

Fluvial sandbody architecture, cyclicity and sequence stratigraphic setting - implications for hydrocarbon reservoirs: the Westphalian C and D of the Osnabrück-Ibbenbüren area, northwest Germany

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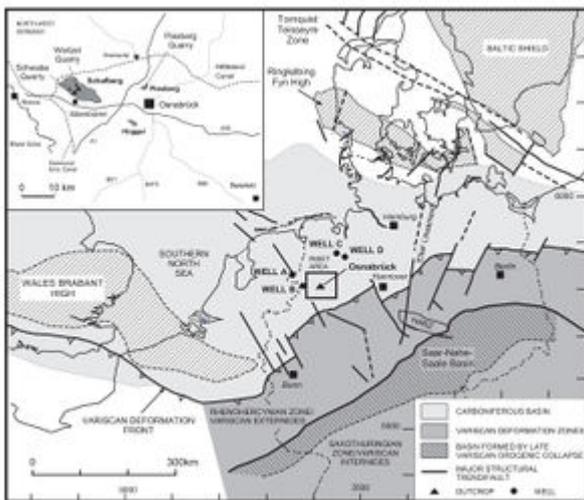


Figure 1 Main structural elements of part of the West European Carboniferous Basin . Inset map shows the location of the main Upper Carboniferous (Bolsovian and Westphalian D) outcrops in the northwestern part of Germany described in this paper. Wells A-D are illustrated in Figure 7.

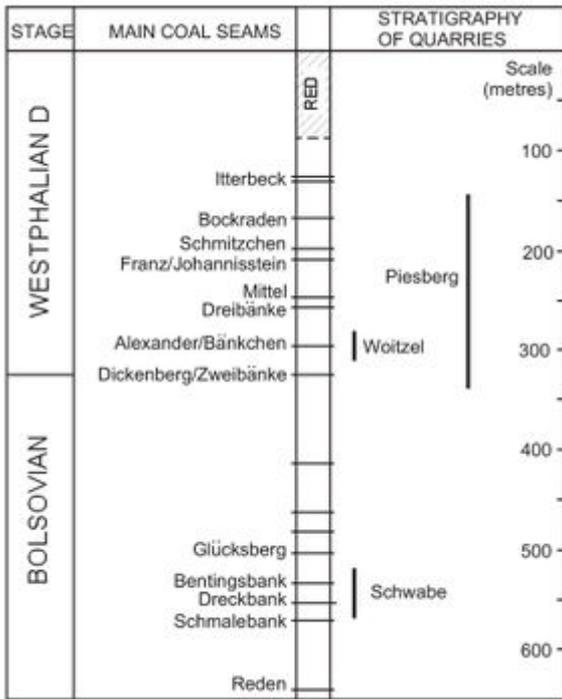


Figure 2 Stratigraphy of the Ibbenbüren area (modified from David 1990).

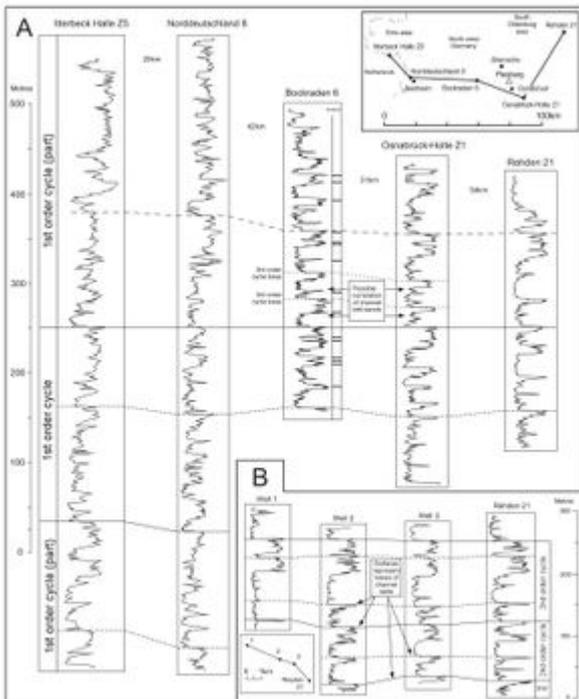


Figure 3 (a) Gamma-ray geophysical log correlation of wells between South Oldenburg and the Ems area of northern Germany to show the first-order scale of cyclicity in the upper Bolsovian to lower Westphalian D successions (b) Gamma-ray geophysical log correlation of wells from the South Oldenburg area of northern Germany to show the lateral correlation of sandbodies in second- and third-order cycles.

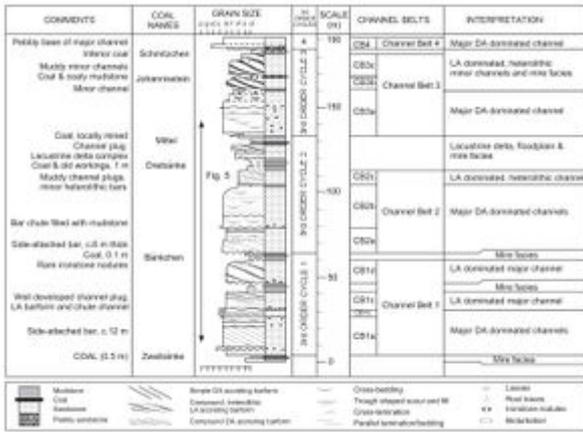


Figure 4 Log of basal Westphalian D succession at Piesberg quarry. DA = downstream accretion, LA = lateral accretion. This represents an almost complete second-order cycle.

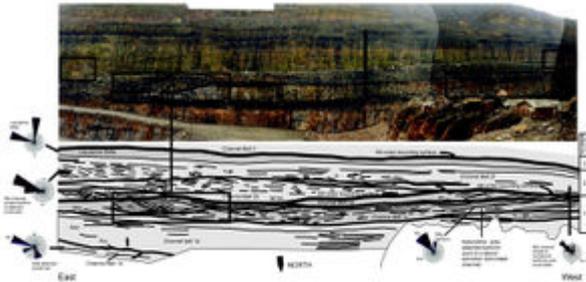


Figure 5 Detailed architecture of the three main channel belts at Piesberg quarry.

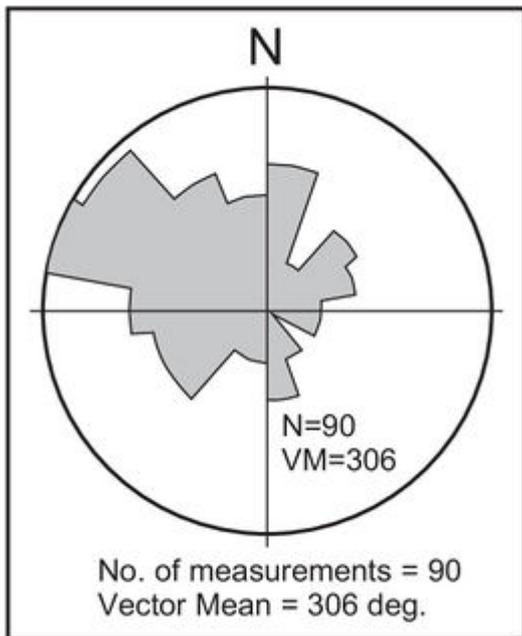


Figure 6 Rose diagram of palaeocurrent measurements from the Upper Carboniferous (upper Bolsovian and lower Westphalian D) outcrops in the Osnabrück-Ibbenbüren area, northwest Germany.

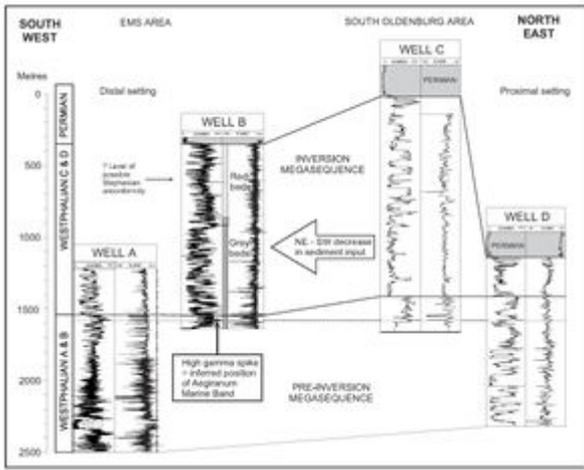


Figure 7 Northeast-southwest log correlation to show variations in the quantity of sand deposited in the basin prior to (pre-inversion megasequence) and after (inversion megasequence) Variscan activity began to affect the basin.

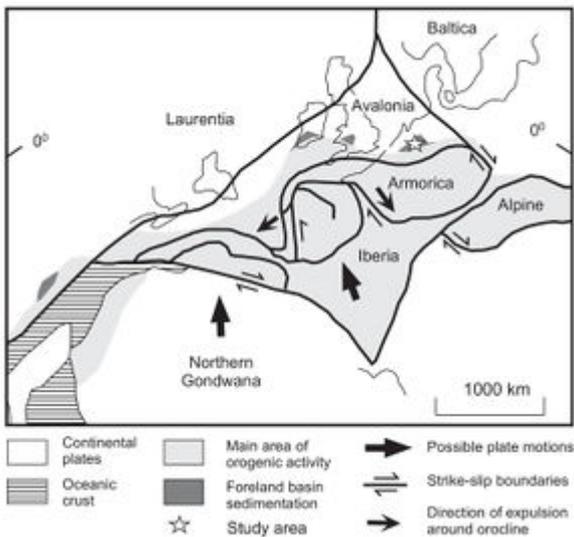


Figure 8 Plate-tectonic model for the Late Carboniferous (Sudetic and Asturian) phase of the Variscan orogeny. This shows the final amalgamation of Pangaea as a result of the indentation and formation of the Iberian-Armorican arc.

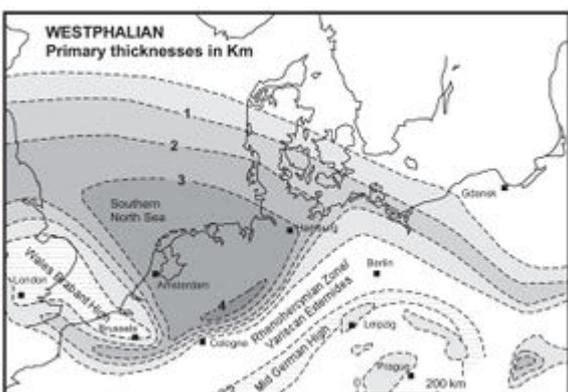


Figure 9 Isopach map (in kilometres) of the

Type	Description	Interpretation	Sketch	Examples
SIPPLE, SIDE-ATTACHED	SIPPLE Thick, locally bedded (up to 20 m) beds developed in the trough or on point bars or on slightly raised areas in the trough. They consist of a sequence of thin beds, some of which are cross-bedded. They are typically sandstone or siltstone with some claystone or shale. They are typically 10-20 m thick and 100-200 m long.	Overbank deposits of sand and siltstone or claystone and shale. They are typically 10-20 m thick and 100-200 m long. They are typically sandstone or siltstone with some claystone or shale.		
	COMPOSITE Locally bedded (up to 20 m) beds developed in the trough or on point bars or on slightly raised areas in the trough. They consist of a sequence of thin beds, some of which are cross-bedded. They are typically sandstone or siltstone with some claystone or shale. They are typically 10-20 m thick and 100-200 m long.	Local-scale channel and barform deposits. They are typically 10-20 m thick and 100-200 m long. They are typically sandstone or siltstone with some claystone or shale.		
SIPPLE, MID-CROSSBED	SIPPLE Thin, locally bedded (up to 20 m) beds developed in the trough or on point bars or on slightly raised areas in the trough. They consist of a sequence of thin beds, some of which are cross-bedded. They are typically sandstone or siltstone with some claystone or shale. They are typically 10-20 m thick and 100-200 m long.	Overbank deposits of sand and siltstone or claystone and shale. They are typically 10-20 m thick and 100-200 m long. They are typically sandstone or siltstone with some claystone or shale.		
	COMPOSITE Locally bedded (up to 20 m) beds developed in the trough or on point bars or on slightly raised areas in the trough. They consist of a sequence of thin beds, some of which are cross-bedded. They are typically sandstone or siltstone with some claystone or shale. They are typically 10-20 m thick and 100-200 m long.	Local-scale channel and barform deposits. They are typically 10-20 m thick and 100-200 m long. They are typically sandstone or siltstone with some claystone or shale.		

Table 2 Main types of barform channel elements recognized from the Upper Carboniferous succession in northern Germany.

Channel elements	Sub-elements	Description	Interpretation
Thalweg deposits	Mixer bar	Sand-dominated. Small-scale, single bars within thalweg axis. Similar to simple, mid-channel bars. Up to 3m thick, deposits up to 10m thick and lengths >100m.	Small, slip-face bounded bars within channel thalweg.
	Bedforms	Sand-dominated. A variety of sedimentary structures including trough and planar-tabular cross-bedding, cross-lamination, and parallel lamination. Typically present as sets and coasts with subhorizontal bounding surfaces. Palaeocurrents variable but dominantly unidirectional. Beds up to 2m thick, deposits up to 10m thick, lengths up to 100m.	Downstream migration of asymmetrical bedforms, under the influence of lower flow regime conditions.
	Thalweg channel plugs	Lenticular shaped deposits. Variable lithological fills, including sandstone, siltstone, claystone and coal, commonly heterolithic. Small scale trough and planar-tabular cross-bedding and cross-lamination. Up to 100m across and 6m thick.	Deposition of clastics from suspension & traction in abandoned channels. Coals formed by autochthonous accumulation of organic material in the abandoned channel.
Chute/belt channel	Bedforms	Sand-dominated. A variety of small-scale sedimentary structures. Typically cross lamination, some small scale trough and planar-tabular cross-bedding and parallel lamination. These form sets and coasts with subhorizontal bounding surfaces. Palaeocurrents variable but dominantly unidirectional. Beds up to 1m thick and less than 30m across.	Chute channels form by scouring across the top of barform during lowering of flow stage. Sedimentary structures produced by the migration of asymmetrical bedforms, under the influence of lower flow regime conditions.
	Suspension deposits	Typically carbonaceous siltstones and claystones, plant-rich. Massive or laminated. Dark grey to black. Beds up to 2m thick and less than 30m wide.	Deposition of mud from suspension in abandoned chute channels.
Channel lag	Winnow lag	Pebbly conglomerate, composed of well-sorted, well-rounded, small pebbles. Clast-supported. Occurs along the base of a channel. Lenses up to 5.2m thick and 5m in length.	Prolonged reworking and winnowing of pebbles at the base of a channel.
	Lag conglomerate	Pebbly conglomerate, composed of poorly to moderately sorted, subrounded granules to large pebbles. Clast-supported. Occurs at the base and at random levels within a channel. Contains woody plant stems. Beds up to 1m thick and tens of metres in length.	Deposition of coarser sediment traction and waterlogged plant stems typically at the base of the channel. Some reworking and winnowing.

Table 3 Detailed descriptions of other elements within the channel-belt facies association.

FACIES ASSOCIATION	FACIES	MAIN FEATURES	INTERPRETATION
Poorly drained alluvial floodplain	Alluvial pebbled overbank	Clypeus and alluvium, reddish brown, purple grey, pebbled grey, sandy loams, mud, mottles, lentic, laminated, detrital, rare desiccation cracks, sphaerulitic. It contains up to 1m thick, locally continuous for hundreds of metres.	Suspensive deposits in a regional alluvial floodplain. Shallow, water bearing, unconsolidated or firm. Successive to post-lateral and down stream, they are attributed to periodic flooding and winnowing.
	Channel splay	Individual beds of fine to medium grained sandstone. Generally less than 1m to 1.5m thick, from laterally continuous down a low handed stream towards banked with fine-grained loess. Red loess clay or silt, commonly fine grained. Curved ripple cross-lamination, climbing ripple, vertical scale of cross-bedding, sub-lateral lamination, flow bedding.	Sand-filled, unconfined flood events. Breaching of main channel forms anastomosing channels which introduce flood deposits into adjacent floodplain area. Unidirectional, lower flow regime conditions. Occasional upper flow regime conditions indicated by planar beds.
Lake	Open lacustrine	Grey to dark grey and black siltystone and claystones, laminated, some plant material, carbonaceous, silty beds. Up to 2m thick, > 300 metres wide.	Deposited from suspension in the central parts of a perennial lake. Reducing conditions.
	Shallow lacustrine	Dark grey to black claystone and siltstone, sphaerulitic, silty, laminated, laminated, mud. Up to 0.2m thick, > 300 metres wide.	Deposited from suspension in a perennial lake. Reducing conditions indicated. Shallow water conditions suggested by rooting.
	Lacustrine delta	Coarsening-upward succession, with silty sandstones passing upwards into fine to medium grained sandstone. Cross-lamination & climbing ripple in lower parts, area bedded in upper parts. Upper part typically evenly bedded. Up to 3.2m thick, > 300 metres wide.	Deposited from locally unconfined flows in the proximal parts of a small lacustrine delta. Truncation lines, associated with high failure of sediments from suspension. Upper, evenly bedded part probably represents channelised flow in a small distributary channel that supplied sediment to the delta.
Mire	Mixed silt/clay	Clay, silty siltstone, occasionally claystone, occasionally siltstone. Generally clayey, occasionally laminated. Up to 1m thick, locally continuous for hundreds of metres, possibly tens of kilometres. Can also occur as locally discontinuous lenses.	Autochthonous accumulation of organic material in a post-flooding mire. Clastic intercalations represent flooding events. Discontinuous lenses represent deposits in abandoned 'over channels'.
	Clay	Claystone, siltstone, occasionally sandy, extensively rooted, desiccated, carbonaceous, some silty, siltstone. Up to 2m thick, locally continuous for hundreds of metres, possibly tens of kilometres.	Poorly drained soil horizons, limited by pedogenesis in a waterlogged, reducing environment. Low aggradation rates. Features are indicative of mature clay grey silts.
	Sand/silt	Grey and green grey, sandstone, massive with sporadic root traces and desiccation, mostly unbedded, minor signs of opto-diagenetic oxidation such as nodding down root traces or the oxidation of sphaerulitic nodules.	Similar to grey (or yellowish) formed through groundwater hydrolysis. However, short periods of water table lowering brought to the formation of root nodules in the upper parts of the profiles and down soil traces.

Table 4 Detailed descriptions of the poorly drained alluvial floodplain, lake and mire facies associations recognized from the Upper Carboniferous in the Osnabrück-Ibbenbüren area.

Cycle order	Thickness	Description	Cause
1	Hundreds of metres	Large-scale upwards-fining succession, with coarse-grained multi-storey channel sands at base and mudstone prone tops.	?Orogenic/tectonic cycle in the hinterland – likely source in the east (?Baltica region) – a Caledonide zone formed by collision between Eastern Avalonia and Laurussia into Baltica.
2	Typically 120–200 m	Upwards-fining cycles, characterized by thick, stacked, coarse-grained channels at base and multiple coal-palaeosol horizons at the top. Typically contain 2–3 smaller-scale upwards-fining third-order cycles; each successive third-order cycle containing less sand.	Hinterland tectonic pulses, e.g. movement along the Tornquist–Teisseyre or Rynkåbing Fyn High Zone. Produces large pulses of sediment flux.
3	40–60 m	Upwards-fining successions, characterized by thick, stacked, coarse-grained low-sinuosity channels at base passing upwards into meandering channel systems, lacustrine muds and poorly drained palaeosols and coals.	?Tectonically driven source area climatic fluctuations resulting in variations in the amount of precipitation. This affects sediment flux and base level in the basin.

Table 5 Main characteristics of the different scales of cyclicity recognized in the Upper Carboniferous of northern Germany.

By Neil S. Jones & Brian W. Glover

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Summary

During the Upper Carboniferous (Westphalian), northern Germany formed part of the Variscan foreland basin. Coal-forming conditions interdigitated with lacustrine environments on a low-lying, low-gradient, poorly drained alluvial floodplain. By late Bolsovian (Westphalian C) times, the effects of Variscan orogenic processes to the south led to much coarse-grained sediment entering the basin via major perennial river systems, resulting in the formation of large fluvial sandbodies. Outcrop and subsurface studies in the Osnabrück-Ibbenbüren area of northern Germany demonstrate that these sandbodies are not randomly organized, but show cyclicity on three scales. First-order cycles, hundreds of metres thick, define gross upwards-fining cycles. Second-order cycles, 120–200 m thick, also show upwards-fining, but demonstrate predictable facies-stacking patterns, characterized by channel-belt dominated sandstone facies in the lower parts and floodplain-dominated mudstone facies in the upper parts. Third-order cycles, 40–60 m thick, show a systematic upwards change from sandy downstream accretion-dominated channels (low sinuosity) to heterolithic, lateral accretion-dominated channels (high sinuosity) upwards through each cycle. It is believed that these cycles are controlled by a combination of tectonics and climatically moderated base-level changes, developed in response to the increasing influence of the northwards-propagating Variscan orogeny. In the nearby subsurface, the Upper Carboniferous is similar to that at outcrop, characterized by high net-to-gross sands with accompanying intraformational mudstone seals, and represents a realistic reservoir target. Critical appraisal of core and geophysical log data has allowed the recognition of similar facies and scales of cyclicity to those at the surface, making outcrop studies a valuable source of data for the likely facies stacking patterns, and permits a higher degree of confidence in the prediction of the spatial distribution of potential reservoirs. Understanding the development and distribution of large-scale fluvial systems is critical in predicting reservoir development and prospectivity in the subsurface. Outcrop studies such as these can aid this process, by providing important information on the likely subsurface distribution of the reservoir sandbodies, their geometry and connectivity, and on likely positions and types of heterogeneity. This can assist in subsurface exploration and reservoir modelling.

Introduction

Coal-bearing strata of Upper Carboniferous Bolsovian (= Westphalian C) to Westphalian D age are generally poorly exposed in northwest Germany, but crop out in quarries in the Osnabrück-Ibbenbüren area, close to the Dutch border ([Figure 1](#)). This paper describes the sedimentology and sedimentary architecture of the fluvial-channel sandbodies present in the succession, identifies cyclicity on different scales, and attempts to attribute such regular patterns of sedimentation to intrinsic and extrinsic influences upon the basin fill.

Successions of similar age are also present in the nearby subsurface, where they are characterized by high net-to-gross sands in upwards-fining successions. These form realistic hydrocarbon targets, although the absence of good seismic-reflection data has hindered progress in mapping potential reservoirs. Studies of core and geophysical log data from wells in northern Germany have allowed the recognition of facies and scales of cyclicity similar to those seen at outcrop, and hence outcrop studies can provide important information on the likely subsurface distribution of the reservoir sandbodies, their geometry and connectivity.

In recent years, research has emphasized the role of sea-level changes upon the architecture of coal-bearing successions. Such work has demonstrated that cyclic sedimentation of varying scales

probably resulted from relative sea-level rise and fall, which in turn was caused by orbital forcing, glacio-eustasy and climatic change, all of which were probably intimately linked. However, just as important in alluvial plain settings is the interaction between changes in both the rate of sediment supply and the rate of generation of accommodation space. These result either from tectonism or climatic change in the source area or by variations in basin subsidence respectively. This paper will discuss the possible controls on the observed architecture.

1. Geological and sedimentological setting

During Upper Carboniferous times, northern Germany formed part of the West European Carboniferous Basin, outcrops of which today stretch from Ireland into Poland (Maynard et al. 1997; [Figure 1](#)). Throughout much of the early Westphalian, coal-forming conditions interdigitated with lacustrine environments on a low-lying, low-gradient, poorly drained alluvial floodplain. By Bolsovian times, hinterland uplift, linked to Variscan orogenic processes in the south, led to the formation of major perennial sandy fluvial systems that transported large volumes of sediment into the basin. Although coal-forming environments persisted into Westphalian D times, the gradual change from a humid to a semi-arid climate, brought about by the rain-shadow effect of the rising Variscan mountain chain, meant that poorly drained conditions were gradually replaced by a better-drained redbed setting (Besly 1987). By late Carboniferous (Stephanian) times, sedimentation was dominated by redbed alluvial plain facies, including well drained calcrete palaeosols. Ultimately, in Stephanian to Autunian times, the foreland basin was partially inverted and its deposits cannibalized as the effects of the Variscan Orogeny spread northwards.

Outcrops and many coal exploration boreholes in the Osnabrück-Ibbenbüren area have proved strata of upper Bolsovian and Westphalian D age (Bässler et al. 1971). The entire Bolsovian succession is believed to be approximately 850 m in thickness and the Westphalian D is about 700 m thick (David 1990). Hydrocarbon wells have also confirmed younger (Stephanian) strata in the Ems area to the northwest (Schuster 1968, Hedemann et al. 1984, Josten et al. 1984). The outcrops in the Osnabrück-Ibbenbüren area form faulted inliers surrounded by younger Permian (Zechstein) and Triassic successions. They form part of the more extensive northwest-trending Nordwestfälisch-Lippische lineament on the northern margin of the Mesozoic Munster Basin (Bässler et al. 1971). This Upper Carboniferous succession has undergone major compressional deformational episodes, particularly linked to late Carboniferous (Variscan) and late Cretaceous inversion events (Drozdowski 1985). The coals are typically bituminous to semi-anthracites and show an increase in rank towards Piesberg, where the coals attain anthracite rank (Hoyer et al. 1971, Stadler & Teichmüller 1971).

Little previous detailed sedimentological work has been published on these successions, although the work of David (1987, 1990), Selter (1990), Jankowski et al. (1993) and Glover & Jones (1997) are notable exceptions. David (1990) recognized various depositional environments, of which braided rivers, overbank siltstones, swamps (coals), crevasse splays, lacustrine and brackish-water are common. Of these, major northward-flowing channel systems were the most significant (David 1987, 1990). The work presented here agrees broadly with the facies model suggested by David (1990), although no evidence for brackish-water deposits was identified from core or outcrop studies.

This paper focuses on the Bolsovian and lowermost Westphalian D successions exposed in three quarries ([Figure 2](#)). These are Piesberg (Geologische Karte 3614, sheet Wallenhorst: R 34 33 500 / H 57 99 200), Schwabe (GK 3712, sheet Tecklenburg: R 34 10 600 / H 57 96 800) and Woitzel (GK 3612, sheet Mettingen: R 34 11 500 / H 57 98 700) ([Figure 1](#)). The oldest part of the succession is exposed in Schwabe quarry, where approximately 50 m of upper Bolsovian coal-bearing facies are present, spanning the interval from the Dreckbank to just above the Bentingsbank coal ([Figure 2](#)). At

Woitzel Quarry about 25 m of coal-bearing lower Westphalian D strata are exposed, with one main coal present (the Alexander), which is thought to be equivalent to the Bänkchen coal of Piesberg (Figure 2). The Piesberg quarry exposes approximately 190 m of a coal-bearing sandstone-dominated succession, believed to be of lower Westphalian D age. This age is based on both macrofloral (the presence of *Neuropteris ovata*) and palynological evidence. There are at least seven coal seams present, which are thought to encompass the succession from the Zweibänke to Bockraden coals, although at present the Bockraden coal is not exposed (Figure 2; David 1990).

The successions in all three quarries comprise grey-bed coal-bearing facies. They are typically dominated by thick, commonly coarse-grained, sandstones that define gross upward-fining cycles, and siltstones, claystones and coal seams are present in subordinate amounts. Most of these sandstones can be classified as sub-lithic arenites, with a few lithic wackes, lithic arenites and arenites. The dominant detrital grain types are monocrystalline and polycrystalline quartz (up to 50%), chert, and rock fragments, with feldspar, mica, organic matter, detrital clay and heavy minerals present in minor amounts. The majority of the rock fragments are of re-worked sedimentary, probably intraformational, origin, with some subordinate amounts of meta-sedimentary (welded sandstone fragments), metamorphic and undifferentiated igneous/metamorphic clasts. Feldspar is uncommon, with the current low abundances probably reflecting significant proportions of kaolinitized and illitized pseudomorphs after feldspars. The sandstones have undergone a complex diagenetic history, with the presence of blocky authigenic quartz and carbonate cements a common feature. Porosities in subsurface samples tend to be low and restricted primarily to microporosity, whereas samples from outcrop tend to have secondary intergranular macroporosity.

2. Sedimentary facies, depositional setting and channel style

Detailed sedimentary analysis, carried out at the three main quarries, has allowed the recognition of four main facies associations: channel belt (82%), lake (10%), mire (5%) and poorly drained alluvial floodplain (3%), divisible into ten facies types (Table 1).

2.1 Channel belts

The term “channel belt” describes compound sandbodies comprising the deposits of separate channels that amalgamate to form multi-storey and multi-lateral units. Channel belts are of large lateral extent and thickness (tens of kilometres in width and up to 50 m in thickness) and rest on laterally extensive erosion surfaces. Geophysical log correlations demonstrate that these surfaces are correlatable for many kilometres, possibly even tens of kilometres parallel to flow (Figure 3). In the Piesberg quarry, four channel belts are identified, although only the lowermost few metres of the top one is exposed (Figure 4).

Within each channel belt (Figure 5) it is possible to work out a chronology of channels based on the occurrence of cross-cutting erosion surfaces. The internal architecture of each channel sand-body can be described in terms of large-scale channel elements, of which barforms are the most important. Barforms are macro-forms that scale in width and depth to that of the channel in which they formed and they represent long-term products of river systems (American Society of Civil Engineers 1963, Bridge 1985). These are described in more detail in Tables 2 and 3.

2.2 Channel types

The term “channel” is here used to mean a sandbody or sandbody component that can be inferred to be the deposit of a single active channel. The identification of different barform types, combined with detailed palaeocurrent analysis, allows the identification of two main channel types:

downstream-accretion dominated and lateral-accretion dominated (Tables 1, 2). In nearly every channel belt studied there is a systematic upward change from channels dominated by sandy downstream accretion to those dominated by heterolithic lateral accretion. Their characteristics are discussed below.

2.2.1 Downstream accretion-dominated channel

Channels dominated by downstream accretion form about 52 per cent of the succession and generally occurring in the lower parts of channel belts ([Figure 4](#), [Figure 5](#)). Channels typically vary from 10 m to 20 m in thickness, although complete channel fills are rarely preserved because of erosion by overlying channels. They have widths in excess of the working area of the quarries (i.e. hundreds of metres or more). Channel bases are highly irregular and erosive, scouring down in places by up to 10 m, and typically have an overlying pebbly lag conglomerate composed of intraformational mudstone, coal and extraformational vein quartz, with minor chert and quartzite clasts. Sandstones form up to 95 per cent of the channel fill. This varies from fine- to coarse-grained, and is pebbly in places. In addition, intraformational mudstone, coal and rare siderite clasts occur. Siltstone is present, forming thin, laterally impersistent beds and laminae.

A variety of different bedforms and barforms occur. Both mid-channel and side-attached barforms are present, and simple and compound types can occur ([Table 2](#)). These barforms can be more than 12 m thick. Trough and planar-tabular cross bedding are common sedimentary structures ([Table 3](#)). Foreset and bounding-surface measurements generally show unidirectional trends (towards the northwest) and indicate that downstream accretion was the dominant process, although limited amounts of lateral accretion have been documented ([Figure 5](#)).

2.2.2 Lateral accretion-dominated channel

This type of channel forms up to approximately 30 per cent of the observed facies and is usually restricted to the upper third of an individual channel belt ([Figure 4](#)). Complete channel fills are commonly preserved and each channel may be interbedded with floodplain facies. These channels are smaller than the channels dominated by downstream accretion, 4-15 m thick, and comprise sediment bodies 100-400 m wide. Although sand-dominated, the fill of this type of channel is more varied. Siltstone forms an appreciable component, and claystone and coal are present in minor amounts (<3%), the latter two generally restricted to abandoned channel plugs.

Compound side-attached barforms tend to form important elements in these channels; mid-channel bars are absent. The former are gently inclined (<10°), asymptotic or sigmoidal in form and are heterolithic, generally showing a decrease in both grain size and scale of sedimentary structure up the length of individual beds ([Table 2](#)). Palaeocurrent measurements are usually oblique or normal to the dip of the accretion surfaces in these channels, indicating that lateral accretion was important ([Figure 5](#)). Adjacent to this type of barform a mud-filled lenticular channel plug is usually preserved ([Figure 5](#)).

2.3 Floodplain facies

Non-channelized floodplain deposits are represented by three facies associations: lake, mire and poorly drained alluvial flood-plain, forming up to 18 per cent of the succession. These facies associations can be divided into eight facies ([Table 4](#)). They typically form the upper parts of gross upward-fining successions, where they form discrete layers, 2-10 m thick, that separate the channel belts ([Figure 4](#), [Figure 5](#)).

No particular vertical or lateral changes in lacustrine or palaeosol facies types were recorded at

outcrop, although studies by the authors of subsurface successions in northern Germany reveal a systematic change in palaeosol types, with younger (late Westphalian D to Stephanian) parts of the succession showing evidence for progressively better-drained palaeosol types, including ferrosols and calcretes.

Two types of coals were found in the outcrop successions: laterally continuous ones that can be correlated across large distances (kilometres to tens of kilometres) and thin lenticular ones often restricted to abandoned channel reaches. The presence of coals appears to control the depth of scour of channel bases. Where coals are present within the succession, channels typically erode down to them but not through them. This is probably a function of the cohesive properties of the peat, which was particularly resistant to erosion (McCabe 1984).

2.4 Depositional setting and channel style

The facies described suggest that deposition occurred on a large alluvial plain where laterally extensive fluvial channel systems formed the most important component. This is in general agreement with earlier models proposed for this part of the Westphalian in northwestern Germany (David 1990, Jankowski et al. 1993). Palaeocurrent measurements indicate that the dominant flow direction was towards the west-northwest (Figure 6). Hence, the Bolsovian to Westphalian D succession is believed to record a fluvial system fed from the highlands beyond the Variscan Front to the southeast of the district. A significant southwesterly palaeocurrent component and northeasterly increase in net-to-gross ratio was also recognized during this study (Figure 3, Figure 7), and may indicate the existence, at times, of an axially fed fluvial system, derived from the northeast or east. The lack of marine facies suggests a setting far removed from the open sea.

The identification of two different types of channel sandbody indicates two distinct fluvial styles. The channels dominated by downstream accretion were bedload-dominated rivers, characterized by large barforms that migrated predominantly down stream. Channels were probably braided in form and produced fairly wide and extensive river tracts. The presence of different scales of channels, together with the evidence for large channel barforms, suggests that channel belts formed from multi-channel depositional systems. Their high degree of lateral mobility resulted in channel belts that are much wider than those of the active channels. Minimum channel depths must be greater than the preserved thickness of individual barforms, so deep rivers in excess of 15 m are envisaged in some instances, although they probably ranged from 10 m to 20 m. These should be considered as minimum figures and are derived from the post-compactional thicknesses of the preserved sandbodies. The width of the overall braided river system is difficult to quantify but may have been a kilometre or more.

The channels dominated by lateral accretion produce thinner, more heterolithic deposits. The absence of mid-channel bars suggests that the flow was generally confined within single channels. Palaeocurrent measurements indicate that flow was mainly across the barforms and that lateral accretion processes were important (cf. Smith 1987, Leeder 1999). Hence it is considered that these represent point bars and that the channel deposits were the result of highly sinuous rivers. In many instances the full channel thickness is preserved and a range of channel depths is indicated, varying from 4 m to 15 m. Again, these should be considered as minimum figures, derived from the post-compactional thicknesses of the preserved sandbodies. Active channels were narrower than the channels dominated by downstream accretion, and widths, based on preserved abandoned channel plugs and point bar length, probably ranged from 40 m to 150 m. The sandbodies produced by the process of lateral accretion are obviously larger than the original channel widths, and typically range from 100 m to 400 m across.

The channels dominated by lateral accretion deposited a mixture of bedload and suspended

sediment load. The finer grain size of some (not all) of these channels indicates that they were probably muddier than those formed by downstream accretion. Flow fluctuations are indicated by mud-filled scours on bar tops. Channel abandonment was an important process, possibly linked to meander (neck or chute) cut-off. Following abandonment, these channels formed shallow oxbow lakes that filled with a variety of low-energy deposits, mainly muds, but including peat.

Flanking the river channels were fairly extensive floodplains. Floodplain facies are typically grey, indicating that waterlogged reducing conditions were prevalent. Deposition in shallow lakes that occupied much of the floodplain is envisaged. Muddy suspension deposits dominate, although small-scale upward-coarsening successions indicate that minor deltas and minor channel systems were present. Areas on the margins of the lakes and closer to the channels were vegetated, as indicated by the preservation of root traces. Limited amounts of reddening and colour mottling indicate periods of slightly better drainage, possibly linked either to water-table fluctuations or to a better-drained location on the floodplain (e.g. in overbank-levee settings close to channels).

Following periodic abandonment of the fluvial systems, shallow-water conditions were developed and vegetated mires were able to form. Gley and semi-gleys are common and represent soil profiles formed under poorly drained hydromorphic conditions. Histosols (peats) also formed, now represented by coal seams.

Table 3 Detailed descriptions of other elements within the channel-belt facies association.

Channel elements	Sub-elements	Description	Interpretation
Thalweg deposits	Minor bars	Sand-dominated. Small-scale, simple bars within thalweg areas. Similar to simple, mid-channel bars. Up to 3m thick, deposits up to 10m thick and lengths >100m	Small, slip-face bounded bars within channel thalweg.
	Bedforms	Sand-dominated. A variety of sedimentary structures including trough and planar-tabular cross-bedding, cross-lamination, and parallel lamination. Typically present as sets and cosets with subhorizontal bounding surfaces. Palaeocurrents variable but dominantly unidirectional. Beds up to 2m thick, deposits up to 10m thick, lengths up to 100m.	Downstream migration of asymmetrical bedforms, under the influence of lower flow regime conditions.
	Thalweg channel plugs	Lenticular shaped deposits. Variable lithological fills, including sandstone, siltstone, claystone and coal; commonly heterolithic. Small scale trough and planar-tabular cross-bedding and cross-lamination. Up to 100m across and 6m thick.	Deposition of clastics from suspension & traction in abandoned channels. Coals formed by autochthonous & allochthonous accumulation of organic material in the abandoned channel.

Chute/ bartop channel	Bedforms	Sand-dominated. A variety of small-scale sedimentary structures. Typically cross-lamination, some small scale trough and planar-tabular cross-bedding and parallel lamination. These form sets and cosets with subhorizontal bounding surfaces. Palaeocurrents variable but dominantly unidirectional. Beds up to 1m thick and less than 30m across.	Chute channels form by scouring across the tops of barforms during lowering of flow stage. Sedimentary structures produced by the migration of asymmetrical bedforms, under the influence of lower flow regime conditions.
	Suspension deposits	Typically carbonaceous siltstones and claystones; plant-rich. Massive or laminated. Dark grey to black. Beds up to 2m thick and less than 30m wide.	Deposition of mud from suspension in abandoned chute channels.
Channel Lag	Winnow lag	Pebbly conglomerate, composed of well-sorted, well-rounded, small pebbles. Clast-supported. Occurs lining the base of a channel. Lenses up to 0.2m thick and 5m in length.	Prolonged reworking and winnowing of pebbles at the base of a channel.
	Lag conglomerate	Pebbly conglomerate, composed of poorly to moderately sorted, subrounded granules to large pebbles. Clast-supported. Occurs at the base and at random levels within a channel. Common coaly plant stems. Beds up to 1m thick and tens of metres in length.	Deposition of coarser sediment fraction and waterlogged plant stems typically at the base of the channel. Some reworking and winnowing.

3.1 Scales of cyclicity

Analysis of outcrop and subsurface Bolsovian and Westphalian D successions in northwest Germany indicate a repetitive sequential development of strata such that several large-scale fining-upwards cycles may be recognized (Figure 3). These are best demonstrated from geophysical well logs, of which approximately 200 (mostly proprietary) logs were examined. Three orders of cyclicity have been recognized (Table 5).

First-order cycles are typically hundreds of metres thick (i.e. generally within biostratigraphic control) and are beyond outcrop resolution. They commence with a widely developed sandstone complex (Figure 3), the base of which is typically coarse grained and conglomeratic. In relatively proximal locations (east and southeast) these thick multi-storey-multi-lateral complexes (up to several tens of metres thick) form packages of sandstone that are remarkable in their lateral extent; log correlation suggests that they cover areas of hundreds of square kilometres (Figure 3). In more distal settings (west and northwest), the percentage of sandstone decreases and the sands are typically finer grained, but still amalgamate at the bases of cycles (Figure 3, Figure 7).

Each first-order cycle can usually be further divided into four or five smaller-scale second-order cycles (Figure 3). These are usually beyond outcrop resolution, although excellent exposures at Piesberg quarry enabled a near-complete second-order cycle to be examined (Figure 4, Figure 5). A typical second-order cycle comprises a gross upward-fining succession typically 120–200 m thick (Table 5). Coarse-grained, often conglomeratic, sandstones form thick sandbody complexes at the base of such cycles, passing upwards into floodplain mudstones and multiple palaeosols (including coal) at the top. These cycles can usually be correlated for tens of kilometres laterally (Figure 3).

Third-order cycles produce fining-upwards successions up to about 60 m thick (Table 5, Figure 4). Outcrop studies allowed for the detailed examination of this order of cyclicity. The sedimentary

facies show a predictable stacking pattern, characterized by channel-belt-dominated facies in the lower part (82%) and floodplain-dominated facies in the upper part (18%) ([Figure 4](#), [Figure 5](#)).

Table 4 Detailed descriptions of the poorly drained alluvial floodplain, lake and mire facies associations recognized from the Upper Carboniferous in the Osnabrück-Ibbenbüren area.

Facies association	Facies	Main features	Interpretation
Poorly drained alluvial floodplain	Alluvial palaeosol/overbank	Claystone and siltstone, reddish brown, purple grey, greenish grey, sandy lenses, rooted, mottles, listrics, brecciated, destratified, rare desiccation cracks, sphaerosiderite. In successions up to 6m thick, laterally continuous for hundreds of metres.	Suspension deposition on a vegetated alluvial floodplain. Shallow water becoming well-drained at times. Succession is pedoturbated and shows features attributed to periodic gleying and semi-gleying.
	Crevasse splay	Individual beds of fine to medium-grained sandstone. Generally less than 0.6m in thickness; form laterally continuous sheets a few hundred metres across. Interbedded with floodplain facies. Bed bases sharp or erosive, commonly fine upwards. Current ripple cross- lamination, climbing ripples, small-scale sets of cross-bedding, undulatory lamination, plane bedding.	Sand-laden, unconfined flood events. Breaching of main channel forms crevasse channel which introduces flood deposits into adjacent floodplain area. Unidirectional, lower flow regime currents dominant. Occasional upper flow regime conditions indicated by plane beds.
Lake	Open lacustrine	Grey to dark grey and black siltstones and claystones, laminated, some plant material, carbonaceous, siderite beds. Up to 2m thick, > 100's metres wide	Deposition from suspension in the central parts of a perennial lake. Reducing conditions.
	Shallow lacustrine	Dark grey to black claystone and siltstone, carbonaceous, siderite beds, laminated, listricated, rooted. Up to 0.5m thick, > 100's metres wide.	Deposition from suspension in a perennial lake. Reducing conditions indicated. Shallow water conditions suggested by rooting.
	Lacustrine delta	Coarsening-upward succession, with silty sandstones passing upwards into fine- to medium-grained sandstone. Cross-lamination & climbing ripples in lower parts, cross-bedded in upper part. Upper part typically erosively based. Up to 3.5m thick, > 100's metres wide.	Deposition from largely unconfined flows in the proximal parts of a small lacustrine delta. Tractional flows, associated with high fallout of sediment from suspension. Upper, erosively based part probably represents channelised flow in small distributary channel that supplied sediment to the delta.

Mire	Histosol (coal)	Coal, inferior coal; banded, occasional clastic intercalations. Generally sheet-like, occasionally lenticular. Up to 1m thick, laterally continuous for hundreds of metres, possibly tens of kilometres. Can also occur as laterally discontinuous lenses.	Authochthonous accumulation of organic material in a peat-forming mire. Clastic intercalations represent flooding events. Discontinuous lenses represent deposition in abandoned river channels.
	Gley	Claystone, siltstone, occasionally sandy, extensively rooted, destratified, common listrics, some siderite nodules. Up to 2m thick, laterally continuous for hundreds of metres, possibly tens of kilometres.	Poorly-drained soil horizon, formed by pedogenesis in a waterlogged, reducing environment. Low aggradation rates. Features are indicative of modern day gley soils.
	Semi-gley	Grey and green grey mudstone, massive with sporadic root traces and rhizocretions, weakly mottled, minor signs of syn-pedogenic oxidation such as reddening down root traces or the oxidation of sphaerosiderite nodules	Similar to gleys (i.e. palaeosols formed through groundwater hydromorphism). However, short periods of water table lowering have led to the formation of iron oxides in the upper parts of the profiles and down root traces.

In nearly every channel belt studied, there is a systematic upwards change from sandy channels dominated by downstream accretion to heterolithic channels dominated by lateral accretion ([Figure 4](#), [Figure 5](#)). This is believed to reflect a temporal change in channel form from a low sinuosity multi-channel braided-channel type to a high-sinuosity single-channel system. The upper parts of both second- and third-order cycles have greater thicknesses of finer-grained floodplain deposits and coals. Coals tend to have a systematic distribution in the succession and stack at the tops of both the second- and third-order cycles. The presence of coals at the top of third-order cycles may have acted as baffles to erosion during subsequent channel incision. The result has been to produce layered large-scale multi-storey and multi-lateral sandbodies.

3.2 Driving mechanisms controlling cyclicity

The change in fluvial style upwards through a cycle represents a long-term change in channel form, and slope, discharge, sediment load and vegetation all affect channel patterns (Leopold et al. 1964, Schumm 1977). Channels adjust to an alteration of hydrological regime by changing channel widths, depths, gradient, meander wavelength, sinuosity, and width-depth ratios. It is known that channel meandering is favoured by relatively low slopes, a high suspended load to bedload ratio and cohesive bank sediments (Leopold & Wolman 1957). The possible cause of the cyclicity and the associated change in channel form are the subject of the following discussion.

Table 5 Main characteristics of the different scales of cyclicity recognized in the Upper Carboniferous of northern Germany.

Cycle order	Thickness	Description	Cause
1	Hundreds of metres	Large-scale upwards-fining succession, with coarse-grained multi-storey channel sands at base and mudstone prone tops.	?Orogenic/tectonic cycle in the hinterland – likely source in the east (?Baltica region) – a Caledonide zone formed by collision between Eastern Avalonia and Laurussia into Baltica.
2	Typically 120–200 m	Upwards-fining cycles, characterized by thick, stacked, coarse-grained channels at base and multiple coal-palaeosol horizons at the top. Typically contain 2–3 smaller-scale upwards-fining third-order cycles; each successive third-order cycle containing less sand.	Hinterland tectonic pulses, e.g. movement along the Tornquist-Teisseyre or Rynkøbing Fyn High Zone. Produces large pulses of sediment flux.
3	40–60 m	Upwards-fining successions, characterized by thick, stacked, coarse-grained low-sinuosity channels at base passing upwards into meandering channel systems, lacustrine muds and poorly drained palaeosols and coals.	?Tectonically driven source area climatic fluctuations resulting in variations in the amount of precipitation. This affects sediment flux and base level in the basin.

The principal controls on the stratigraphical architecture of sedimentary systems in basins are rates of accommodation-space generation and sediment supply (Shanley & McCabe 1994).

Accommodation space is generated by the combined effects of thermal subsidence, eustasy, loading and compaction, and sediment supply determines how much of this accommodation space is filled up (Jervey 1988, Weltje et al. 1998). Recent advances in our understanding of the sedimentary response to relative sea-level variations means that the cyclicity recognized here could be fitted into a model whereby eustasy forms the dominant controlling mechanism. However, this is not thought to be the case, as there is good evidence that both Variscan tectonics and changes in climate were more important during late Carboniferous times (Besly 1987, Jankowski et al. 1993), and it is proposed that the cyclicity observed results from these controls.

3.2.1 Evidence for Variscan tectonic influence

Towards the end of the Carboniferous ([Figure 8](#)), the Gondwanan plate collided with both the Laurentian plate to the west and the Iberian plate to the south, linked as part of the Asturian deformation phase of the Variscan orogeny (Warr 2000). The principal direction of Variscan convergence was probably towards the north and northwest as part of an oblique (dextral) collisional regime. By about Bolsovian–Westphalian D times the final Asturian phase of deformation began, which ultimately led to the formation of the Pangaeon supercontinent ([Figure 8](#)). This closed off the Rheic Ocean such that all access to the sea was cut off in central Europe and the UK (Maynard et al. 1997). There is clear evidence that Variscan orogenic processes affected northern Germany during the Westphalian and Stephanian, and that the deformation front migrated northwards. This gave rise to a flexural foreland basin and the northwards migration of the depocentre, with the result that alluvial-plain sedimentation became dominant in Germany, with sediment being supplied from the uplifted Variscan mountain belt to the south and east. The evidence for this includes:

- Isopachs with a strongly asymmetrical pattern ([Figure 9](#)), with up to 4 km of strata accumulating in northern Germany (Drozdowski 1993). This can be explained by flexure of the crust in advance of loading by Variscan nappes.
- The recognition of a disconformity between Westphalian and Stephanian strata in northern

- Germany (Hedemann & Teichmüller 1971, Hedemann et al. 1984), linked to Variscan uplift.
- During Bolsovian and younger times, Variscan uplift led to a significant increase in the amount of sediment delivered into the basin, with some associated re-working of pre-existing basin material (Gayer et al. 1993, Jankowski et al. 1993). This high proportion of sandstones is particularly marked in the east, in the Hamwiede Schneverdingen and South Oldenburg areas, and there is a progressive decrease westwards and northwestwards towards the Ems area ([Figure 3](#), [Figure 7](#)). Palaeocurrent data for these channel sandbodies show strongly unidirectional flow directions towards the west and northwest, away from the rising Variscan mountains ([Figure 6](#)).
 - Studies of potassium/argon (K/Ar) cooling dates for detrital muscovites from Upper Carboniferous sandstones in northwest Germany show two distinct cooling ages and indicate that strong rejuvenation of the upper crust occurred during the Bolsovian (Küstner 2000).
 - Heavy-mineral and detrital-zircon age variations in sandstones from the southern North Sea show that a significant provenance change occurred between the Duckmantian and the Bolsovian, linked to Variscan tectonic activity (Morton et al. 2001, 2005).
 - Limited heavy-mineral data are also available from the northwest German Upper Carboniferous subsurface succession (R. Knox & C. Hallsworth, personal communication 2003). The occurrence of rounded tourmaline overgrowths appears to display the strongest stratigraphical control, with common overgrowths in Westphalian D and younger sandstones. The rounding of the overgrowths indicates that they must have been derived from the transportation of older metasedimentary source rocks. Younger Stephanian successions have higher amounts of chrome spinel than older strata. A heterogeneous source is indicated, comprising metasediments, gneisses and ultramafic rocks. The most obvious source of sediment would be the rising Variscan mountain belt to the south, possibly in the Rhenish Massif area, although the Fenno-Scandinavian Shield and Baltic depression area may also have contributed sediment (Hallsworth & Chisholm 2000, Morton et al. 2001).

On the basis of the evidence outlined above, it is clear that Variscan tectonics had a strong influence on both the generation of accommodation space in the West European Carboniferous Basin area and by providing detritus to fill the basin. These effects became more pronounced in the late Westphalian and during the Stephanian. The source of the Westphalian sediments in northern Germany probably lay to the east or the south, in the area of the Fenno-Scandinavian Shield and Baltic depression and the Rhenish massif. The source area comprised predominantly metamorphic rocks, although with some granites and associated hydrothermal deposits. The variations in composition described are likely to represent either progressive unroofing of different rock types or switching of sediment source areas and changes in the regional palaeoslope. The presence of sandstone clasts (in Stephanian sandbodies) indicates re-working and cannibalization of earlier lithified sedimentary successions during progressive uplift of the hinterland.

3.2.2 First- and second-order cyclicity

Following on from the evidence presented above, it is believed that the largest-scale cycles (first and second order) were tectonically driven, related to the Variscan–Asturic phase of deformation. First-order cycles are attributed to periods of large-scale tectonic activity such as terrane docking and accretion. The first-order scale is probably equivalent to the inversion megasequence described by Fraser et al. (1990) and relates to the onset of tectonically influenced sedimentation within the basin. The main feature of such deformational events was the relatively large volume of sand that entered into the basin by erosion of the newly emergent orogen ([Figure 7](#)). This would be deposited as clastic wedges in proximal parts of the basin. Generation of accommodation space was linked to foreland-basin development, primarily controlled by downflexing of the lithosphere in response to thrust loading and, in some cases, to subsurface loads transmitted from the subduction zone (Jordan

1981). Flexural downwarping resulted in rapid subsidence adjacent to the thrust load, with subsidence rates gradually decreasing away from the thrust front (Figure 9), producing the asymmetrical depression described by Drozdowski (1993).

The relationship between tectonics and sedimentation is not a simple one in which the syntectonic wedges of clastic sediment prograde from the basin margins following tectonic activity, but depends on the interaction of various processes, including sediment supply, sediment type, configuration and rigidity of the basement, flexural isostatic compensation, the development of accommodation space and the response to eustatic sea-level changes (Johnson & Beaumont 1995, Miall 1997). There will generally be a timelag between tectonic activity and the response of the fluvial system, such that periods of high sediment flux often coincide with periods of reduced, rather than increased, subsidence (Crews & Ethridge 1993). Ultimately, high sediment yields from the source area result in rapid progradation of the fluvial systems and the formation of a first-order cycle.

It is proposed that second-order cyclicity is also tectonically driven and that these cycles are linked to regional tectonic events along major fault systems. These stresses are transmitted laterally by intraplate stress (see Cloetingh et al. 1985, Cloetingh 1986). Whether these movements represent intrabasinal tectonic events, such as movement along the Elbe Lineament or Tornquist-Teisseyre Zone (Figure 1), or far-removed hinterland events, is unknown.

It could be argued that a tectonic control is unlikely to be responsible for the repetitive nature of these cycles and that such regular cyclicity is more likely to represent a response to eustatic changes. Albeit at a different frequency to the likely Westphalian examples described here, Talling et al. (1994) described regular phases of coeval motion on multiple contractional structures in the Cretaceous–Eocene thrust belt of central Utah (Axhandel Basin). Similar major clastic wedges are present in the Gulf of Mexico, dating back to early Tertiary times (Fisher & McGowan 1969, Galloway 1989). These clastic wedges are a few hundred metres thick and can be linked to Laramide orogenic pulses, such that each cycle represents a period of major sediment supply driven by hinterland tectonism (Galloway 1989).

3.2.3 Third-order cyclicity and changes in fluvial style

It is suggested that each third-order cycle represents the sedimentary response to stratigraphical base-level changes (*sensu* Shanley & McCabe 1994), although the driving mechanism behind this remains speculative. Stratigraphical base-level represents a surface of equilibrium that fluctuates in response to allocyclic controls, such as tectonic subsidence, eustasy, sediment supply and discharge. In such situations, variations in stratigraphical architecture are produced by the interaction of the rate of sediment supply and the rate of change in accommodation (*ibid.*).

Although it is clear that a sea-level linkage could produce the cyclicity described, there is no direct evidence for such a control. Elsewhere in Europe and North America there is good support for Upper Carboniferous base-level changes being driven by glacio-eustatic sea-level rises (Holdsworth & Collinson 1988, Maynard & Leeder 1992, Flint et al. 1995). However, most of this evidence comes from Namurian and early Westphalian strata, and, as discussed previously, the structural setting of northern Germany in the Bolsovian suggests that the Rheic Ocean had closed and that there was no direct marine connection to this basin (Maynard et al. 1997). In an inland basin such as this it is often difficult to be sure of the role that sea level has on facies patterns. If sea level was controlling the local base level, then this must represent a subtle influence that is not represented in the preserved succession by marine facies. No marine or tidal facies were identified from upper Westphalian and Stephanian successions in this area.

Alternatively, third-order cycles could be driven purely by tectonic processes, possibly linked to

short-term episodes of crustal loading (see Miall 1996: 477). However, such a mechanism alone may not produce the high-frequency events required to drive the cyclicity at this scale. Although not well constrained, it is thought likely that these third-order cycles have a timespan comparable with fourth-order sea-level cycles (10^5 years).

Hoffman & Grotzinger (1993) suggest that the climatic belt in which an orogen develops influences the tectonic style of the orogen and the architecture of the adjacent foreland basin. Monsoonal belts, such as those that would have characterized Upper Carboniferous times, would be typified by high rates of precipitation, leading to rapid erosional unroofing, deep erosion and the rapid filling of the foreland basin with sediment (Sinclair & Allen 1992, Hoffman & Grotzinger 1993). Drier periods would have less vegetation cover and hence would be characterized by increased erosion of bedrock, which would result in large volumes of material being available for transportation (Schumm 1968, Cecil 1990).

Olsen (1990) recognized two scales of cyclicity from Devonian meandering channel systems from east Greenland, one of the order of *c.* 20 m thick and a higher-order one at *c.* 100 m. He attributed these to climatic variations as a result of changes in Earth's orbital parameters, reflecting 20000 yr Milankovitch precession cycles with modulation by *c.* 110000 yr eccentricity cycles. Although it is possible that Milankovitch orbital forcing could account for the third-order cycles described here, the structural setting in northern Germany at this time makes it more likely that these cycles represent the product of changes in the balance between tectonically induced accommodation and climatically modulated sediment supply. Similar climatic controls on Carboniferous and Devonian non-marine successions have been described respectively by Glover & Powell (1996) and McKie & Garden (1996).

It is proposed that times of hinterland uplift resulted in greater orographic precipitation and hence the basal channel-belt-dominated parts of each third-order cycle reflect the rapid expansion of fluvial systems as the amount of clastic flux outstrips the accommodation space available. The change in fluvial style upwards through a cycle and the increased frequency of coals and other floodplain deposits indicates a decrease in the efficiency of the fluvial systems, a reduction in stream gradients and an elevation of the groundwater table. In a hydrographically enclosed system such as this, high rates of precipitation and any concomitant basinal subsidence would increase both the amount of sediment aggradation and raise the base level. Thus, relative base-level (effective lake-level) rise results in the progressive drowning of fluvial systems. The resulting decrease in the efficiency of the fluvial systems to transport the coarse clastic fraction is thought to be the main cause of the change from low- to relatively high-sinuosity fluvial systems and ultimately into floodplain conditions.

This hypothesis is difficult to prove conclusively, as evidence for intra-cycle variations in climate is lacking in these successions. However, climatically controlled facies changes have been proven from the Westphalian D and younger successions of northern Germany and the UK, and primary redbed facies, including calcretes and localized alluvial fans, all indicate deposition under increasingly drier and more arid conditions, linked to the growth of a rain shadow associated with uplift of the Variscan mountains (Besly 1987, 1988). It is also known that in younger Westphalian D and Stephanian successions, the effects of increased evapotranspiration are manifested by a change to better-drained palaeosols and an absence of coals upwards through a cycle. This may indirectly support the view that climatic controls operated during earlier times.

4. Implications for reservoir studies

Approximately 95 per cent of known German gas reserves are from the Lower Saxony area in the northwest. Reservoirs are mainly the Rotliegend (Permian) sandstones and, although most of the

obvious larger structures have been tested, the underlying Carboniferous remains underexplored. The Carboniferous play in northern Germany has been described by Gautier (2003). The principal source rocks are Westphalian coals and carbonaceous shales, with derived hydrocarbons dominated by type III kerogen (Cornford 1998). There is little published information concerning gas composition available, but sweet dry gas is likely. Channel sandstones form the reservoirs, with the seal provided by overlying Rotliegend shales or evaporites. In this setting, trapping configurations could be structural closure or stratigraphical, against the overlying Saalian unconformity or where Carboniferous sandstones are enclosed by mudrocks.

Producing Carboniferous fields do exist in northern Germany, but reservoirs are complex and burial-related diagenesis of the highly feldspathic lithic-rich fluvial sandstones is commonly severe and typically results in the reduction of reservoir quality. However, Gautier (2003) predicted that, given significantly improved seismic resolution and more reliable sedimentological and stratigraphical models, the Carboniferous play probably holds the greatest potential for new gas discoveries in this area. Hence, it is clear that an understanding of the development and distribution of these large-scale Carboniferous fluvial systems is critical in predicting reservoir development and reducing risk. In addition to Permian subcrop patterns and diagenetic variations, the most obvious questions from an exploration perspective relate to prediction of reservoir units within structural closure. This necessitates an understanding of Westphalian depositional systems in both time and space, based on a well constrained stratigraphical framework or model. Regional subsurface studies indicate that the cyclicity described from the Bolsovian-Stephanian of northern Germany is deterministic, characterized by repetitive facies stacking patterns. Hence, the recognition of the different types and scales of cyclicity can have a significant impact on basin-, field- and reservoir-scale understanding.

4.1 Exploration scale

Reservoir distribution is related to basin-scale processes that have interacted to produce cyclical sequences such that potential reservoirs are not randomly distributed through the stratigraphical succession, as would be predicted by a purely stochastic model. Correlations shows that thick stacked sandbodies with high net-to-gross ratios not only occur in the more proximal (southeastern) parts of the basin but can also be predicted to occur in the medial parts, where they will be preferentially stacked at the bases of first-order cycles on a repetitive vertical scale of approximately 160–200 m ([Figure 10](#)). On a regional scale, second- and third-order cycles are more difficult to correlate, indicating some lateral variability.

This work has identified stratigraphical levels within the Bolsovian, which are more sand prone, providing a predictive framework for exploration. Typically, a cycle is 160–200 m thick and commences with a widely developed sandstone complex, covering areas of tens to hundreds of square kilometres ([Figure 10](#)). Such sandstone-prone intervals locally form important gas reservoirs in northwest Germany and also in northeast Netherlands (e.g. the “Tubbergen Sandstone”). Although probably part of a different depositional system, similar sequences and regionally developed sandstone complexes have been identified in the Dutch-UK offshore (S. Kelly, personal communication, 2003).

4.2 Field scale

The distribution of reservoir and reservoir-quality variations within a Carboniferous field is typically a complex problem, with reservoir volume, connectivity and productivity being particular issues. In the early phase of field life, there is little hard data; reservoirs are modelled either stochastically or objectively with a stochastic component to try to “capture” uncertainty. Volumetrics, well planning and production profiles rely on the accuracy of actual data and analogue input to these models. A

robust correlation framework and an understanding of sandbody types and distribution are needed.

The work presented here predicts that high net-to-gross reservoirs should be field wide or greater in extent and possess a distinct layering, alternating with floodplain fines. These sandstone bodies are concentrated towards the bases of second-order cycles, with narrower, more ribbon-like, heterolithic sands located higher in the cycles. The reservoirs are clearly layered on a second-order scale, with the tops of cycles comprising mud-dominated floodplain and lacustrine associations that are laterally continuous on a field scale and hence form potential barriers to fluid flow (see [Figure 3b](#)). The recognition of second- and third-order cyclicity allows correlation of channel-belt scale sandbodies rather than individual channels.

The upper Bolsovian and lower Westphalian D channels are interbedded with coals that formed from peat mats that were resistant to channel erosion (cf. McCabe 1984). Hence, depth of incision of these channel systems is commonly controlled by the locations of the coals. In the middle to upper Westphalian D and lower Stephanian, coals are mostly absent, so there is the potential for the sandbodies to incise deeply into floodplain mudstones. Sandbodies within the middle to upper Stephanian are not well understood and sandbody architecture may differ as a result of changes to a more arid climate. Studies of Stephanian successions in the Saale Basin to the southeast by one of the authors indicate that less-confined ephemeral channel systems are increasingly important, but this change appears to be accompanied by an overall decrease in sediment flux, resulting in smaller channel systems.

The observations and concepts described here allow a greater deterministic component in modelling early in the life of a field with less dependence on a stochastic approach.

4.3 Reservoir scale

Sedimentary architecture plays an important role in flow performance, particularly where internal baffles and barriers are present in the reservoir. Hence, the characterization of internal heterogeneity has important implications for the reservoir assessment, particularly the recovery strategy. In some Carboniferous fields in Germany the productivity of individual sand-bodies is often highly variable, despite apparent similarities in thickness or log character. Variability within and between sand-bodies is a complex issue with many obvious controls, e.g. grain size, sorting, compaction and cementation, in addition to the geometry, orientation and connectivity of the sandbodies themselves.

The third-order scale of cyclicity controls the fluvial style and hence the degree of sandbody heterogeneity in medial and distal settings. This is an important factor for more detailed production-focused reservoir modelling, including the prediction of field-scale baffles. This work shows that third-order cycles, and potential reservoir sands (channel-belt deposits) in particular, are traceable on a field scale, but correlation becomes more difficult over distances in excess of a few kilometres. Within channel belts, individual channel sands are not correlatable; they are laterally impersistent and are commonly truncated by other channels. Heterogeneity is uncommon and, where present, is laterally discontinuous (e.g. as lenticular, bar-top scour fills), tending not to compartmentalize the sandbody. Hence, barriers to flow tend not to exist in the lower channel-belt sands. In the upper parts of third-order cycles, lateral accretion-dominated channels become important. These channels are generally smaller, finer grained, and have a greater degree of heterogeneity, with mud-draped laterally accreted barforms and muddy channel plugs a common feature. They are often enclosed by mud-prone floodplain facies, resulting in a strong vertical and lateral compartmentalization in the upper parts of third-order cycles.

5. Discussion and conclusions

The outcrops in the Osnabrück-Ibbenbüren area of northern Germany provide important new information on the sedimentology of these Upper Carboniferous successions. In particular their study provides a better understanding of the nature and geometry of the fluvial sandbodies. Determination of channel types and a detailed understanding of the internal architecture of sandbodies is not easy, using core or wireline studies alone. However, work such as this, while helping with reservoir characterization in general, also assists the understanding of the Upper Carboniferous of the northern German subsurface, as the nearest wells are only a few tens of kilometres away.

The observed stacking patterns and cyclicity would fit into a sequence stratigraphical model, whereby base-level changes, controlled by glacio-eustatic sea-level oscillations, and there is good evidence for such processes occurring in the Upper Carboniferous. However, tectonic processes operating in both the basin and adjacent orogenic zones are thought more likely to have exerted the dominant control. Variscan compressional activities which took place farther to the south during the Bolsovian-Westphalian D, not only affected the amount and type of sediment delivered into the basin but also controlled the generation of accommodation space in the basin. This is good evidence that tectonic processes controlled the generation of cycles and stacking patterns within each cycle. It is also suggested that there is a distinct climatic signature controlling cyclicity, modulating the stacking patterns and ultimately impacting on fluvial style.

A better understanding of fluvial style, architecture and stacking patterns leads to benefits in the understanding of hydrocarbon reservoirs. The deterministic nature of the facies is an important feature to bear in mind when modelling reservoirs. It is evident that these high net-to-gross Upper Carboniferous reservoirs are clearly layered and vertically compartmentalized. Thus, the implications for modelling is that such systems cannot be modelled simplistically as a “tank of sand” and detailed assessment and correlation is required in order to identify and distinguish intra-reservoir baffles, such as remnant overbanks and barform drapes.

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