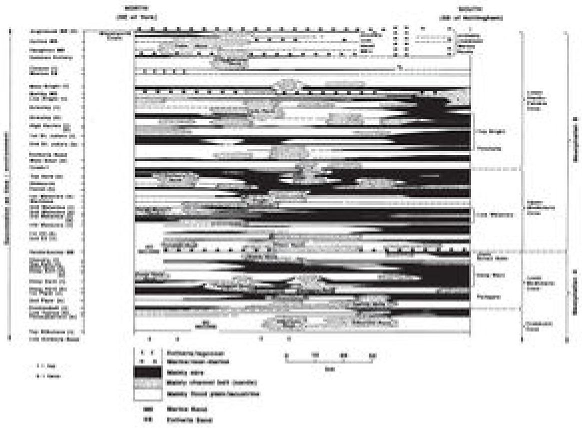

Figure 4 Variations in mid-Westphalian A to top Westphalian B palaeo-environments, north to south through eastings 470– 480. As for Figure 3, the vertical axis is the geological succession normalized for regional thickness variations to give a timeequivalent display (see main text); the horizontal axis is a north–south section through the succession; see Figure 5 for location. Again, the suppression of actual thickness variations allows a more ready assessment of the spatial variations in timeequivalent environments. Note: the unions of coals towards the basin margin southeast of Nottingham; basin-marginal areas where late Westphalian B marine strata occupy a specific condensed succession; the general lateral continuity of the named coals; and the persistence of channel belts, evidenced by significant fluvial sandstones throughout most of the succession. See also the caption for Figure 3.

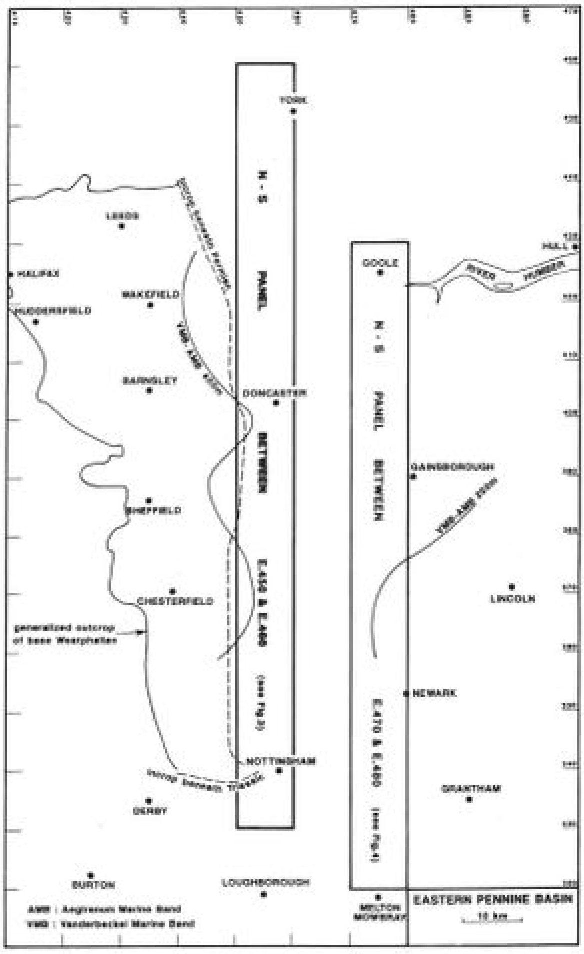

Figure 5 Locations for [(Figure 3)](), [(Figure 4)]()

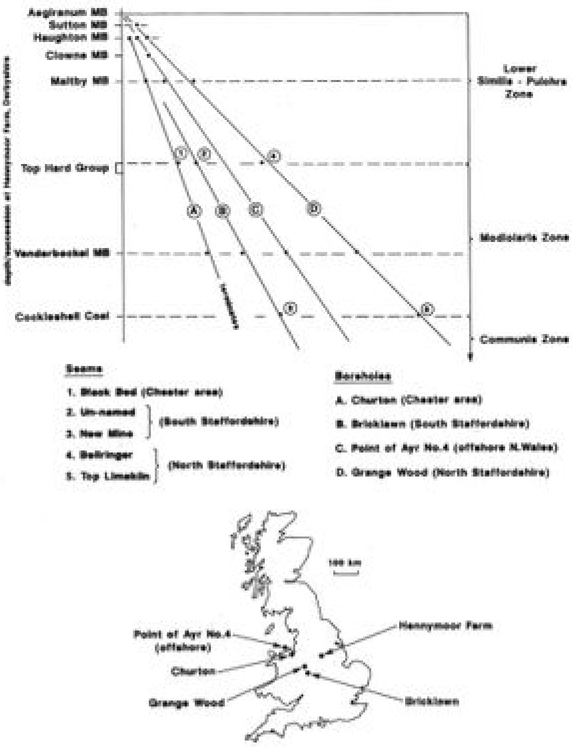

Figure 6 Mid-Westphalian A to top Westphalian B: comparisons between the western and eastern sides of the Pennine Basin using cross-plot correlation (see text). Note that the scale is presentational only, derived from detailed work. The vertical axis

is depth to key horizons from a structurally undisturbed borehole in a typical part of the eastern Pennine Basin, and the horizontal axis (same scale) is depth to the same horizons (using inter-basin correlation; see text) in various coalfields of the western Pennine Basin. The western and eastern parts of the Pennine Basin would have been in depositional continuity during Westphalian times, with a similar syn-depositional tectonic setting.

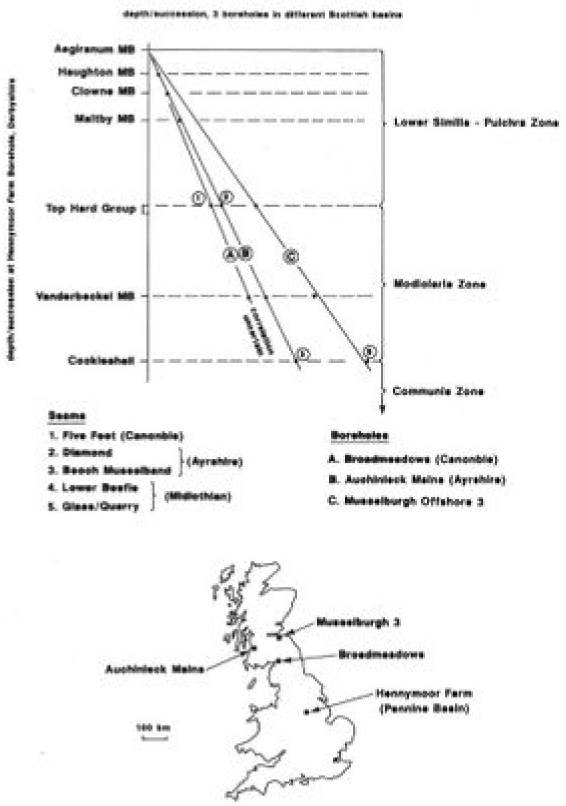

Figure 7 Mid-Westphalian A to top Westphalian B: comparisons between the eastern Pennine Basin and varied Scottish sub-basins using cross-plot correlation (see text). Note that the scale is presentational only, derived from detailed work. The vertical axis is depth to key horizons from a structurally undisturbed borehole in a typical part of the eastern Pennine Basin, and the horizontal axis (same scale) is depth to interpreted correlative horizons (see text) in three structurally distinct Scottish basins. Some depositional continuity between the Pennine Basin and Scotland is inferred, whereas the tectonic settings were different (see Rippon 1996 for discussion).

By J. H. Rippon

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Summary

The Westphalian mid-A to mid-C Coal Measures of the eastern part of the Pennine Basin are very well documented and also serve as useful analogues for stratigraphically equivalent successions in the North Sea. However, there are still conflicting interpretations of the onshore successions, mainly regarding the application of sequence stratigraphy. Sequence stratigraphical interpretation is not straightforward, particularly as major sandbodies occupy nearly all stratigraphical intervals; thus, potential sequence boundaries, defined by erosion surfaces at the bases of channel belts, could lie at virtually all horizons. Sandstone thicknesses and connectivities relate mainly to their location within the evolving basin. Coal and mudstone thicknesses and connectivities are also mainly related to basin location, although the stratigraphical distribution (and some thicknesses) of coal seams indicate control by marine base level. The paper also considers the validity of interpretations relevant to North Sea hydrocarbon fields. The onshore conclusions are derived from study of an extensive dataset across varied basin settings; the more restricted spatial and stratigraphical scope of offshore data significantly limits the interpretation of depositional relationships and trends. The paper's main conclusions relate to investigative scales, to the achievable inter-basin correlation resolution, to the 3 D connectivity and thickness patterns of coals, mudstones and sandstones (reflecting specific basin subsidence), and to more robust sequence stratigraphical interpretations.

Introduction

The Westphalian mid-A to mid-C Coal Measures of the eastern part of the Pennine Basin are very well documented, following intensive mining and exploration, and there is an extensive literature. The main aim of the paper is to consider basinwide relationships that can be substantiated from the detail, and then to evaluate their application to other depositional areas, including southern North Sea gas fields. The paper discusses regional correlation and controls on sedimentation for the Pennine and other onshore basins, and attempts to discuss the succession in a sequence stratigraphical context.

1. Background and previous work

1.1 The Westphalian of the Pennine Basin

Westphalian strata were deposited widely across the British Isles, in various tectonic settings. The Pennine Basin was a large area of enhanced subsidence, extending across much of central– northern England and into North Wales (Fig. 1). Basin subsidence began as a result of late Devonian to early Carboniferous rifting, with post-rift basin fill characterizing the later Carboniferous (Fraser & Gawthorpe 1990, Corfield et al. 1996, Rippon 1996). The overall basin may be considered to be a composite of individual structural units, with subsidence being progressively less well defined and possibly less localized through Carboniferous times. A compacted thickness in excess of 2km of Westphalian sediments was probably deposited in the depocentre (Staffordshire to Lancashire area). The succession (Fig. 2), which thins towards the basin margins, comprises typical cyclical Coal

Measures facies. Coals, claystones and siltstones, representing mire and lacustrine environments, are crossed by channel-belt lithofacies, notably sandstones. There are a few thin marine and quasi-marine horizons. Gradual changes through time, involving overall basin-fill character, sandstone provenance, marine influence and climate, are discernible, allowing the succession to be divided into five phases, as follows.# *Base Westphalian A (Langsettian) to mid Communis Zone*. A few thin (<1m) coals, relatively common marine incursions, sandstones with varied provenances.

1. *Westphalian A, later Communis Zone, to Maltby Marine Band (later Westphalian B: Duckmantian)*. Common thicker coals, very rare immediate marine influence, sandstones mainly derived from the west (Chisholm et al. 1996; Rippon 1996).
2. *Later Westphalian B (Duckmantian), Maltby Marine Band to Aegiranum Marine Band*. Generally thinner coals, more common marine bands, sandstones mainly derived from the west.
3. *Westphalian C (Bolsovian), Aegiranum Marine Band to Cambriense Marine Band*. Thinner coals, more common marine bands, sandstones mainly derived from the east (Aitken et al. 1999); gradual progression to common primary redbeds.
4. *Later Westphalian*. No direct marine influence, occasional thin coals, sandstones with varied provenances; local coarse sandstones and grits; characterized by redbeds.

These phases can also be recognized in other major UK onshore coalfields, although channel sandstone provenances differ (Rippon 1996, Hallsworth & Chisholm 2000). The seismic character of the Westphalian succession in North Sea settings has been described by Evans et al. (1992), and by McGlen & Rippon (2005). However, these five phases are not all readily discriminated on seismic profiles, because of differences related partly to sand provenance, and to changes in the incidence of thicker coals.

Overall patterns of Westphalian isopachs have been established across the Pennine Basin (e.g. Calver 1968: fig. 1). Detailed work shows that Westphalian B isopachs are much less controlled by basin subsidence than those for the Westphalian A, the later succession overstepping the earlier in many areas. The evolving tectonic setting, particularly with respect to the Variscan deformation front, has been described by Corfield et al. (1996) and Rippon (1997). Rippon (1998) discussed syndepositional structures and showed that, apart from the basin-marginal areas, syn-depositional fault growth during the Westphalian appears to have been rare, presumably reflecting a thick mantle of earlier Carboniferous sediments above the faulted basement. However, marginal areas record significant intraCarboniferous deformation, including a major unconformity below redbeds of Westphalian C–D age (e.g. Corfield et al. 1996).

1.2 Previous work and available data

There is an extensive Pennine Basin literature; the bibliography in Rippon (1996) includes relevant earlier contributions. Recent publications have focused mainly on interpretations of the palaeo-environments and depositional controls (see, for example,

Flint et al. 1995, Guion et al. 1995a, Rippon 1996, 1999, Aitken et al. 1999). Various authors, including Rippon (1996), Aitken et al. (1999) and Hallsworth & Chisholm (2000) have discussed palaeoflows and sandstone provenance. Bailey et al. (2002) and Keogh (2002) interpreted the eastern Pennine Basin, particularly with regard to reservoir analogue modelling. There is general agreement on overall palaeo-environments and sandstone provenance. However, considerable disagreement remains over major controls on deposition and syn-depositional preservation with some authors (e.g. Flint et al. 1995, Keogh 2002) favouring an approach emphasizing sea-level changes, whereas others (Rippon 1996, 1999) emphasize the role of basin subsidence. A key question addressed by recent literature is the degree to which structurally specific, actively subsiding basins affect the channel-belt pathways and lithological connectivities of the contemporary sedimentary systems. The term “basin subsidence” is used here in a structurally specific sense, rather than relating to more generalized settings.

There is a similarly extensive literature on the onshore Westphalian successions and settings beyond the Pennine Basin (see Rippon 1997 for a representative bibliography). In particular, O’Mara & Turner (1999) discuss the sequence stratigraphy of time-equivalent strata in northeast England and the North Sea. There is also an growing body of literature on the Westphalian of the North Sea, for example Ritchie et al. (1998) and Martin et al. (2002).

The Westphalian strata of the Pennine Basin are very well documented by mining-industry data, with many boreholes and detailed underground information. Borehole data density is commonly greater than 50 per National Grid Quarter Sheet (25km2). Most boreholes were extensively cored, and many were described in sedimentological detail, accompanied by wireline geophysical logs. Coals were geochemically analyzed, and subdivided into main coal lithotypes. Geological logging of underground and open-pit workings provided spatial information, for example on the loci of seam splits, the 3-D geometry of sandbodies, and palaeocurrent directional indicators such as sole structures and cross bedding. Extensive high-resolution seismic coverage adds to the structural data provided by the mine workings.

The extensive coalfield of the eastern Pennine Basin (Yorkshire, Nottinghamshire and adjacent areas) is particularly valuable for regional studies because the dataset extends without significant interruption for nearly 150km south to north, from the southern Midlands north to the York area, and up to 70km west to east (Fig. 1). The stratigraphical range extends from base Westphalian A to Westphalian D (with progressive loss of succession to the west, through later erosion).

2. Correlation and regional depositional variations

One of the key derivatives of the dataset is a robust correlation, which enables reliable and detailed reconstruction of the changing palaeo-environments through time, and consequent discrimination of controls on deposition and preservation. The following sections describe aspects of correlation resolution.

2.1 Correlation: introduction

Correlation is well established across all onshore coalfields. Coals, although involved in multiple splittings and reunions, can commonly be correlated across thousands to tens of thousands of square kilometres. This results from the density of high-quality data, the availability of many different correlation features (palaeontological, lithological, geochemical, geophysical), and

the influence of regional base level control, which appears to have determined coal concentrations at particular stratigraphical levels. It is emphasized that practical correlation, relevant to hydrocarbon-reservoir appraisals as well as to mining, requires resolution not only of individual horizons (particularly coals, volcaniclastic beds and marine bands) but also discrimination of separate sandbody systems. Such systems may well be of the same (or a very similar) age, but they are not spatially linked.

Regional correlations, and the palaeo-environmental interpretations that follow, will now be considered. The eastern Pennine Basin is discussed first, because of its wide geographical extent and excellent correlation resolution. Extrapolations to the western coalfields of the Pennine Basin are then discussed, followed by correlations with other areas, particularly in Scotland. It is acknowledged that inter-coalfield correlations are not new. The intention here is to emphasize the degree to which regional coals and faunal indicators may confidently be correlated between different basins, and to demonstrate some contemporaneity in palaeo-environments.

2.2 Correlation and regional depositional variations: eastern Pennine Basin

Correlation resolution in the eastern Pennine Basin is commonly fine enough for essentially deterministic mapping of the palaeoenvironments of each coal and inter-coal succession. This includes depositional and preservational variations, the discrimination and correct spatial linkages of relatively minor channel sandstones, and detailed shoreline positions of some marine incursions (e.g. Rippon 1984).

The term "preservational variations" is used here to capture the net results of the interactions between the erosional capabilities of channel systems and accommodation space. As discussed by Rippon (1996), erosion within and at the base of a sandbody system is likely to be at a maximum in the areas of reduced subsidence at basin margins (where channel belts enter, and perhaps exit from, an actively subsiding basin). Individual sandbodies would be thinner, with thicker sandbodies resulting only where later systems eroded into earlier sandbodies. Coals and claystones would be more liable to syn-depositional erosion, with a resulting increase in sandbody connectivity. Towards the basin depocentre, individual sandbodies would achieve their maximum thickness, and coal and claystone thicknesses would typically be maximized, with claystones encasing individual sandbodies. Preservational variations also result from more local effects. For example, lithofacies within and proximal to active channels would have a reduced preservational potential. Whereas late-stage channel fills are usually preserved in Coal Measures successions, the deposits of earlier phases are commonly, at least partially, eroded.

It is beyond the scope of this paper to provide specific examples of detailed correlation and deterministic mapping. Rather, the intention is to convey understanding of depositional and preservational variations on a regional scale. Figure 3, [[:File:YGS_CHR_07_WEST_FIG_04.jpg|Figure 4)] illustrate gross palaeo-environmental variations along two north–south panels from the York area south to Nottinghamshire–Leicestershire (Fig. 5). Figure 3, [[:File:YGS_CHR_07_WEST_FIG_04.jpg|Figure 4)] are small-scale and stylized, but detailed correlations using many boreholes give similar results. Each panel has been built up using key boreholes wherever possible. The left-hand axis of Figure 3 shows the geological succession in the Hennymoor Farm borehole in Derbyshire. This cored, unfaulted and fully correlated borehole lies in the main part of the basin in a position that is neither near the depocentre nor near the basin margins. Note that correlative coals, marine bands and Estheria bands through each panel are displayed not by depth but by normalization of horizons and intervals with those at Hennymoor Farm, to give a time-equivalent display of palaeo-environments.

The following paragraphs summarize the main conclusions from Figure 3 and Figure 4 . Other panels, whether north–south or east– west, show similar relationships, although details are different to those illustrated.

2.2.1 General comments: Figure 3 and Figure 4

A basin-margin setting is likely for the area northwest of York. Here, long-residence peats (united coal seams) above the Low Estheria Band indicate an area of reduced subsidence (Fig. 3). The trend begins some 30km south from the northern end of the diagram, presumably reflecting progressive shallowing of the basin. Figure 4 also shows seams uniting above the band, southeast of Nottingham towards a basin margin; the trend is noticeable from some 40km north from the known basin margin.

2.2.2 Coals

The main named coals may be traced throughout the area, although thicknesses and splitting vary geographically, mostly reflecting the incidence of local fluvial-channel systems. These coals are typically linked vertically through splitting and reunions (not all these links are shown by Figs 3 and 4), although there are key exceptions, which have sequence stratigraphical relevance. These are the cycles containing the Vanderbeckei, Maltby and Haughton marine bands (and also the Aegiranum, at a higher stratigraphical level). There are no well documented cases of coal beds linking across these intervals.

The Top Hard (Westphalian B, latest Upper Modiolaris Zone) is the most consistently thick coal across the coalfield (and, see later, across the full Pennine Basin) and must be assumed to have a particular sequence stratigraphical significance.

2.2.3 Marine and Estheria bands

The diagrams illustrate the paucity of marine and quasi-marine (Estheria) bands between the Low Estheria Band and the Maltby Marine Band, but rather more above the Maltby. Coal continuity is significantly lower in more marine-prone sequences. In some cases this results from later channel-belt erosion: however, some coals thin towards contemporary marine areas. Further, the more marine-prone parts of the succession are characterized by a lower incidence of coal-seam splitting. Although not visible at the scale of the diagrams, marine bands may be absent locally through erosion, through non-deposition because of continuing fluvial outflows at a contemporary shoreline, or through onlap onto topographic highs that acted as shorelines. Detailed field relationships (Rippon 1984) suggest that some black-shale marine bands, certainly the Clowne, and probably the Sutton, were deposited in water depths of only a few metres. In the case of the Clowne Marine Band, the shallow water depths are indicated by shoreline relationships with a contemporary mire. The Sutton Marine Band (poorer data) may partly represent flooding of local topographic lows that resulted from differential compaction of underlying sediments. (Figure 3) and (Figure 4) are too generalized to reveal such relationships, although the lateral impersistence of marine bands (because of the above factors) can be demonstrated on the basis of more detailed data.

2.2.4 Sandbodies

Only the main sandstones are shown in (Figure 3) and (Figure 4), where encountered in selected boreholes. Because the generalized trend of many channel belts was east–west, these north–south sections typically cross many of the channel belt axes at a high angle. Note that the diagrams display not sandbody thicknesses but their stratigraphical range (as discussed earlier).

Large channel systems continued to enter the Pennine Basin and adjacent areas during times dominated by lacustrine or mire environments. Some large sandbodies were therefore coeval with certain regional coals. Note that some sand-rich channel systems existed for considerable lengths of time. Sandbodies that are the time equivalent of several regional coal seams may represent deposition over periods of hundreds of thousands of years, whereas other mainly single-storey sandbodies were probably short lived. Apparent concentrations of sandbodies at certain horizons on (Figure 3) and (Figure 4) are considered to be mainly artefacts of panel choice. Figures 3 and 4, and additional supporting work, indicate that major sandbodies existed in different places through nearly all stratigraphical intervals; interpreting their erosional bases as sequence boundaries is therefore inappropriate. Nonetheless, (Figure 3) and (Figure 4) do suggest that sandbodies became fewer during times of major widespread inter-basin peat accumulation, perhaps implying some allocyclic control. Overall, the apparently sand-poor or sand-prone intervals shown by such diagrams may relate to data capture and display, to source area variations, or to variations in base-level control.

2.3 Correlation and depositional comparisons: all onshore coalfields

The validity of detailed correlation between the eastern Pennine Basin (Nottinghamshire–Yorkshire coalfield), and related coalfields to the west (Staffordshire, Lancashire, North Wales, etc.) requires careful evaluation. The main marine horizons and the non-marine bivalve zones are readily correlated, but the exact coal-seam equivalence is more difficult to assess. This is partly because the western coalfields are tens to hundreds of kilometres distant from the eastern Pennine Basin, whereas seam splittings and reunions can take place over distances of less than 1km to low tens of kilometres. Also, the western coalfields are themselves separated from one another by outcrops of older and younger strata, large structures and variable depths. Variation in seam nomenclature is both a symptom and a cause of some correlation problems.

Rippon (1997) discussed aspects of correlation, including the value of cross plotting horizons against depths from boreholes. This involves cross plotting a significant stratigraphical range, normally hundreds of metres thick, from two or more locations. Any variation from a 45° plot will (apart from any drilling deviations) have geological significance, and such cross plots may be used for both correlation and the identification of structural and depositional variations. After structural (and any igneous) variations are allowed for, the scatter produced by cross plotting individual features (e.g. a marine band) or packages (e.g. multistorey sandbodies) is mainly a measure of the fluvial influence in the succession. The marine bands plot linearly, reflecting direct base-level control. This simple technique has been used by the author in various UK coalfields for identification of faults, fault throws, and unconformities, given a robust horizon correlation. It is also useful for analyzing various depositional factors, including the correlation of coal seams over considerable distances, and is valuable for inter-coalfield seam correlation across the full Pennine Basin.

(Figure 6) illustrates a generalized cross plot of boreholes from four coalfields in the western Pennine Basin. The selected bore-holes were cored, and show only minor structural disturbance. The vertical axis is again based on Hennymoor Farm borehole in the eastern Pennine Basin. This acts as a reference against which the other borehole sections are plotted against the horizontal axis. As with (Figure 3) and (Figure 4), generalization and small scale are necessary for presentation, but considerable correlative accuracy can be established by more detailed work. Note that time-environment panels, such as illustrated in (Figure 3) and (Figure 4), can be constructed for these western coalfields, but their value is reduced because of the data gaps between the individual areas.

From the background work reflected in Figure 6, it is concluded that the main marine bands and non-marine bivalve-zone boundaries may be readily matched between the western and eastern coalfields of the Pennine Basin. The main named coal seams of the eastern Pennine Basin can confidently be correlated with the equivalent seams to the west, although structural disturbance is locally a problem. Other general conclusions include the importance of the Top Hard and correlative seams in both the western and eastern coalfields of the Pennine Basin. This may be expected, as these coalfields were originally in depositional continuity, and within the same tectonic setting.

Correlation is relatively easy in the varied coalfields of Scotland, which have large and detailed datasets. Figure 7 illustrates cross plots with Hennymoor Farm borehole in the eastern Pennine Basin, using boreholes in different parts of Scotland, selected because of good cored sections, and a lack of significant structural disturbance. Broadmeadows borehole, in the Canonbie coalfield, lies within the Northumberland–Solway Basin (Chadwick et al. 1995). Auchinleck Mains and Musselburgh 3 boreholes lie within different structurally defined parts of the Midland Valley rift system. The cross plots are again necessarily generalized small-scale illustrations of more detailed analysis. The same conclusions on correlation, including continuity of prominent coal seams, may be drawn as for the western Pennine Basin.

Coal-seam correlation is more difficult in South Wales and southern England, where significant thrust deformation has commonly produced large inter-seam variations and multiple-seam repeats. This is particularly the case in Kent, where the Westphalian A to mid-C succession is poorly understood.

3. Controls on deposition and preservation

Correlation of the main coal groups can therefore be undertaken for all major onshore coalfields, strongly suggesting that more detailed correlation might be extended to offshore areas too. The correlation framework allows analysis of contemporary variations in palaeo-environments and regional variations in basin fill. This in turn can lead to more robust interpretations of the depositional controls, some aspects of which are now discussed.

3.1 Basin fill: the interaction of differing depositional systems

A simple sequence-stratigraphical interpretation could view the mid-A to mid-C Westphalian fill of the Pennine Basin as essentially a single depositional system. Variations in fluvial input and erosion, together with the incidence of coals and marine bands, would be dominantly controlled by marine base level, with progressive regional subsidence generating accommodation space. In this interpretation, even if gross regional thickness variations were influenced by subsidence (see Section 2), the general stratigraphical incidence of the main palaeo-environments would be determined mainly by marine base-level variations.

However, the regional analysis outlined above indicates that the fluvial systems, at least, did not conform to this single system of basin fill: their stratigraphical incidence, locations and trends, and thickness and connectivity patterns appear to be normally independent of base-level indicators. This is the case even during periods of relatively lower incidences of sandbodies, such as during intervals of regional peat mantling, when some significant channel systems were still present ((Figure 3) and (Figure 4)). There are no regional changes comparable to those reported, for example, by Hampson et al. (1999) for the Namurian C to Westphalian A succession in the Ruhr coalfield, where there is a contemporary progression from fluvial to marine delta-front environments, albeit in a somewhat different setting.

Rippon (1996, 1999) considered that the preserved sedimentary volume records the interaction of three distinct depositional regimes:* *Background lithofacies* represent a near-continuum through the sedimentary pile, comprising fine-grained clastic rocks and coals, of lacustrine and mire environments. There is a general thinning of all these deposits towards the basin margins.

- *Channel belt lithofacies* represent near-continuous inflows into and across the basin, irrespective of the background environment; that is, some channel systems became established during times of mainly lacustrine sedimentation, others during times of mainly mire accumulations. Channel-belt pathways do not primarily reflect basin form, but their thicknesses and connectivities do reflect such a control.
- *Marine incursions* occurred infrequently, interrupting both of the above regimes. Faunal variations within the marine strata are considered by the author to be more complex than those implied by Calver (1968), who related progressively more marine faunal populations to basin form (see Rippon 1997). Marine-band thicknesses decrease towards the basin margins, but not to the same degree as the lacustrine mud-stones; this is presumably because the marine sediments were deposited over much less time, so that the effect of reduced subsidence at the basin margins is muted. The directions of marine incursions, which remain uncertain, may not necessarily have related to the (very gentle) gross palaeoslopes as

indicated by fluvial-channel pathways. These observations suggest that the marine bands represent distinctive events, controlled by eustatic (global) sea-level rise. Detailed field observations suggest that they were typically not in depositional continuity with the lacustrine deposits. It is considered that the onshore UK coalfields, and the southern North Sea areas, were all significantly distant from a fully marine setting. From this brief review, it is concluded that the preserved basin fill does record the interaction of three essentially different depositional regimes. The relative importance of marine base-level and basin subsidence, with respect to these three regimes will now be assessed.

3.2 Marine base level

Given their extensive lateral continuity, it is concluded that the named coal seams or groups represent base-level rises across very wide areas. Some diachronism is implicit, given coal thickness variations and seam splits; diachronism is also demonstrated by the gradual onlap of marine bands where known (see Section 2.2.3). However, the main periods of coal accumulation are taken to reflect regional rises, with only a few leading to a distinctive marine deposit. Regional correlations of main coals are therefore interpreted as reflecting definitive events, giving a fundamental sequence stratigraphical signature to the succession. Ramsbottom (1979) presented a similar interpretation for the British coalfields. The long-established non-marine bivalve zones (Fig. 2), characteristic of all British Westphalian coalfields, might also reflect inter-basin base-level changes.

However, despite a strong marine base-level influence on the succession, the major sandbodies, which are distinctively aggradational (Rippon 1996, Aitken et al. 1999), cannot be assigned a straightforward sequence-stratigraphical interpretation. It is inapplicable to place sequence boundaries at all their bases, because, as noted earlier, major sandbodies occupy nearly all stratigraphical intervals. Hence, potential sequence boundaries could lie at virtually all horizons. Most basal-erosion surfaces can readily be ascribed to local scouring, and the degree of downcutting is partly related to basin setting, there being more prominent erosion where condensed successions are present towards basin margins.

It is proposed, therefore, that the stratigraphical incidence of the marine bands and main coals, together with progressive changes in lacustrine bivalve faunas, all reflect variations in marine base level. However, because major channel-belt lithofacies are found at nearly all stratigraphical intervals, the control on all fluvial systems cannot readily be attributed uncritically to marine base-level fluctuations. It is further concluded that most channel-belt pathways (within the confines of the UK onshore– offshore depositional areas; see later for discussion of exceptions) were not directly related to any contemporary marine shoreline, which would have been quite distant. As noted earlier, sandbody incidence was reduced, but not eliminated, during times of major widespread inter-basin peat accumulation. It might therefore be argued that some rejuvenation could be ascribed to falling base level. However many of the major sand-bodies mapped across the Pennine Basin are known to terminate in the region, into essentially freshwater settings. Identification of fluvial rejuvenation caused by eustatic fall is therefore not straightforward.

3.3 Basin subsidence

Basin subsidence is considered to control the overall patterns of thickness variations (and therefore connectivities) of all the deposits, but not the channel-belt pathways, which were mainly influenced by upstream and gross palaeoslope factors (Rippon 1996). Individual sandstones, coal beds, lacustrine deposits and marine bands are typically thicker in the more rapidly subsiding parts of the Pennine Basin, where enhanced subsidence allowed greater accumulations with minimum contemporary erosion. Towards the basin margins the full succession is thinner, but thicker sandstones and coals can occur, representing condensed composites of individual beds.

Contemporary erosion is common both within the sandbodies and at their bases. Basin marginal areas are particularly instructive where they are not coal rich. In some areas, for example in parts of Lincolnshire (National Grid Square SK86) much of the succession between the Low Estheria Band and the Vanderbeckei Marine Band (see (Figure 3), (Figure 4)) consists of sandstone, reflecting the existence of long-lived channel belts throughout this interval. Other areas are known where an abnormally high proportion of marine or near-marine strata (including the Clowne, Haughton, Sutton, and Aegiranum marine bands) occur in the succession between the Clowne Seam and early Westphalian C strata (e.g. in parts of Lincolnshire, SK88). It may be argued for such locations that significant sandstones (e.g. the Oaks Rock, see (Figure 4)) must therefore be coeval with the marine strata. However, the relationship between the Oaks Rock and coeval strata is considered to be complex, involving marine-band attenuation against topographic highs (e.g. Sutton Marine Band) and erosion in channel-belt areas (e.g. Haughton and Sutton marine bands). There is also a possibility of non-deposition of the marine phase in places, with the channel belt prograding into marine waters (see Section 2.2.3). It is concluded that some channel systems did prograde into essentially marine environments in the Pennine Basin area, but only in exceptional cases, reflecting the rarity of the marine invasions themselves.

Some onshore coalfields include areas that were not in basin settings. In the UK the largest of these is the southern part of the English Northeast coalfield, in County Durham. In the Durham area, Westphalian deposition took place across the concealed easterly extension of the Alston Block ((Figure 1)), a positive structural unit during Carboniferous times. The succession here is relatively condensed throughout, compared with other areas of the Pennine Basin. There was also a different dominant sandstone provenance, with sediment derived mainly from the northeast (see for example Guion & Fielding 1988). The combination of a more proximal channel-source area (Rippon 1996) with a relatively condensed succession has led to a significantly greater proportion of sandstone. Furthermore, the lower subsidence rates have led to more closely spaced erosion surfaces within and beneath the sandbodies.

It is also possible to have a sand-poor structurally defined basin because it lies away from main channel-belt pathways. Some parts of the Pennine Basin itself are relatively sand poor, and others relatively sand rich. The organization of the distributive networks that supplied sand into the region would have been an important factor in determining these differences in sand content. The illustration of these points is beyond the scope of this paper, but Rippon (1996) presented a schematic representation of sand-prone and sand-poor areas.

3.4 Potential mechanisms for the lateral continuity of the coals

The above review suggests that base-level rise was the dominant control on the lateral continuity of key coals. However, other mechanisms may also have operated, especially upstream sediment starvation during coal-forming times and climatic changes. These would probably have been related, but are worth considering separately, as they provide different emphases.

Quite varied source areas contributed to Westphalian sediments in the onshore successions. These source areas are thought to have been to the east and south of Britain, in Fennoscandia, and to the west, perhaps in North America (Rippon 1996). Given such an extensive and varied provenance, it is unlikely that sediment starvation would have been the common and dominant control on major coal-forming horizons in quite different coalfields. This could only have been reflected in all upstream systems if a global event were involved, which itself could probably be related to a rise in sea level. Widespread climate change could have imposed similar settings across different basins, leading to cyclical accumulations of peat and related reductions in channel-belt activity. Repeated climatic change could reflect glacioeustatic control, affecting environments in both source lands and the developing coalfields, together with the intervening fluvial networks. Again, this is most likely to be revealed through base-level fluctuations.

Therefore, it is concluded that base-level change, perhaps driven by glacio-eustatic cyclicity, was the most likely dominant control on the lateral continuity of the coals.

4. Applicability of onshore analysis for offshore interpretations

The onshore relationships described are now considered for their analogue value to offshore fields, where data densities are very different and where the detailed spatial information is not available, especially from mining.

4.1 Investigative scales

The geographical extent and stratigraphical range that ideally should be used for regional modelling can be assessed using the Pennine Basin dataset. Inevitably, the more extensive the data, the better the model. Offshore interpretations that are limited to relatively detailed but very localized datasets, supplemented by rather variable regional information, must be used to the best advantage. However, it is important that any interpretations recognize both limitations of scale and adequacy of datasets. The practical forecasting of channel-belt pathways, the internal organization and correlation of sandbodies, and any sequencestratigraphical interpretations, requires minimum-extent data-sets, which need to be placed within known regional contexts wherever possible. (Figure 3) and (Figure 4) provide some illustration of the variations that would be encountered using restricted data-sets.

In characterizing sandbodies, the key issue must be the typical spacing and distribution of major channel belts analogous to significant hydrocarbon reservoir bodies. The spacing between contemporary very large channel belts (long-lived, multi-cycle, several kilometres wide and, depending on basin location, several tens of metres thick) across most of the Pennine Basin varies, but is commonly several tens of kilometres. The Silk-stone Rock (Fig. 4; see Guion et al. 1995b) and its correlative sandbodies farther north have this spacing. Others may be separated by much more than 50km. The separation distance will of course depend partly upon the location of the source area and the organization of the distributive networks. Data restricted to particularly sand-rich or sand-poor intervals are of limited value for understanding sequence-stratigraphical relationships; limitations of data availability are themselves an obvious but important consideration.

A further conclusion from the present study is that, based upon the understanding that the stratigraphical distribution of the main coal horizons is determined by marine base level, detailed inter-basin correlations should be achievable for many fields, particularly when used in conjunction with other established correlation tools. It follows that some regional palaeoenvironmental mapping, to the resolution of the major correlatable seams, might be achievable.

4.2 Controls on sedimentation and preservation

Across the onshore coalfields, the main control on preserved thicknesses, and therefore connectivities (coal-bed splits and unions, syn-depositional preservation of sandbodies, etc.) of all the main lithofacies was the rate of specific basin subsidence. This is known to be the case in tectonic settings as varied as South Wales, the Pennine Basin, and the differing sub-basins of the Scottish Midland Valley. Lower subsidence rates across the shelf-like areas such as the Durham coalfield led to relatively condensed successions, also supporting this conclusion.

The onshore data and their interpretation indicate that local sequence-stratigraphical schemes, based on geographically and stratigraphically restricted penetrations of main sandbodies off shore, are not dependable. However, the main coal incidences, which extend across several basins, may be representative of significant sea-level rises. A robust sequence-stratigraphical model must take account of these two issues, with an essential separation of the inferences drawn from the fluvial and marine palaeoenvironments in these basically marine-distant successions.

Simple sequence-stratigraphical interpretations based solely on the occurrence of sandbodies, and designed primarily to aid sandbody prediction in northwestern European Westphalian successions, are unlikely to be dependable. This is because the distribution of the sandbodies is not thought to relate exclusively to marine base level, the great majority of the channel systems prograding into freshwater settings. It may be argued that a sequence-stratigraphical approach might nonetheless aid in the prediction and definition of rock-volume heterogeneity. However the evidence from the onshore data indicates that the keys to determining reservoir architecture are, of course, data density and good correlation. Given the restricted offshore data settings, probably any analytical scheme will aid interpretation in a particular field, but regional sequence-stratigraphical extrapolations based solely on local schemes are likely to be misleading.

5. Conclusions

This paper has attempted to refine understandings of several interrelated matters. These are:* achievable intra- and inter-basin correlation resolution

- contemporary palaeo-environment distributions
- depositional and preservational controls on lithological connectivities
- the investigative scales necessary for realistic interpretations.

The lateral continuity of major coal seams forms the basis for robust inter-coalfield correlation resolution. This is commonly to the scale of the traditional cycle in onshore fields, and this may locally be achievable in offshore locations. This correlation precision can allow some mapping of detailed contemporary palaeo-environments throughout, and beyond, individual basins.

The discrimination of contemporary environments then allows the interpretation of depositional and preservational controls: the main conclusions are as follows.* The overall fill of the Pennine Basin and comparable depositional areas represents depositional and preservational interactions between three distinct depositional regimes, which led to background deposition of coals and mud rocks, the channel-belt lithofacies, and the marine bands.

- Marine base level was the main control on the stratigraphical incidence of coals, marine bands and quasi-marine bands.
- The stratigraphical incidence of major sandbodies is not reliably predictable in terms of marine base-level change, although there was a reduction during times of widespread peat accumulation. Very occasionally, channel systems pro-graded directly into marine waters.
- The geographical distribution of most channel belts was essentially independent of both contemporary marine shorelines and of gross basin subsidence.
- Variation in subsidence rate, related to basin (specific tectonic feature) location, was the main control on bed thicknesses and connectivities, whether coals, shales or sandstones.

In summary, the preserved depositional volume represents a complex interaction between fluvial channel influxes, marine base-level changes and specific subsidence patterns. The geographical extents and stratigraphical ranges of many offshore datasets are inadequate on their own for any detailed interpretation of depositional controls and sandbody distribution. The present paper is an attempt to aid offshore interpretations by defining and summarizing relationships demonstrable from the onshore areas, where datasets are much more complete.

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