Dinantian and Namurian depositional systems in the southern North Sea

From Earthwise

Jump to navigation Jump to search

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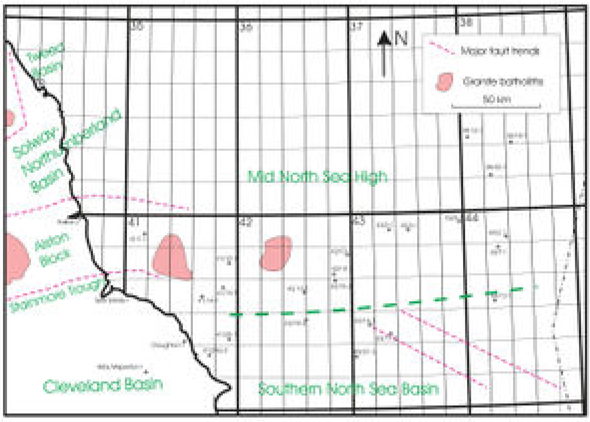

Figure 1 The UK sector of the southern North Sea, showing many of the wells with deeper Carboniferous penetrations and some of the main tectonic elements.

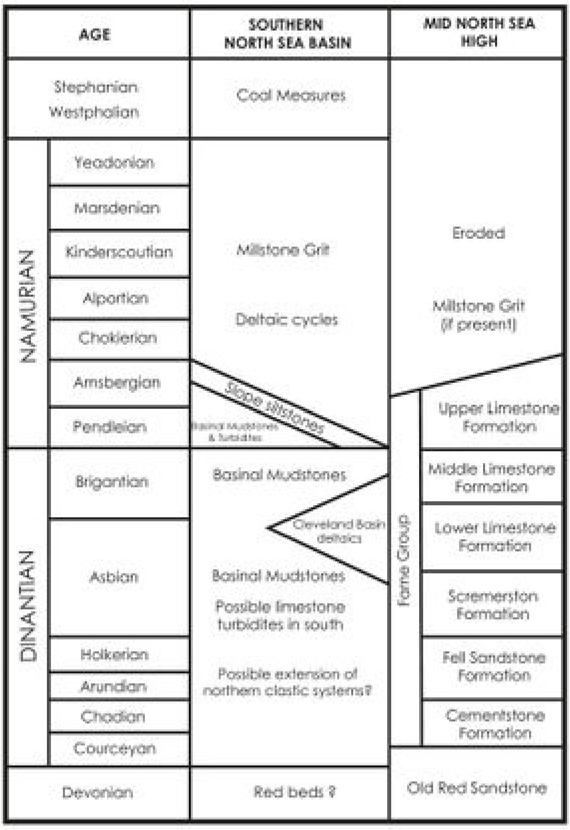

Figure 2 Stratigraphic frameworks for the Dinantian and Namurian sediments of the

Mid North Sea High and the Southern North Sea Basin.

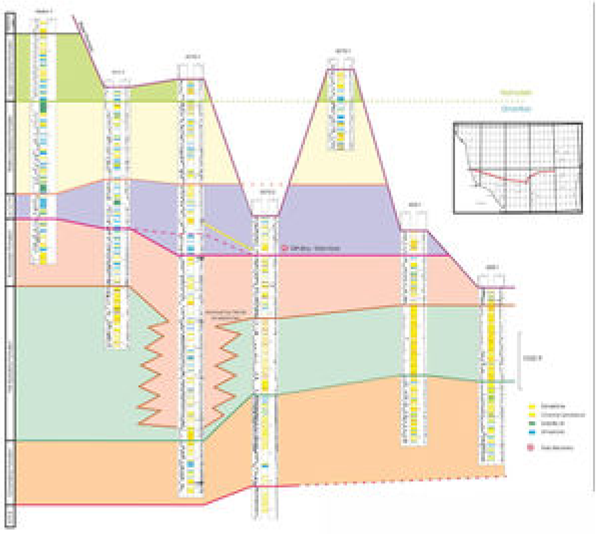

Figure 3 A correlation panel for key well sections in the Dinantian and Lower Namurian of the Mid North Sea High.

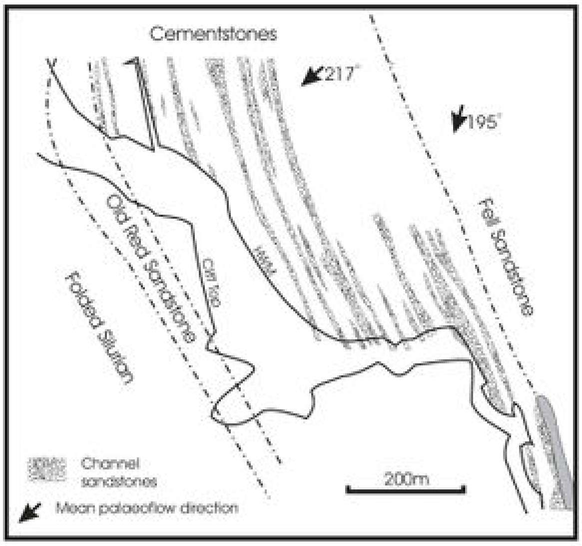

Figure 4 A map of the intertidal foreshore at Burnmouth, Berwickshire (c. NU 960605), showing the extents and stacking patterns of the channel sandbodies in the Cementstones.

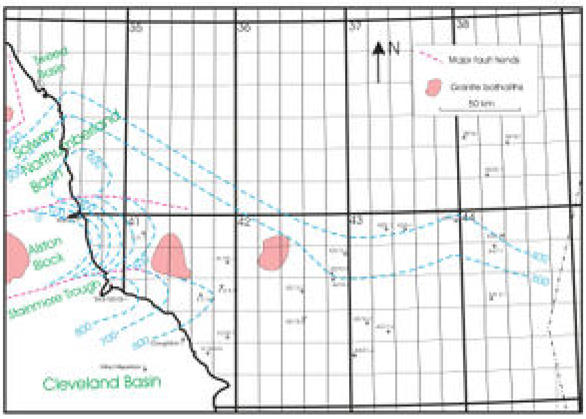

Figure 5 An isochore map of the Fell Sandstone Group with thicknesses in

metres.

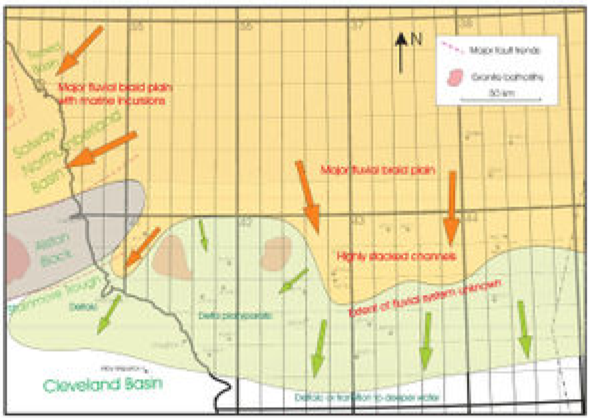

Figure 6 A palaeogeographic map for the Fell Sandstone Formation interval.

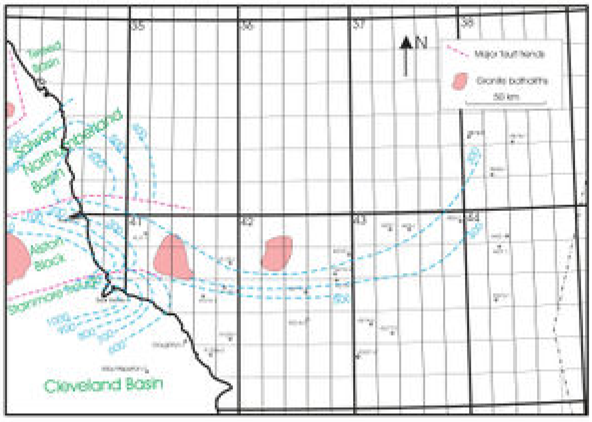

Figure 7 An isochore map of the Scremerston Coal Group and its equivalents.

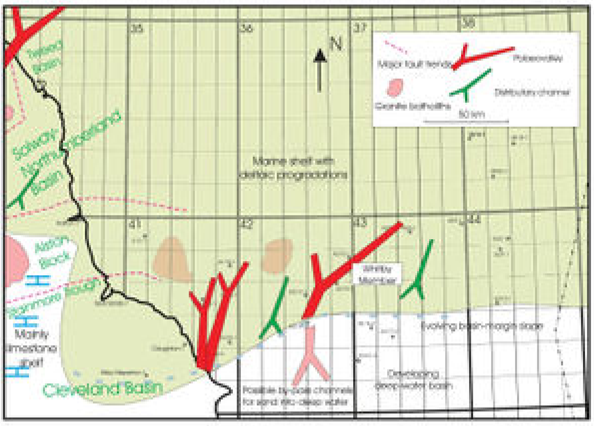

Figure 8 The palaeogeography of the Lower Limestone Group, highlighting the occurrence of two types of channel sandbody, regular delta distributaries and larger palaeovalleys.

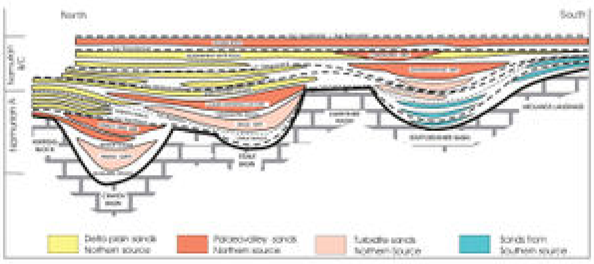

Figure 9 An idealized cross section through

the Pennine Basin complex, showing the progressive basin fill from north to south through the progradation of turbidite-fronted deltas fed by a northern sand provenance.

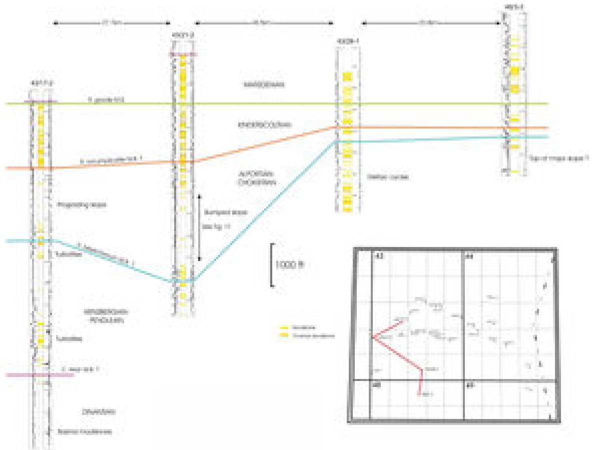

Figure 10 Correlation panels showing the major deep penetrations of Namurian strata in the Southern North Sea Basin.

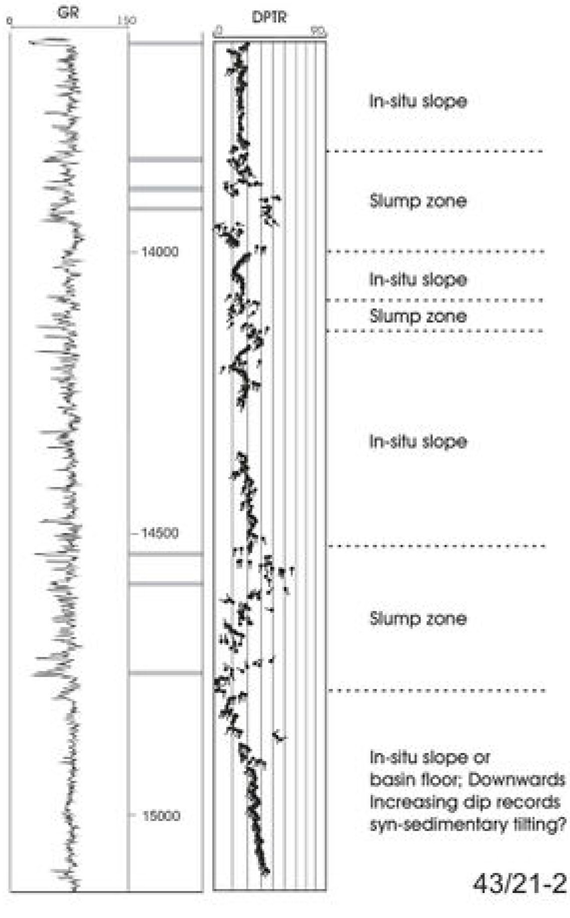

Figure 11 An interpreted dipmeter log, shown alongside a gamma log of part of well 43/21-2.

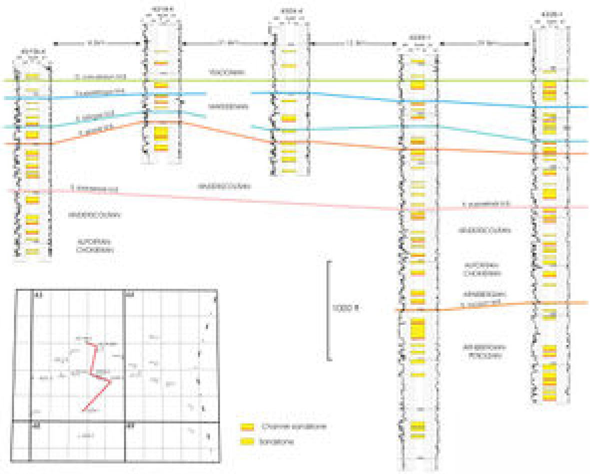

Figure 12 A correlation panel for wells that penetrate typical cyclic Millstone Grit Namurian successions.

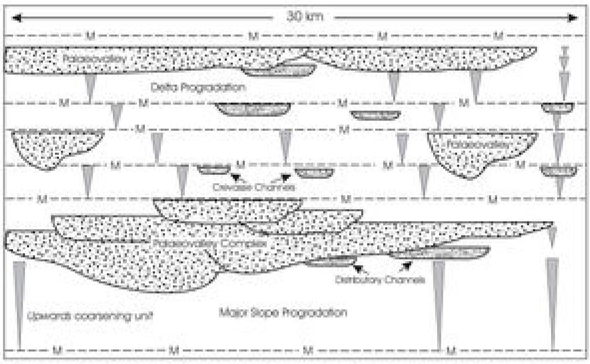

Figure 13 A cartoon showing the idealized relationships between marine bands (M), upwards-coarsening units, distributary channel sandstones and palaeovalleys in a typical Millstone Grit association.

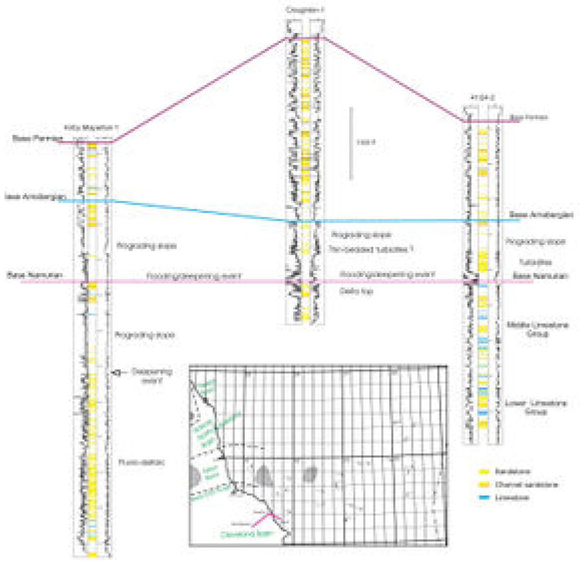

Figure 14 Correlation panel of key wells in the Cleveland Basin and offshore Yorkshire.

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Contents

Summary

On the southern margin of the Mid North Sea High, large areas of Dinantian and early Namurian strata subcrop the base-Permian Unconformity. To the south, beneath the Southern North Sea Basin, stratigraphically equivalent units lie below the penetration of all but the deepest wells and are overlain by younger Carboniferous strata. The Dinantian and early Namurian succession of the Mid North Sea High compares closely with that of the Northumberland coast. All the main stratigraphical units recognized in Northumberland extend across the area, although thicknesses vary somewhat. Vertical changes in sedimentary character probably resulted from a changing subsidence regime, changes in supply from a distant northern provenance and the increasing importance of eustatic changes of sea level. The Dinantian of the Southern North Sea Basin is rarely penetrated by wells. It is likely to be dominated by basinal mudstone successions, but may include turbidite sandstones derived from northern deltas and also limestone turbidites derived from carbonate platforms to the south. The area is probably fragmented into sub-basins defined by northwest–southeast–trending structures. The transition between the northern Yoredale facies and the southern deepwater facies is poorly understood. Deepwater conditions persisted into the early Namurian in the Southern North Sea Basin, where a thick mudstone succession includes both marine bands and thin turbidite sandstones. Deep water was eliminated by the advance of a major fine-grained slope from the northeast, characterized by large-scale slumping and sliding. This probably occurred in Arnsbergian times. Above the slope succession, the Namurian compares closely with the Millstone Grit of the Pennines. Marine bands, mainly Yeadonian and Marsdenian in age, have been recovered in cores from several wells; extrapolation from these key wells and into older strata, using palynostratigraphy, spectral gamma data and an appreciation of onshore marine bands, has allowed a stratigraphical framework to be developed. The upper parts of upwards-coarsening deltaic units comprise mouth-bar and thin distributary-channel sandstones, as well as interdistributary bay and delta-plain intervals that include thin coals. Much thicker, multi-storey and coarser-grained channel sandstones also occur at several stratigraphical levels. These palaeovalley fills provide the main reservoir potential in the Namurian, as their coarser grain size allows better reservoir properties to survive burial. In addition, thin transgressive quartzitic sandstones retain good permeability, in spite of their fine grain size, and can flow gas at high rates. Potential source rocks include Scremerston Formation coal seams, Dinantian basinal mudstones and Namurian basinal mudstones, including marine bands that are oil prone. Together these could have generated very significant volumes of gas. Palaeovalley fills within the Yoredale succession and palaeovalleys and transgressively reworked sandstones in the Namurian provide the greatest reservoir potential.

Introduction

The main thrust of Carboniferous hydrocarbon exploration in the southern North Sea has focused on the Westphalian succession as a provider of both gas-prone source rocks (coals) and sandstone reservoirs in both coal-bearing and redbed facies. Older Carboniferous intervals have received less attention, because their sourcing potential is less obvious, they tend to be very deep, reservoir quality is generally rather poor, and some traps require intra-Carboniferous seals, which are thought less obvious than the well established Permian Zechstein and Silver-pit seals. In spite of rather low levels of encouragement from exploration efforts targeting Namurian and Dinantian reservoirs, the deeper Carboniferous levels remain relatively unexplored, and potential remains. Gas discoveries in Dinantian and Namurian sandstone reservoirs in areas distant from Coal Measures Group occurrences point to both source and reservoir potential in these older rocks. The comparative lack of field developments is a function of field size, reservoir quality and distance from existing infrastructure. Oil and gasfields sourced from Namurian and Dinantian mudstones and, in some cases with Namurian sandstone reservoirs, are features of both onshore eastern England and the Irish Sea. Although most offshore gas accumulations depend on sealing at the base-Permian Unconformity, onshore oilfields demonstrate the viability of intra-Carboniferous seals for oil and there is evidence that some Carboniferous mudstone intervals act as seals for gas in the southern North Sea (e.g. well 43/20b-2).

This paper attempts to summarize the sedimentary regimes in which Dinantian and Namurian successions of the southern North Sea were deposited and the constraints that this places on the hydrocarbon potential of the area. It is derived, to a large extent, from work over the past 12 years on multi-client studies and on an appreciation of time-equivalent outcrop analogues in northern England and Ireland.

1. Structural framework

Like many areas north of the Variscan tectonic zone, the structural history of the southern North Sea is one of successive reactivation of older, mainly Caledonoid, lineaments during periods of both extension and compression. Across the southern North Sea, the main structural grain trends northwest to southeast. The present-day patterns of sub-Permian subcrop and the trapping structures of Carboniferous-reservoired gasfields reflect late Carboniferous Variscan compression, which inverted many faults that, in the early Carboniferous, had acted as extensional structures, controlling hanging-wall depocentres. A similar history prevailed onshore (e.g. Fraser & Gawthorpe 1990). Later movements on major structures such as the Sole Pit Lineament, led to exceptionally deep burial of Carboniferous sediments, with deleterious effects on reservoir quality.

1.1 Early Carboniferous tectonics, bathymetry and sediment provenance

Variscan extension of dominantly north–south orientation began to influence the British Isles and adjacent offshore areas in late Devonian or early Dinantian times (Leeder 1986, Fraser & Gawthorpe 1990). It persisted with variable intensity into the early Namurian, after which a phase of thermal subsidence prevailed until late Westphalian times, when a compressional tectonic regime took over, inverting many of the earlier extensional structures. The early extensional regime acted upon a heterogeneous crust in which older, mainly Caledonoid, lineaments were reactivated. In the southern North Sea, these structures had a dominantly northwest–southeast orientation, reflecting Caledonian compression along the northeastern edge of the Midlands–Brabant micro-craton (Coward 1990) and the general trend of the Avalonia and Baltica suture (e.g. Soper & Woodcock 1990). Farther west, onshore northern Britain and Ireland, a northeast–southwest structural trend dominates, reflecting the Iapetus suture and earlier lineaments such as those through Wales and the Welsh Borders (Fraser & Gawthorpe 1990, Kirby et al. 2000). Further heterogeneity, which strongly influenced crustal response to extensional stress, was provided by granite plutons of Devonian and older ages ((Figure 1); Donato et al. 1983, Donato & Megson 1990). These are known at outcrop in northern England (e.g. Cheviot) and southern Scotland, and in the subsurface of northern England and in the southern North Sea. The influence of the Weardale and Wensleydale granites on the Dinantian subsidence history of the Alston and Askrigg blocks is well documented (e.g. Chadwick et al. 1995, Kirby et al. 2000) and similar influences can be inferred or predicted for the Market Weighton, Amethyst and other offshore granites (Collinson et al. 1993).

The major extensional faults onshore that were active in the Dinantian led to the development of tilt blocks and half-graben basins (e.g. Lee 1988, Fraser & Gawthorpe 1990, Leeder & Hardman 1990, Kirby et al. 2000). Depending on the abundance of clastic sediment supply, different areas developed different bathymetric patterns. The main source of sediment supply to both the onshore and offshore basins, throughout the Dinantian and the Namurian, was from the north. A prolific source area of dominantly feldspathic sand, probably in the Norwegian or Greenland Caledonide belt, made the major contribution, with components from Archean and other older terranes (e.g. Drewery et al. 1987, Morton & Witham 2002). The Midlands micro-craton (Midlands Landmass; St George's Land) shed much smaller volumes of sediment northwards (e.g. Trewin & Holdsworth 1973). This was dominantly quartzitic sand, which penetrated only short distances northwards in onshore areas from Anglesey to the Widmerpool Gulf in Dinantian and early Namurian times. Similar sandstones have not been recognized in the Southern North Sea Basin. In the UK sector, the only known southerly derived sands have a high lithic component and are associated with late Westphalian uplift in the main Variscan fold zone and with the development of a foreland basin.

During the Dinantian, both onshore UK and across the southern North Sea, sediment supply led to systematic differences in depositional styles and bathymetry. South of the Craven faults onshore, where clastic supply was small or non-existent, carbonate deposition dominated during the Dinantian. The higher parts of tilt blocks became sites of shallow-water limestone deposition, while deepwater basinal conditions developed over more rapidly subsiding areas (Miller & Grayson 1982). The Derbyshire Massif provides an excellent outcrop example of such a setting. A great thickness of shallow-water platform limestones in Asbian times became fringed by a narrow reef belt and steep marginal slopes covered by submarine talus aprons.

The southern edge of the Askrigg Block also behaved in this way in late Dinantian times, with reef knolls developed within the Craven Fault zone. An important difference compared with Derbyshire is that the Askrigg Block was buoyed up by granite, resulting in a much thinner and incomplete Dinantian limestone succession on the block. Also, the intermittent encroachment of northerly derived clastic sediment to the block margin, at the southern extent of Yoredale facies, gave a more mixed depositional regime. Other block margins, for example the Pendle Lineament, produced more gently inclined ramps extending into deep water, with associated Waulsortian facies in the Worston Shale Group (Earp et al. 1961, Miller & Grayson 1982). Elsewhere within the Pennine Basin and offshore, a similar Dinantian regime can be inferred, from seismic reflection (e.g. Fraser & Gawthorpe 1990, Kirby et al. 2000) and gravity data (e.g. Lee 1988). A carbonate shelf probably extended northwards from the Midlands Landmass close to the north Norfolk coast, before falling off rapidly into a deeper-water basin. The consequence of these depositional regimes was that by end-Dinantian times the area had a highly differentiated bathymetry, with deep mud-dominated basins and shallow limestone platforms causing topographic relief on the sea floor of several hundreds of metres. This bathymetry survived into the Namurian and, in spite of being blanketed by early Namurian mudstones, the inherited accommodation space acted as a template for early episodes of Namurian sand-rich deposition (Collinson 1988).

To the north of a line roughly corresponding with the North Craven Fault onshore and offshore probably trending eastwards from around the mouth of the Tees, a contrasting depositional regime prevailed. There, clastic sediment supply balanced or exceeded subsidence causing alluvial plains and shallow-water deltas to dominate the area. Onshore, differential subsidence associated with tilt-block extension had no topographic expression, but thicknesses of cyclothems change across major faults (e.g. Chadwick et al. 1995). As a result, no deepwater facies were developed in this area throughout the Dinantian and Namurian.

The offset in the latitude of the boundary between these contrasting basinal regimes, probably occurring close to the present-day coastline, may have resulted from later sinistral strike-slip movements on a northern extension of the Dowsing Fault zone (Coward 1990), although this is far from clear. The subsurface Cleveland Basin appears to have had a rather complex history, with distal deltaics in mid-Dinantian times, followed by an episode of subsidence that gave deeper-water basinal conditions at the end of the Dinantian, as shown by the succession in the Kirby Misperton-1 well. This basin was eliminated by the progradation of a basin-margin slope in the early Namurian. The nature and timing of tectonic activity along the transition zone between the northern block area and the southern basin, and its relationship with activity in the Cleveland Basin, are discussed later.

2. Stratigraphical framework

The two areas of contrasting depositional style, outlined above, when encountered offshore in sparsely cored and widely spaced wells, require different working stratigraphical frameworks (Figure 2). In the north, both onshore from Northumberland to North Yorkshire and offshore, on the Mid North Sea High, an essentially lithostratigraphic scheme can be applied with reasonable consistency. In the virtual absence of appropriate biostratigraphic data, which might allow a more rigorous chronostratigraphic framework to be applied, such an approach is the only way forwards. Farther south, in basinal areas both onshore and offshore, a chronostratigraphic framework, based on ammonoid-bearing marine bands, can and must be established before any lithostratigraphic scheme is meaningful.

2.1 The Mid North Sea High

The sub-Westphalian succession in the northern area, both onshore and along the Mid North Sea High, mainly comprises strata with a more or less complete Dinantian succession present (Figure 3). Offshore, this has been termed the Farne Group (Cameron 1993), an interval that extends into the lower Namurian. Cameron divided this group into several formations, whose names are based to some extent on those of units of the Northumberland outcrop, which have been previously called "groups" (e.g. Scremerston Coal Group is equivalent to the Scremerston Formation offshore). The upper part of the Farne Group is lumped together as the "Yoredale Formation" by Cameron. This is thought to be unsatisfactory and there is clearly some uncertainty in the literature (e.g. Maynard & Dunay 1999) about the stratigraphical status of some of these lithostratigraphic units. The Yoredale Formation, equivalent to the Lower, Middle and Upper Limestone groups of the onshore area, can be subdivided in a similar fashion offshore. In this paper, therefore, Cameron's (1993) "Yoredale Formation" is not used and the equivalent strata are described using the old group designations as formation names (e.g. Middle Limestone Formation) within the Farne Group. The Namurian succession is restricted to the lowermost part (Pendleian–Arnsbergian), the Upper Limestone Formation.

The facies characteristics on which these formations are distinguished appear to be remarkably constant across the southern North Sea, and the offshore succession can be confidently correlated back to the outcropping section on the Northumberland coast, even though the diachroneity, which characterizes the onshore area, almost certainly continues in the offshore subsurface. The lithostratigraphy, and its relationship to Dinantian and Namurian stages, is set out in (Figure 2).

Although the palaeontology and palynology of the Dinantian and Namurian successions broadly constrain the ages at the level of stages, the most refined stratigraphical framework in all but the lowest part of the Dinantian succession is based on the recognition of limestone beds. Onshore, these define the individual Yoredale cyclothems and they can be mapped extensively at outcrop. Particular limestones are used locally as markers for the boundaries of larger-scale stratigraphical units such as the Scremerston Coal Group and the Middle Limestone Group. However, when traced across larger areas, the facies differences, which are the main basis for defining the lithostratigraphic units, are shown to cut across the limestone stratigraphy and, therefore, to be diachronous.

The boundary between the Middle to Upper Limestone formations coincides with the Great Limestone at outcrop. It is identified in the subsurface at the thickest limestone and it coincides with an upward increase in sandstone content. It can be regarded as broadly coinciding with the base of the Namurian, defined in basinal sections by the *Cravenoceras leion* Marine Band, although *C. leion* has been found both above and below the Great Limestone (Johnson et al. 1962, Dunham & Wilson 1985). Other boundaries are identified in wells by changes in the overall character of the succession, mainly as inferred from wireline logs (Figure 3). The base and top of the Fell Sandstone are marked by the incoming and dying out respectively of thick massive sandstones, the Scremerston Coal Formation is characterized by conspicuous coals seams, whereas the boundary between the Lower and Middle Limestone formations is distinguished by an upward reduction in the proportion of sandstone. In these last cases, the limestone that most closely coincides with the overall change is arbitrarily selected as marking the boundary. As that selection is usually based on wireline logs alone, it may not coincide precisely with the named limestones that mark the boundaries at outcrop, or even with limestones selected in other wells. In the absence of extensive core, such uncertainty is unavoidable.

The Millstone Grit, if present offshore, is likely to be of late Arnsbergian or younger in age, by analogy with the succession on the Northumberland coast (Turner & Spinner 1992). However, there are no known occurrences of such a unit across the Mid North Sea High where Dinantian or Namurian Yoredale facies subcrop the base-Permian Unconformity.

2.2 The Southern North Sea Basin

In the southern basinal part of the onshore area, Dinantian strata are in either shallow-water limestone facies or are deepwater mudstones or limestones, or both, as in the Derbyshire Massif and the Craven Basin. Offshore the shallow-water facies are poorly known, at least within the UK sector, and the name Zeeland Formation has been proposed by Cameron (1993). Dinantian deep basinal mudstone facies are seldom penetrated by wells. Where encountered, they are assigned ages based on palynology. The name "Bowland Shale Formation" within the Whitehurst Group has been suggested for similar Namurian facies, but nothing explicit has been assigned to Dinantian examples (Cameron 1993).

A wide range of markedly diachronous Namurian siliciclastic facies is present offshore in the basin. It is thus important to establish a stratigraphical framework independent of facies if the basin-fill history is to be reliably reconstructed. Onshore, this type of framework has been achieved through high-resolution chronostratigraphy, using stages based on and subdivided by ammonoid-bearing marine bands (Figure 2). Over 60 such bands are present throughout the Namurian, each with its own distinctive ammonoid fauna. In addition, other fossiliferous bands have less diagnostic faunas and are thought to reflect less than fully marine conditions. Marine bands are believed to record eustatic highstands and are associated with flooding and condensation events, irrespective of overall facies context (Holdsworth & Collinson 1988, Martinsen et al. 1995). The current estimate of the duration of the Namurian, based on SHRIMP age analysis of zircons, is about 5.5 million years (Riley et al. 1995), suggesting that marine bands, on average, formed at intervals of about 90000 years. Such resolution is exceptional within the stratigraphical record, especially in the Palaeozoic.

The recognition and optimum use of marine bands depends upon the identification of ammonoids and this has limited their use offshore. Traditionally, coring focused on reservoir intervals and often began in the top of a sandstone reservoir, just below the point where a marine band is most likely to occur. Consequently, marine bands were rarely cored, and reliance was placed on the much lower resolution of palynology. Spectral gamma logs allow the recognition of marine bands through their high uranium content, but assigning a name to such marine bands is poorly constrained in the absence of core. The appraisal and development of the Trent and Cavendish gasfields, which have Namurian reservoirs, led to the deliberate coring of non-reservoir intervals in order to recover marine bands and rigorously establish the local stratigraphy. The detailed palaeontology carried out on these wells has provided a much firmer calibration for the spectral gamma logs around those fields, especially within the Kinderscoutian–Yeadonian interval (see (Figure 12)). However, the farther removed, both geographically and stratigraphically, from those key sections, the greater the uncertainty, and reliance has to be placed on palynology, on log character of the marine bands and their adjacent strata, and on intuition based on knowledge of the onshore marine-band succession. Although marine bands inferred from gamma logs have been named in most wells, identifications below the Kinderscoutian are very uncertain, although ages at the stage level are probably fairly secure.

Under the lithostratigraphic scheme proposed by Cameron (1993), the Namurian equates with the Whitehurst Group, which comprises a lower Bowland Shale Formation and an upper Millstone Grit Formation.

3. Depositional systems

The depositional systems that characterize the different areas of Dinantian and Namurian strata of the eastern England onshore and the offshore subsurface are known from relatively sparse well penetrations, especially on the Mid North Sea High. Well spacing is very variable with interwell distances of many kilometres typical. Only close to and within gas discoveries is well spacing occasionally less than 1km. Most of the well successions are known from wireline logs, with only a very small proportion cored. This is especially true for the Dinantian and Namurian on the Mid North Sea High, where many wells were drilled early in the exploration campaign. Around discoveries, particularly in the southern basin area, core coverage is more extensive as operators sought to understand better both the stratigraphy and structure of reservoir intervals and the important issues of reservoir quality. Faced with such a database, understanding the depositional systems, reconstructing palaeogeographies and predicting parameters such as sand-body dimensions have had to draw on analogues onshore.

This discussion outlines the evolving palaeogeography of the area and tries to assess the extent to which onshore analogues in Northumberland and the Pennines are valid, and the extent to which it is necessary to cast the net more widely in order to characterize the successions fully.

3.1 The Dinantian and early Namurian of the Mid North Sea High

The early Carboniferous rocks of the Mid North Sea High comprise a series of fluvial and deltaic intervals, which were supplied from a northern source area. They conformably overlie late Devonian and early Carboniferous Upper Old Red Sandstone, where seen onshore in Northumberland and southeast Scotland. The base of the Carboniferous is possibly penetrated offshore in well 42/10-2, where Old Red Sandstone facies are inferred. However, it is possible that Old Red Sandstone facies may have persisted there into the earliest Carboniferous, so that no Devonian is confidently identified.

3.1.1 The Cementstone Formation

The lowest Carboniferous unit, the Cementstone Formation is Courceyan to Chadian in age and is penetrated by three wells (42/10-2, 43/2-1 and 43/5-1), in none of which is it cored. Wireline logs suggest that the formation is characterized by interbedded mudstone and siltstone and sharply based sandstones with scattered thin limestones, similar to the assemblage seen at outcrop, for example at Burnmouth, Berwickshire ((Figure 4); Scott 1971, Leeder et al. 1981). Here, the sandstones are seen to be quite small and narrow channel sand-bodies, with lateral accretion surfaces suggesting the migration of small meandering streams on a floodplain. The occurrence of ferroan dolomite beds, pseudomorphs after evaporites, calcrete palaeosols, and reddened and variegated sediments, suggests a floodplain with ephemeral lakes in a rather arid setting.

The sparse well penetration on the Mid North Sea High, and the total lack of penetration of equivalent strata farther south, make it impossible to estimate the southern extent of the Cementstone fluvial system. Onshore, the Boulsworth-1 well in Lancashire shows evidence of a (?late Devonian) redbed facies beneath the Dinantian succession (Kirby et al. 2000). The Cementstone system offshore could have passed distally, presumably southwards, into a similar but younger terminal playa beneath the southern North Sea, prior to the development of a deep basin. Alternatively, the distal equivalent might have been a more marine-influenced deltaic succession similar to the Lower Border Group of the Bewcastle area of the Northumberland– Solway Trough, which is the lateral correlative of the outcropping Cementstones (e.g. Leeder 1974).

3.1.2 The Fell Sandstone Formation

At outcrop in Northumberland, the top of the Cementstone Formation is very sharply drawn at the base of the thick massive sandstones of the Fell Sandstone Group of Chadian to Holkerian age. A similarly sharp contact characterizes the boundary offshore where the Fell Sandstone Formation is encountered in wells 42/10-2, 43/2-1 and 43/5-1. However, the Fell Sandstone in the subsurface is not uniform in either thickness or facies (Figure 3), (Figure 5). For instance, in wells 42/10-2 and 43/2-1, the unit is 418m and 382m thick respectively, and comprises almost continuous sandstone with a very few thin finer-grained partings. To the east, at well 43/5-1, the thickness is similar (1351 ft, 412 m), but the unit is more heterogeneous with thin fine-grained siltstone interbeds and possible thin limestones in the lower part. Farther to the west, in Quadrant 41 and onshore, the situation is more variable.

In well 41/10-1, there is very little thick massive sandstone present at what appears to be the equivalent stratigraphical level. A 60 m-thick massive sandstone, probably equivalent to the base of the Fell Sandstone seen in other wells, is overlain by some 600 m of dominantly fine-grained strata, which is inferred also to include limestones, coals and thin sandstones, similar in character to the overlying Scremerston Formation. Still farther west, at well 41/1-1, thicker-bedded sandstones are again present, but they are interbedded with finer rocks and the base of the unit is not penetrated; similarly in the onshore subsurface, the situation is not clear.

In the Harton-1 well (Ridd et al. 1970) just south of Tynemouth, equivalents of the main stratigraphical units down to the Scremerston Formation are recognized. A thick-bedded sandstone, whose base is not seen, could be an equivalent of the Fell Sandstone, but is more likely to be a basal sandstone to the Scremerston Formation (Chadwick et al. 1995). Over the Alston Block, the Fell Sandstone thins to zero, illustrating the effects of the concealed Weardale Granite on accommodation space.

In contrast, the very deep well, Seal Sands-1, drilled at the mouth of the Tees in an eastern extension of the Stainmore Trough, shows a highly expanded section of equivalent strata. There is no clear-cut equivalent of the Fell Sandstone and it is less easy to split the very thick succession of Yoredale cyclothems into the formations recognized to the north and offshore. The deepest 800 m of the well section are thought likely to be distal fine-grained equivalents of the Fell Sandstone, but there is no proof of this. At Kirby Misperton-1, a sandy section about 300 m thick, may also be a distal equivalent of the Fell Sandstone, although in a different facies. This may be a proximal to distal facies transition similar to that from the Fell Sandstone of Northumberland to the Middle Border Group of Bewcastle along the Northumberland–Solway Trough (Day 1970).

At outcrop, it is clear that the Fell Sandstone is the product of a major sandy braided river system (Turner & Munro 1987). The lateral mobility of the channels led to multi-storey channel units that tended to stack in hanging wall areas of syndepositionally active faults (Turner et al. 1993). Shallow boreholes and detailed mapping show that, in its outcrop area, the unit comprises a series of multi-storey sandbodies separated by mudstone intervals, some of which have marine microfaunas. The combination of low relief, active tectonics and episodic changes in relative sea level probably gave rise to shallow marine flooding of the alluvial tract along the Northumberland–Solway Trough. Across the Mid North Sea High, the depositional regime was probably very similar, with even greater stacking of channel sandbodies across Quadrants 42–43, possibly localized by tectonic control. Differential subsidence, possibly influenced by buried granite plutons, may have influenced this control, but the database is too scattered to demonstrate this. Dominant palaeoflow offshore is thought, on regional grounds, to have been to the south. To the west of the zone of intense channel stacking, higher proportions of finer-grained strata suggest overbank or shallow coastal plains with fewer and smaller channels at well 41/10-1 (Figure 3), (Figure 6). This change takes place over a data gap of some 60 km and it quite possible that migration of the larger river channels to the west was blocked by tectonically controlled topography, as implied by Maynard & Dunay (1999), who suggested that faulting was the prime control. It seems equally possible that well 41/10-1 is drilled in a depositional shadow zone of a granite-cored block, with or without associated faulting (Figure 6). The thick finer-grained succession at 41/10-1 includes limestones and thin coal seams, and compares with the overlying Scremerston Formation; on lithostratigraphic grounds it should be included in that formation. However, thickness criteria suggest that it was deposited at a time when thick multi-storey channel sandstone units of the typical Fell Sandstone were being deposited along strike. Picking an equivalent of the top of the Fell Sandstone in the expanded Scremerston Formation in this well is somewhat arbitrary.

To the south, distal equivalents of the Fell Sandstone are unknown offshore. It is possible that continuing extension had started to create a deep basin with a well defined northern margin by this time. Fluvial sand could then have been bypassed to deeper water. On the other hand, more gradual subsidence may have created a gently inclined ramp across which deltas prograded. The succession in the Kirby Misperton-1 well can be interpreted as a possible marine equivalent but of unknown water depth. Such a transition, if correct, would compare with the increasing marine influence seen in the Fell Sandstone equivalents as they are traced down current to the southwest along the Northumberland–Solway Trough. Alternatively, they may represent a deeper-water facies. Either way, they need not provide an analogue to the depositional system that existed offshore.

3.1.3 The Scremerston Formation

This formation is the lowest of four that can be characterized as of essentially deltaic facies. It is broadly late Holkerian to early Asbian in age. Its base is drawn at the top of the massive sandstones of the Fell Sandstone, a change that is typically quite abrupt (Figure 3). The unit is characterized by the presence of coal seams, by a variable incidence of major channel sandstones and by thin limestone beds. The clear cyclicity, which characterizes later Yoredale intervals, is less apparent in the Scremerston Formation. The gamma-log signature of typical Scremerston Formation is high frequency and irregular, with few pronounced upwards-coarsening units. Some thicker channel sandstones are present, the most conspicuous being those near the bottom of the Harton-1 well, which may be somewhat anomalous at a regional scale. Coal seams are usually quite thin, but can be up to several metres thick in the Dutch sector and onshore in Northumberland.

Where channel sandbodies occur, they typically range up to about 20 m in thickness. Their distribution shows no obvious pattern. Wells such as 41/1-1 and 43/5-1 are almost channel free, whereas wells such as 41/10-1, 42/10-2 and 43/2-1 have channel sandbodies scattered throughout the interval. The thicker channel bodies are probably multi-storey and may be incised. Some thin sandstone units are characterized by very low gamma values and may be transgressively reworked units similar to the Arnsbergian Harthope Ganister of the onshore outcrop (Percival 1992). Alternatively, they may be genuine palaeosol ganisters, developed beneath coal seams.

The Scremerston Formation records the development of a low-relief coastal plain traversed by river channels. The area was episodically transgressed to allow shallow-water marine limestones to accumulate. During regressive phases, shallow lakes and lagoons were filled by minor deltaic progradations and coal swamps formed on emergent areas, probably developing thick peats during the early stages of transgression. There is a suggestion that upwards-coarsening units are more common in the south, from which one might infer a more seaward setting, where greater water depths were created during transgressions. This accords with a broadly southerly palaeoflow.

The thickness pattern of the Scremerston Formation is difficult to reconstruct in detail because of the scattered data and the generally incomplete penetration (Figure 7). Across the southern margin of the Mid North Sea High, thicknesses appear to be about 300 m, but, a little to the south, wells 41/14-1 and 41/15-1 suggest thickening to more than 500 m. This may reflect an offshore extension of the Stainmore Trough or a more local, tectonically controlled depocentre. At Seal Sands-1, the probable equivalents are about 1300 m thick. This contrasts with the near absence of equivalent strata on the Alston Block and illustrates the scale of syndepositional movement on the Butterknowle Fault. At Seal Sands-1, the section has only widely scattered and thin coals, suggesting a more offshore setting and one in which subsidence rates were too rapid to allow coal accumulation, a setting that might compare with the Upper Border Group, which is the distal equivalent of the Scremerston Formation at Bewcastle (Day 1970). In the Cleveland Basin, the nature of Scremerston Formation equivalents is somewhat speculative. In Kirby Misperton-1 well, an interval about 330 m thick of inferred thinly interbedded sandstones and siltstones, indicated by a highly serrated gamma trace, could be their equivalent but, without better biostratigraphy, this remains speculative. Their depositional setting is also uncertain. They could be a deepwater facies separated by an unseen slope from the deltaic cyclothems to the north.

3.1.4 The Lower Limestone Formation

This unit, of late Asbian age, is extensively penetrated by wells offshore. It is distinguished from the Scremerston Formation by a lower incidence of coal seams and by a much clearer pattern of upwards-coarsening cyclothems with limestones at their bases, features typical of a Yoredale facies (Figure 3). It is the earliest Carboniferous unit in which palaeovalleys, infilled by thick multistorey channel sandstones, are known to be developed (Figure 8). Large multi-storey channel units are also conspicuous at outcrop on the Northumberland coast (Gardiner 1984). The incoming of both clear cyclicity and incision may relate to an increasing eustatic control on sea level, driven by the onset of continental glaciation in the Southern Hemisphere.

One inferred palaeovalley sandstone in well 42/10-2 is the reservoir for a gas discovery and has been named the Whitby Member ((Figure 8); Maynard & Dunay 1999). Interpreted borehole image logs from that sandstone suggest cross bedding directed to the south. Maynard & Dunay (1999) suggested on the basis of similar log signatures that this sandstone could be correlated over an east–west distance of some 50 km to well 41/10-1; but, as the wells in question lie normal to the palaeoflow, it seems more likely that the log similarities are fortuitous. The southern limit of deltaic progradation is poorly constrained, as there are no certain penetrations of stratigraphical equivalents in the basin. This was a time when deepening of the Southern North Sea Basin may have started and so periods of low-stand incision could have coincided with the bypassing of sand to distal deepwater areas.

Thickness changes in the Lower Limestone Formation are quite small across most of the offshore area, with about 200 m being typical. Only at Harton-1, on the fringes of the Alston Block, and at Seal Sands-1, is the unit respectively thinner and thicker. The differences in thicknesses, and the fact that the Alston Block was flooded at this time, suggest diminishing differential subsidence. Also, the offshore area is considerably more sand rich than the equivalent intervals in the onshore Harton-1 and Seal Sands-1 wells, where limestones are much more important. The interval extends southwards in a Yoredale facies at least as far as well 41/24a-2, offshore from Scarborough. However, at Kirby Misperton-1 a relatively sand-free section some 300 m thick seems a likely correlative, although lack of robust biostratigraphy makes for uncertainty. The section at Kirby Misperton-1 is possibly in a slope or deepwater facies.

3.1.5 The Middle Limestone Formation

At outcrop in Northumberland, the base of the Middle Limestone Formation is defined at the base of the Oxford Limestone, which occurs just above the base of the Brigantian. The top is defined by the base of the Great Limestone, which broadly coincides with the base of the Namurian. The cyclothems of the Middle Limestone Formation, at outcrop, tend to be less sandy than those of the Lower and Upper Limestone formations, and the progradational parts of cyclothems show greater reworking by wave energy (Reynolds 1992). Channel sandbodies are relatively uncommon and the majority of sandbodies are of delta-front or mouth-bar origin.

Offshore, this formation is generally distinguished from its neighbours by a lower proportion of sandstones. It is characterized by abundant thin limestones, by rather thick upwards-coarsening cyclothems and by a low incidence of channels. The incidence of coal seams is somewhat variable between wells. Offshore, the interval appears to have a relatively uniform thickness, varying between 400 m and 500 m. A similar thickness occurs at Harton-1, suggesting that differential subsidence around the Alston Block continued to decline. Thickness calculations from well data are complicated by the Whin Sill, which is intruded at several levels at Harton-1 and in nearshore wells. Onshore, the expanded thickness at Seal Sands-1 suggests that the Butterknowle Fault remained active. It is clear that the expanded overall thickness at Seal Sands-1 is accompanied by an expansion in both the number and typical thickness of cyclothems. The sections at Kirby Misperton-1 and Cloughton-1 are both cyclothemic in character, although lacking the typical Yoredale facies limestones. The sections suggest that the main front of deltaic progradation advanced farther south during this interval to create shallow-water conditions in the Cleveland Basin. Offshore, the southern limit of the deltas is constrained between the deltaic facies of well 43/10-1 and the deepwater facies of Brigantian age at well 43/17-2. The lack of penetration of the unit in wells to the south of 43/10-1 is attributable to erosion at the base-Permian Unconformity and it likely that the transition zone broadly follows the mid-latitude of Quadrants 43–44.

3.1.6 The Upper Limestone Formation

At outcrop, the base of this unit is drawn at the base of the Great Limestone, which roughly coincides with the *Cravenoceras leion* Marine Band of the basinal succession. Its age in the northern Pennines and Northumberland is Pendleian to early Kinderscoutian. Strata of Chokierian–Alportian age are not certainly present, suggesting a hiatus in the succession, although no mappable unconformity has yet been detected. The Upper Limestone Group includes some thick multi-storey channel sandbodies, which are most likely incised palaeovalleys (e.g. Elliott 1976, Hodge & Dunham 1991).

Offshore, the base of the Upper Limestone Group is drawn at a thick limestone that coincides broadly with an upward change to a more sandstone-rich succession. In most wells in the north, the limestone is sufficiently prominent for the boundary to be quite confidently identified. Farther south, the boundary changes character, along with the overall sedimentology, to a more basinal aspect. At well 41/24a-2, a condensed mudstone interval with prominent inferred marine bands is thought to equate with the boundary, whereas in intermediate wells (41/14-1, 41/15-1) inferred marine-band mudstones and thin limestones seem to coincide broadly. The base-Permian erosion truncates the Upper Limestone Group and makes for rather patchy preservation. Most recorded thicknesses are minimum values. These range up to just over 300 m on the Mid North Sea High. Farther south in the Cleveland Basin onshore, thicknesses exceed 500 m in the Cloughton-1 and Kirby Misperton-1 wells, and just offshore at well 41/24a-2. The lesser thickness of 415 m at 41/20-1 suggests that original depositional thicknesses probably decreased to the north. Farther north onshore, a reduced thickness (268 m) at Harton-1 was attributed by Ridd et al. (1970) to the early incoming of Millstone Grit facies. However, the recognition of Millstone Grit facies is considered somewhat insecure (Holliday, personal communication 2003) and the thickness could therefore be greater. At Seal Sands-1, base-Permian erosion prevents meaningful comparison of thicknesses, and it is not easy to judge how far into the Namurian the highly differential subsidence seen in the Dinantian persisted. By analogy (e.g. with the Craven Basin), it is likely that differential movements were much reduced.

In the north (e.g. 41/10-1 and in Northumberland), the Upper Limestone Group shows a broadly Yoredale character, with limestones present at the bases of many cyclothems. Farther south, towards the Cleveland Basin (e.g. wells 42/24a-2, 41/14-1, 41/15-1), thicker and apparently rather silty upwards-coarsening units are prominent, and limestones are scarce or absent. This suggests a transition southwards into deeper water, where marine bands replace limestones as records of highstands, and where progradations of fine-grained slopes were more important.

3.1.7 The Millstone Grit

Rocks that have been termed “Millstone Grit” on the Northumberland coast at Longhoughton appear to be a development of late Arnsbergian coarse channel sandstone within the Upper Limestone Formation. The basal erosion surface was shown by Turner & Spinner (1992) to account for part of Arnsbergian time, but it is unlikely that it is the significant unconformity that they suggested. For the most part, Millstone Grit facies (i.e. coarse pebbly sandstones in large channel systems) of the northern Pennines occurs in rocks of Kinderscoutian or younger age.

Offshore, Millstone Grit facies have not been encountered in wells on the Mid North Sea High. They are most likely to have been eroded at the base-Permian Unconformity. However, it is possible that age equivalents of the coarse sandstones of Longhoughton are represented by finer facies in the upper parts of the Upper Limestone Formation offshore. Farther south, around the Cleveland Basin, the upwards-coarsening units, which typify the early Namurian of the Cloughton-1, Kirby Misperton-1 wells and the wells in the southern half of Quadrant 41 offshore, are overlain by channel sandstones that may, in part, correlate with the Millstone Grit of Northumberland. They are discussed along with the Namurian of the Southern North Sea Basin.

3.2 The Dinantian of the Southern North Sea Basin

Hard data on the Dinantian of the Southern North Sea Basin are very scant. They are mainly confined to well 43/17-2, which penetrated the whole Namurian basin-fill succession and continued into Dinantian strata. Some 520 m of inferred Dinantian mudstones were penetrated, all probably falling within the Brigantian. These were referred to by Cameron (1993) as the Bowland Shale Formation and are broadly analogous with the Lower Bowland Shales of the Craven Basin (Earp et al. 1961) and with the mud-rich successions beneath the Edale Shales of Derbyshire, known from the Alport borehole (Stevenson & Gaunt 1971). These onshore examples differ from the succession in 43/17-2 in that they have interbedded turbiditic sandstones. The Lower Bowland Shales include the Pendleside Sandstone, which probably resulted from the bypassing of sand from Yoredale deltas on the Askrigg Block. The Dinantian mudstones at Alport have thin limestones, which were probably derived from the Derbyshire Massif carbonate platform to the south. Both of these onshore cases may be relevant in predicting what might occur offshore.

The relationship between Dinantian deltas on the Mid North Sea High and any coeval deepwater areas to the south, and the nature and history of the basin margin, remain conjectural. However, it is difficult to imagine a situation where sands did not bypass to distal deepwater areas once such a differentiated bathymetry developed. Early Namurian turbidite sandstones at well 43/17-2 (discussed in more detail in section 3.3 below) were presumably bypassed through Upper Limestone Group deltas and there may be similar Dinantian examples elsewhere in the basin. The main problem is to identify the time at which accelerated subsidence led to the development of deep water in the Southern North Sea Basin. Distal parts of the fluvial and deltaic systems, known from the early Dinantian of the Mid North Sea High, may have extended southwards in similar shallow-water facies before differential subsidence created the bathymetric contrasts inferred from available well data for the late Dinantian. These uncertainties impact on estimates of volumes of deepwater mudstones, which are potentially important source rocks in the basin. The Kirby Misperton-1 well may provide a clue to the timing of accelerated subsidence in the area. This is discussed further in Section 4.

Dinantian limestones are known to be present on the northern fringes of the East Midlands Shelf, offshore north Norfolk, where they are referred to as the Zeeland Formation (Cameron 1993). There may also be intrabasinal highs within the wider Southern North Sea Basin, comparable to the Derbyshire Massif or the Central Lancashire High of the Pennines, which grew as carbonate platforms and formed sources of debris for carbonate turbidites. Such local highs probably also acted as barriers to sediment gravity flows and ponded turbidite sands within restricted sub-basins, similar to the situation in the Staffordshire Basin (Trewin & Holdsworth 1973).

3.3 Namurian of the Southern North Sea Basin

Most of the wells that penetrate the Namurian in the southern North Sea Basin provide sections in only its upper parts. In many cases, Westphalian rocks occur beneath the base-Permian Unconformity so that the top Namurian strata can be identified. Where base-Permian erosion has cut down into the Namurian, strata as old as Kinderscoutian may be present directly beneath the unconformity.

As reviewed earlier, reconstruction of the palaeogeographic evolution of the Namurian depends on establishing a reliable chronostratigraphic framework through ammonoid-bearing marine bands. Offshore, only around extensively cored wells, and only in Kinderscoutian and younger sediments, is it possible to have a reasonably secure framework. Beyond and below these well constrained sections, stratigraphical resolution is less precise, because it relies on palynology and on the recognition of marine bands from gamma and spectral gamma logs.

Onshore, in the Pennines, the basin-fill history involves successive progradations of turbidite—slope—fluvial sequences that progressively filled sub-basins from north to south (Figure 9) (Reading 1964, Ramsbottom 1966, 1969, Collinson 1988). The earliest of these is the Pendleian fill of the Craven Basin, after which there was an apparent slowdown in sediment supply, at least as seen at outcrop. This lasted until the Kinderscoutian, when basin-filling extended southwards to north Derbyshire. Progradations in the Marsdenian filled remaining basinal areas in west Lancashire, Derbyshire and Staffordshire. In the subsurface, the Gainsborough Trough was filled by major progradations ending in the Alportian (Steele 1988).

Offshore, wells that penetrate the Namurian no deeper than the Alportian show a sedimentary style that compares closely with the cyclic Millstone Grit of the Pennine outcrop (see (Figure 12)). These higher stratigraphical levels will be discussed further below. The comparatively rare wells with deeper penetrations mostly give only a partial section through the basin-fill succession, so a full reconstruction is impossible (Figure 10). Only well 43/17-2, which penetrated late Dinantian basinal mudstones, demonstrates the full basin-fill sequence. This includes, in its lower part, thick intervals of mudstone with prominent high-gamma units, inferred to be basinal marine bands, and thin units of fine-grained turbidite sandstones, one of which shows prominent dish structures in core. Above the turbidites in 43/17-2 is a 400 m thick mudstone and siltstone succession that becomes conspicuously coarser in its upper part. This is interpreted as the main basin-filling slope progradation, analogous in context to the Kinderscoutian Grindslow Shales of Derbyshire and the Pendleian Pendle Shales of the Craven Basin. In well 42/25-1, where this interval was partially penetrated, dipmeter analysis shows large-scale interbedding of units with constant low-angle dips and units in which dips are highly variable in both magnitude and direction (Figure 11). Both types of unit are tens of metres thick. The dip patterns suggest interbedding of undisturbed slope siltstones and slumped and rotated masses of similar sediment. Such deformation is not commonly recognized in the Pennines, but it matches closely the Kinderscoutian Gull Island Formation in County Clare, interpreted as the product of a prograding slope and an associated apron of slumped material (Martinsen 1989, Collinson et al. 1991). The top of the main upwards-coarsening sequence is characterized in well 43/17-2 by particularly thick sandbodies of inferred channel origin (Figure 10). These compare with the major channels at the top of basin-filling sequences in the Pennines (i.e. Warley Wise, Kinderscout, Fletcher Bank and Roaches grits) and which may relate to low-stand incision in a shelf-edge position (e.g. Jones & Chisholm 1997, Hampson et al. 1999). However, the multiple cut and fill, which characterizes most of such channel complexes at outcrop, suggests that processes intrinsic to the depositional setting, perhaps related to distributary switching, may be as important as base-level controls.

The age of the inferred slope succession in 43/17-2 is poorly constrained, but it is suggested to be Chokierian and Alportian with underlying basinal mudstones and turbidites extending back into the late Dinantian. If this age is correct, then the Southern North Sea Basin and the Gainsborough Trough were filled at broadly similar times. The intervening Humber Basin is likely to have filled in the same interval but that basin could have survived until later if nearby granite-cored blocks diverted river systems. In wells 43/28-1 and 48/3-3, cyclic deltaic facies are developed in rocks of inferred Chokierian or possibly Arnsbergian age, suggesting that infilling of any deepwater areas there took place in the Arnsbergian or earlier. Previously estimated Namurian ages in well 48/3-3 (Leeder et al. 1990) are now thought to be too young on the basis of comparisons with nearby wells. As these two wells lie to the south and east of wells 43/17-2 and 43/25-1, the basin-fill progradation across Quadrant 43 probably took place from east to west rather than from north to south. This inference, and the fact that the Arnsbergian to Alportian was a time of limited sand supply to the Pennine basins, suggest that the main sand-supply route was deflected to the east and possibly entered the Southern North Sea Basin from somewhere near the position of the Central Graben.

Once the main basin-filling progradation had taken place, conditions apparently never reverted to a deep basin, and sediment supply balanced continuing thermal subsidence. Relatively shallow-water conditions prevailed across the Southern North Sea Basin throughout the remaining Namurian and into the Westphalian. This regime produced a markedly cyclic succession, with marine bands defining cyclothem boundaries, as well as providing a chronostratigraphic framework (Figure 12). It is generally accepted that Namurian cyclicity and, particularly, the occurrence of marine bands, was driven by eustatic fluctuations in sea level (e.g. Holdsworth & Collinson 1988, Martinsen et al. 1995). These are thought to have acted as controls, both on the base level for sedimentation and on the salinity of the water bodies into which deltaic progradations took place (cf. Collinson 1988). The dominant style of deposition is the upwards-coarsening unit, usually initiated at a marine band. The more sand-rich upper parts of the units include both gradationally and sharply based sandstones, the former interpreted as mouth bars, the latter as channels (see (Figure 13)).

Channel sandstones range in thickness from simple units (as little as 2 m thick) up to multi-storey units several tens of metres thick. The thinner simpler channel sandbodies are attributed to delta distributaries, whereas some of the thicker units are thought to be fills of incised palaeovalleys (Figure 12), (Figure 13). Palaeovalleys are inferred on the basis of being out of scale with associated cyclothems, in cutting down to and even removing underlying marine bands, and in having significantly coarser-grained fills than the associated distributary channels. Both the coarser grain size and larger dimensions make the palaeovalley sandstones the main potential reservoirs. By analogy with onshore examples (e.g. Chatsworth Grit) and with some support from well data, palaeovalleys are inferred to be typically several tens of kilometres wide. The stratigraphical equivalent of the Chatsworth Grit is the main reservoir in the Trent field (O'Mara et al. 1999, O'Mara 2004), where it appears to fill the palaeovalley only partially. The later stages of the palaeovalley fill include a finer-grained quartzitic sandstone, thought to be a reworked transgressive channel unit of possible estuarine origin. This unit has maintained good permeabilities in spite of its small grain size. It is interesting to note that the apparently underfilled palaeovalley of the Trent field is matched at outcrop by the Chatsworth Grit, which has an overlying progradational interval, the Redmires Flags, confined to the area of the inferred palaeovalley and underlying the Cancellatum Marine Band. This underfilling may have resulted from a high rate of sea-level rise, which outstripped the fluvial valley-floor aggradation. The higher incidence of marine trace fossils in the Marsdenian of Quadrant 43 (Lawrence & Sutter 2002), compared with the situation at outcrop, suggests that the connection of the Southern North Sea Basin to the open ocean may have been to the east.

In contrast with the Pennine outcrop, the Yeadonian of the Southern North Sea Basin is characterized by a relative lack of sandstone. The Rough Rock, which is present as a sheet-like multi-storey channel complex across most of Pennines and the subsurface of the East Midlands (Bristow 1988), is weakly represented offshore, and in some wells the Yeadonian strata lack sandstones of any significance. This may again relate to large-scale diversions of sand-supply routes.

4. The northern margin of the basin

The character and history of the transition between the Mid North Sea High and the Southern North Sea Basin is still poorly understood. Seismic data do not clearly resolve structures deep within or below the Carboniferous, so the margin must be constrained by well data. It is clear from the comparison of well 43/17-2 with wells to the north that the differentiation between the Mid North Sea High and the Southern North Sea Basin was well established by late Dinantian times. It is also clear that the margin must have passed in a broadly east–west orientation through the middle of Quadrants 41–44. The narrow zone in which the margin is constrained by well data suggests that it involved faulting rather than a flexure. The lack of seismic resolution makes it impossible to judge whether it was a single major fault or a staircase of fault blocks.

The deepest well in the basin probably penetrates only the highest Dinantian strata (Brigantian) and it is therefore impossible to demonstrate when this basin margin developed. It is possible that the early Dinantian saw the shallow-water depositional systems of the block extending southwards without significant change across what is now the basin. Redbeds of latest Devonian or earliest Dinantian age are features of wells onshore and the same sort of extensional subsidence regime probably prevailed offshore at that time. In that case, a phase of intra-Dinantian tectonic activity must have led to the inferred differentiated bathymetry.

A more precise idea of when this movement took place may come by analogy with wells in and around the Cleveland Basin, Cloughton-1, Kirby Misperton-1 and 41/24-2 (Figure 14). In well 41/24-2, the section penetrates into inferred Lower Limestone Formation strata, which appear to have a broadly Yoredale cyclic character. This pattern of deposition persists through the Middle Limestone Formation to the base of the Namurian. In the lowest part of the Namurian, a unit some 50 m thick has very high gamma values and is inferred to be a mudstone with well developed marine bands. This interval is overlain by some 85 m of sandstones, apparently with finer-grained interbeds. The lower part of this interval shows an upwards-coarsening upwards-thickening trend. It is sharply overlain by an upwards-coarsening sequence just over 100 m thick, at the top of which are coarse cross-bedded channel sandstones whose age is thought to be late Pendleian, based on uncorroborated ages indicated on the composite log. The lower sandstones, which are not cored, are thought most likely to be turbidites, with a basin-filling slope progradation above. The succession therefore compares quite closely with the Pendleian fill of the Craven Basin. If the inferred stratigraphical breakdown is correct, the main deepening event at this well would appear to have occurred around the Dinantian/Namurian boundary.

At Cloughton-1, by comparison, the high-gamma mudstones at base Namurian are clearly present, although somewhat thicker. The rest of the Pendleian comprises an upwards-coarsening unit but possible turbidite sandstones within it appear more thinly bedded. Immediately below the high-gamma mudstones are thick sandstones and inferred coal seams suggestive of a delta top setting and again indicating a significant deepening event around the Dinantian/Namurian boundary. The

Cloughton-1 well terminated a short distance into the Dinantian so that the earlier history cannot be deduced.

At Kirby Misperton-1, the Namurian section compares quite closely with that at Cloughton-1 and 41/24-1. The gamma peaks in the basal mudstone are less conspicuous and the large-scale upwards-coarsening succession of the Pendleian is thicker and has thicker channel sandbodies in its upper part. In contrast, inferred turbidite sandstones in the lower part of the pro-gradation are thin in comparison. The Dinantian strata just below the inferred Dinantian/Namurian boundary are similar to those in the other wells with channel sandstones but no obvious coals. This again suggests a significant deepening event at the Dinantian/Namurian boundary. However, the Dinantian penetration extends for some 1150 m and this provides a unique view of the earlier history of the Cleveland Basin. The latest Dinantian channel sandstones themselves occur at the top of a major fine-grained upwards-coarsening succession, some 300 m thick. Beneath that are some 300 m of thinly interbedded sandstones and finer grained rocks, which in turn overlie a sandy succession within which there are small-scale upwards-coarsening units that probably record minor deltaic progradations. The occurrence of a thick fine-grained upwards-coarsening unit above older deltaics suggests a phase of deepening. There is no control on the age of these deepest Dinantian sediments, but on thickness grounds they are likely to extend back at least well into the Asbian. The earlier phase of deepening could therefore be of Asbian age, but without tighter control on the age of the section in the deeper parts of the well, it is not possible to be more precise.

It is clear from well 43/17-2 (Figure 10) that major deepening had occurred offshore prior to the Brigantian and, therefore, it might be reasonable to speculate that such movements were associated with those that caused the Dinantian deepening in the Cleveland Basin, which are tentatively inferred to be Asbian in age. A phase of well constrained Asbian extension is also recognized in the Craven Basin, although deepening of the sea began earlier here (Kirby et al. 2000). If this age were correct, the deepening in the southern North Sea would be broadly contemporaneous with the deposition of the Scremerston Formation. A consequence of the deeping is that the shallow-water strata of the Scremerston and Lower and Middle Limestone formations of the Mid North Sea High passed into deeper-water facies to the south, possibly with bypassing of sand to contemporaneous turbidite settings. This would compare with the spilling of sand across the Craven faults in the Brigantian to give turbidite units such as the Pendleside Sandstone in the Craven Basin as equivalents of Yoredale deltaic strata on the Askrigg Block. Another consequence is that the pre-deepening Cementstones, Fell Sandstone and the earlier parts of the Scremerston Formation may extend as fluvial and deltaic facies beneath the Southern North Sea Basin. This contrasts with what is seen onshore, where these units are mainly restricted to the Northumberland and Stainmore troughs.

5. Source-rock potential

Potential source rocks for both oil and gas are present in the Dinantian and Namurian successions. The coals of the various Yoredale units are potential sources for gas, but they are generally very thin, and gas volumes are likely to be insignificant. However, some coals of the Scremerston Formation are locally up to several metres thick and the group is areally extensive. Recent non-proprietary studies for the hydrocarbon industry have calculated that the coals of the Scremerston Formation could have yielded in excess of 10 trillion cubic feet of gas. In addition, carbonaceous mudstones and siltstones within the Yoredale succession, although lean in organic matter, may have been capable of generating a similar volume. Scremerston Formation coals under the basin would probably have become mature for gas generation prior to the Variscan uplift, although later generation could also have occurred.

However, the major hydrocarbon source-rock potential is provided by the basinal mudstones of the late Dinantian and early Namurian. These strata are proven source rocks in onshore eastern England, where they generated the oil for the many small East Midlands oilfields. Similar rocks, the Holywell Shales, provide the source for gas and oil in the eastern Irish Sea and the oils at Formby. The marine bands, which constitute only a small proportion of the thickness, are the richest oil-prone source rocks, with total organic carbon (TOC) values averaging about 4 per cent. The more abundant barren mudstones, between the marine bands, are less rich (TOC typically 2 per cent), but their much greater volumes mean that they are capable of having generated the largest volumes of gas. Together, the marine and non-marine basinal mudstones could have generated in excess of 100 tcf of gas and a minor oil phase. For all the large potential volumes, only a small proportion of this gas appears to have been trapped within Carboniferous or younger reservoirs. This may be because significant generation and migration occurred in pre-Variscan times before traps were established. However, the scarcity of traps and the patchy nature of good reservoirs may be more important during later phases of generation, which could have continued until Tertiary uplift.

Migration may also have been impeded by the nature of the basin-fill succession. Very thick mud-dominated successions are not readily drained, although any interbedded turbidite sandstones would help this process. In any event, migration is likely to have been up-dip to the north from the Southern North Sea Basin, and traps for this gas are most likely to occur along and to the north of the basin margin. The role of any basin-margin faults in helping or hindering migration is not known.

6. Reservoir potential

Proven gas reservoirs in the Namurian and Dinantian of the southern North Sea are mainly coarser sandstones of palaeovalley fills and quartzitic sandstones of probable transgressive origin. The coarser grain sizes of the palaeovalley fills help to maintain reservoir quality, and the sandbodies themselves provide large reservoir volumes. To date, only one Namurian reservoir has been put into production, namely the Trent field, where much of the production is via the clean, transgressively reworked sandstone in the upper part of the palaeovalley, even though the coarser fluvial sandstone of the main valley fill constitutes the main reservoir volume (O’Mara et al. 1999, O’Mara 2004). Several undeveloped gas discoveries in Namurian reservoirs rely to a greater or lesser extent on the enhanced reservoir properties of quartz-enriched sandstones. Most of these are the result of transgressive reworking and are difficult to predict geographically. Stratigraphically they are most likely beneath major marine bands whose associated mudstones may act as extensive intra-Carboniferous seals for the good-quality reservoirs as, for example, in well 43/20b-2.

The gas discovery in block 42/10, with a Dinantian palaeovalley sandstone reservoir (Whitby Member), remains undeveloped on account of its size and the distance to existing infrastructure. Although palaeovalleys appear to be relatively common features of the Dinantian and Namurian successions, both the difficulty of predicting their occurrence and the relatively low probability of their coinciding with a trapping structure make for a high-risk play. The sensitive control exercised by grain size on reservoir quality means that, even with palaeovalley fills, there are likely to be heterogeneities that reduce production from the whole sandbody. Coarse local lags, either at channel bases or in the toes of crossbeds may provide higher permeability streaks that dominate the production.

The most abundant sandstone-dominated unit, the Fell Sandstone, which is an extensive and generally thick sheet, is also a potential reservoir. Its main drawback is the difficulty of envisaging a seal, except at the base-Permian Unconformity. The Scremerston Formation and the Yoredale formations are thought unlikely to provide effective intra-Carboniferous seals.

7. Conclusions

Analogues for most of the Carboniferous depositional settings inferred from rather widely spaced well data offshore occur onshore in rocks of broadly similar aged facies. The Dinantian and early Namurian succession on the southern part of the Mid North Sea High compares closely with that seen at outcrop in Northumberland. Coals provide limited source-rock potential and palaeovalley sandstones are proven, although unexploited, reservoirs. Some of the Dinantian depositional systems may have extended beneath the Southern North Sea Basin but, by end Dinantian times, a deep basin had developed whose basinal mudstones and Namurian fill compare with those of the southern Pennine basins onshore. Turbidites are of limited extent but major slope progradation, probably in Arnsbergian–Chokierian times, infilled the basin and allowed a succession of Millstone Grit type deltas to dominate the later part of the Namurian. Basinal Namurian mudstones provide potentially important source rocks, and palaeovalley sandstones are the most promising reservoirs, possibly augmented by transgressive sandbodies.

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