

# A sequence-stratigraphy scheme of the Late Carboniferous, southern North Sea, Anglo-Dutch sector

From Earthwise

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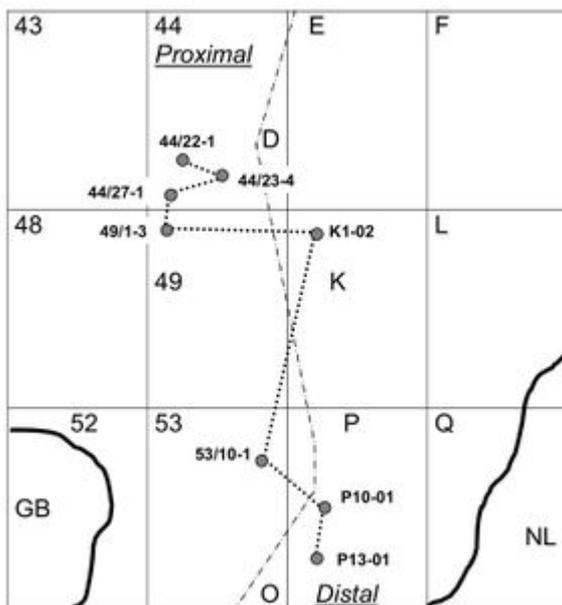


Figure 1 Location map, southern North Sea, Anglo-Dutch sector, showing location of reference and correlated wells.

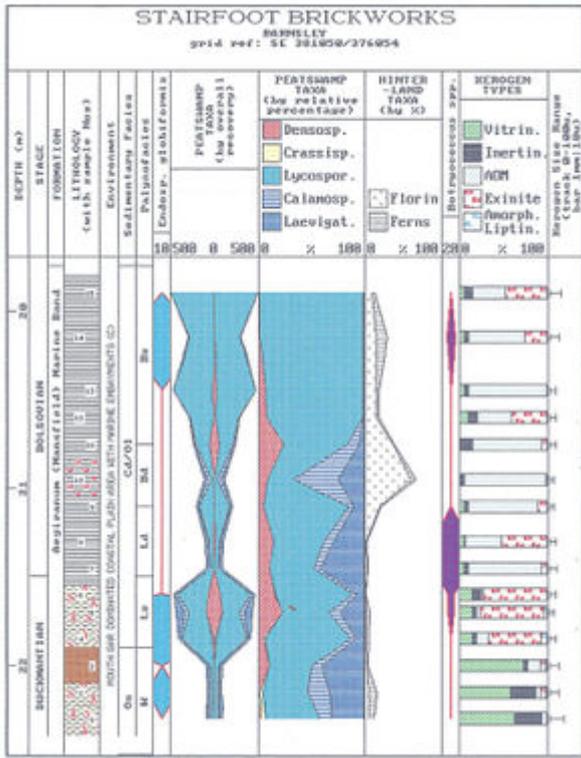


Figure 2 Palynofacies sequence, Aegiranum (Mansfield) Marine Band, Stairfoot quarry, Barnsley.

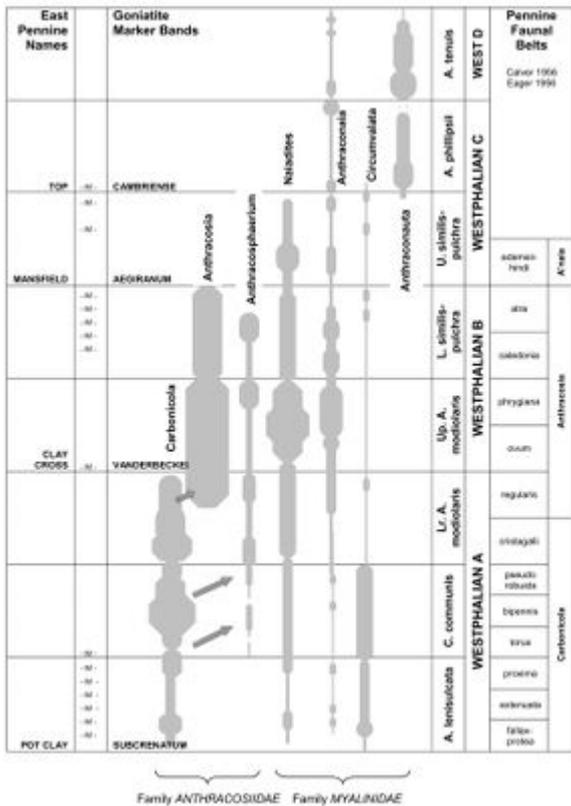


Figure 3 Ranges of non-marine bivalves (after Eagar 1994).

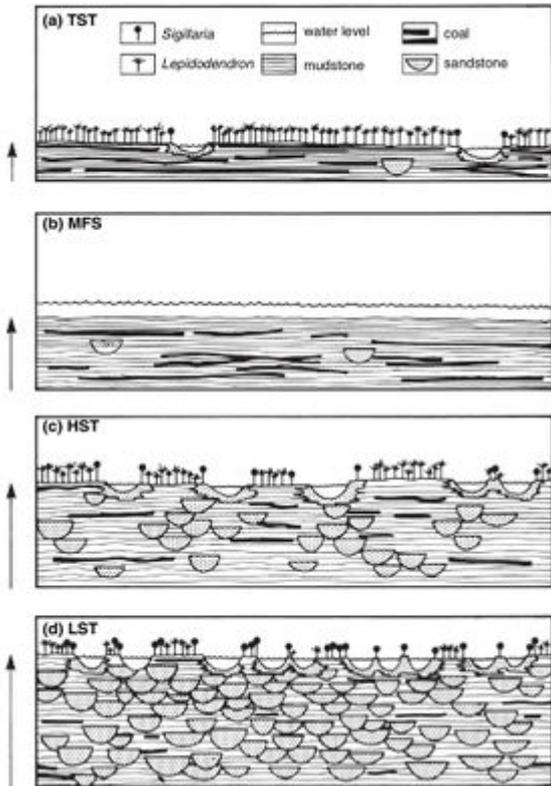


Figure 4 Lithofacies and vegetation structure of sequence tracts. The arrow height indicates the sediment surface elevation relative to base level.

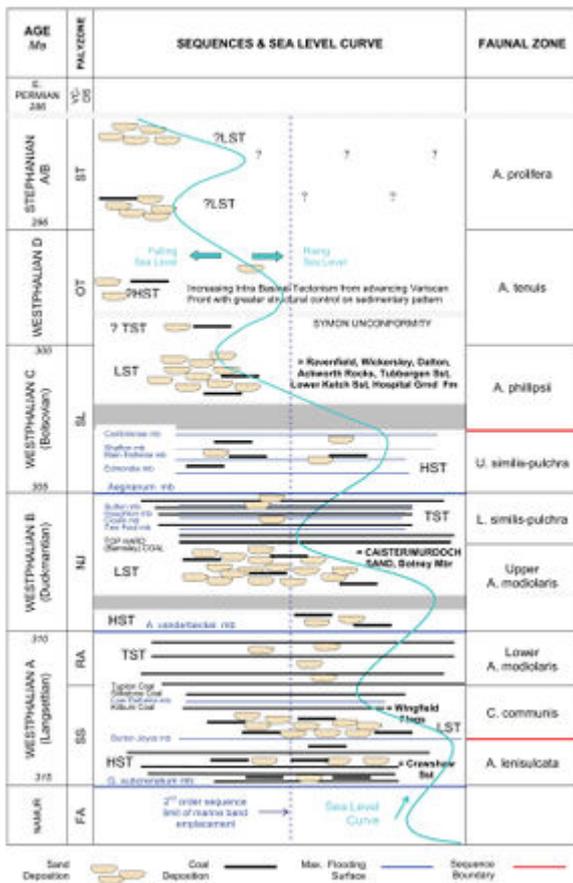


Figure 5 Late Carboniferous stratigraphy and sequences.





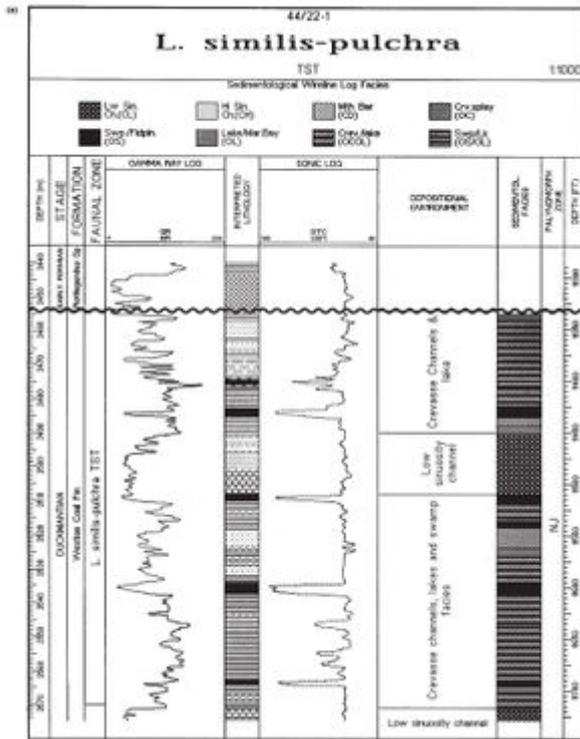


Figure 6E Depositional facies in well 44/22-1: (e) Lower similis-pulchra zone. Scale 1:1000

By J. M. Cole, M. Whitaker, M. Kirk, S. Crittenden

From: Pages 75-104 of *Carboniferous hydrocarbon geology: the southern North Sea and surrounding onshore areas*, edited by J. D. Collinson, D. J. Evans, D. W. Holliday, N. S. Jones. Published as volume 7 in the Occasional Publications series of the Yorkshire Geological Society, © Yorkshire Geological Society 2005.

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## Summary

A scheme is outlined that places the Late Carboniferous (Westphalian) of the southern North Sea in a sequence stratigraphical context. Intervals of pronounced sandstone development in the mid-Langsettian (Westphalian A), early Duckmantian (Westphalian B) and Late Bolsovian (Westphalian C) have been placed within lowstand systems tracts (LSTs). Intervals of important coal-seam development in the latest Langsettian and Late Duckmantian have been placed within transgressive systems tracts (TSTs). Highstand systems tracts (HSTs), characterized by abundant coal seams and marine bands, are recognized in the early Langsettian, earliest Duckmantian and early Bolsovian. Intermittent thick sandstone units occur within them. The earliest Duckmantian HST (possibly equivalent in part to the informally named Lower Caister Sand) may be extensively removed beneath the highly erosive base of the LST Caister-Murdoch reservoir sandstones of the UK sector and equivalent Klaverbank Formation (Botney Member) sandstones of The Netherlands sector. The bases of the HSTs are taken at the major Westphalian maximum flooding surfaces that define stage

boundaries, the Subcrenatum (base Langsettian), Vanderbeckei (base Duckmantian) and Aegiranum (base Bolsovian) marine bands. These mark the phase of maximum rate of sea-level rise at the boundary between TSTs and HSTs. After the Bolsovian, the effects of the advancing Variscan front progressed to the point where uplift and tectonism within the basin had a greater effect than sea-level change on sedimentation. Wireline logs of this part of the sequence cannot be correlated over the same long distances as for the Langsettian to Bolsovian strata. Base level in a possible TST in the early Westphalian D never rose enough for maximum flooding surfaces to be expressed basin wide as marine bands, although they may be represented as coal seams or carbonaceous mudstones. Sequences may be present in the Stephanian, but strata of this age are too rarely preserved, and palynological recovery and preservation are too poor in well sections below the Saalian (base Permian) unconformity to elucidate these in detail at present.

## Introduction

The southern North Sea gas basin is one of many depositional basins throughout the UK and northwest Europe where substantial thicknesses of Late Carboniferous rocks are preserved. In this basin, Carboniferous rocks occur beneath a considerable overburden of Permian, Mesozoic and Tertiary strata. The basin is located over a large area of the Anglo-Dutch sector south of the mid-North Sea High, in UK quadrants 43-53 and Netherlands quadrants D-S ([Figure 1](#)). The offshore succession has been penetrated by many wells with wireline logs, and most of these data are now in the public domain (e.g. Cameron 1993 and Van Adrichem Boogaert & Kouwe 1993).

The authors have studied about 80 wells from the Anglo-Dutch sector. Specific details on these cannot be provided at the moment, since analysis of many wells, including many in the public domain, was carried out in the course of industry-contracted studies or unpublished non-exclusive industry reports. However, interpreted sedimentological and palynological data are presented on two public domain wells, 44/22-1 and 44/27-1. These wells penetrated extensive thicknesses of Late Carboniferous rocks, 44/22-1 from Namurian to Bolsovian in age and 44/27-1 from Langsettian to Westphalian D, and together they illustrate most of the Westphalian succession of the southern North Sea. Thus, these wells provide for the Westphalian of the southern North Sea, reference sections of their component systems tracts and depositional units.

Until recently, Westphalian rocks in Britain and the adjacent offshore areas were collectively referred to as Coal Measures. The term has now been replaced by more formal lithostratigraphical classifications: Pennine Coal Measures and Warwickshire groups on shore (Waters et al. in press) and Coneybeare Group off shore (Cameron 1993). However, it has been found convenient to retain the older term in this account for descriptive purposes.

## 1. Basin setting

The Coal Measures were deposited between 315 and 296 Ma within an equatorial belt that stretched from the Moscow-Donetz Basin to the eastern USA (Harland et al. 1982, Lippolt et al. 1984, Leeder 1988). This region formed a large, low-lying, shallow marine or lowland alluvial coastal plain to the north of the Variscan orogenic belt (Bambach et al. 1980). Coal seams are derived from peat accumulation that kept pace with conditions of slowly rising base level, allowing the mire to be sustained (Aitken 1994, Aitken & Flint 1994). The overall effect of slowly rising relative base level is to retard clastic supply as rivers aggrade and the increase in accommodation space moves landwards (Moore 1987, Anderson 1983). Large areas of high water table and limited introduction of clastic material provide ideal conditions for widespread ombrotrophic (rainwater-fed and dome shape) peat swamp development. These conditions persisted for long periods of time over large areas of the Coal Measures basin until terminated by a rise in sea level that led to flooding of the forest

area, or until crevassing of alluvial channels introduced large quantities of clastic sediments. The encroachment and continental collision forming the Variscan orogeny were complete by the Stephanian and they terminated Coal Measures sedimentation.

The main source of sediments into the basin during the Late Carboniferous was from the north (Leeder & Hardman 1990, Collinson et al. 1993, Guion et al. 1995, Morton et al. 2005). There is a gradation from proximal areas in the north to distal environments and palaeotopographically lower areas to the south. Wireline log profiles of wells across the southern North Sea show a northward regional coarsening trend and development of thicker and more numerous sandstones. Calver (1968) recognized lateral changes in facies belts within individual marine bands across the coalfields of the UK, which reflect the extent of marine incursion and associated salinity variations. However, for most of the Westphalian sequence, this north-south facies change occurred within freshwater environments, from upper coastal plain with low-sinuosity channels, through lower coastal plain with high-sinuosity channels, into a fluviolacustrine environment (Guion et al. 1995). Similar north-south aligned facies belts can be recognized in the southern North Sea gas basin (Quirk 1993).

The Wales-Brabant Island that formed the southwestern boundary of the Anglo-Dutch Southern North Sea Basin was an area of subdued topography throughout much of Westphalian time. It has been generally considered as being a limited source of detritus to the basin except in southerly areas (Kirk 1989, Besly 1990, Fraser & Gawthorpe 1990, Quirk 1993). However, Hallsworth & Chisholm (2000) and Morton et al. (2005) have presented evidence that sediment from this source was more widely dispersed from Late Duckmantian times onwards. Southerly derived detritus is also relatively abundant in The Netherlands (Collinson et al. 1993). Evidence for a major westerly source of detritus in the Westphalian has been found in northern England (Hallsworth & Chisholm 2000), but so far this is unknown off shore.

The Langsettian to Bolsovian (Westphalian A to C) of the UK and the southern North Sea is an overall regressive succession laid down during a period of sustained non-marine sedimentation, even though global sea levels were relatively high. It provides an opportunity to study the effects of sea-level changes within a mainly non-marine setting. This setting is often poorly illustrated on the landward side of many sequence-stratigraphy diagrams that deal mainly with shelfal and deepwater depositional systems (i.e. to the far left of the “slug” diagram, *sensu* Vail et al. 1977). A transition zone to the marine realm is not seen in the depositional facies of the Coal Measures. Such transitional facies lay outside the present erosional limits of the basin area. Marine incursions were too rapid and brief to develop shoreline facies within the basin. Yet sea-level change over such a low-lying region influenced sedimentation over many thousands of square kilometres throughout a basin that had little internal topographic relief.

**Table 1 Summary of Late Carboniferous sedimentary facies.**

Facies	Lithology
Cl - Low-sinuosity channel	Erosively based, medium to coarse grained, poorly to well sorted clean sandstone
Ch - High-sinuosity channel	Erosively based very fine to fine grained, well sorted, argillaceous sandstone
Cd - Distributary mouth bar	Overall upward-coarsening sequences comprising lower mudstones or siltstones, passing gradationally upwards into well sorted clean to argillaceous very fine to fine-grained sandstones
Oc - Crevasse splay	Erosive or gradationally based, thin, very fine to fine-grained argillaceous sandstones
Ol - Lake/marine bay	Laminated mudstones or siltstones

Os - Floodplain/ swamp      Coal seams and root-disrupted mudstones, siltstones and very fine-grained sandstones

[Table 2](#) Late Carboniferous facies associations.

Facies association	Dominant facies
A - Channel-dominated coastal plain	Cl/Ch dominant, Oc/Ol, Os, Cd associated
B - Overbank-dominated coastal plain	Oc/Ol dominant, Os, Cl, Ch, Cd associated
C - Distributary mouth-bar-dominated coastal plain	Cd, Oc/Ol dominant, Cl, Ch, Os associated
D - Basin margin alluvial fan	Not represented in southern North Sea

## 2. Sedimentology

Published and unpublished sedimentological information for various parts of the Carboniferous basin, and extensive field work on shore by some of the authors in the East Midlands and Yorkshire, where exposure is very good, have allowed a sedimentary facies scheme to be erected ([Table 1](#), Appendix). This scheme is based on sediment grain size, sediment body geometry, upper and lower boundaries, and sedimentary structures. Six sedimentary facies have been recognized and these occur in three facies associations (A, B and C) indicative of deposition in proximal and distal coastal-plain dominated environments ([Table 2](#)). These facies and facies associations also occur extensively in wells from the southern North Sea and display very similar characteristics.

Facies association A (proximal coastal plain) is well represented in mid-Langsetian to lower Duckmantian and upper Westphalian C sequences from the study area. It comprises well developed fluvial channel facies (Cl and Ch) and many floodplain/swamp and crevasse-splay deposits (Os and Oc) with relatively thin lake/bay-fill facies units.

Facies association B (distal coastal plain) occurs in several sequences from the study area. It is especially common in the early Langsetian and late Duckmantian to early Bolsovian. A gradation can be recognized from relatively proximal sequences, containing comparatively thin, areally restricted lake deposits, to more distally deposited sequences with thicker, more laterally extensive lacustrine units. Some marine influence occurs in larger more distally situated lakes. Although high- and low-sinuosity channel deposits are observed, they are both less common and generally display features indicative of lower energy than in facies association A. Nevertheless, some high-energy coarse-grained low-sinuosity channel deposits occur in places. Facies association B, where persistently developed, characterizes inter-channel areas and is not associated with major reservoirs. Such intervals are most likely to be encountered within transgressive deposits.

Facies association C, a coastal plain dominated by mouth bars, occurs extensively in Namurian strata and is characterized by distributary mouth bars prograding into shallow marine embayments or large freshwater lakes. Smaller and more localized mouth-bar deposits also occur within Westphalian sequences. Delta-top or coastal-plain sediments comprising low- and high-sinuosity channel, crevasse-splay and lake or floodplain sediments are in places associated with Namurian mouth-bar facies.

The recognized sedimentary facies do not define individual sequences. However, subdivision of well sections using this scheme allows major facies changes to be recognized as candidate sequence boundaries.

### 3. Lithostratigraphy versus sequence stratigraphy

The erection of a standard lithostratigraphical scheme for the Coal Measures is difficult because of the repetition of persistently re-occurring lithologies. On shore, key marine-band markers have been used to subdivide the succession (Stubblefield & Trotter 1957, Ramsbottom et al. 1978, Waters in press; Table 3). The Langsettian-Bolsovian Pennine Coal Measures Group is subdivided into Lower Middle and Upper Coal Measures formations, and is overlain with a diachronous boundary by the red-beds of the Warwickshire Group, Bolsovian-Westphalian D in age. Off shore, in the UK sector of the southern North Sea, the key marine bands cannot be recognized with certainty in many wells, and the onshore scheme is not readily applicable. Thus, the offshore lithostratigraphical scheme of Cameron (1993) was based on lithological criteria rather than on the identification of key marine bands. The Caister Coal Formation includes the sandy strata of Langsettian to earliest Duckmantian age, and very broadly is equivalent to the onshore Lower Coal Measures Formation. The Westoe Coal Formation encompasses rocks of mainly Duckmantian age, and the Schooner Formation includes strata of mainly Bolsovian age, i.e. approximately equivalent to the onshore Middle and Upper Coal Measures formations respectively. The three offshore formations together comprise the Coneybeare Group (Cameron 1993), and their boundaries are locally markedly diachronous. The base of the Group is taken locally at the lowest coal seam in the well, not at an age-constrained or regionally correlatable datum. It locally occurs up to 100 m above the Namurian-Westphalian boundary in wells with good biostratigraphical control. The Westoe Coal Formation is also strongly diachronous at its base, including both Duckmantian and Langsettian strata in the southern area where sandy lithologies cannot be distinguished. A similar situation occurs in the Netherlands sector where the base of the lithologically defined Baarlo Formation can range from intra-Langsettian to intra-Namurian B in age (Van Adrichem Boogaert & Kouwe 1993).

The lateral continuity of the major coal seams and marine bands between the main Upper Carboniferous basins is well known on shore in the UK, and is likely to continue off shore. Seismic profiles across the offshore basin reveal a consistent lateral continuity of reflectors well below the stage scale, making the highly diachronous lithostratigraphical units of lesser practical application. This invites the application of sequence stratigraphy to well sections with wireline logs and cuttings and cores that can be age constrained by palynology.

Coarse-grained intervals typically are made up of multistorey fluviatile sandstone bodies. Comparison of closely spaced wells indicates that, although individual sandstone bodies are laterally impersistent, they are commonly laterally persistent and of a consistent overall regional thickness. The lower boundaries of some of these sandstones may be sequence boundaries, the onset of major sand deposition within the Coal Measures coastal plain being a response to sea-level fall.

**Table 3** Westphalian systems tracts.

Chronostratigraphy	Onshore lithostratigraphy	Non-marine bivalve zone	Systems tract	Base age (approx. Ma)	Lower boundary	Lithofacies	Palynol. zone	Palynofloras
Westphalian D	Warwickshire Group	<i>A. tenuis</i>	TST/?LST/?HST	300	Top of highest West C sandst.	Crevasse splay mdst / sltsts and low sinuosity channel ssts	OT	Appearance of <i>T. obscura</i> , <i>T. pseudothiesseni</i> and <i>C. magna</i> plus increase in <i>Disacciti striatiti</i>

Westphalian C (Bolsovian)	Upper Coal Measures Formation	<i>A. phillipsi</i>	LST	302	Cambriense MB	Major low and high sinuosity channel ssts with crevasse/lake/swamp intervening	Upper SL	Highest acme of <i>C. kosankei</i> . Extinction of <i>D. sphaerotriang.</i> , <i>V. costata</i> , <i>V. pseudoreticulata</i> , <i>S. nux</i> , <i>D. falsus</i> and <i>G. varioreticulatus</i> . Appearance of <i>S. dimorphus</i> , <i>V. laevigata</i> Common <i>Lycospora</i> spp. & <i>C. kosankei</i> .
	Middle Coal Measures Formation	<i>U. similis-puchra</i>	HST	305	Aegiranum MB	Crevasse splay mdsts/slst, some sst bodies	Lower SL	Extinction <i>C. loricatus</i> . Appearance of <i>V. fenestrata</i> , <i>T. securis</i> , <i>T. bransonii</i> & <i>P. granifer</i> Common <i>Lycospora</i> spp. and <i>Densosporites</i> spp. Appearance of <i>V. pseudoreticulata</i> , <i>P. granifer</i> , <i>Triquitrites</i> spp., <i>P. perinatus</i> & <i>C. solaris</i> Extinction <i>R. fulva</i> , <i>D. bireticul.</i> & <i>C. bucculentus</i> Common <i>Crassispora kosankei</i> , <i>Vestispora costata</i> and <i>Laevigatosporites</i> spp. Appearance of <i>D. bireticulatus</i> and <i>Endosporites globiformis</i>
Westphalian B (Duckmantian)		<i>L. similis-pulchra</i>	TST	307.5	Top Hard (Barnsley) Coal	Swamp/lake mdsts with common coals and marine bands in the upper part. Local high sinuosity ssts	Upper NJ	Appearance of <i>V. pseudoreticulata</i> , <i>P. granifer</i> , <i>Triquitrites</i> spp., <i>P. perinatus</i> & <i>C. solaris</i> Extinction <i>R. fulva</i> , <i>D. bireticul.</i> & <i>C. bucculentus</i> Common <i>Crassispora kosankei</i> , <i>Vestispora costata</i> and <i>Laevigatosporites</i> spp. Appearance of <i>D. bireticulatus</i> and <i>Endosporites globiformis</i>
		<i>U. A. modiolaris</i>	LST/HST	310	Vanderbecke MB	Well developed low sinuosity ssts with some mouth bar and crevasse splay units	Lower NJ	Appearance of <i>D. bireticulatus</i> and <i>Endosporites globiformis</i>
Westphalian A (Langsettian)	Lower Coal Measures Formation	<i>L. A. modiolaris</i>	TST	311.5	Tuption Coal	Crevasse splay mdsts & sltsts with some low sinuosity ssts	RA	Common <i>Lycospora</i> spp, <i>Krauselisporites</i> spp., <i>P. nitidus</i> & <i>P. limbatus</i> . Marker <i>S. rara</i> extinct at top
		<i>C. communis</i>	LST	313.5	Burton Joyce MB	High sinuosity ssts, with intervening swamp/lake & crevasse units	Upper SS	Acmes of <i>C. kosankei</i> and <i>Vestispora</i> spp. Paly. marker <i>R. aligerens</i> became extinct within zone
		<i>A. lenisulcata</i>	HST	315	Subcrenatum MB	Lake/swamp mdsts and sltsts with some prominent high sinuosity sst units	Lower SS	Acmes of <i>Lycospora pusilla</i> and <i>Densosporites</i> spp. including <i>D. duritti</i> at base. Other acmes of <i>C. loricatus</i> , <i>R. difformis</i> , <i>C. bucculentus</i> & <i>G. varioreticulatus</i> .

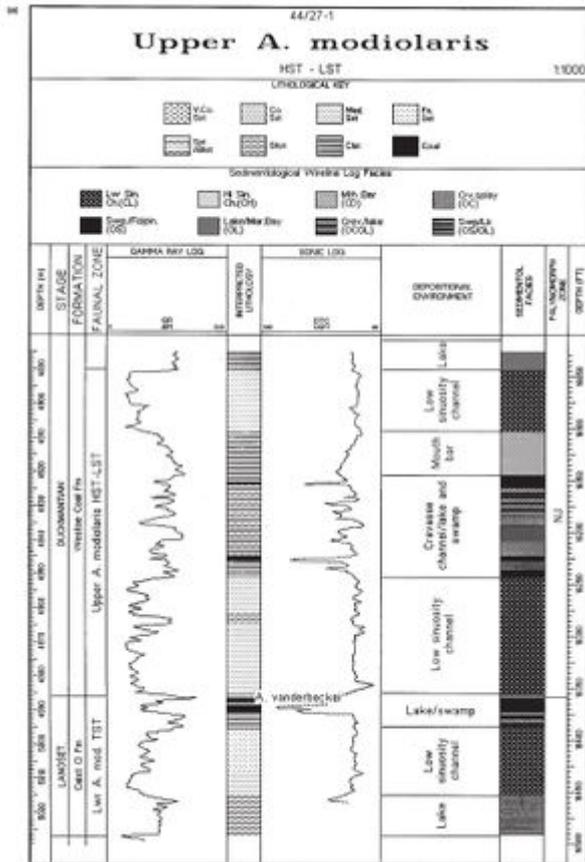


Figure 7A Depositional facies in well 44/27-1; (a) Upper *A. modiolaris* zone. 1:0000 scale.

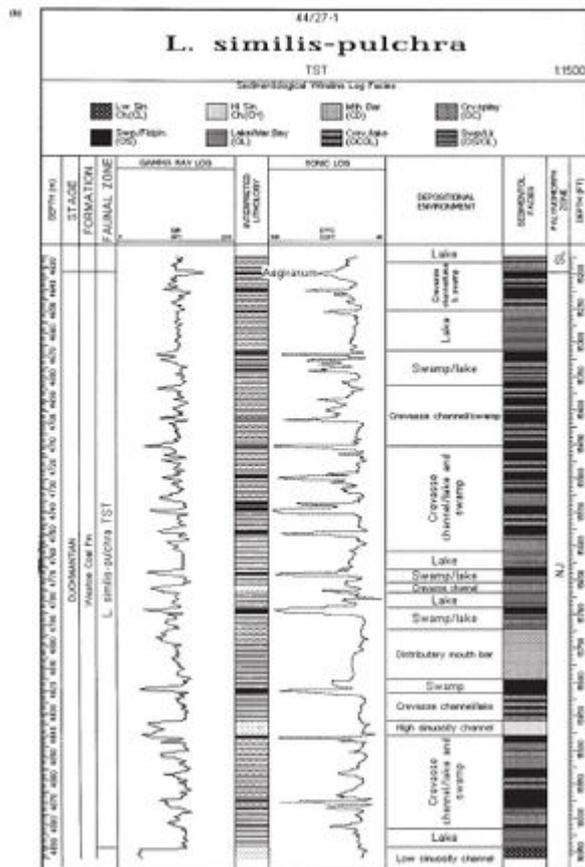


Figure 7B Depositional facies in well 44/27-1; (b) Lower *similis-pulchra* zone.

1:1500 scale.

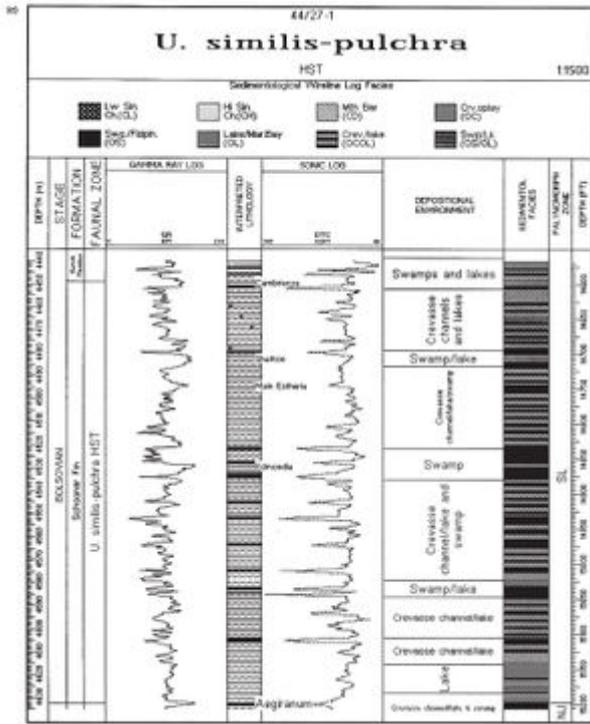


Figure 7C Depositional facies in well 44/27-1; (c) Upper similis-pulchra zone. 1:1500 scale.

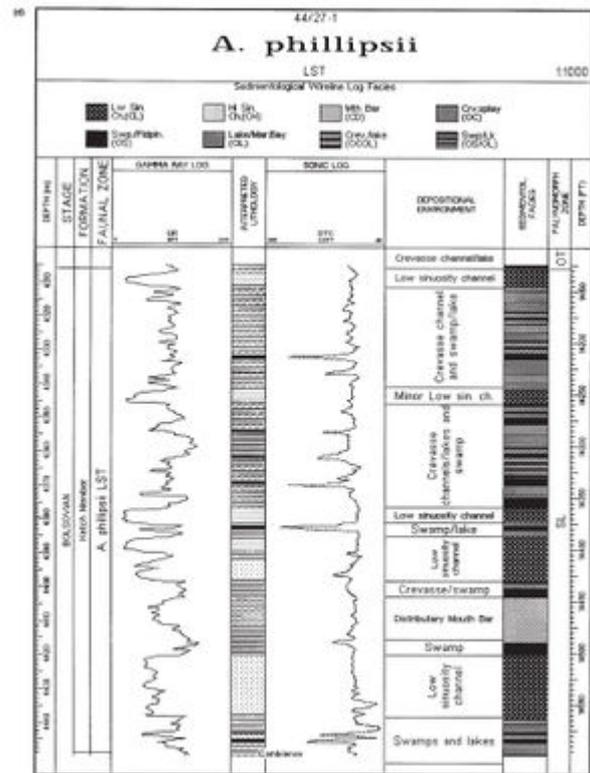


Figure 7D Depositional facies in well 44/27-1; (d) A. phillipsii zone. 1:1000 scale.

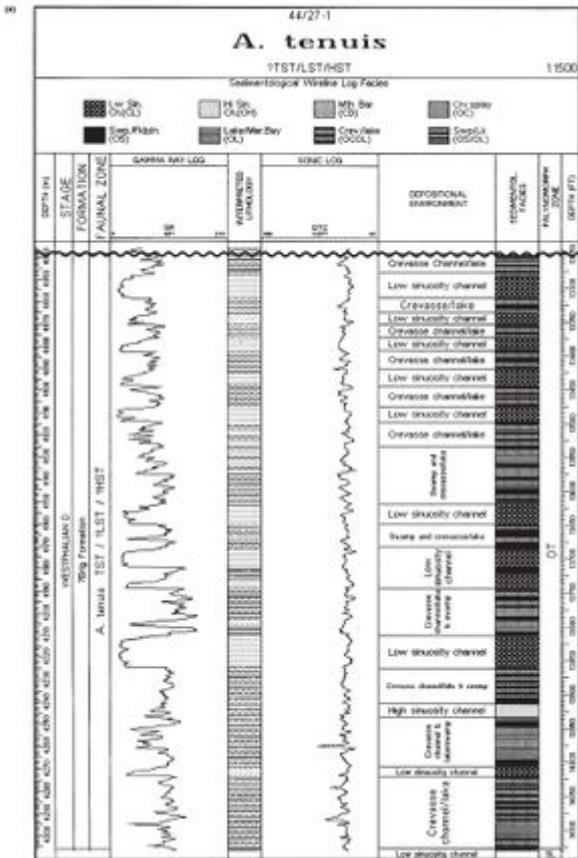


Figure 7E Depositional facies in well 44/27-1; (e) A. tenuis zone. 1:1500 scale.

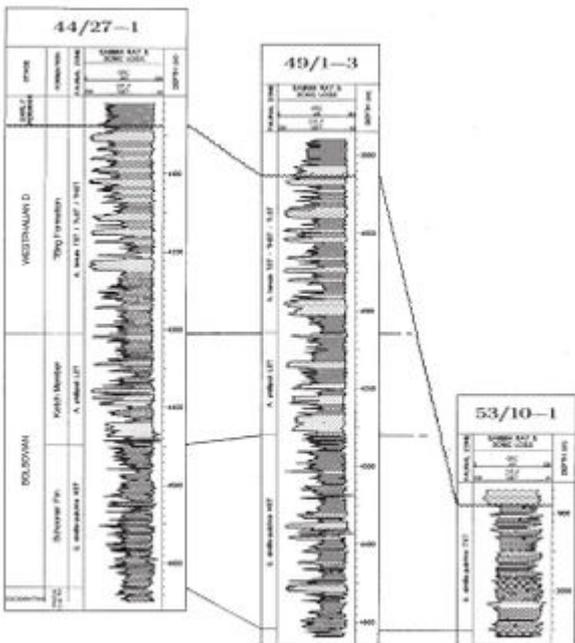


Figure 8 North-south correlation of Bolsovian (Westphalian C) and Westphalian D systems tracts, wells 44/27-1, 49/1-3 and 53/10-1.

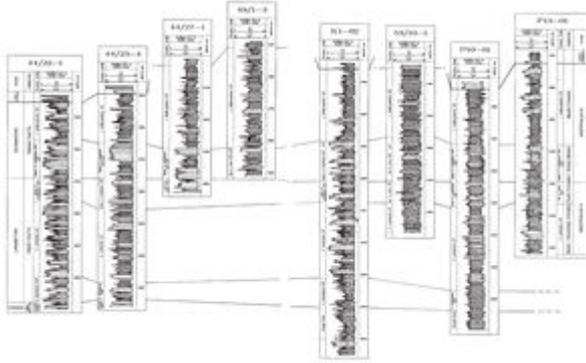


Figure 9 North-south correlation of Langsettian (Westphalian A) and Duckmantian (Westphalian B) systems tracts, wells 44/22-1, 44/23-4, 44/27-1, 49/1-3, K1-2, 53/10-1, P10-1 and P13-1.

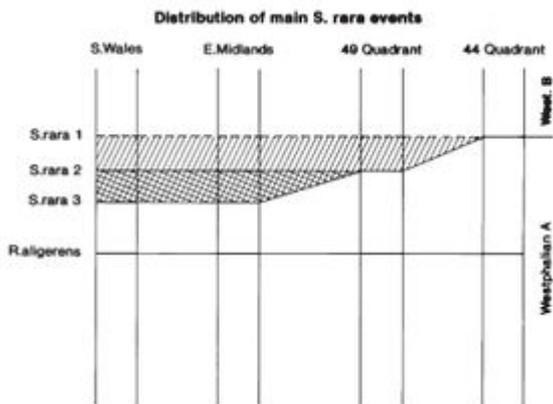


Figure 10 Lateral variation in occurrence of horizons with *Schulzospora rara*, on shore and off shore; no vertical scale implied.

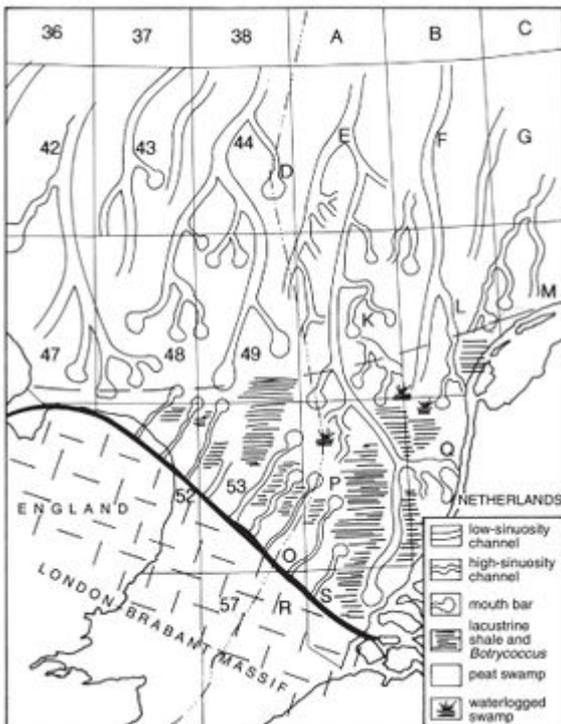


Figure 11 Palaeogeographical map, Coal Measures, southern North Sea.



2005) has made it possible to recognize Westphalian stages independently of the intermittent quasi-marine events. Marine bands do not have a characteristic age-diagnostic palynomorph assemblage, although they display a characteristic palynofacies signature (Figure 2). Characteristic palynofacies assemblages reflect the environmental changes that took place during each short-term regional flooding event.

Marine bands are intervals of condensed mudstone deposition under stratified water conditions, and they tend to have a higher overall gamma-ray log response. Correlation of individual marine bands with particular gamma-ray peaks is not always straightforward in offshore wells, although this can commonly be attained, particularly when this is done as part of a wider stratigraphical appraisal involving biostratigraphy, sedimentology and palynofacies (Rippon 1984, Hollywood & Whorlow 1993, Cameron 1993).

Acritarchs occur rarely and intermittently throughout the Westphalian, and may be an aquatic rather than a marine indicator. A sudden rise in sea level within a low-lying tropical region of very intense precipitation would cause ponding of runoff and a basinwide flooding event of water more fresh than brackish. The two microplankton events noted by Spode (1964) may correlate with such freshwater flooding events, immediately above and below the goniatite-bearing maximum marine pulse of the Aegiranum (Mansfield) Marine Band. Spode was unable to explain why supposedly marine acritarchs occurred in two zones within this marine band, as they were not coincident with the principle marine macrofauna. Palynofacies sampling by us of the Aegiranum Marine Band at Stairfoot Quarry, Barnsley (SE 381050 to 376054; Figure 2), indicates that there is no associated distinct marine palynoflora (see also Van de Laar & Fermont 1990). The freshwater alga *Botryococcus* occurs in two zones above and below the principle goniatite-bearing main marine pulse at Stairfoot quarry, similar to the pattern noted by Spode (1964) for the acritarchs.

The terrestrial plant-spore palynofloral assemblage shows a response to marine incursion. The Neves effect, described by Chaloner (1958) and Neves (1958), is an increase of the allochthonous upland flora (*Florinites* spp.) when the local arborescent swamp flora was destroyed by flooding (see also Davies & McLean 1996). This effect is well displayed in our analysis of the Stairfoot quarry section (Figure 2). This analysis also shows the terrestrial palynomorph recovery diminishing to a minimum over the brief period of the maximum marine ingress, with remaining spore assemblages dominated by *Calamospora* spp. derived from the water-loving horsetail shrubs *Sphenopsida* (Scott 1977, 1979). Such palynofloral effects are extremely short-lived events and cannot normally be detected in spaced and composited cuttings samples across a marine-band section and are non-specific within marine bands.

## 5. First-order and second-order cycles

First-order transgressive and regressive cycles in the Palaeozoic are associated with the separation and accretion of continental masses (Ross & Ross 1985, 1988) and are well in excess of 50 million years' duration (Vail & Wornardt 1991). First-order transgression would be at the period of maximum continental separation, one such period reaching its peak in the Ordovician. The Late Carboniferous Coal Measures were laid down towards the end of the ensuing first-order marine regressive cycle that culminated in the Permian with the formation of Pangaea.

Fraser & Gawthorpe (1990) divided the Late Palaeozoic sequence of northwest Europe into major tectonic units. These form a basis for defining second-order seismic sequences that typically coincide with cycles of 3–50 million years' duration (Vail & Wornardt 1991). The Coal Measures fall within the upper part of the post-rift megasequence (as defined by Fraser & Gawthorpe 1990) that formed during the Namurian and Westphalian, and may have been deposited under a regime of

thermal sag that was most pronounced on shore in Lancashire and Staffordshire. Sedimentation exceeded the rate of accommodation generation, with the result that deltaic and coastal-plain deposits prograded southwards across the basin. A similar area of thermal subsidence has been suggested for the southern North Sea gas basin (Leeder & Hardman 1990).

## 6. Third-order cycles

Non-marine bivalve fossils are comparatively abundant in the Coal Measures on shore and have been used extensively to subdivide and zone the onshore Westphalian, based on the work of Davies & Trueman (1927), Trueman & Weir (1946–68) and Eagar (1994) (Table 3). The faunal zones provide a good starting point in the identification of sequence stratigraphical units. They define intervals of distinctive sedimentary character and are a powerful correlation tool on both a local and regional basis. The zone boundaries coincide with major marine bands and can be identified off shore (Figure 3, Table 3). Some of the zones are distinctly sandstone-dominated and are candidate lowstand systems tracts (LSTs or lowstand sequence sets as incised valley fill) caused by relative sea-level fall. Others are very fine-grained, with abundant marine bands and coals, suggesting deposition during relative sea-level rise as transgressive systems tracts (TSTs). Intermediate between these are sandstone-claystone intervals that may be highstand systems tracts (HSTs). Some third-order sequences are interpreted as subdivisions within individual faunal zones, for instance the Early Duckmantian Upper *A. modiolaris* zone, where a lowstand systems tract is believed to be highly erosive into the underlying highstand systems tract.

Floral changes associated with these sequences are reflected in the overall palynomorph assemblage (Figure 4). Extinction and inception points of certain important terrestrial miospore palynostratigraphical markers are also associated with major marine bands at stage boundaries. This suggests that these flooding events were sufficiently profound as to cause faunal and floral overturn. Major marine bands can therefore be regarded as classic genetic sequence boundaries (*sensu* Galloway 1989), strengthening the inferred relationship between faunal zones and third-order sequences.

Third-order sequence cycles are normally of the order of duration of 0.5–3.0 Ma (Vail & Wornardt 1991). The systems tracts defined in this paper were deposited during a similar time period of 0.5–2.0 Ma. Based on the timescale of Harland et al. (1982), the deposition of the tracts has an approximate average duration of 1.5 Ma; the timescale of Lippolt et al. (1984) suggests a duration of around 1.0 Ma or less.

The great lateral persistence of dark shale marine bands in the Namurian containing thick-walled goniatites has been related to slow sedimentation during allocyclical sea-level rise (Read & Forsyth 1989, Read 1991). These sea-level changes are glacioeustatically controlled and are of high frequency and magnitude during a period of global “ice-house” climates, controlled by Milankovitch orbital parameters (Ramsbottom 1979, Leeder 1988, Elliot 1993). Heckel (1986, 1990) has demonstrated the same control on limestone–shale cycles of the Westphalian D to Stephanian B of central North America, and identified Pennsylvanian minor cycle periods that conform with the Milankovitch insulation theory controlling the Pleistocene ice ages. The longer of the major Pennsylvanian eccentricity cycles is about 400 000 years, which very broadly conforms to system-tract duration identified in this paper.

## 7. Macrofaunal biozones

Each of the macrofaunal zones and their systems tracts (Figure 3, Figure 5, Table 3) are now considered in detail in stratigraphical order, with comparison to the onshore area where possible.

Reference should also be made to the interpreted section of 44/22-1 (Figure 6) and 44/27-1 (Figure 7) and the correlation panels (see [Figure 8](#), [Figure 9](#)). Published palynostratigraphical schemes (Smith & Butterworth 1967, Clayton et al. 1977, Van Adrichem Boogaert & Kouwe 1993, McLean et al. 2005) permit age dating of cuttings and core samples.

## 7.1 Early Langsettian (*A. lenisulcata* zone)

The Early Langsettian is characterized by generally argillaceous swamp or lake sediments ([Figure 6A](#)) and contains many marine bands and thin coals (facies association B). The Subcrenatum Marine Band at the base of the Langsettian is in the expected position for the underlying maximum flooding surface. The underlying Namurian Rough Rock on this basis therefore would be a TST, as suggested by Church & Gawthorpe (1994). Collinson et al. (1992) interpreted the latest Namurian as a lowstand sequence, and Hampson (1995) demonstrated several sequences in the Rough Rock with a TST at the top.

The nine marine bands recorded by Calver (1968) in the overlying strata of the East Midlands and elsewhere, up to and including the Burton Joyce Marine Band, may be flooding surfaces of fourth-order sequences or parasequence boundaries within a third-order composite sequence. Such common flooding surfaces might be expected within an HST characterized by continually rising sea level, although at a diminishing rate of rise to that represented at the MFS. In upward progression, the marine bands are the Holbrook, Second Smalley, First Smalley, Alton, Parkhouse, Forty Yard, Norton and Upper Band.

The *A. lenisulcata* zone is generally argillaceous in the UK onshore area, although in the East Midlands the Crawshaw Sandstone is locally well developed, forming the main reservoir rocks of several small oil fields. Flint et al. (1995) have demonstrated significant incision by this sandstone, which in the Bothamsall-5 well has removed the Rough Rock and underlying strata to the Cancellatum Marine Band. However, when examined regionally, it is apparent that the Crawshaw Sandstone is discontinuous. Intermittent development of thick (10 m or more) high-sinuosity sandstones of Early Langsettian age is also seen in offshore wells ([Figure 6A](#)). Such sandstone bodies may represent more proximal (landward) clastic-dominated parasequences.

The acmes of arborescent lycopod spores (lycospores) of *Lepidodendron/Lepidophloios* forests in this HST is in keeping with a time of marine transgression and the formation of major areas of peat swamp. Other taxa that show temporary acmes within the zone include *Cingulizonates loricatus*, *Radiizonates difformis*, *Camptotriletes bucculentus* and *Grumosporites varioreticulatus*. Influxes of inertinitic kerogen may be associated with structural changes in the Coal Measures flora and substrate associated with many intermittent and short-lived flooding events. Towards the top of the *A. lenisulcata* zone, pale amorphous organic matter appears, together with the persistent up-hole appearance of *Laevigatosporites* spp.

## 7.2 Mid-Langsettian (*C. communis* zone)

In the East Midlands, the Burton Joyce Marine Band is taken as the base of the *C. communis* zone. Thick (up to 25 m) low-sinuosity channel sandstones occur towards the base of the zone, e.g. Grenoside Sandstone, Greenmoor Rock and Wingfield Flags, but the overall proportion of sandstone decreases upwards. The degree of downcutting and erosion above the Burton Joyce Marine Band is uncertain. A higher proportion of sandstone occurs in the zone, mostly high-sinuosity channel deposits (facies association A - channel-dominated coastal plain), in the offshore 44/22-1 ([Figure 6B](#)) than in the preceding *A. lenisulcata* zone, leading to the interpretation of *C. communis* zone as an LST. In 44/22-1 it is 236 m thick. Finer-grained, more argillaceous lithotypes with marine bands and coals become more common in the upper part of the zone (e.g. Kilburn Coal, Low Estheria Marine

Band and Silkstone Coal). These may be associated with a diminishing rate of sea-level fall in the later stages of the LST, prior to the onset of renewed sea-level rise during the ensuing TST.

The *C. communis* zone is characterized particularly by persistent and commonly marked local acmes of *Crassispora kosankei*. This spore type is often particularly associated with coarser-grained sediments of an “alluvial swamp”, rather than a lycospore dominated peatswamp depositional environment. This form of swamp deposition may have characterized the interchannel areas during this time. Other important spore occurrences within this zone include *Vestispora costata* and *V. tortuosa*, as well as the local development of *Lophotriletes* sp. A, together with the persistence of common *Laevigatosporites* spp.

The important Early Langsettian palynomorph marker *Radiizonates aligerens* became extinct within this zone, possibly reflecting the regional basinwide change to channel incision and major sandstone deposition of the following lowstand deposits, conditions that the donor plant could not tolerate. However, this palynomorph can occur in large numbers in the earlier parts of the zone and could be reworked into the overlying erosive HST and LST sandstones for more than 100 m above.

### **7.3 Late Langsettian (Lower A. *modiolaris* zone)**

Above the basal flooding surface, taken at the Tupton Coal, this zone is characterized by channel sandstones of low and high sinuosity, such as the Penistone Flags and the Parkgate Rock equivalents. It also contains significant intervals of finer-grained crevasse-splay and swamp and lake strata, with coals ([Figure 6C](#)). This zone has been designated a TST; it is 70 m thick in well 44/22-1. Many important coals also occur in the uppermost part of the zone, the Parkgate-Piper, Deep Hard, Flockton and Joan, possibly representing flooding surfaces, although no marine bands have been recorded within it up to the MFS of the Vanderbeckei (Clay Cross) Marine Band.

This interval is characterized by common *Lycospora* spp., with reduced abundances of *Crassispora kosankei* and *Laevigatosporites* spp. *Krauselisporites* spp., *Punctatisporites nitidus* and *P. limbatus* are particularly prominent within this zone, which may be a direct response to the transgressive depositional regime. Several other spore groups also dominate lake clay-stones and associated coal swamps. For example, *Schulzospora rara* is a very distinctive form, which reaches its acme in the uppermost part of the Langsettian and then terminates within the Joan Coal and coeval equivalents at the Westphalian A/B boundary. In South Wales, this form is commonly observed associated with coals at three distinct horizons. In the 49 Quadrant it has been observed commonly at two distinct horizons. Farther north in Quadrant 44 and onshore UK it is only widely observed within the uppermost horizon (Joan Coal). Even farther north, towards Tyneside and the Scottish coalfields, this taxon is rare or absent (see [Figure 10](#)). A possible interpretation of this distribution may be that *S. rara* was associated with coastal brackish swamps and that its decreasing frequency northwards records the brackish edge of marine incursion that progressively diminished up palaeoslope within this TST.

### **7.4 Early Duckmantian (Upper A. *modiolaris* zone)**

The base of this zone is taken at the Vanderbeckei Marine Band. Sedimentary sequences within this zone are distinctly arenaceous in character, with a dominance of coarse clastic lithologies comprising low-sinuosity sandstone bodies up to 35 m thick (facies association A), commonly best developed within the upper part of the zone. Intervening lithofacies comprise mouth-bar and crevasse-splay units ([Figure 6D](#), [Figure 7A](#)). In contrast to the offshore area, the upper part of the A. *modiolaris* zone, in the central Pennine Basin, mostly comprises argillaceous strata, although more sandstone-dominated sequences are locally present (Parkgate-Deep Hard rocks). This zone is considered to be an HST overlain erosively by an LST. Apart from the basal MFS, marine bands are

not a feature of this zone, as would be expected during lowstand sedimentation. Off shore, the highstand deposits may be equivalent to the informally named Lower Caister Sand, the unconformably overlying lowstand deposits equivalent to the Caister upper and lower Main Sand (*sensu* Ritchie & Pratsides 1993, Ritchie et al. 1998). Its thickness is 122 m in 44/22-1 and 96 m in 44/27-1.

Following the deposition of the Vanderbeckei Marine Band, a reduced rate of sea-level rise, followed by a rapid fall in base level, caused a reduction in the rate of formation of accommodation space and markedly increased (low- and high-sinuosity) channel sandstone sedimentation. Evidence of incision, erosion and reworking over this zone is provided by the occurrence of reworked Langsettian spores, and rarer Namurian spores. Some more sandstone-prone wells may yield consistent occurrences of *Radiizonates aligerens* from this interval, a Langsettian marker, some 100 m and more above the base of the Duckmantian. In other instances the coarse sandstone units yield only very poor palynomorph assemblages, because of the high energy of deposition. Incision during sandstone deposition may have removed a large interval of highstand strata deposited immediately above the preceding marine band.

The spore *Crassispora kosankei* is prominent in this zone, commonly occurring in very great abundance. This is in keeping with the alluvial swamp depositional environment that has been associated with this arborescent lycopod spore. This can be compared with its abundance in the previous *C. communis* LST, although in the latter it is less prominent than here in the Early Duckmantian. *Laevigatosporites* spp. are, like the *C. communis* zone, also in abundance within the Upper *A. modiolaris* zone, reflecting the waterlogged ephemeral depositional environment. Another spore taxon that is prominent within this zone and the *C. communis* zone is *Vestispora costata*, which may, like *C. kosankei*, come from a plant that favoured an environment of alluvial swamps and levee depositional environments. The important Duckmantian and younger palynological marker taxa *Endosporites globiformis* and *Dictyotriletes bireticulatus* make their appearance within this zone.

## 7.5 Late Duckmantian (*L. similis-pulchra* zone)

The base of the Late Duckmantian is taken at the Barnsley (Top Hard) Coal, coincident with a marked seismic break that is inferred to be the initial flooding surface heralding the renewed onset of marine transgression. This zone shows a return to the dominance of argillaceous lithotypes (facies association B), and is interpreted as a TST. The zone is dominated by alternating crevasse-splay mudstone-siltstone units and coal swamp and lacustrine mudstones ([Figure 6E](#), [Figure 7B](#)). Its thickness in 44/27-1 is 258 m.

The zone contains several coal seams in the lower part and several marine bands in its upper part. Intervals containing low-sinuosity sandstones are locally developed in places (more so in 44/22-1 than 44/27-1 - [Figure 6e](#)). Flooding surfaces near the top of the zone are indicated in the East Midlands by the Two Foot, Clowne, Haughton and Sutton marine bands. This transgressive sequence is terminated by the MFS of the Aegiranum (Mansfield) Marine Band, which marks the Westphalian B/C boundary.

This zone yields palynological assemblages overwhelmingly dominated by lycospores, although this cannot be considered to be diagnostic of the zone, as such spores are ubiquitous throughout the Coal Measures. However, they are accompanied by a consistent prominence of *Densosporites* spp. that reflects the major development of mature coal seams within this zone. The zone is also characterized by the evolutionary appearance of taxa that may be associated with large areas of persistent peat swamps; these include *Vestispora pseudoreticulata*, *Punctatisporites granifer*, *Triquitrites* spp., *Perotriletes perinatus* and *Cristatisporites solaris*.

Certain other taxa may not have been able to survive the demise of these very extensive and persistent settled swamp environments. This may have been associated with a decline in the rate of sea-level rise, and the sedimentation rate may have begun to exceed subsidence rates. Various taxa became extinct at the top of this zone, including *Raistrickia fulva*, abundant *Dictyotriletes bireticulatus* and *Camptotriletes bucculentus*.

## 7.6 Early Bolsovian (*U. similis-pulchra* zone)

The widely recognizable Aegiranum Marine Band marks the MFS at the base of the zone, which is interpreted as a HST. The zone is 183 m thick in well 44/27-1. It is characterized by argillaceous lithologies, crevasse-splay and lake deposits, with intervening swamp or lake units. Several coals are present in the lower half of the zone, and marine bands (Edmondia, Main Estheria and Shafton) indicative of flooding events are recognizable higher up in the sequence. Some sandstone bodies, up to 15 m in thickness (facies association B), are locally present (e.g. above the Edmondia Marine Band), although none is evident in the reference well 44/27-1 ([Figure 7C](#)).

Lycospores, indicative of peat-swamp sedimentation, and the alluvial swamp spore *Crassispora kosankei*, are consistently present throughout this zone. In contrast with the extinctions associated with Vanderbeckei marine incursion, noted above, several spore taxa continue into the *U. similis-pulchra* zone. However, the widespread Aegiranum Marine Band must have caused a major disturbance within the basin, severely limiting the area from which swamp taxa could later repopulate the basin. One taxon that became extinct at this horizon was *Cingulizonates loricatus*. Spore taxa appearing within this zone include *Vestispora fenestrata*, *Torispora securis*, *Triquitrites bransonii* and *Punctatisporites granifer*.

## 7.7 Late Bolsovian (*A. phillipsii* zone)

A final marine flooding event, the Cambriense Marine Band, occurs at the base of this zone (Calver 1968, Flint et al. 1995, Guion et al. 1995). After this marine band was deposited, uplift and tectonic inversion prevented any further marine incursions (Leeder & Hardman 1990). Grey coal-bearing rocks become much reduced in volume, and redbed sedimentation was more widespread. The zone is interpreted as representing an LST, and is 143 m thick in 44/27-1. It is characterized by a relatively high proportion of sandstone, as base-level fall led to a significant increase in alluvial vigour, with incision and deposition of thick sheets of laterally and vertically linked low- and high-sinuosity channel sandstones up to 30 m thick (facies association A). On shore, widespread sandstones include the Ackworth, Wickersley and Ravenfield rocks. Subordinate claystones and siltstones and several thin, laterally impersistent coal seams are developed. Several such sandstone units are developed in 44/27-1, although in this well none exceed 20 m in thickness ([Figure 7D](#)). Finer-grained crevasse-splay, mouth bar and lake or swamp sedimentation in interchannel areas was comparatively shortlived. Coals developed within this zone are therefore liable to be of a poorer quality with a higher ash content. Interchannel areas were also prone to erosion by the stream avulsion.

The alluvial swamp spore *Crassispora kosankei* reaches its acme within this zone, reflecting a final period of major alluvial swamp deposition prior to the Late Westphalian climatic change. Lowstand sedimentation, with its reduced accommodation space had a profound effect on the palynofloras. *Densosporites sphaerotriangularis*, *Vestispora costata*, *V. pseudoreticulata*, *Savitrissporites nux*, *Dictyotriletes falsus* and *Grumosissporites varioreticulatus*, seen since the Early Westphalian, became extinct within this zone. New taxa appearing within the zone include *Schopfites dimorphus* and *Vestispora laevigata* (Van Adrichem Boorgaert & Kouwe 1993). Palynological assemblages from this zone commonly contain reworked Early Westphalian or Namurian taxa.

## 7.8 Westphalian D (*A. tenuis* and *A. prolifera* zones)

Westphalian D strata are not present in many southern North Sea wells. Where rocks of this age have been penetrated, they tend to be characterized by finer-grained lithologies indicative of an increase in accommodation space. However, this is not always the case and, in some wells, thick low-sinuosity channel sandstones are developed. Well 44/27-1 ([Figure 7E](#)) has several of these sandstone units within an interval of over 250 m of inferred Westphalian D age.

Tectonic changes associated with the advancing Variscan Front may have been the principal control on sedimentation in the southern North Sea Westphalian D, lifting the swamps above the level that permitted further marine ingress (Leeder & Hardman 1990; [Figure 5](#)). Thick sandstones are likely to be a response to localized tectonic uplift outside the basin rather than to sea-level change. In addition, coals are rare in the *A. tenuis* zone in the southern North Sea, although again this is not a universal feature of the Westphalian D elsewhere in northwest Europe (e.g. the Newcastle and Halesowen formations of Staffordshire). The Westphalian D rocks of the southern North Sea tend to be reddened, reflecting a climatic change, associated with the formation of Pangaea, that lead to increasing aridity and an overall oxidizing influence. Associated with this environmental change was the evolutionary appearance of several new palynomorph taxa such as *Thymospora obscura*, *T. pseudothiesseni*, *Cadiospora magna* and an increase in the occurrence of various striate bisaccate taxa that are the dominant palynoflora of the Permian.

The *A. tenuis* zone of the southern North Sea is tentatively interpreted as representing a TST in the lower part (4306–4225 m in [Figure 7E](#)), with possible LST and HSTs developed subsequently. An LST may be present in 44/27-1 from 4225–4150 m over an interval of prominent low-sinuosity channel sandstones. The succeeding strata, characterized by alternating crevasse-splay and thin low-sinuosity channel sandstones, up to the Saalian unconformity at 4038 m, are interpreted as an HST. As the lateral extent of some of the Westphalian D sandstone bodies becomes better known, a more refined third-order subdivision of the substage into transgressive, highstand and lowstand systems tracts may be possible. Evidence of fourth-order sea-level fluctuation may be suggested in the redbeds by the interdigitation of, on the one hand, originally grey siderite-bearing strata laid down under poor drainage conditions and, on the other, palaeosols indicative of good drainage (Besly et al. 1993). In the view of these latter authors, these alternations are attributable to tectonic causes.

Strata of the *A. prolifera* zone are too poorly preserved or too little known at present off shore to allow the elucidation of sequences. However, considerable thicknesses of strata of this age may be present off shore, possibly containing several third-order systems tracts.

## 8. Discussion and conclusions

Sea-level control on Coal Measures sedimentation has been known since the recognition of brackish and marine faunas within the many marine bands on shore (although the marine bands do not yield definitively marine microplankton palynomorphs). The Coal Measures are therefore highly suitable for the recognition and study of systems tracts in an essentially non-marine setting.

Subdivision of the offshore Coal Measures section using the onshore macrofaunal biozone scheme of marine-band faunas will always be partly subjective, when only cuttings samples are available and palynology is the only available biostratigraphical tool. Sequence stratigraphical subdivision off shore is also partly subjective and will be subject to changes and refinements in future studies. Nevertheless, the basinwide macrofaunal biozones provide a good starting point for recognizing systems tracts, as they are generally lithologically discrete. Offshore wells, particularly those

penetrating a significant interval thickness and furnished with a good suite of wireline logs, permit large parts of the Coal Measures to be examined in terms of broad lithofacies trends at a scale often not available in the onshore section.

Sequence analysis is best achieved where there are good biostratigraphical data and well dated neighbouring offset wells. A combination of terrestrial plant miospore zonal markers and palynofacies influxes can provide reasonably refined dating of the Coal Measures section and give good pointers towards the probable correlation of a particular gamma-ray spike with a named marine band. If a full suite of spectral gamma-ray logs is available, selection of one particular gamma-ray spike may be enhanced using the method of Hollywood & Whorlow (1993). This has been successfully demonstrated by the authors on unpublished wells with spectral gamma-ray logs available in digital format, doing the necessary arithmetical manipulation of a large log file with a digital spreadsheet. Expected interval thickness and wireline-inferred sedimentary facies of particular parts of the section are key parts of the analysis. As a very generalized rule, transgressive deposits are characterized by abundant coals and marine bands. Highstand deposits (if preserved un-eroded by the succeeding lowstand deposits) have common marine bands. Lowstand sediments are characterized by thick, regional, stacked, alluvial channel sandstones (i.e. potential reservoirs).

Released wells from The Netherlands and UK sectors permit the study of lateral changes within systems tracts of the Coal Measures over a significant part of the southern North Sea. A north-south transect of the western side of the southern North Sea ([Figure 1](#), [Figure 8](#), [Figure 9](#)) based on the correlation of eight wells selected from UK quadrants 44, 49 and 53, and Dutch quadrants K and P, has been compiled. The correlations demonstrate a significant degree of continuity of interval thicknesses and show lateral facies changes within individual systems tracts.

There is a generalized north to south decrease in sandstone, e.g. the thick sandstones within the *A. lenisulcata* and *C. communis* zone recognizable in 44/22-1 and 44/23-4, and in the *C. communis* zone in K1-02, are hardly evident in well P/10-1. The sandstone-dominated interval of the upper *A. modiolaris* zone HST-LST (Caister-Murdoch sandstone play of Quadrant 44) diminishes in prominence farther south into quadrants 49 (49/1-3) and 53 (53/10-1). This southward reduction in Early Duckmantian sandstone development continues into The Netherlands quadrant P (P10-1 and P13-1). Associated with it, the "coal-break" upper boundary of this unit with the overlying *L. similis-pulchra* zone is clear in quadrants 44, 49 and K, but much less so in quadrants 53 and P.

Converse to this reduction in net sandstone development, there is an increase in overall thickness of the mudstone-dominated *L. similis-pulchra* zone TST southwards, from Quadrant 44 through 49 and into Quadrant P. The base Permian unconformity truncates this interval in K1-02, P10-1 and P13-1, but P13-1 still has a greater thickness of this interval than 44/27-1. This trend may reflect a southward decrease in the development of alluvial channels within this TST that may have significantly reduced this interval thickness in quadrants 44 and 49. The upper Bolsovian, *A. phillipsii* zone, LST sandstone unit is clearly developed above a prominent c. 20 m basal sandstone body in quadrants 44 and 49. Farther south, however, these strata have been eroded away at the base Permian unconformity.

These trends in the sandstone development of the LSTs reflect increasing distance from the northerly sediment source. During periods of HST and TST, with more numerous marine incursions, topographically lower regions in the south of the basin would be flooded first and to greater water depths. There would have been a general northward shallowing in depth of flooding, together with a reduction in salinity towards some areas of peat swamp coal deposition that avoided flooding. Between flooding events, areas of forested peat swamps would be coeval with more continuously waterlogged areas farther south and more areas occupied by lakes.

Such trends may provide an explanation of the distribution of *Schulzospora rara* (Figure 10) in the Late Langsettian. Wells of southern quadrants 49 and L, and quadrants 53, P, Q, R and S (approximately south of 53°N) are in particular distinguished by intervals containing an abundance of the lacustrine alga *Botryococcus* sp. This reflects a greater degree of freshwater “ponding” in this region from the effects of sea-level rise. More widely developed major marine bands at stage boundaries were laid down during major incursion events when sea-level rise was high enough for brackish marine waters to extend over the entire basin.

Figure 11 summarizes these north-south trends and depicts broad basinwide Westphalian depositional facies. No particular phase of transgressive, highstand or lowstand is indicated, nor is any particular Westphalian age. A broad picture applicable throughout the Langsettian-Bolsovian is represented. The sequential scheme of systems tracts presented in this paper are envisaged as the product of a southward shift of the northern sand-prone facies belt during phases of regressive LST, and a northward shift of lacustrine and swamp facies during transgressive phases of TST and HST. North-to-south facies changes across the southern North Sea have a direct bearing on the hydrocarbon prospectivity of this region in terms of reservoir and source-rock quality. Reservoir sandstone units are thicker and more commonly developed to the north, where to date most drilling in the UK sector has taken place in the gas province of quadrants 43, 44, 48 and 49.

In the southern part of the gas basin (southern Quadrant 49, quadrants 53, O, P, Q and R/S), reservoir sandstones are less common and, although there is no Silverpit seal, there is greater potential for intra-Carboniferous sealing. Source-rock potential may be greater to the south within finer-grained strata, laid down within more prevalent lacustrine environments. These have a greater preservation potential for oil-prone liptinitic kerogen, in contrast to mainly woody gas-prone kerogens within more fluvial regimes farther north. The southern province may therefore be oil prone as well as gas prone.

## Acknowledgements

We wish to thank G. Hampson and S. S. Flint for their useful reviews of an earlier version of the text.

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## **Appendix**

### **Facies C1 - low-sinuosity channel deposits**

#### **Description**

Low-sinuosity channel deposits consist mainly of sandstones, locally up to 50-60 m thick, with generally minor fine-grained partings and intraformational conglomerates. These sandstones are typically clean, fine to very coarse-grained and range from well sorted to poorly sorted as grain size increases. Grain size may vary widely within sandstone bodies, and overall upward-fining profiles may be apparent. In places, especially in more distal coastal plain areas, low-sinuosity channel sandstones are entirely fine to very fine grained and well sorted. The base of low-sinuosity channel sandstones is typically erosive and the top sharp. Internally, cross bedding is commonly well developed, with asymptotic sets up to c. 1 m thick forming erosively based cosets 2-5 m thick. Larger planar crossbed sets and downcurrent descending compound cosets (cf. Haszeldine 1983) also occur locally.

## **Interpretation**

The erosive base, predominance of sandstones varying widely in grain size and the development of complex cross bedding suggest a low-sinuosity fluvial channel origin (cf. Haszeldine 1983, 1984, Fielding 1986). Consistently fine-grained to very fine-grained well sorted facies C1 sandstones (cf. Kirk 1983) are interpreted as more distal deposits. Comparable modern analogues include the Brahmaputra (Coleman 1969), Tana (Collinson 1970) and South Saskatchewan rivers (Cant & Walker 1978).

## **Geometry**

Mapping in onshore areas with good well control indicates that facies C1 is typically 20–30 m thick, but locally may reach 50–60 m or more. Lateral continuity is good, with channel sandstones extending for several kilometres perpendicular to palaeoflow and at least several tens of kilometres parallel to palaeoflow. Localized zones of stacked low-sinuosity channel sandstones have resulted from contemporaneous tectonism in places (e.g. Haszeldine 1983, Fielding 1984, Leeder & Hardman 1990, Ritchie & Pratsides 1993), and have major implications for reservoir geometry and prospectivity.

## **Wireline log characteristics**

Facies C1 is characterized by blocky and consistent gamma-ray and sonic-log responses, with pronounced basal and upper inflexions. Gamma response is typically 30–60 API and sonic response 70–80  $\mu\text{ft}^{-1}$ . Localized fluctuations in log response are attributable mainly to the presence of finer-grained strata towards the top of major depositional units.

## **Facies Ch - High-sinuosity channel deposits**

### **Description**

High-sinuosity channel deposits are characterized by variably interbedded sandstones and finer-grained units. The sandstones are typically argillaceous, fine-grained to very fine-grained, and well sorted. Beds with mudstone intraclasts are present locally and an overall upward fining grain-size profile is commonly apparent. High-sinuosity channel deposits are erosively based, with a gradational top, and commonly display epsilon cross bedding, inclined perpendicular to palaeoflow in outcrops. Small-scale cross bedding, ripple cross lamination and continuous and discontinuous parallel lamination characterize graded units, which may form cosets up to several metres thick.

### **Interpretation**

The erosive base, fine sandstone grain size, frequency of argillaceous interbeds and the development of epsilon cross bedding suggesting lateral accretion - clearly indicate that facies Ch was deposited by high-sinuosity fluvial channels. High-sinuosity channel deposits similar to those developed in the Carboniferous have been described in detail from other depositional systems (e.g. Puidefabregas & Van Vliet 1978, Plint 1983 and Stewart 1981, 1983).

### **Geometry**

High-sinuosity channel deposits have been mapped in detail on shore in the UK by us at and around Waverly East opencast site, and previously by BP (Eagle Sandstone reservoir) in the Beckingham oilfield. These studies indicate a maximum thickness of 20–25 m and lateral continuity for up to 1 km perpendicular to palaeoflow and for several kilometres or tens of kilometres parallel to palaeoflow. Although produced by high-sinuosity channel activity, the deposits preserved consist of many point

bar units and commonly form relatively straight channel belts.

### **Wireline log characteristics**

Facies Ch is invariably characterized by sharp basal gamma-ray and sonic-log inflexions. However, the upper contact may be either sharp or more gradational, depending upon the lithologies developed. The gamma log response is typically in the range 60-75 API reflecting the argillaceous nature of the sandstones. It is typically accompanied by a sonic log response of 80-90  $\mu\text{st}^{-1}$ . The main variations in wireline log profiles occur in the upper part of sandstone units where gamma log response and  $\delta T$  values may increase markedly because of the presence of finer-grained units.  $\delta T$  values tend to decrease sharply at well cemented or concretionary beds.

## **Facies Cd - Distributary mouth bar**

### **Description**

Distributary mouth-bar deposits coarsen upwards overall and comprise an upper sandstone unit overlying a lower mudstone- siltstone unit. The lower mudstone-siltstone unit is typically 10- 15 m thick and may contain either a marine or non-marine fauna. Overlying sandstones are well sorted and fairly clean, and they generally increase in grain size upwards from very fine to fine; however, they may locally be coarse and may fine upwards. Mudstones and siltstones are mostly parallel laminated or locally homogenized by bioturbation, particularly at marine horizons. The sandstones tend to be ripple cross laminated near the base and trough cross bedded at higher levels. Distributary mouth-bar units are commonly underlain and overlain by coal seams or rooty horizons.

### **Interpretation**

Overall upward coarsening from mudstone/siltstone into sandstone suggests a distributary mouth-bar origin. Coarser-grained upward-fining units are interpreted as channel sandstones. The overall thickness of distributary mouth-bar units indicates a genetic relationship with major fluvial channels (facies Cl), rather than minor crevasse-type channels (facies Oc).

### **Geometry**

Mapping suggests that distributary mouth-bar deposits have a lobate geometry and diameter of *c.* 10-15 km. Thicker, Namurian shallow-water delta-front deposits may, however, be of greater lateral extent.

### **Wireline log characteristics**

The gamma-log response of basal mudstones and siltstones is in the range 125->150 API and they have a sonic-log response of 90-100  $\mu\text{st}^{-1}$ . The gamma log response gradually decreases upwards to about 35-40 API in clean distributary mouth-bar sandstones and to 60-70 API in more argillaceous deposits. A corresponding upward decrease in  $\delta T$  values to an average of 80-90  $\mu\text{st}^{-1}$  is also observed. The gradational upward increase in gamma-log response from the basal mudstones-siltstones into sandstone and sharp upper inflexion are characteristic of distributary mouth-bar deposits.

## **Facies Oc - Crevasse splay**

### **Description**

Crevasse-splay deposits are widely developed in the Upper Carboniferous, and almost invariably

occur overlying lake or marine-bay deposits (facies Ol) and underlying swamp or flood-plain deposits (facies Os). The predominant lithology is very fine to fine-grained well sorted argillaceous sandstone, typically 2-5 m thick, which is closely associated with interbedded siltstones. Sandstones typically have a gradational base and coarsen upwards from parallel laminated mudstones and siltstones; however, they may occasionally be erosively based and fine upwards. Sedimentary structures include convolute and ripple cross lamination, discontinuous parallel lamination and small-scale trough cross bedding. Rootlets are invariably developed in the upper parts of crevasse-splay sequences.

### **Interpretation**

The overall upwards coarsening of grain size, thickness and nature of associated deposits (facies Ol/Os) suggests that facies Oc results from the infilling of shallow lakes by prograding crevasse splays. Erosively based fining-upward units may represent either crevasse-splay or crevasse-channel deposits (cf. Fielding 1984). Similar modern environments have been described by Coleman & Gagliano (1964), and Butzer (1971), and Carboniferous examples have been documented by Fielding (1984), Guion (1984) and Haszeldine (1984).

### **Geometry**

Mapping of crevasse-splay deposits during this study and previous published studies (Fielding 1984, Guion 1984, Haszeldine 1984) indicates a lobate geometry with major lobes averaging a few metres in thickness and about 5 km across. Within these major lobes, individual lobes measuring a few hundred metres across are often discernible in large-scale outcrops (cf. Fielding 1984). Crevasse-splay feeder channels are typically up to 5-6 m thick, several hundred metres across, perpendicular to palaeoflow and several kilometres long parallel to palaeoflow.

### **Wireline log characteristics**

Facies Oc is characterized by very erratic gamma-ray and sonic-log responses, reflecting the variable interbedding of lithologies. Gamma-log response increases from 120-→150 API in the underlying facies Ol mudstones-siltstones to 75-105 API in argillaceous very fine to fine-grain crevasse-splay sandstones. A corresponding change also occurs in sonic-log response from 90-100 to 80-90  $\mu\text{ft}^{-1}$ . Crevasse-splay deposits are characterized by gradationally based upwards-decreasing log responses with sharp inflections at the upper contact with overlying coal seams or lake or marine mudstones.

## **Facies Ol - Lake and marine-bay deposits**

### **Description**

Lake and marine-bay deposits consist essentially of blocky, dark grey to black mudstones and siltstones, which may contain either freshwater or marine faunas. Thin very fine-grained sandstones and nodular horizons are interbedded locally in places. Deposits range in thickness from a few tens of centimetres to exceptionally 15-20 m, with an average thickness in the range 2-10 m. The main sedimentary structure is parallel lamination; however, convoluting and bioturbation may also occur in places. Lake and marine-bay deposits almost invariably overlie swamp or flood-plain sediments (facies Os) with a sharp contact, and are overlain gradationally by either crevasse splay (facies Oc) or distributary mouth-bar (facies Cd) sediments.

## **Interpretation**

Fine grain size and lack of obvious current-generated structures indicate sedimentation from suspension in standing water. Preserved faunas indicate either a lake or marine-bay setting.

## **Geometry**

Mapping of lake and marine-bay facies reveals an uninterrupted areal extent of several hundred square kilometres. Thickness variations suggest that the depth of lakes and bays ranged from less than 10 m to over 30 m in places.

## **Wireline log characteristics**

Lake and marine-bay mudstones and siltstones are characterized by high gamma-log responses of 120-→150 API and  $\delta T$  values of 90-105  $\mu\text{st}^{-1}$ . Marine horizons commonly display particularly high gamma responses, often in excess of 150 API. The presence of nodular beds causes a marked reduction in gamma-log response and  $\delta T$  values.

## **Facies Os - swamp/floodplain deposits**

### **Description**

This facies comprises coal seams and associated rootlet-disrupted mudstones, siltstones and fine-grained sandstones. Coal seams are up to 2-3 m thick and are typically banded, whereas the associated clastic strata, also on average 2-3 m thick, are invariably structureless, because of disturbance by rootlets. Nodules of pyrite or siderite may be developed within all these lithologies. Swamp/floodplain sediments occur mainly at the top of cyclothems overlying channel (facies Cl and Ch), distributary mouth-bar (facies Cd), crevasse-splay (facies Cl) and locally lake or marine bay (facies Ol) deposits.

### **Interpretation**

Coal seams are interpreted as the deposits of compacted peat swamps. Rootlets in associated lithologies indicate an emergent floodplain environment, which was colonized by plants.

### **Geometry**

Published studies (e.g. McCabe 1984) and mapping by us in the East Midlands indicate a laterally extensive sheet geometry extending over several hundred square kilometres. Total thickness is typically 2-4 m, perhaps exceptionally reaching 6m or more in localized areas.

### **Wireline log response**

Coal seams exhibit a very distinctive wireline log response characterized by relatively high gamma ray (*c.* 75 API) and very high sonic-log values ( $>110 \mu\text{st}^{-1}$ ). Associated floodplain clastic strata typically give gamma log responses of 75-105 API, reflecting the predominantly silty lithology and sonic responses of 80-90  $\mu\text{st}^{-1}$ . Compared with lithologically similar facies Ol deposits, the relatively low log values are probably attributable to the common occurrence of ironstone nodules in clastic floodplain sediments.

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