Bolsovian fluvial sandstone overlying a coal in the Schwabe quarry in Ibbenbüren, Germany.

Chapter 6 Carboniferous

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1 Introduction

From a petroleum geological point of view, the Carboniferous sedimentary sequence in the SPB area is of primary importance (**Figure 6.1**). It was one of the first geological systems to be described because of its value during the Industrial Revolution. The Carboniferous Limestone series, Millstone Grit and Coal Measures had already been defined by Whitehurst in 1778 (Paproth et al., 1983a; Harland et al., 1990). Despite the dramatic decrease in mining activities during the 20th century as cheaper coals were imported, the coals continued to have economic value as they turned out to be a very important source of hydrocarbon gas. Dinantian and Namurian basinal shales also proved to be a source of oil and gas in parts of the SPB area.

Carboniferous rocks have been proven in the greater part of the SPB area (see **Figure 6.4**). Most of the sediments were deposited in a broadly east–west-trending basin, which is named in this chapter as the Northwest European Carboniferous Basin (NWECB) (**Figure 6.2**). Having formed during the final amalgamation of Pangea, the NWECB may be regarded as the precursor of the SPB, although the tectonic setting of the two basins is fundamentally different. The NWECB developed in front of an actively deforming mountain belt and experienced a compressional regime during the Late Carboniferous. The SPB was characterised by broad thermal subsidence following the final stage of the Variscan Orogeny in latest Carboniferous and Early Permian times, when the NWECB underwent disruption and large-scale uplift.

Prior to hydrocarbon exploration, knowledge of the Carboniferous geology was limited to places of mining activity (mainly at the SPB margins) and where Carboniferous rocks are found at shallow depths or at outcrop (**Figures 6.4** & **6.17**). In the UK, the Carboniferous can be traced from outcrop in the north-east of England through the Pennine area to the Midlands (**Figure 6.1**). In Belgium, there are many classical Paleozoic type-sections (Tournai, Visé, Dinant and Namur) and the famous Meuse profile between Namur and Givet in the folded Namur-Dinant Basin south of the London-Brabant Massif (see **Figure 6.5**). Namurian and Lower Westphalian rocks crop out in the far south of the Netherlands in the Geul Valley. The only Carboniferous outcrops in Germany are found along the southern SPB margin in the Eifel, Rhenish and Harz mountains, the Aachen and Ruhr coalfields and the Ibbenbüren/Osnabrück and Flechtingen hills. In Poland, Carboniferous rocks crop out in the Upper and Lower Silesian Coal Basin, the Holy Cross Mountains and the Kraków area.

The discovery of gas in the 1960s stimulated exploration throughout the entire SPB. Parts of the basin have therefore been relatively well known since then. Areas with a relatively high well density include the Silverpit area and Cleaver Bank High of the UK and Dutch offshore sectors respectively (see **Figure 6.20**). The Carboniferous has often been drilled along the northern margin of the London-Brabant Massif in the UK, Belgium and the Netherlands. The Westphalian sedimentary succession of the north-east Netherlands and neighbouring Germany are also well known. Farther east, the island of Rügen is an important source of information on Carboniferous rocks. In Poland, the Upper Silesian, Lublin and Pomeranian basins (**Figure 6.3**) are the best known areas. Little is known about Carboniferous rocks in the western Dutch offshore sector and adjacent UK area, the German offshore and northern onshore area, and central Poland.

Despite the large amount of data that has been collected, there are still two aspects of the Carboniferous that prohibit a detailed and comprehensive geological reconstruction. Firstly, the top of the Carboniferous occurs at considerable depths (up to 7000 m in the North German Basin and 8000 m in the Fore-Sudetic Monocline) and secondly, the sequence is anomalously thick (up to 6000 m in the southern SPB area) and so nearly all wells penetrate only the upper part of the Carboniferous.

There are several published compilations on the Carboniferous geology of the entire SPB in addition to many regional and local studies. These include Paproth (1989), Ziegler (1990a), Bénard & Bouché (1991), Maynard et al. (1997) and Gerling et al. (1999c). 'The Geology of Central Europe' has recently been updated in two volumes (McCann et al., 2008a). There has been no systematic review of the UK Carboniferous stratigraphy onshore since the 1970s (George et al., 1976; Ramsbottom et al., 1978) although a review is currently in preparation. Offshore, Cameron (1993) proposed a stratigraphic scheme that was considerably revised by Besly (2005) and Collinson (2005). Belgian lithostratigraphy has been described by Paproth et al. (1983a), Paproth et al. (1983b), Delmer et al. (2001) and Poty et al. (2001). Overviews of the Namur-Dinant Basin were published by Poty (1997) and Hance et al. (2001) and of the Campine Basin by Langenaeker (2000). Van Buggenum & Den Hartog Jager (2007) recently updated the Carboniferous geology of the Netherlands. The Carboniferous of the Danish Central Graben was reviewed by Bruce & Stemmerik (2003), whereas little attention has been paid to the onshore stratigraphy since the original work of Michelsen (1971) and Bertelsen (1972). The Carboniferous stratigraphy and palaeontology of Germany has been described in two volumes by Wrede (2005) and Amler & Stoppel (2006). An overview of the Carboniferous of Poland was published in 'The Carboniferous System in Poland' (Zdanowski & Żakowa, 1995). The latest stratigraphic schemes were published in the 'Stratigraphic Table of Poland' (Wagner, 2007). Numerous regional studies in Poland include Szulczewski et al. (1996), Żelaźniewicz et al. (2003), Buła et al. (2004), Narkiewicz (2005), Matyja, H. (2006), Krzywiec (2007b), Narkiewicz (2007b) and Matyja (2008).

Figure 6.1 Geographical locations and hydrocarbon wells/fields referred to in the chapter.

Clearly there have been many new publications since the last study that integrated the Carboniferous geology of the SPB area. This chapter provides an up-to-date overview that incorporates information from these publications and also includes many new maps and illustrations. The first section describes the Carboniferous stratigraphy and basin development and presents a stratigraphic correlation chart (**Figure 6.3**), a new Permian subcrop map (**Figure 6.4**), well-correlation panels (**Figures 6.6**, **6.7**, **6.9**, **6.10**, **6.12**, **6.13**, **6.15** & **6.16**) and palaeogeographic maps (**Figures 6.5**, **6.8**, **6.11** & **6.14**). The second section addresses the petroleum geological aspects of the Carboniferous of the SPB, illustrated by maps showing the areal extent of the most important source rocks (**Figures 6.17** & **6.18**), the maturity at the top Carboniferous (**Figure 6.19**) and the ages/locations of Carboniferous reservoirs (**Figure 6.20**). Field examples are given to describe the Carboniferous play concepts within the SPB area (**Figures 6.23** to **6.28**).

1.1 Plate-tectonic setting

The NWECB developed on predominantly (Eastern) Avalonian crust (Chapter 3) (Pharaoh, 1999; Verniers et al., 2002; **Figure 6.2**). Avalonia was a Gondwana-derived microcontinent that consolidated with Baltica during the Late Ordovician resulting in closure of the Tornquist Ocean (Cocks & Fortey, 1982; Tait et al., 1997; Cocks & Torsvik, 2005). The Iapetus Ocean, which separated Baltica/Avalonia from Laurentia, closed during the Silurian to form the Old Red Continent or Laurussia (Chapter 3). These events took place during the Caledonian Orogeny (Cambrian to Early Devonian).

During the later Variscan Orogeny (Early Devonian to Early Permian), Gondwana and Gondwana-derived microcontinents collided with Laurussia. An important event during the Variscan Orogeny was the development of the Rheno-Hercynian Basin along the southern margin of the Old Red Continent in late Early Devonian times (along a line dissecting the Rheno-Hercynian Zone, **Figure 6.2**; Ziegler, 1990a; Oncken et al., 1999; Burgess & Gayer, 2000; Narkiewicz, 2007). From then on, the southern continental margin became passive and a thick pile of Devonian and Lower Carboniferous sediments was deposited. The Rheno-Hercynian Basin started to close again during the Late Devonian as it was subducted to the south-east (Franke, 2000), although it must have remained relatively narrow as it can not be detected by palaeomagnetics (Tait et al., 1997). During Mid- to Late Devonian times, Laurussia began to converge with Gondwana in a dextral-oblique, clockwise rotational mode, with initial collision in the area of present-day Iberia and in north-west Gondwana during the Famennian (Ziegler, 1990a).

During the Early Carboniferous, the Rheno-Hercynian Ocean floor was subducted southwards beneath the mid-European terranes (Gondwana-derived microcontinents) leading to the formation of the Variscan Mountains (Franke, 2000; Stampfli & Borel, 2002). Early collision between the former Rheno-Hercynian

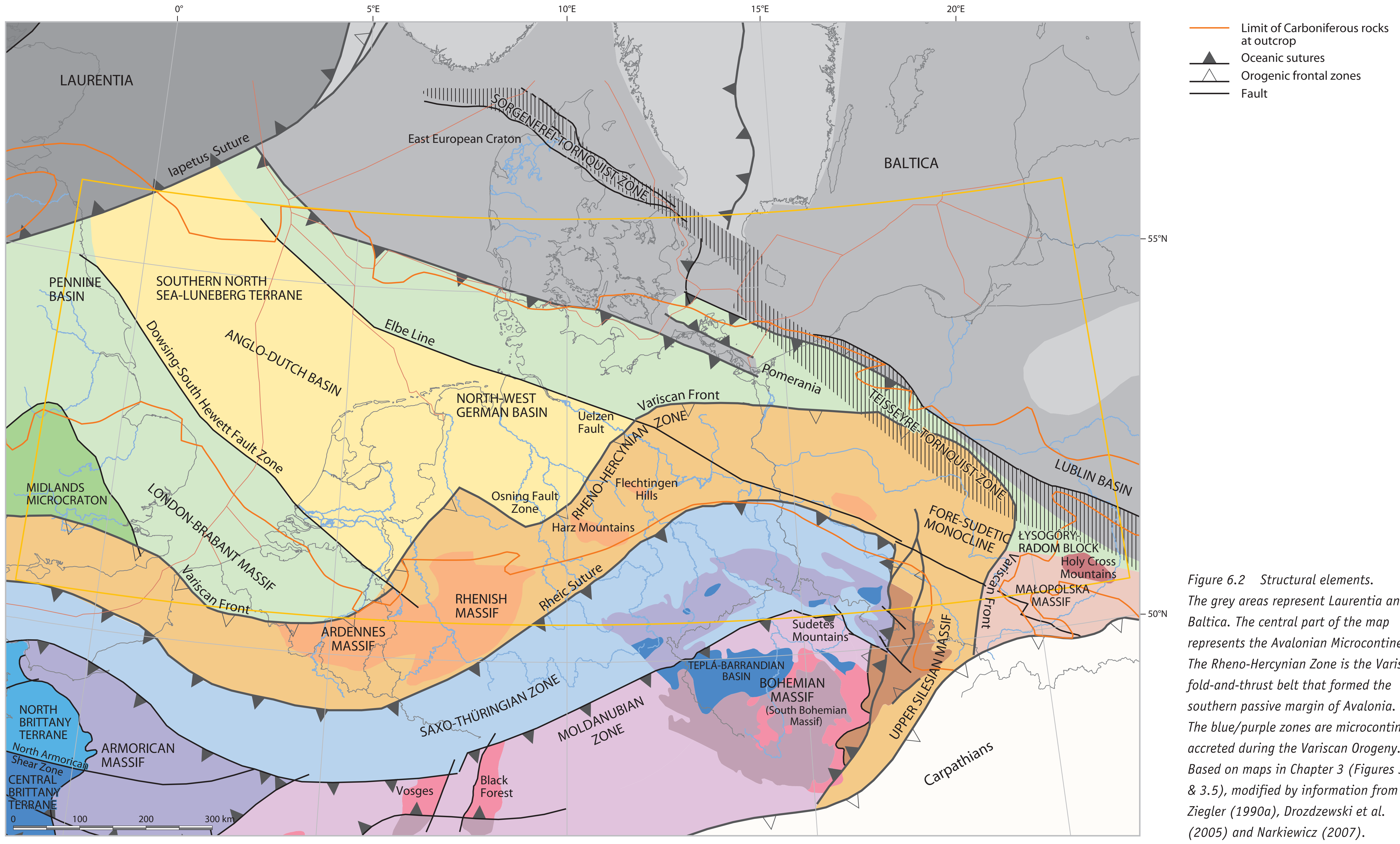


Figure 6.2 Structural elements. The grey areas represent Laurentia and Baltica. The central part of the map represents the Avalonian Microcontinent. The Rheno-Hercynian Zone is the Variscan fold-and-thrust belt that formed the southern passive margin of Avalonia. The blue/purple zones are microcontinents accreted during the Variscan Orogeny. Based on maps in Chapter 3 (Figures 3.3 & 3.5), modified by information from Ziegler (1990a), Drozdzewski et al. (2005) and Narkiewicz (2007).

passive margin and the continent to the south took place about the time of the Visean-Namurian transition (Oncken et al., 1999; Narkiewicz, 2007) followed by accretion during the Namurian. Large-scale folding and inversion of the NWECB had taken place by end-Westphalian times (Drozdzewski & Wrede, 1994). The Variscan Mountains collapsed during the Stephanian, resulting in widespread Stephanian to Early Permian magmatism across the NWECB (Timmerman, 2004). Ziegler et al. (2004) related the deformation of the Variscan Orogen and its northern foreland to a change in the Gondwana-Laurussia convergence from oblique collision to a dextral translation.

1.2 Stratigraphy

In central and western Europe, the Carboniferous has traditionally been subdivided into the 'Lower Carboniferous' and 'Upper Carboniferous', with the boundary at the base of the Namurian Stage. The Namurian is defined by the first occurrence of the goniatite species '*Cravenoceras*' (= *Emstites*) *leion*, which is equivalent to the Brigantian-Pendleian boundary (**Figure 6.3**). The 'Dinantian' and 'Silesian' subsystems were formally established in 1960, synonymous with the 'Lower' and 'Upper Carboniferous' in this definition. However, in 1996 the IUGS-Executive-Committee ratified the definition of the Mid-Carboniferous boundary between the Mississippian and the Pennsylvanian in the GSSP Arrow Canyon (Nevada, USA) by the first occurrence of the conodont *Declinognathodus noduliferus*, which is more-or-less equivalent to the boundary between the *Eumorphoceras* and *Homoceras* ammonoid (goniatite) zones in central Europe (Lane et al., 1999). These ammonoid zones are equivalent to the Arnsbergian and Chokierian substages. It is difficult to verify this international boundary in central Europe due to the lack of diagnostic fossils in the Carboniferous. The traditional stage names Namurian, Westphalian and Stephanian are therefore still valid as regional units, in accordance with the rules of stratigraphic nomenclature (Herbig, 2005; Dusar, 2006). In the SPBA, we use the central and west European stratigraphic nomenclature at stage level (e.g. Visean, Namurian) and substage level (e.g. Namurian A or Langsettian; Menning et al., 2006) because almost all literature is based on regional nomenclature rather than the global stage-levels (e.g. Bashkirian). For clarity, the correlation of regional and global Carboniferous geological timescales (Gradstein et al., 2004) is given in **Figure 6.3**.

The Carboniferous has been classically subdivided using marine goniatites, corals, brachiopods and nonmarine bivalves and later by microfossils (conodonts, foraminifers, palynomorphs) and volcanic ash beds (tonsteins). For example, Dinantian stratigraphy was established mainly using corals and brachiopods, although foraminifera, conodonts and microflora were also used later (Paproth et al., 1983b; Riley, 1993; Stoppel & Amler, 2006). Stage boundaries in the Namurian are defined by the arrival of new goniatite faunas, whereas in the Westphalian the boundaries are taken at the base of the most widespread marine bands (Ramsbottom et al., 1979). Since the start of oil and gas exploration, palynostratigraphic subdivisions of (mainly) the Westphalian have been developed to allow more effective dating of rocks that have relatively scarce and seldom-recovered macrofossils. These subdivisions are based on the pioneering work of Neves et al. (1973), Clayton et al. (1977) and Owens et al. (1977); the most recent work is by McLean et al. (2004). The disadvantage of the palynostratigraphic approach is that the resolution is generally poorer than that based on marine bands, which has inhibited detailed correlation (Bruce & Stemmerik, 2003). Stratigraphic control can be improved by chemostratigraphy in barren sequences such as the Bolsovian to Stephanian (Pearce et al., 1999; Pearce et al., 2005). However, the relative lack of reliable biostratigraphic information across large areas of the NWECB (especially in the central deeper part) has led to the use of lithostratigraphy to correlate Carboniferous strata. For example, the clear lithological differences on which the Dinantian subdivision of the UK is based (**Figure 6.3**), and the poor biostratigraphic constraints on any diachroneity, makes lithostratigraphy the most appropriate correlation technique. Furthermore, the subdivision of the Carboniferous of the Netherlands is entirely lithostratigraphic, except in the mining areas in the south.

2 Dinantian

2.1 Subsidence mechanisms

The greater part of the basin experienced an extensional regime during the Dinantian. Late Devonian to Early Brigantian rifting (north–south extension) in northern England (north of the London-Brabant Massif) initiated a series of linked, distinctly asymmetric half-grabens acting along a series of north-west–south-east and north-east– south-west-trending faults related to Caledonian structural weakness (Fraser & Gawthorpe, 1990; Coward, 1993; Hollywood & Whorlow, 1993). Some fault blocks are underpinned by buoyant Devonian granites, which markedly reduced subsidence in areas such as the Askrigg and Alston blocks of northern England (**Figure 6.5**). Gravity data suggest that there are similar granite-cored highs in the southern North Sea (Donato et al., 1983; Donato & Megson, 1990). Rifting eventually gave rise to a platform and basin topography with carbonate platforms in the footwall areas (e.g. Derbyshire Block) and relatively deep-water settings in the adjacent hanging-wall areas (e.g. Craven and Widmerpool basins).

A similar topography developed north of the London-Brabant Massif, where carbonate shoals formed on fault blocks with reduced subsidence, although shallow-carbonate shelf facies also developed in the intervening basins (Muchez et al., 1991). Until recently, it was not clear if these carbonate platforms also existed beneath the southern North Sea, the Netherlands and north-west Germany. However, seismic data from the northern Netherlands has now revealed several distinct carbonate buildups (Kombrink, 2008; **Figures 6.5** & **6.22**). In combination with the tilted fault blocks in the same area (De Jager, 2007), a model of Dinantian extension comparable to the UK is suggested for the Netherlands. A tensional setting is also proposed for the eastern NWECB (Ziegler, 1990a; Narkiewicz, 2007b). The development of the Lublin Basin in Poland was associated with a system of approximately north-west–south-east-trending longitudinal fault zones related to Variscan reactivation of the Teisseyre-Tornquist Zone (Krzywiec, 2007b).

A series of (underfilled) foreland basins developed along the southern margin of the NWECB (from the UK to Poland) during the Dinantian (**Figure 6.5**). These basins were formed by loading of the subducting plate, which changed the formerly passive northern margin of the Rheno-Hercynian Basin into an active margin (Ziegler, 1990a; Burgess & Gayer, 2000; Ricken et al., 2000; Narkiewicz, 2007). These foreland basins are normally referred to as Culm basins. The term 'Culm' is also associated with a typical facies (found in the same area) that reflects sediment-starved conditions and deposits with high organic-matter contents. Sediments deposited in these flexural basins can be found in the Rhenish Massif of western Germany. Ricken et al. (2000) showed that the sediments were deposited in asymmetrical wedges, indicating a foreland-basin setting. The transition zone from the Culm basin towards the shelf area farther north (**Figure 6.5**) is poorly defined due to deep burial and intense deformation (McCann et al., 2008a).

2.2 Basin fill

Transgression of the Old Red Continent continued after a relative sea-level lowstand during the Devonian to Carboniferous transition (Johnson & Tarling, 1985). This led to a change in depositional environments from the predominantly red-bed facies of the central and northern NWECB during the Devonian, to the carbonate and deltaic environments of Early Carboniferous times. In areas where carbonate deposition was already taking place during the Late Devonian, this continued into the Carboniferous (along the south-western margin of the NWECB; Hance et al., 2001; Gursky, 2006). The Dinantian carbonates are commonly referred to as 'Kohlenkalk', which simply means carbonates deposited below the Coal Measures. The Devonian-Carboniferous boundary in north-east Germany is characterised by a regional unconformity (McCann, 1999b), although sedimentation seems to have continued in places such as the present-day Holy Cross Mountains and Pomerania in Poland; elsewhere, there was non-deposition or condensed sedimentation (**Figure 6.3**). In the northern and eastern Lublin Basin, the Carboniferous may rest upon older Paleozoic, and Meso- to Neoproterozoic (Vendian and Riphean) formations, or on the crystalline basement (Cebulak, 1988).

Whereas the Dinantian succession in the southern and central NWECB is typical of carbonate deposition and sediment-starved conditions, a major fluviodeltaic system developed farther north. Evidence of this system can be found in northern England and the southern North Sea (**Figures 6.3**, **6.5** & **6.6**; Collinson, 2005). Based on palaeocurrent and heavy-mineral evidence, the source of these sediments appears to have been to the north or north-east, probably a mountainous area of the Scandinavian or Greenland Caledonides. Following deposition of the Scremerston Formation, there was an increase in marine influence that eventually led to deposition of the Yoredale facies (Limestone Formations, **Figures 6.3** & **6.6**). Overall, the three Yoredale formations have a distinctly cyclothemic pattern of deposition with laterally extensive limestones overlain by upward-coarsening units. These units can be several tens of metres thick with sandstones at the top, which may be of mouth-bar, shoreface or channel origin (e.g. UK well 41/10-1, **Figure 6.6**). Wells along the southern Mid North Sea High margin, from the UK coast to the German sector, have penetrated comparable sequences of fluviodeltaic Dinantian rocks (**Figures 6.5** & **6.6**). Farther east in Denmark, the Dinantian succession (well Ørslev-1, **Figures 6.3** & **6.5**) indicates that the region

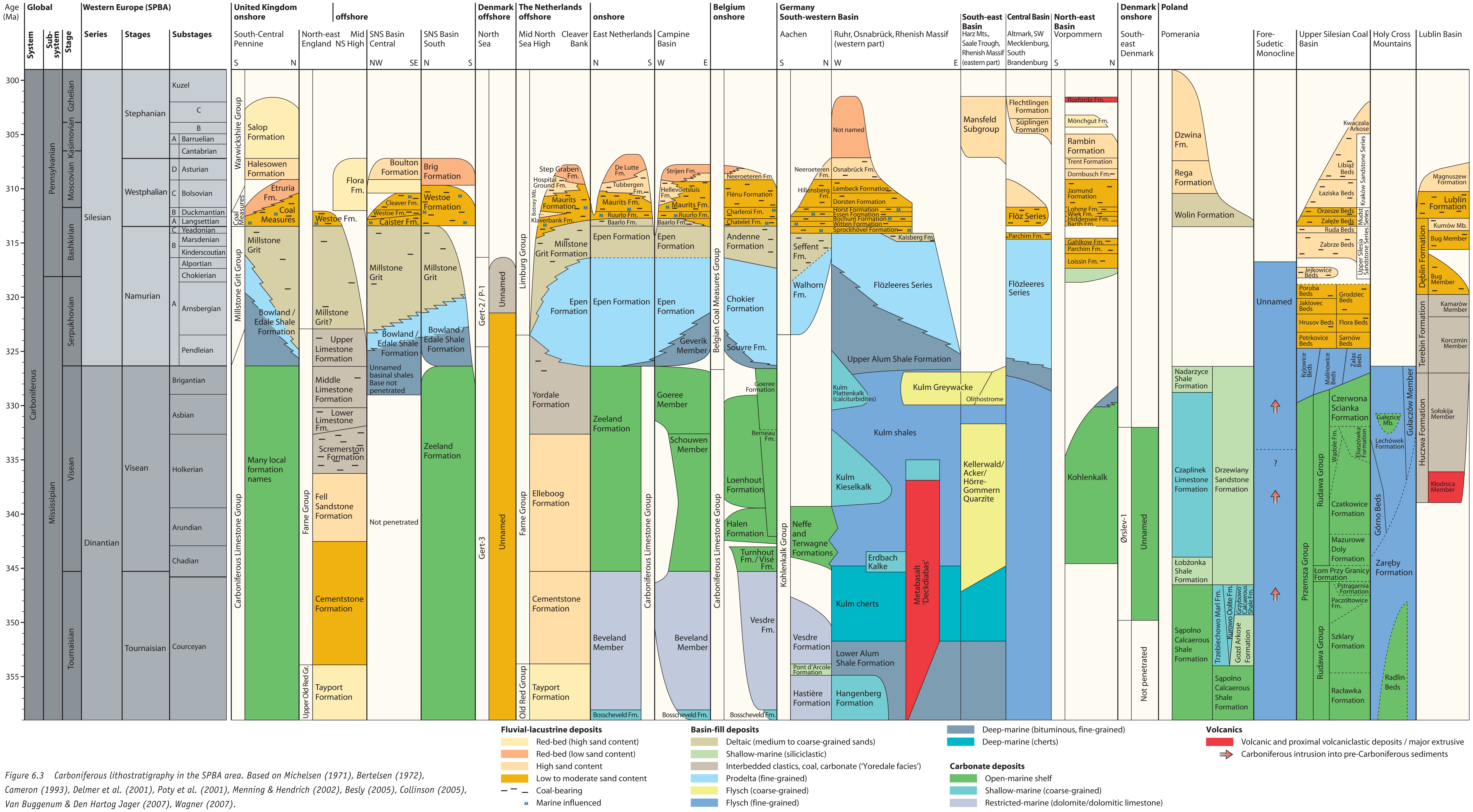


Figure 6.3 Carboniferous lithostratigraphy in the SPBA area. Based on Michelsen (1971), Bertelsen (1972), Cameron (1993), Delmer et al. (2001), Poty et al. (2001), Menning & Hendrich (2002), Besly (2005), Collinson (2005), Van Buggenum & Den Hartog Jager (2007), Wagner (2007).

repeatedly changed from an open-marine carbonate ramp to a siliciclastic-dominated shelf area during Late Devonian and Early Carboniferous times.

South of this fluviodeltaic belt in the north-western NWECB, the Dinantian succession consists of limestones and mudstones in the onshore UK area. This is because the areas were either distal from coarse-grained clastic supply, as on the southern margin of the Askrigg Block, or because they were isolated from all clastic supply, as on the Derbyshire Block (**Figure 6.5**). There were steep margins between the carbonate platforms that formed on intrabasinal highs, such as the Askrigg and Derbyshire blocks, and the adjacent deep-water basins, and they were fringed by limestone turbidites. The basins were characterised by carbonate-rich mudstone deposits.

From the Aachen area and Lower Rhine Embayment along the southern margin of the London-Brabant Massif to present-day Ireland, mid- to late Visean sedimentation was controlled by an aggrading carbonate shelf. The shelf carbonates smoothed out irregularities in the submarine topography that were formed by Waulsortian buildups during the Tournaisian. A comparable situation is seen in the Campine Basin directly north of the London-Brabant Massif. Tournaisian carbonates are intensely dolomitised (over 300 m) in the eastern part of the basin (**Figures 6.3 & 6.5**) whereas time-equivalent rocks are mostly absent in the western part. Visean deposits are typically shallow-marine shelf carbonates with microbial/cryptalgal buildups and breccias. The Visean succession thickness varies in response to the general half-graben structure of the basin, but also as a result of local block-faulting. The maximum drilled thickness of Visean rocks is about 760 m (at the Halen-Citrique borehole in the eastern Campine, **Figure 6.7**) compared to 314 m on the Heibaart Dome in the western Campine (**Figure 6.5**). Proximal carbonate turbidites derived from the productive shallow platforms were deposited on steep ramps of relatively deep basins (such as the Maastricht-Puth Basin) that were filled during the Visean (well Geverik-1, **Figures 6.5 & 6.7**).

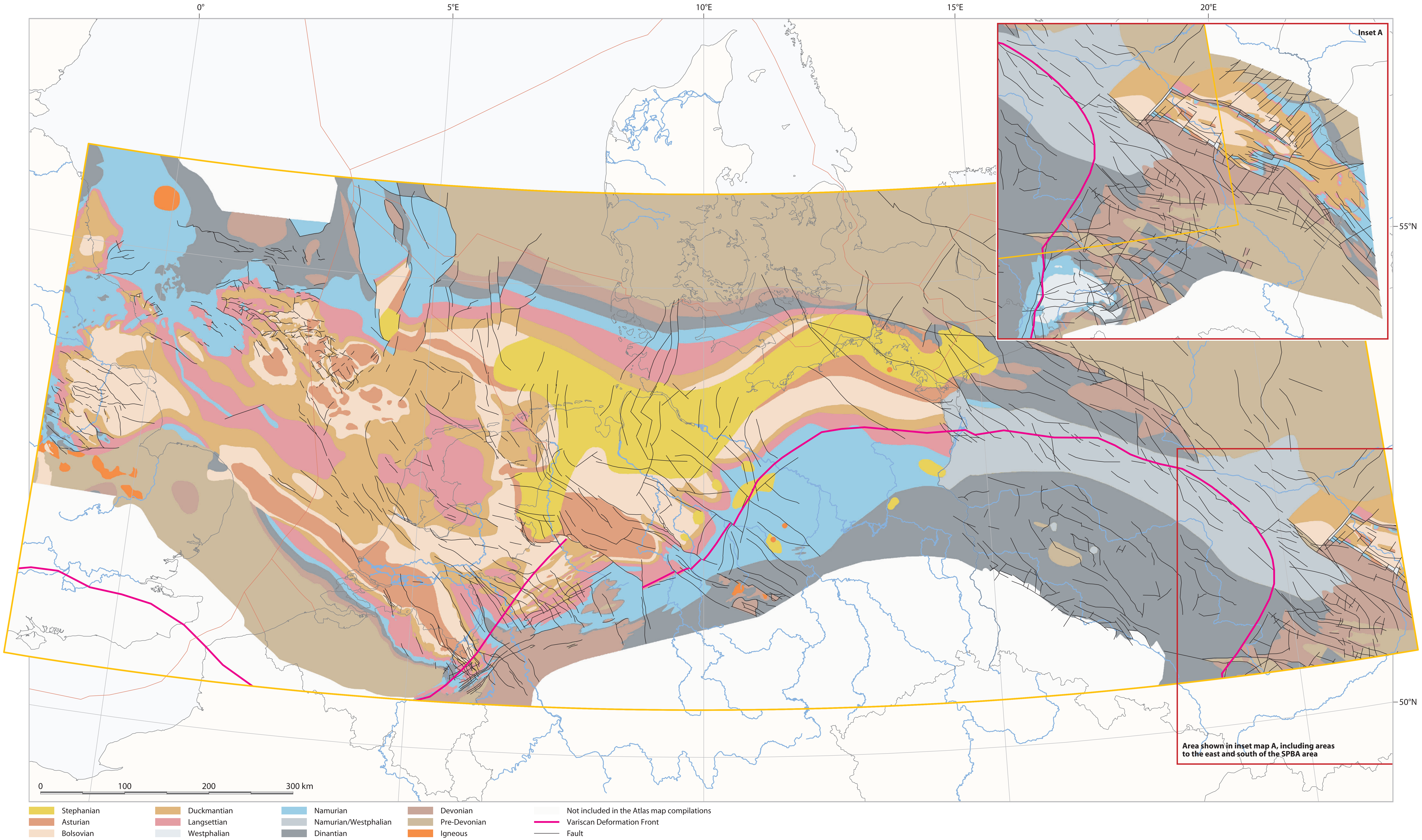


Figure 6.4 Permian subcrop in the SPBA area.

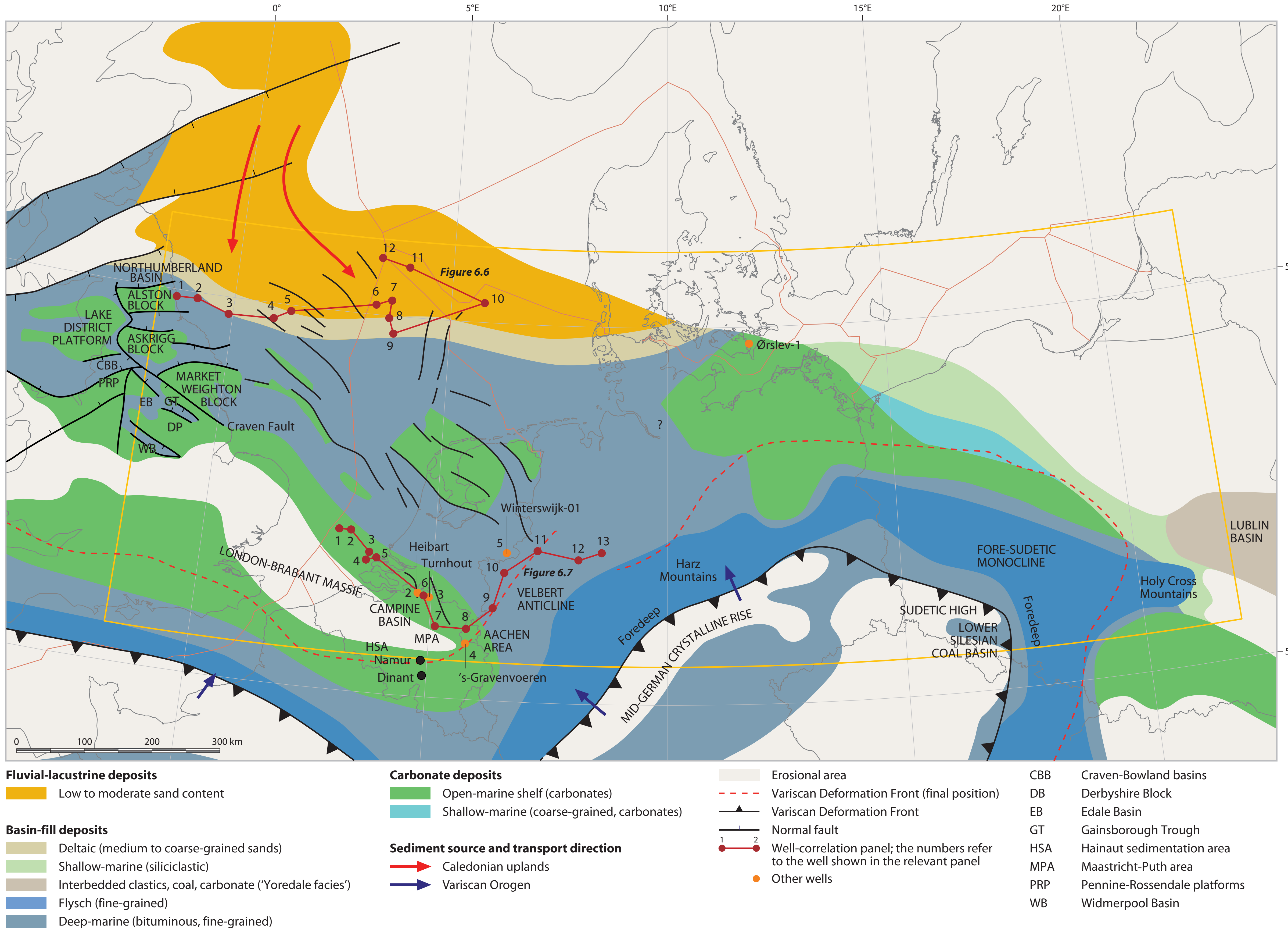


Figure 6.5 Dinantian palaeogeography.

Despite a lack of wells that penetrated the Dinantian sequence in the central NWECB, Visean carbonate platforms have recently been interpreted by Kombrink (2008) from 3D-seismic data (see **Figure 6.22**). Van Hulten & Poty (2008) reported a similar structure on the western Dutch shelf area (**Figure 6.5**). These results suggest that carbonate platforms were not confined to the margins of the NWECB (onshore UK and London-Brabant Massif) and so a similar setting is proposed for the basin centre. The carbonate platforms were probably separated by deep-water basins. The thin Lower Carboniferous succession found in wells Münsterland-01 (**Figure 6.7**) and Winterswijk-01 may have been deposited in such basins. Here, the Dinantian sequence is a thin layer of carbonates overlain by a series of black shales, which suggests a relatively deep-water setting.

A foreland basin developed along the southern margin of the NWECB (Culm basin; **Figure 6.5**), which was filled with clastics derived from the Mid-German Crystalline Rise (MGCR). The MGCR started to deliver sediments from early Frasnian times (Franke, 1989). Slope sediments have been found in the Velbert Anticline (**Figure 6.5**) marking the transition between the Culm basin and the London-Brabant Massif in the west (Amler & Herbig, 2006). It is assumed that the depositional depth within the Culm basin was less than 200 m and that quiet-water conditions prevailed. The basin was differentiated into deep swells and intrabasinal shallow-water platforms (Gursky, 2006) that provided sedimentary detritus (Amler & Herbig, 2006). The sediments are shales and claystones, alum shales, siliceous sediments, cephalopod limestones, carbonate and siliciclastic turbidites (**Figure 6.3**). Sediment thicknesses decrease northwards due to the asymmetry of the foredeep (Ricken et al., 2000) as seen in the Schwalmtal and Versmold wells (both located north of the foredeep, **Figure 6.5** & **6.7**) where the Dinantian sequence is very thin. Sediment-starved conditions must have prevailed during the Dinantian in this part of the NWECB. This is also likely to be the case for much larger basinal areas in the central NWECB; sediments from the south were trapped in the foredeep, whereas the northerly derived deposits only reached the northern NWECB. The Dinantian succession in the western Harz Mountains is similar to that farther west. The sequence developed in Culm facies with broadly equivalent lithostratigraphic units ('Liegende Alaunschiefer', 'Kulm Kieselschiefer', 'Kulm Tonschiefer', 'Kulm Grauwacken', **Figure 6.3**; Buchholz et al., 2006).

Like the western NWECB, the east is characterised by the development of platform carbonates on intra-shelf highs and coastal basement blocks. Shallow-marine siliciclastic sedimentation prevailed elsewhere (Paszkowski & Szulczewski, 1995; Belka et al., 1996; Narkiewicz, 2007). In the north-east German area, carbonate deposition started during the Visean following a period of erosion (McCann, 1999b; **Figures 6.3** & **6.5**) whereas in the Pomeranian region sedimentation had already started during the Tournaisian. Here, the most characteristic feature is the evolution from a deep-water carbonate ramp to a rimmed carbonate shelf. At the end of the Visean, clastics were shed into the basin from the north-east, whereas open-marine shales were deposited in the south-west (Matyja, 2008). In the proximal parts of the Lower Silesian Coal Basin, deposition of flysch-type clastics (up to 1500 m thick) derived from the Sudetic High in the west had already commenced during Late Devonian times and became progressively more important during the Dinantian (Ziegler, 1990a). This Culm flysch is also found in the Fore-Sudetic Monocline where the sediments are also derived from the Sudetic High (Unrug & Dembowski, 1971). The deposition of clastics alternating with Yoredale-facies limestones took place in the Lublin Basin during the Visean (Huczwa Formation and lower Terebin Formation, **Figures 6.3**, **6.5** & **6.16**; Skompski, 1996).

3 Namurian

3.1 *Subsidence mechanisms*

Following the Dinantian rifting event north of the London-Brabant Massif, subsidence during the Namurian was largely controlled by a broad thermal component (Fraser & Gawthorpe, 1990). However, subsidence rates may have continued to be high, even with much reduced extensional movement. The relict Visean bathymetry and compaction of the predominantly fine-grained basin-fill ensured that Namurian sedimentation was influenced by the fault-bounded blocks and basins (Davies et al., 1999). As described above, it is likely that a rifting event similar to that which took place in the UK also occurred in the central NWECB. Kombrink et al. (2008) suggested that Namurian stretching may have been necessary to accommodate the very thick Namurian-Westphalian succession in the central part of the basin.

Subsidence of the Variscan Foreland Basin was generally controlled by thrust-loading along the southern margin of the NWECB (Gayer et al., 1993; Warr, 1993; McCann, 1999b; Burgess & Gayer, 2000; Drozdzewski, 2005; Kornpihl, 2005). During Namurian A and early Namurian B times, maximum subsidence in the area of eastern Germany was in Altmark, south-west Mecklenburg and northern Brandenburg (Kornpihl, 2005). During Namurian B times, the area of maximum subsidence moved northwards to the Vorpommern region (Hoth et al., 2005a). The Polish part of the NWECB was considerably restructured during the Namurian (Narkiewicz, 2007). As Pomerania had been uplifted, the area acted as a source of clastic material for the sedimentary basins of central and southern Poland; the Holy Cross region also became a land area (**Figure 6.8**). The Lublin Basin experienced an extensional regime until Namurian A times, followed by strike-slip movements along the Teisseyre-Tornquist Zone during the remainder of the Namurian.

3.2 *Transition from carbonate to siliciclastic sedimentation*

Carbonate production gave way to siliciclastic sedimentation about the time of the Visean-Namurian transition (**Figure 6.3**), although sedimentation rates continued to be low resulting in marine black-shale deposition in large parts of the NWECB during early Namurian times. In areas such as north-east Germany and the London-Brabant Massif, the Visean-Namurian transition is marked by a regional unconformity (McCann et al., 2008a), which may be related to a eustatic sea-level lowstand at that time.

In the Czech Foreland Basin, the carbonate platforms had already been drowned during the early Visean (Hartley & Otava, 2001; Kornpihl, 2005). Farther to the north-west in the Upper Silesian Coal Basin, the transition took place at the Holkerian-Asbian boundary (**Figure 6.3**; Szulczewski et al., 1996), whereas in the Variscan Foreland Basin of north-east Germany it occurred during the Asbian (Kornpihl, 2005). In the western Ruhr Basin, the transition from carbonate-platform facies to the 'Hangende Alaunschiefer' (**Figure 6.3**) is within the Brigantian succession (Amler & Herbig, 2006). During Namurian A times, the Visean carbonate platforms in the western NWECB (UK and Belgium) were drowned and covered mainly by black shales (see for instance the basal part of the Bowland Shale Formation in well 41/24-2 (**Figure 6.9**) or the Geverik Member in well Geverik-01; **Figure 6.7**). It is important to note that the Bowland Shale Formation not only comprises black shales, but also the normal (marine) shales of the overall basin-fill succession (**Figure 6.3**).

Namurian black shales onlapping the London-Brabant Massif (as seen in Belgium and the Netherlands) overlie a karst surface, indicating that there was a hiatus at the contact (Bouckaert, 1967; Dreesen et al., 1987; Poty, 1997; Dusar & Lagrov, 2008). The Namurian is absent in places, and Westphalian rocks directly overlie Visean carbonates (018-1 in **Figure 6.7**). The more rapidly subsiding areas, such as the Hainaut Trough south of the London-Brabant Massif and the Visé-Puth Basin around Maastricht to the north-east of the London-Brabant Massif (**Figures 6.3** & **6.8**), were characterised by more continuous silica-rich sedimentation. The siliciclastics alternated with carbonates during the Brigantian, giving way to black shales of Arnsbergian age (Langenaeker, 2000). In the southern North Sea, the earliest Bowland Shale Formation deposits are Brigantian, suggesting that the area had also been a basin during late Visean times (**Figure 6.3**).

3.3 *Basin fill*

The Namurian basin-fill succession in the northern and western NWECB can generally be subdivided into four units (Collinson, 2005). The first is a basinal shale unit, the base of which may be earliest Namurian or even Visean age (see above). The shale is overlain by a unit of variably thick turbiditic sandstones (e.g. between 4500 and 5000 m in well 43/27b-2; **Figure 6.9**). These are overlain in turn by a generally upward-coarsening siltstone succession (see the Bowland Shale Formation at around 4500 m depth in well 43/21-2 and the Epen Formation in wells TJM-02 and NAG-01; **Figure 6.9**), which has thicknesses related to the basin depth. The final unit is a complex of channel sandstones, some of which may be tens of metres thick and multi-storey (top Bowland Shale Formation / Epen Formation / Flözleeres Series and base of overlying formations, **Figures 6.7** & **6.9**; e.g. BHG-01 in **Figure 6.7**). Palaeosols and coals deposited in

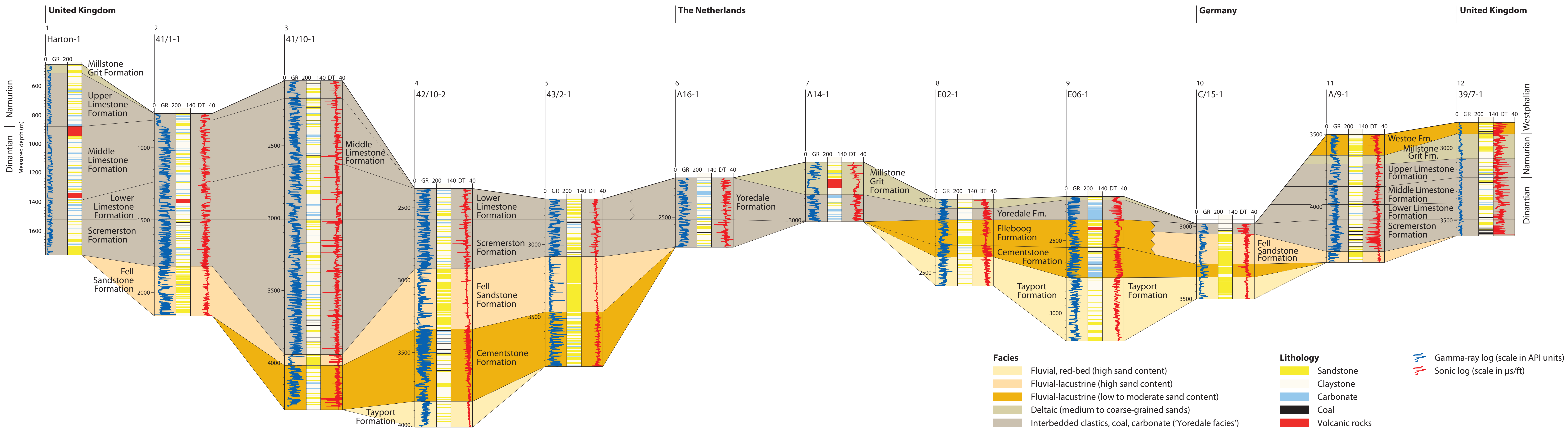


Figure 6.6 Well-correlation panel of the Dinantian succession of the southern North Sea. The German wells used for this correlation panel have been subdivided according to the UK stratigraphic classification scheme. The basal sandy beds of the Elleboog Formation in well E02-1 may be a lateral equivalent of the Fell Sandstone Formation found farther west in the UK sector. The thick limestone from 2319 to 2343 m in well A16-1 may be the boundary between the Lower and Middle Limestone formations. Although the Scremerston Formation is not formally known in the Dutch Carboniferous nomenclature, the basal part of the succession in well A16-1 is interpreted as the Scremerston Formation because of the close correspondence with UK wells. See Figure 6.5 for locations.

near-emergent conditions first appear above these channel-sand bodies. In contrast, coal seams directly overlie the black shales to the south of the London-Brabant Massif, where sedimentation took place under the influence of the Variscan Deformation Front. The whole basin-fill succession represents progradation of a turbidite-fronted delta system in which turbidity currents by-passed the silt-dominated slope via feeder channels. The rapidly deposited slope deposits may be affected by soft-sediment deformation in the form of slumps and growth faults. Above the basin-fill succession, the remainder of the Namurian is typically 'cyclic' as seen in the Millstone Grit in the UK and time-equivalent formations elsewhere in the NWECB (**Figure 6.3**). The cyclothems are upward-coarsening and overlie marine-band mudstones (e.g. Cloughton-1 or 43/21-2, **Figure 6.9**). The individual cyclothems are typically a few tens of metres thick and the sandstones that form their upper parts are both mouth-bar and channel deposits. The sandstones are the result of successive progradations of a major delta system from the north, comparable in scale and style to the present-day Lena Delta of eastern Siberia. Most channel-sand bodies in the cyclothems are distributary deposits, although some thicker (20-30 m), multi-storey, coarse-grained sediments may be incised palaeovalley fills formed following periods of more rapidly falling base level.

In the northern Netherlands, the Namurian succession consists of distal deposits with a very thick (>2000 m) shale sequence and thin sandstone beds (wells TJM-02, NAG-01, **Figure 6.9**). In this area, a boundary may be expected between areas with a northern source (Fennoscandia and the Old Red Continent) and those with a southern source (Variscan Mountains). However it is still unclear where this boundary lies (Frank et al., 1992). The Campine Basin was infilled from the south-east (**Figure 6.8**), where there are coal seams and seat earths as old as late Kinderscoutian (Namurian B) age. In the western Campine Basin, no coals or seat earths are known in the Namurian (**Figure 6.3**, Langenaeker, 2000). These sediments progressively overlap the London-Brabant Massif (Bouckaert, 1967). Coal had already been deposited in the southernmost coal basins during Arnsbergian times (in the Dinant Synclinorium and eastern Namur-Vesdre Syncline, closer to the current location of the Variscan Deformation Front; **Figure 6.8**).

Lower Namurian A deposits are poorly developed (20-200 m thick) or absent in most of the Ruhr Basin (**Figure 6.8**), indicating that sediment-starved conditions continued to prevail in this area of the NWECB (Drozdzewski, 2005). As noted above, flysch deposits (**Figure 6.3**) accumulated farther south during Early Carboniferous times. The sedimentation rate accelerated during late Namurian A and B times such that about 1350 m of flysch sediments were deposited in the Ruhr Basin (Wrede & Ribbert, 2005; Flözleeres Series; **Figures 6.3** & **6.7**). The Niederrhein Graben (**Figure 6.8**) possibly acted as the main discharge zone from the Variscan foredeep to the north (Drozdzewski, 2005). In the Aachen Basin, the first coal seams are found in the Namurian A succession, similar to the neighbouring area of Belgium south of the London-Brabant Massif. Paralic sedimentation started during Namurian B times in the Ruhr and Campine basins to the north of the London-Brabant Massif (Kaisberg Formation; **Figure 6.7**). In the area of north-east Germany, paralic depositional environments prevailed throughout the entire Namurian (as indicated by coal seams), grading to a deeper-marine setting in the south (McCann, 1999b; **Figure 6.7**). In the Altmark area, there was gradual shallowing from a deep-marine environment during the Namurian A interval to paralic deposition in the Westphalian (Hoth et al., 2005a). For example, paralic Namurian B rocks have been found in the well Parchim 1/68 (Loissin Formation; **Figure 6.10**).

In the Lublin Basin, coal-bearing successions were deposited in cycles of shallow-shelf, deltaic and fluviolacustrine environments with low to moderate sand content (Waksmundzka, 2007b; see **Figure 6.16**). These deposits form part of the upper Terebin Formation and the Bug Member of the Deblin Formation (**Figure 6.3**). In the Upper Silesian Coal Basin, paralic sedimentation had already started during Namurian A times (Kotas, 1995; **Figures 6.3**, **6.8** and see **6.16**). These coastal and delta-plain sediments are up to 3800 m thick in the western part of the basin.

4 Westphalian

4.1 *Subsidence mechanisms*

In the western NWECB north of the London-Brabant Massif, the passive thermal cooling that had started during the Namurian continued into the Westphalian (Fraser & Gawthorpe, 1990). At the southern NWECB margin, the foreland basin gradually migrated northwards (McCann, 1999b; Burgess & Gayer, 2000; Drozdzewski, 2005; **Figure 6.11**) as a consequence of the northward drift of Gondwana relative to Laurussia. In addition to regional thermal subsidence, Drozdzewski et al. (2009) suggested that sedimentation in the NWECB was fault-controlled by predominantly north-west–south-east-trending faults (e.g. the Elbe Line, Uelzen and Osning faults; **Figure 6.2**) and a less important north–south to north-north-east trend.

During mid-Bolsovian times, intraplate stresses established a compressional tectonic regime in the western NWECB (Fraser & Gawthorpe, 1990; Ziegler & Dèzes, 2006). This can be seen in the Pennine Basin and Silverpit area of the North Sea, where the influx of sand during mid-Bolsovian times marked the onset of tectonic deformation within the basins. This Variscan inversion event led to the development of a series of broad anticlines in the hanging walls of the basin-bounding faults (Fraser & Gawthorpe, 1990). In the Ruhr and Campine basins, Variscan folding only started during or after the Stephanian at about 300 Ma (Drozdzewski et al., 2009). There was a similar situation in the Polish part of the NWECB, where compression started only during the late Asturian and early Stephanian (Narkiewicz, 2007). By end-Westphalian times, the Lublin Basin had undergone structural inversion in the thrust-fault stress regime.

4.2 *Basin fill*

The Westphalian sedimentary sequence in the NWECB generally reflects continued aggradation in or around emergent conditions. The lower Westphalian succession is characterised by deltaic to fluviolacustrine deposits with numerous coal layers, giving way to sediments deposited in well-drained fluvial environments (eventually red beds) during the late Westphalian.

Langsettian
In the western NWECB, the Coal Measures (onshore) and Caister Formation (offshore) in the UK, the Baarlo Formation in the Netherlands, and time-equivalent formations in Belgium, Germany (Ruhr Basin) and western Poland (**Figure 6.3**), broadly represent the continuation of cyclic fluviodeltaic sedimentation during the late Namurian (e.g. wells 44/19-3 and K01-2 in **Figure 6.12** and wells Goldhoorn-01 and Münsterland-01 in **Figure 6.13**). Fluviodeltaic sediments predominated at an earlier stage along the basin margins than in the basin centre, where time-equivalent deltaic sediments were deposited (for instance in the Ruhr Basin; **Figure 6.11** and well logs in **Figure 6.13**). There are fewer marine bands than found in the Namurian succession, and an increasing number of coal seams mark the transition to mainly freshwater lacustrine and floodplain environments (**Figure 6.11**). Uplift in Poland led to erosional conditions in the south and west. Deposition of coal-bearing successions continued in the then-isolated Upper Silesian Coal Basin (Bojkowski & Dembowski, 1988) where fluviolacustrine deposits with a low to moderate sand content accumulated (Mudstone Series, **Figures 6.3** and see **6.16**). The sand content of the Lublin Basin deposits is higher than in the Upper Silesian Coal Basin (see **Figure 6.16**).

Duckmantian
The Duckmantian succession has the highest number of coal seams in the NWECB. The coals accumulated in a lower delta-plain environment at times when the influx of sand was at a minimum in major parts of the basin (Waksmundzka, 1998; Drozdzewski, 2005; Hoth et al., 2005a; Van Buggenum & Den Hartog Jager, 2007). In the UK southern North Sea area, this sand-poor, predominantly fine-grained, succession is part of the Westoe Formation (**Figures 6.3** & **6.12**). These sediments indicate a distal position in the dispersal system, in which the sandstone provenance is from both the north and west. However, in the UK and the Silverpit / Cleaver Bank areas, there were marked pulses of sand input in the Duckmantian coal-bearing succession, partly derived from the Ringkøbing-Fyn High in the north (e.g. the Caister Formation /

Murdoch Sandstone in the UK and the Botney Member in the Netherlands, **Figures 6.3** & **6.12**). In the Campine Basin, changes in the cyclic pattern and increased sand content indicate a change from the lower to upper delta-plain depositional environment that had already been established during the Duckmantian (Paproth et al., 1996). Sand contents are also at a minimum (10-15%) in the lower Duckmantian sediments of the Ruhr Basin (Essen and Horst formations; **Figure 6.13**). The source of these sands was probably the Variscan Mountains from where they were transported parallel to the basin (Drozdzewski, 2005). Palaeoflow directions in the Netherlands indicate transport from both the north-east and south-east (Van Buggenum & Den Hartog Jager, 2007). The maximum number of coal seams is also found in the Duckmantian succession of eastern Germany. The number of sandstones is somewhat higher in Altmark than in Vorpommern (Hoth et al., 2005b). Duckmantian sediments in the Lublin and Upper Silesian Coal basins of Poland indicate a continuation of fluviolacustrine sedimentation (**Figure 6.3**).

Bolsovian

From the Bolsovian upwards, the Westphalian succession contains increasing proportions of fluvial red beds related to changes in fluvial-input patterns. These changes were the result of the onset of intrabasinal deformation and the gradual drying of the climate (**Figure 6.14**). The red beds initially appeared in the western NWECB during Bolsovian times. However, by Asturian times, they were deposited across the whole area. The succession has variable amounts of sandstone depending on the proximity to points of fluvial input and the nature of the fluvial catchment areas. All of the Bolsovian red-bed formations have reddened, bioturbated lacustrine mudstones, lacustrine-delta sediments, palaeosol-dominated overbank successions and alluvial-channel systems.

In UK North Sea area, the northerly derived reddened sediments of the Ketch and Flora formations were deposited during the Bolsovian. Significant development of red beds (Etruria Formation) had already taken place from latest Duckmantian times in the southern Pennine Basin, prograding northwards with time (**Figure 6.3**). These sediments were the first in the UK area of the NWECB to have a clear southerly derived component, and were sourced from uplift of the London-Brabant Massif, reflecting the onset of significant deformation in southern England (Besly, 1988). However, the eastern London-Brabant Massif in the area of Belgium still had a thick Westphalian cover as indicated by subsidence and coalification trends and apatite fission-track data. Between the north-easterly derived Ketch drainage system (Ketch Formation) and the southerly derived Etruria drainage system (Etruria Formation), there is an area in which the absence of Bolsovian red beds indicate that it was not influenced by these drainage systems (**Figure 6.14**). The area is located more-or-less centrally in the Pennine depocentre and marks a region of persistent subsidence and coal-swamp formation. It is possible that fluvial systems derived from the Variscan Front and the Ringkøbing-Fyn area drained westwards through this subsiding centre in northern England, although their subsequent fate is not known.

In the Netherlands area, the number of sandy deposits with a south-eastern provenance increased during the Bolsovian, as shown by the relatively thick fluvial sandstones (up to 40 m; Tubbergen/Hellevoetsluis formations; **Figures 6.3** & **6.13**). There is a similar increase in southerly derived sandstones in the Bolsovian rocks of the Campine and Ruhr basins (Lembeck and Dorsten formations; **Figure 6.3**). In contrast to the UK, there was no significant red-bed development during the Bolsovian in this part of the NWECB, although coal content is lower than in the Duckmantian. The Bolsovian rocks of north-east Germany have a rather low sand content (<25%; Hoth et al., 2005a) and were deposited in a transitional facies from poorly drained sediments with coals to well-drained conditions.

Farther east in the Pomerania area, the transition from deltaic to fluvial environments only started during Bolsovian times (**Figures 6.3**, **6.10** & **6.14**). The amount of sandstone increased in the Bolsovian succession of the isolated Upper Silesian Coal Basin. The Kraków Sandstone Series (up to 1600 m thick) was deposited in a similar environment to that of the underlying Upper Silesian Sandstone Series. Both series represent alluvial-plain deposits of braided-river systems. There are few coal layers, although some are 5 m thick. The fine-grained sediments of the Lublin Formation were deposited mainly in a lacustrine environment. Twenty-five coal seams have been found in this formation, with a maximum thickness of 3.8 m.

Asturian

The Asturian interval was characterised by the establishment of red-bed deposition in large areas of the NWECB, for example the Brig Formation in the UK and the De Lutte/Strijen formations in the Netherlands (**Figure 6.3**). Improved drainage conditions during the early Asturian led to the expansion of fluvial systems from the Variscan fold-and-thrust belt into the southern parts of the Pennine and southern North Sea depocentres, where the Boulton and Brig formations were deposited (**Figure 6.3**). Some red-bed deposits have low sand contents and are interpreted as distal-floodplain sediments with only a minor amount of intercalated sheetflood sandstones. The floodplain deposits are commonly found in the eastern Netherlands (De Lutte Formation, **Figure 6.15**; Pagnier & Van Tongeren, 1996) and the southern North Sea (**Figure 6.12**). Fluvial activity was much more vigorous elsewhere, and sand contents are consequently high. For example, in the Osnabrück area (**Figure 6.15**), Asturian sediments are characterised by sands deposited in major river systems and have up to 80% sand content, although thin coal seams do occur. This is also the case in the Campine Basin, where the Neeroeteren Formation sandstones are a facies equivalent of the Bolsovian Tubbergen Formation of the Netherlands (see above). Farther east in the Rügen area, Asturian rocks indicate deposition under well-drained conditions in a braided-river system (Hoth et al., 2005a) and their sand contents are relatively high. It is uncertain if a connection existed between the Rügen area and the Lublin Basin, or if sedimentation continued in this area during the Asturian.

5 Stephanian

5.1 *Subsidence mechanisms*

The regional stress pattern in the NWECB changed dramatically at about the time of the Westphalian-Stephanian transition. The end of orogenic activity in the Variscan Fold Belt during the latest Westphalian was followed by the establishment of a dextral and sinistral wrench-fault system (Ziegler, 1990a; Ziegler et al., 2006) that led to the development of transtensional and pull-apart basins. The most important example of this type of basin system in the NWECB is the Ems-North Sea-Stralsund basin (**Figure 6.4**; Krull, 2005). This Stephanian basin probably developed due to the underlying Teisseyre-Tornquist Zone (the Caledonian suture zone between Avalonia and the East European Craton). Activation of the Teisseyre-Tornquist Zone is marked by the latest Westphalian to early Stephanian onset of magmatic activity in the Oslo Graben to the north of the SPBA area (Sundvoll et al., 1992). Basins such as the

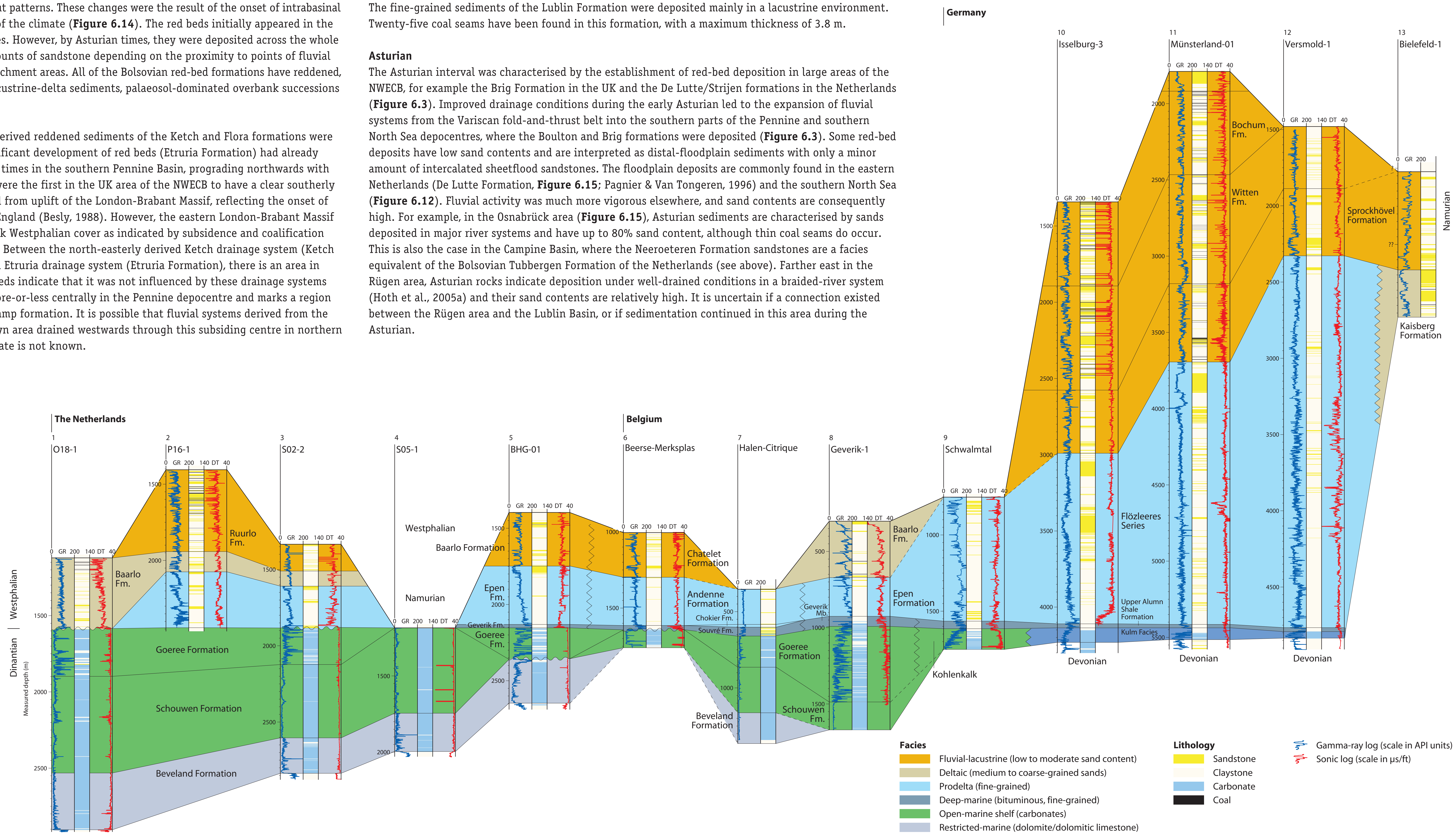


Figure 6.7 Well-correlation panel of Tournaisian to Namurian rocks from the London-Brabant Massif to the Ruhr Basin in the east. The very sandy Andenne Formation in the Halen-Citrique well is probably faulted and therefore the thickness is overestimated in this section. See Figure 6.5 for locations.

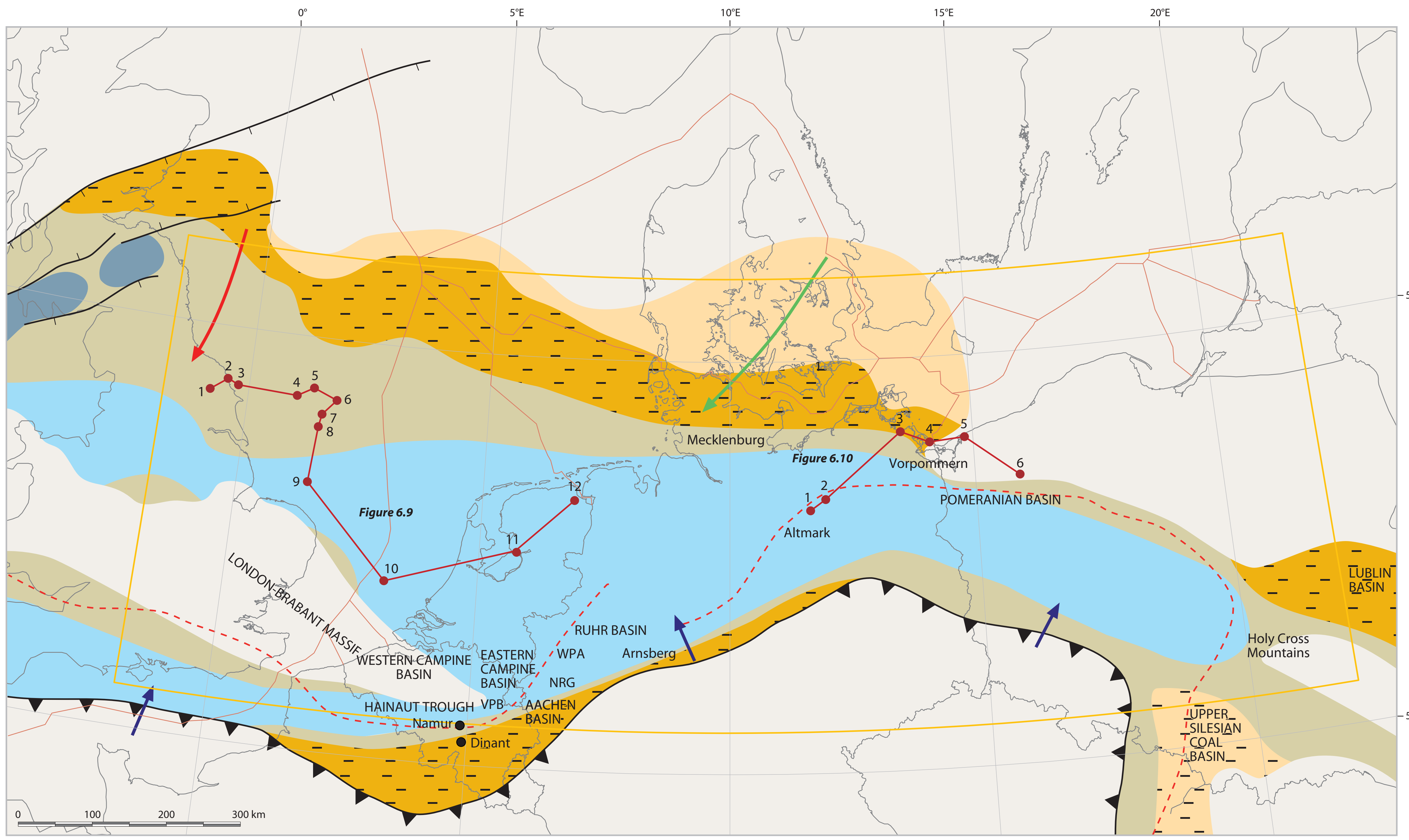


Figure 6.8 Namurian A palaeogeography.

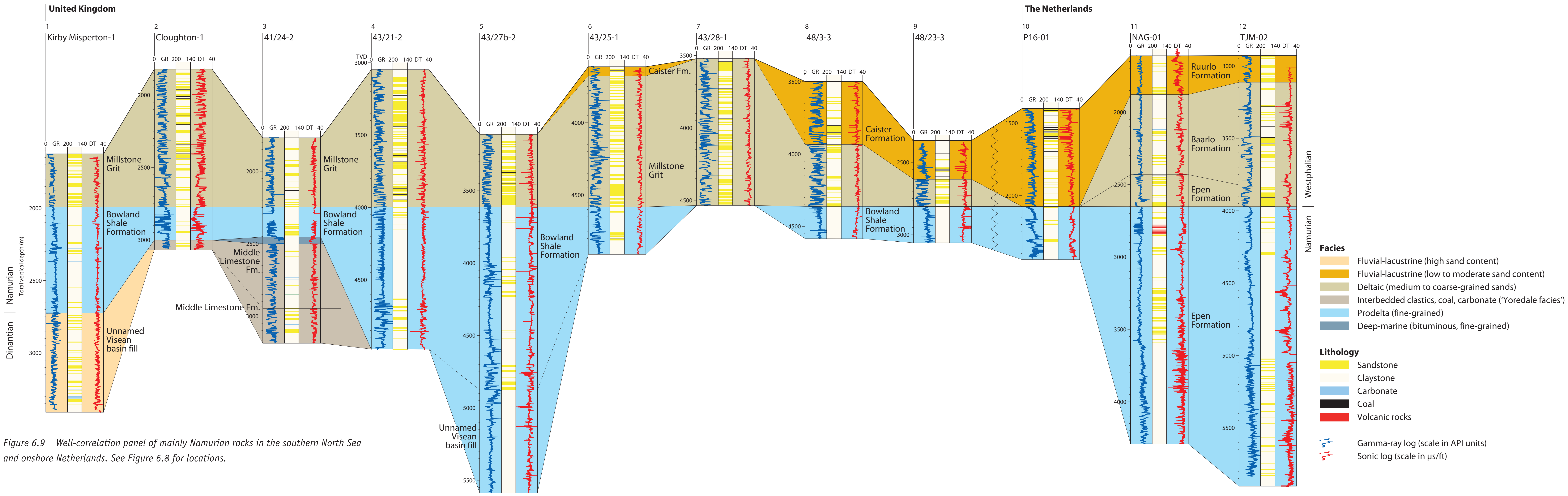


Figure 6.9 Well-correlation panel of mainly Namurian rocks in the southern North Sea and onshore Netherlands. See Figure 6.8 for locations.

Ems Basin (a north–south-trending belt of Stephanian deposits in north-west Germany; **Figure 6.4**) can be considered to be the result of a secondary shear system linking the major systems, such as the Teisseyre-Tornquist Zone (Ziegler et al., 2006).

Stephanian rocks probably had a much wider distribution; however, Early Permian uplift (Saalian or Base Permian Unconformity, see Chapter 7) led to their intense erosion (Ziegler, 1990a; Krull, 2005; see the isolated remnants of Stephanian rocks in eastern Germany, **Figure 6.4**). For example, thermal modelling suggests that a thick sequence of Stephanian rocks may have been present in the Ruhr area (Littke et al., 2000). In most areas, Stephanian rocks unconformably overlie Westphalian or Namurian strata. It is only in the axial parts of the Ems-North Sea-Stralsund basins that the Stephanian deposits are conformable with the Westphalian (Ziegler, 1990a). It should be noted that the area of Stephanian deposits shown in **Figure 6.4** is that of sedimentary rocks. Extensive Stephanian to Early Permian volcanic complexes overlie these sediments in places and so the Stephanian actually covers a larger area (Figure 3.9).

5.2 Basin fill

Stephanian sediment facies indicate accumulation under slightly more arid conditions than Asturian deposits. Moderately developed vertisols and calcretes are common. The most distal facies is found in the North Sea, where wells that penetrate the Stephanian have encountered sedimentary rocks with slightly lower sand contents than those of the Ems Basin (Selter, 1990). Krull (2005) described grey (poorly drained) claystones and even coal layers in this area. According to Selter (1990), the Ems-North Sea-Stralsund basins were probably closed off from the open ocean as there are no indications of a marine influence; however, there is still the problem of how to interpret the marine Asturian facies found in the Oslo Graben (Olaussen et al., 1994). Bergström et al. (1985) and Dahlgren & Corfu (2001) suggest that there was a marine incursion into the Oslo Rift from either the north or east. In the south-western Ems Basin, the sand content of Stephanian sediments is higher than that of the Asturian (maximum 45%), which has been interpreted as being due to a narrowing of the basin (Selter, 1990; **Figure 6.15**). The sands were deposited in northward-draining alluvial-fan systems. The decreasing thickness of sand bodies from west to east in the western Ems Basin could suggest that the present-day Netherlands area and Variscan Mountains to the south were also a significant sediment source. Stephanian sediments on Rügen Island have slightly higher sand contents than those in western Germany, especially the youngest Stephanian (55-70%), which has an unconformable relationship with older Stephanian rocks (Hoth et al., 2005a). These reddened sediments were deposited mainly in alluvial-fan systems. Fluviolacustrine deposition with high sand contents persisted throughout the Stephanian in only a small area in the east of the basin, as seen in Pomerania (Dziwna Formation) and the Upper Silesian Coal Basin (Kwaczała Arkose) (**Figure 6.3**). Elsewhere in the Polish area, conditions were mainly erosional. The youngest Stephanian rocks in north-east Germany are andesitic volcanics, which mark the onset of the Permo-Carboniferous magmatic cycle that led to intrusion of the Greifswald, Roxförde and Flechtingen granitic bodies, each with ages of about 300 Ma.

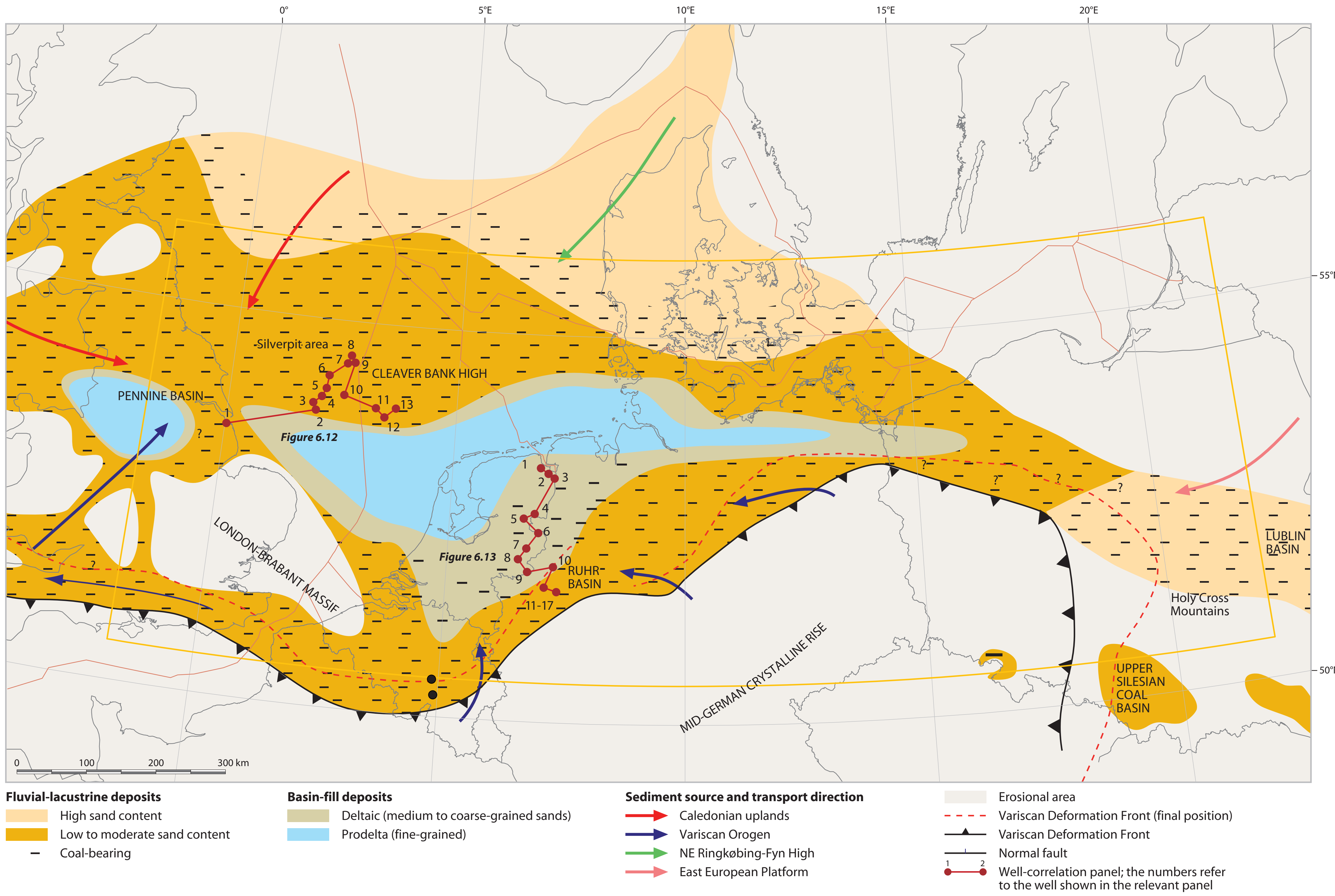


Figure 6.11 Langsettian palaeogeography.

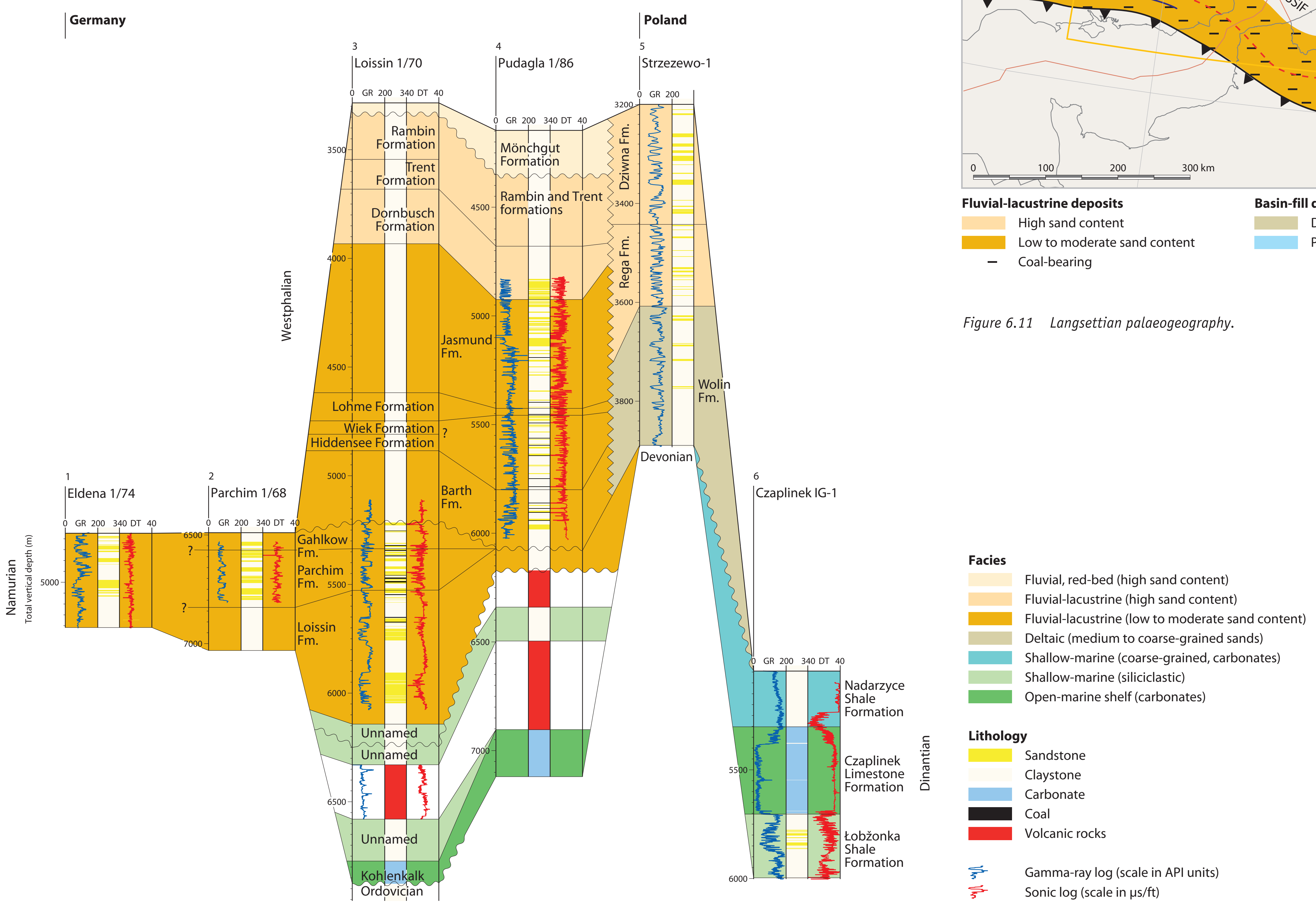


Figure 6.10 Well-correlation panel in the Rügen-Altmark area. The unconformities in Loissin 1/70 are from Kornpihl (2005). See Figure 6.8 for locations.

6 Hydrocarbon systems

6.1 Coals

6.1.1 Coal-mining areas

Carboniferous coals have been mined in the SPB since Roman times; however, large-scale exploitation only began during the Industrial Revolution (see Section 2 in Chapter 16). Only a few mines are still open and many are not economically viable, although there may be renewed interest in coal mining when oil prices are high. The map showing areas where mining has taken place therefore includes areas that have coalbeds at mineable depths, but where there has been no mining so far (**Figure 6.17**).

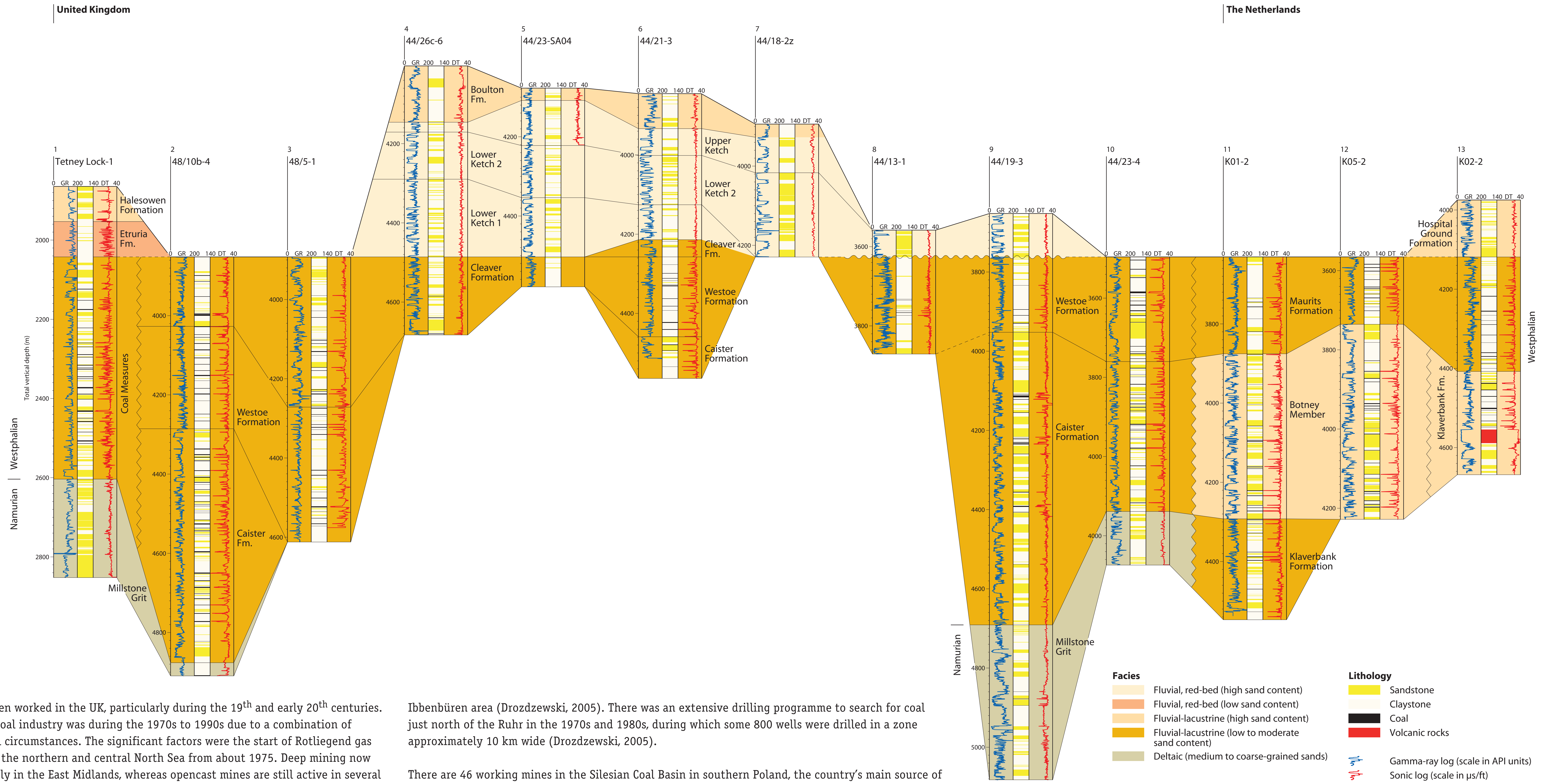


Figure 6.12 Well-correlation panel of mainly Westphalian rocks in the southern North Sea. See Figure 6.11 for locations.

A huge number of mines have been worked in the UK, particularly during the 19th and early 20th centuries. The main decline of the British coal industry was during the 1970s to 1990s due to a combination of technical, economic and political circumstances. The significant factors were the start of Rotliegend gas production in 1967, and of oil in the northern and central North Sea from about 1975. Deep mining now occurs at only a few places, mainly in the East Midlands, whereas opencast mines are still active in several areas of England, Wales and Scotland.

There has been a coal industry in southern Belgium since the 13th century in the narrow Wallonian Basin along the southern margin of the London-Brabant Massif from Aachen (Germany) to Boulogne (France) (**Figure 6.17**). The Campine Basin of north-east Belgium is the largest coal basin in the country and is a continuation of the South Limburg coalfield in the Netherlands and the northern parts of the Aachen and Ruhr coalfields in Germany. The larger western Antwerp Campine Basin has only Namurian and lower Westphalian deposits with limited coal reserves, although these provide good access to the deep saline aquifer in the underlying Visean rocks. The eastern Limburg Campine Basin has a fully preserved coal-rich Westphalian succession. After a period of prosperity between 1910 and 1955, coal production steadily declined until the first mine closures in the Wallonian Basin. The last mine in the Campine Basin was closed in 1992.

In the Netherlands, large-scale coal mining took place from 1847 to 1974 in southern Limburg, producing 582 MMt in total (Van Buggenum & Den Hartog Jager, 2007). Like the situation in the UK described above, the discovery of gas in the Groningen field led to the closure of coal mines during the 1960s and 1970s.

The most important mining district in Germany is the Ruhr area (**Figure 6.17**), where there are about 300 Yeadonian to Asturian coal seams with post-compaction thicknesses from a few centimetres to more than 5 m. The average coal content of the complete sequence is between 4% in the southern part of the basin and 2% in the north (Drozdzewski, 1992). There are four working coal mines in the Ruhr and one in the Ibbenbüren area (Drozdzewski, 2005). There was an extensive drilling programme to search for coal just north of the Ruhr in the 1970s and 1980s, during which some 800 wells were drilled in a zone approximately 10 km wide (Drozdzewski, 2005).

There are 46 working mines in the Silesian Coal Basin in southern Poland, the country's main source of coal (Gientka et al., 2007). The results of geological research in the Upper Silesian Coal Basin are based on data from about 2000 wells. The Carboniferous coal-bearing deposits span the upper Namurian A and the entire Westphalian succession. Their preserved thickness is estimated at about 4500 m, whereas the complete section is about 8000 m thick with approximately 520 coal seams and thin coal layers varying in thickness from 0.4 to 24 m. Their total thickness is 339 m, accounting for 4.12% of the coal-bearing strata. There is one working coal mine in the Lublin Basin. See Chapter 16 for further information on coal deposits.

6.2 Oil and gas

The first hydrocarbon discovery in the Carboniferous of England was in 1919 at Hardstoft in Derbyshire (**Figure 6.1**). The hydrocarbons were found in fractured Visean shelf carbonates, sourced by Namurian basinal shales (Fraser & Gawthorpe, 1990). Although these carbonates were a target for early hydrocarbon exploration, most wells drilled on the play were unsuccessful due to the poor reservoir quality. Subsequent exploration was therefore targeted at Namurian and Langsettian sandstone reservoirs (see Chapter 13). From the 1930s to the present day, this exploration programme has led to several oil and gas discoveries in the East Midlands, around the Gainsborough Trough, and in Yorkshire (**Figure 6.20**). The first commercial discovery in this play was reported in 1939 at Eakring by the D'Arcy Exploration Company (Fraser & Gawthorpe, 1990). None of the discoveries are large, although several have sustained production for many years at relatively low flow rates. In all cases, the source rocks are Namurian basinal shales.

Carboniferous reservoirs are relatively unimportant offshore compared with Rotliegend reservoirs, although numerous Namurian and Westphalian sandstone reservoirs are currently producing gas. Most of this gas is sourced from Westphalian Coal Measures, with possible contributions from Namurian basinal shales (**Figure 6.23**).

There have been no hydrocarbon discoveries in Belgium apart from dissolved gas (mainly CO_2) in the Merksplas-Beerse geothermal test well (Vandenberghe et al., 2000) (see Section 3.2 in Chapter 16). Visean limestones in the western Campine Basin have been drilling targets in areas where there has been reactivation of palaeokarst by fluids expelled from more deeply buried Coal Measures. One domal structure in Visean limestones is used for gas storage.

The first Carboniferous gasfield in the Netherlands (the Coevorden gasfield; see Section 6.3.4) was discovered in 1951, 8 years before the famous Groningen field. Numerous fields have since been found in the eastern Netherlands (**Figure 6.20c**). The Cleaver Bank High is another prolific gas province in the UK-Netherlands offshore sectors, where Carboniferous reservoir sandstones are sealed by Rotliegend shales and salts. The first Carboniferous gas discovery in this area was in 1974 at the K4-FA field (Van Buggenum & Den Hartog Jager, 2007). Carboniferous reservoirs continue to be explored in the Netherlands, especially offshore.

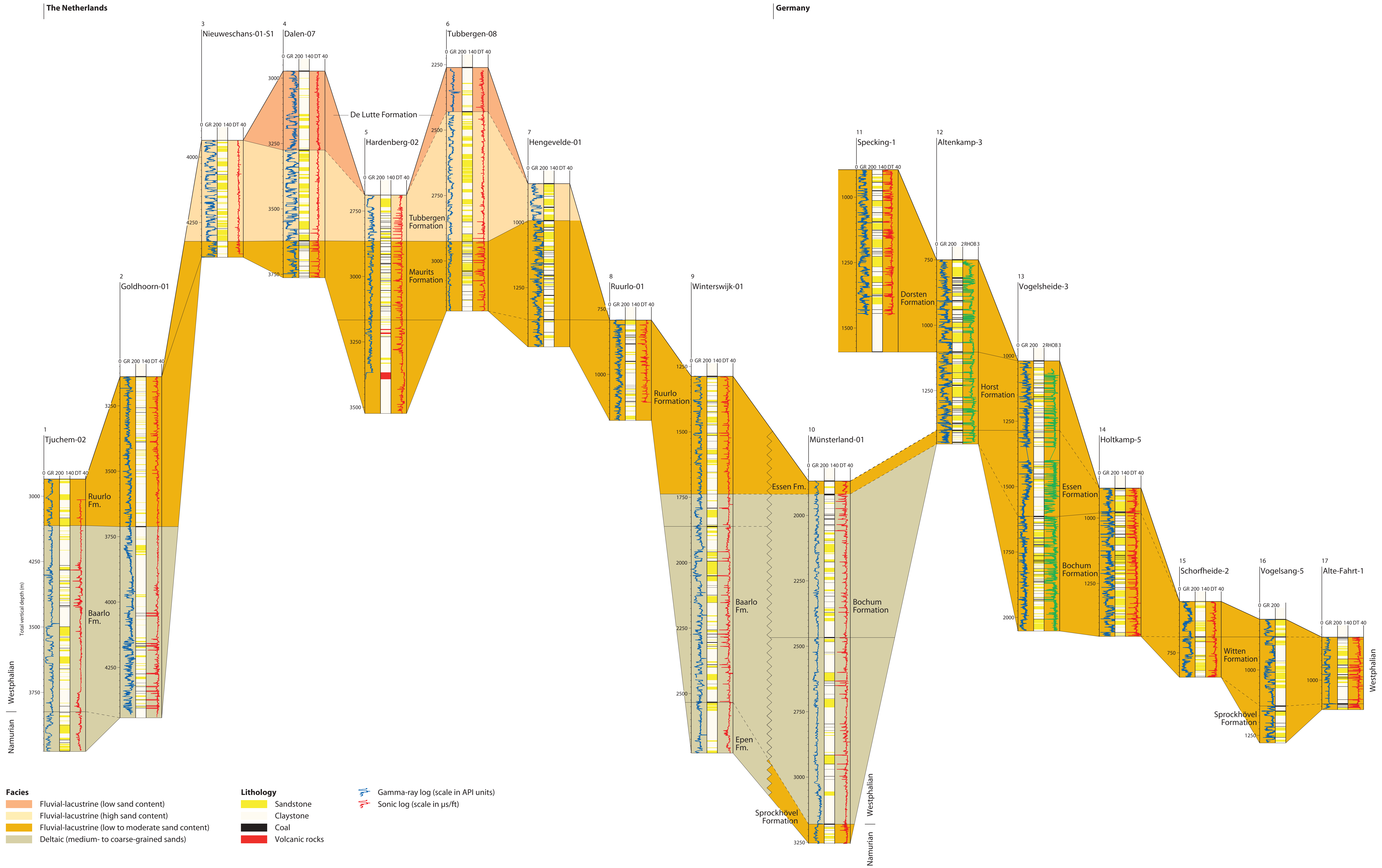


Figure 6.13 Well-correlation panel of Westphalian rocks from the Ruhr Basin to the northern Netherlands. See Figure 6.11 for locations.

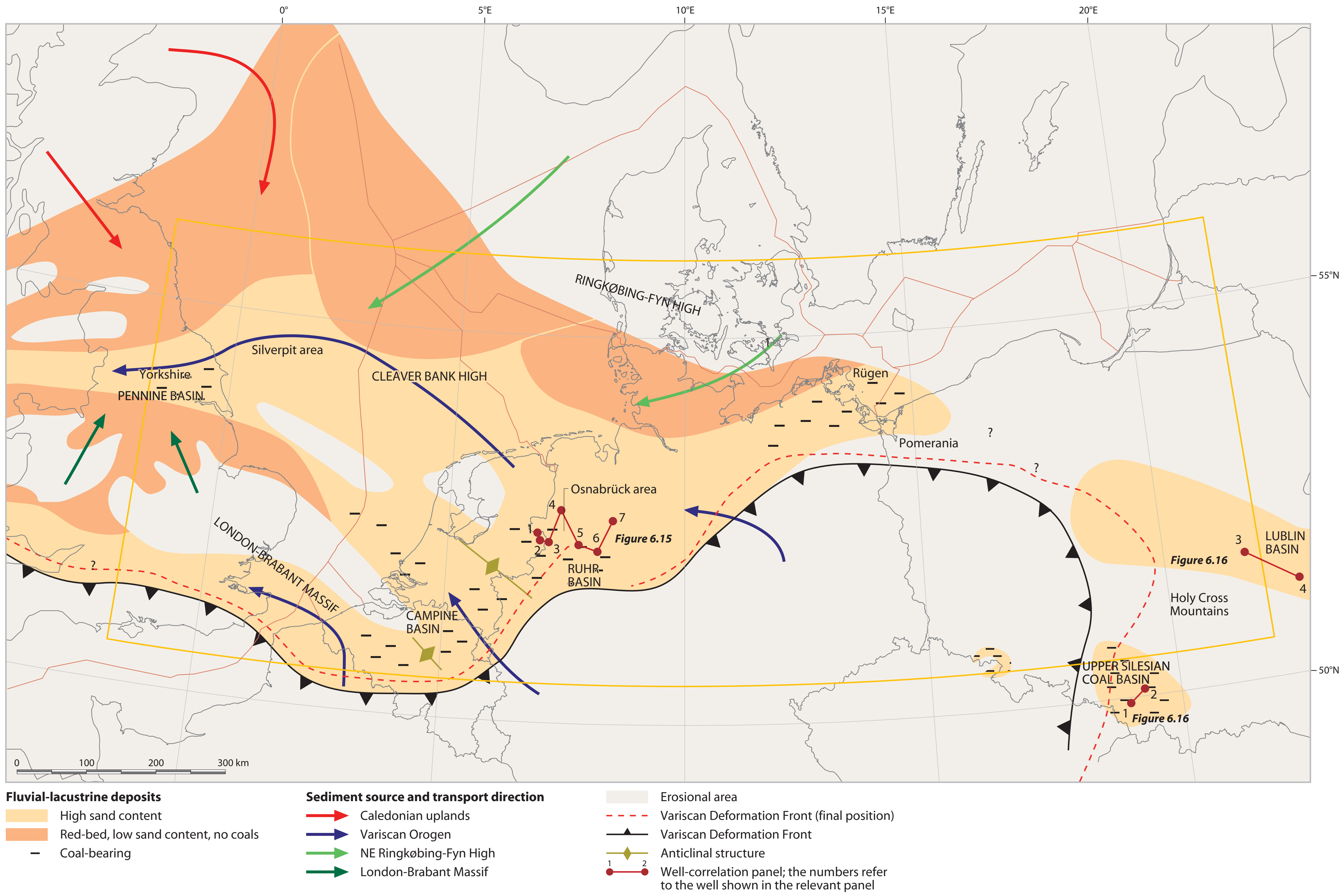


Figure 6.14 Bolsovian/Asturian palaeogeography.

Lower Carboniferous rocks have been drilled in southern Denmark. However, the carbonates here are tight and the shales are too low in total organic carbons (TOC) to be considered hydrocarbon source rocks. At least two wells have penetrated the Carboniferous offshore, but no viable reservoirs have been identified (Bruce & Stemmerik, 2003). The thin coal seams drilled in well Gert-2 have no economic significance (Petersen & Nytoft, 2007a).

Since the 1980s, there have been a number of discoveries in Germany in the same belt as the reservoirs in the Netherlands, and exploration is continuing. Offshore, there have been few drilling targets with the Carboniferous as their primary objective because it is often too deeply buried (Maynard et al., 1997).

In Poland, hydrocarbons have been found in the Carboniferous of Pomerania, the Fore-Sudetic Monocline, the Upper Silesian Coal Basin and the Lublin Basin. The first discovery was in 1972 (the Minkowice field) in the Lublin Basin. There are six known reservoir horizons in Pomerania, in rocks ranging in age from Visean limestones and sandstones to Westphalian sandstones (**Figure 6.20d**, **e** & **f**), two of which are now in production. Two hydrocarbon fields have been found in Carboniferous sandstones in the Fore-Sudetic Monocline; the fields also have Rotliegend (Paproć) and Zechstein reservoirs (Kościan). There is one gasfield in Westphalian fluvial sandstones in the Upper Silesian Coal Basin, which is sealed by Miocene clays/marls. Four hydrocarbon accumulations have been discovered in the Lublin Basin (see field examples below). Current exploration in the Carboniferous rocks of Poland also focuses on unconventional hydrocarbon accumulations such as shale gas and tight gas. More information on the exploration history of the SPB is presented in Chapter 14.

A small amount of gas is produced directly from Carboniferous coals in the NWECB. In the UK, despite the fact that numerous thick coals occur at workable depths, the coal-bed methane (CBM) prospects are thought to be poor due to the relatively low seam-gas contents and uncertainty over the permeability of the coals (Holloway et al., 2005). However, there are exploration activities taking place, especially in Scotland. The producible CBM reserves of the Campine Coal Basin in Belgium are estimated to be 53 bcm. A Flemish-Dutch CBM test was conducted in the Peer pilot test well in the Campine Basin from 1991 to 1993. The total amount of produced gas has been calculated to be about 17 100 m^3. These unconvincing results were due mainly to the positioning of the well close to the Donderslag Fault Zone, which was found to be highly permeable. Formation water with dissolved deep-sourced CO_2 was therefore delivered to the wellbore, and prevented sufficient depressurisation of the coals (Wenselaers et al., 1996) . There is no current production of CBM from the Dutch subsurface. Estimates for the theoretically recoverable volumes of CBM shallower than 1500 m are between 7 and 107 bcm (Van Bergen et al., 2007). However, as a result of international measures to comply with the Kyoto protocol, CBM production might become attractive in combination with storage of CO_2. Some 60 mine gas plants are currently in operation in Germany, producing some 180 × 10^6 Nm^3 CH_4 per year. In the Upper Silesian Coal Basin in Poland, where there was much CBM exploration during the 1990s, two zones of increased methane content were found in Carboniferous rocks (Jureczka, 1995). The first, a few tens to 250 metres thick, occurs at the top of the Carboniferous succession; a zone with up to 6 m^3/t of pure coal. The second (main) zone has absorbed methane within coals or organic matter at a depth of about 1000 to 1500 m. The CBM content in this zone is 2 to 12 m^3/t of pure coal. According to Zdanowski (1995), the CBM potential of the Lublin Basin is low. This is generally due to both low maturity of organic matter and erosion of Carboniferous deposits, which took place in this area from Stephanian through Early Jurassic times.

6.2.1 Source-rock distribution and maturity

Dinantian

Most Lower Carboniferous source rocks in the NWECB are black shales that were deposited in relatively deep-water settings. These source rocks are especially common north of the foredeep that lay along the southern NWECB margin during the Carboniferous. The area was most probably part of the complex of carbonate platforms and sediment-starved troughs that developed throughout the NWECB during Dinantian times (**Figure 6.5**). The basinal shales may have been deposited mainly in these troughs for as long as sediment-starved conditions prevailed. The highly condensed and organic-carbon rich Dinantian succession in wells Münsterland-01 (**Figure 6.7**) and Winterswijk-01 was probably deposited in a setting of this type. This setting is also seen in the UK, where the lower Bowland Shale Formation of the Craven and Cleveland basins are Brigantian in age. **Figure 6.18** shows wells in which black shales of Dinantian and/or Namurian age have been found. As there is almost no well control in the central NWECB, magnetotelluric soundings (e.g. Hoffmann et al., 2001) have been used to infer the distribution of black shales in the basin centre.

Due to the relatively high sedimentation rates in the eastern NWECB (Poland) during the Dinantian, organic matter is found mainly in dispersed form; Grotek (2005) described mixed humic-sapropelic organic matter in the Dinantian rocks of north-east Pomerania. These source rocks are represented by the Tournaisian claystones and carbonates of the Gozd Arkose and Sąpolno Calcareous Shale formations (**Figure 6.3**). The mainly Early Carboniferous rocks in the Fore-Sudetic Monocline (**Figure 6.5**) have locally abundant organic matter (Grotek, 2005). Visean shales are a potential source rock in the Lublin Basin.

The maturity of Dinantian source rocks in the NWECB is generally high to very high. Deep burial, magmatism and hydrothermal veins (Poprawa et al., 2005) have resulted in the source rocks being overmature in most areas (See Chapter 13).

Namurian

The early Namurian was a period of relatively low sedimentation rates when carbonate deposition in the NWECB generally came to an end. As a consequence, black shales are found on top of the carbonate platforms, for example, in the Derbyshire Block of northern England. Condensed sedimentation may well have been uninterrupted in the graben areas during the Visean-Namurian transition. Like the Dinantian black shales, Namurian shales can not be confirmed over large areas of the NWECB (**Figure 6.18**), although either Dinantian or Namurian black shales may be expected based on gas compositions from the basin (Gerling et al., 1999c). The Namurian shales are very mature across most of the NWECB, similar again to the Dinantian. However, the Namurian source rocks at the western and eastern NWECB margins have not been deeply buried and so the Namurian black shales form the most important source rock in the East Midlands oil province of the UK (**Figure 6.20**). These shales have also sourced oil accumulations in the Triassic reservoirs of the East Irish Sea (west of the SPBA area) and comparable source rocks have charged the fields in the Lublin Basin at the eastern SPB margin.

Westphalian

Westphalian coals are the main source rock for Carboniferous and Rotliegend gas accumulations in the SPB area. **Figure 6.17** shows the distribution of Langsettian and Duckmantian rocks, the successions that contain the most economically important coal seams. The absence of information in central Poland is due to limited well control and it is not certain that Westphalian coal-bearing rocks occur in the area. Although major parts of the Coal Measures are in the gas window (vitrinite reflectance >1.15%) at the present day, this is not the case throughout the SPB, as can be seen in **Figure 6.19**. For instance, the Dutch field K04-FA is located in an area where the maturity is less than 1% Ro, implying that the gas has migrated laterally from areas where Carboniferous rocks are in the gas window. In the Lublin Basin, the maturity of Westphalian coals is generally too low to form an important gas source. Elsewhere, for example in Germany and Poland, the Westphalian coal-bearing succession is overmature.

6.2.2 Reservoirs

Most Carboniferous reservoirs in the SPB (**Figure 6.20**) are found in siliciclastic rocks. The oilfields in England (East Midlands) have reservoirs in Namurian or lower Westphalian channel sandstones. Pebbly sandstones of major fluvial systems, such as those of the Bolsovian to Asturian Ketch Formation, form the most important Carboniferous reservoirs in the southern North Sea (**Figure 6.20b**). These reservoirs host gas accumulations in a number of fields in UK Quadrant 44 (e.g. Ketch, Schooner, Boulton, Tyne) and the adjacent Dutch blocks D, E and K (Cleaver Bank High) (Figure 1.4). Another group of gas accumulations in this area have reservoirs in Duckmantian fluviodeltaic sandstones. The Murdoch Sandstone, a braided-channel sandstone in the upper part of the Caister Formation (**Figure 6.3**), is a significant gas reservoir in the Caister/Murdoch and McAdam fields; sandstones near the base of the Caister Formation form reservoirs in the Trent and Cavendish fields. Comparable Bolsovian to Asturian sandstones, the Tubbergen Sandstone, form the most important reservoir unit in the north-east

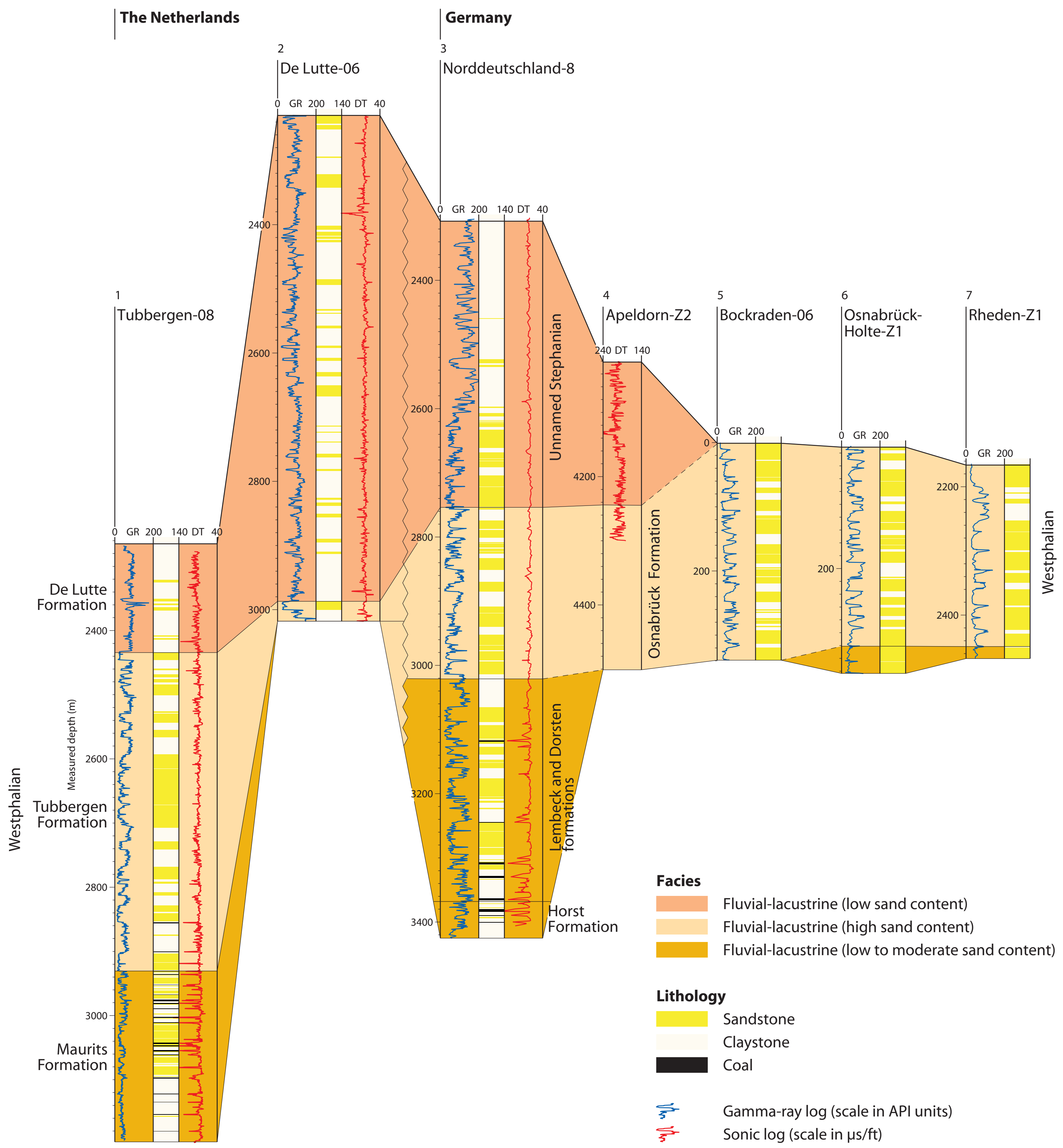


Figure 6.15 Well-correlation panel of Westphalian and Stephanian rocks in the Ems area. See Figure 6.14 for locations.

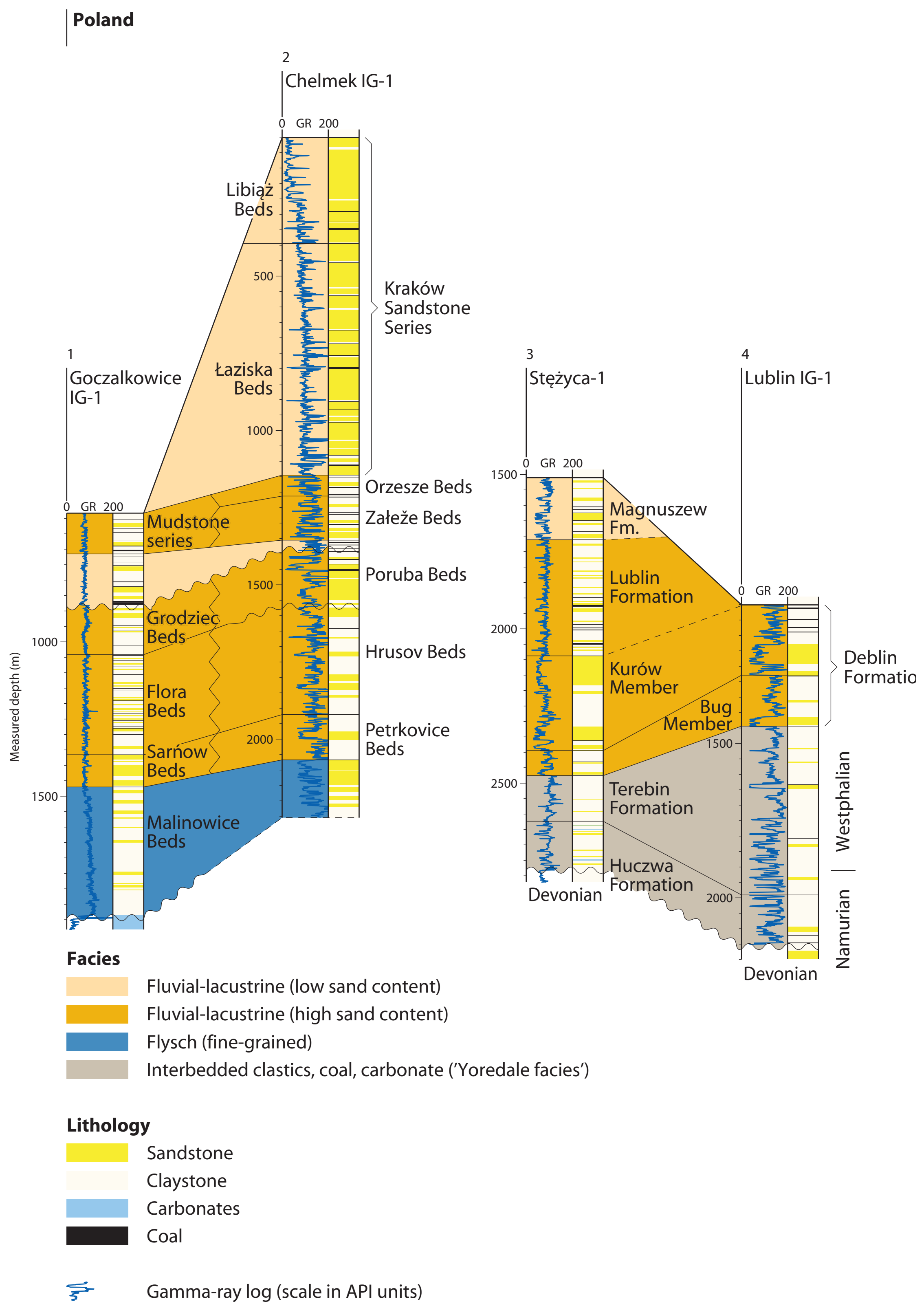


Figure 6.16 Well-correlation panel of Carboniferous rocks in the Upper Silesian Coal Basin and the Lublin Basin in Poland. The transition between the Malinowice Beds and the underlying Devonian cannot be seen in Figure 6.3; this is only a local feature. See Figure 6.14 for locations.

Netherlands and neighbouring Germany (**Figure 6.20c**), although some reservoirs in Germany are Langsettian to Duckmantian in age (see Section 6.3.5). The fluvial sandstones of the Asturian Neeroeteren Formation in the Campine Basin have good reservoir properties, but the depths at which they are found are too shallow and they do not have an effective seal. However, channel geometry indicates that this formation continues into the Roer Valley Graben where better reservoir conditions may exist. Carboniferous reservoirs in the Lublin Basin are found mainly in Namurian and Westphalian fluvial sandstones. The six known reservoirs in Pomerania are found in Visean limestones and sandstones and Westphalian sandstones (**Figure 6.20d**).

6.2.3 Hydrocarbon plays

Westphalian fluvial sandstones

Bolsovian to Asturian fluvial sandstones are the most important reservoir units in the NWECB (**Figure 6.21**, play 1), together with a number of Namurian and Langsettian to Duckmantian reservoirs with broadly similar facies. Westphalian coals are the main source rock, with Namurian basinal shales contributing to the hydrocarbon source in some areas. In most cases, the vertical distance between the source and reservoir units is relatively limited. The main seals are the shales and evaporites of the Silverpit Formation (Rotliegend) in the Cleaver Bank-Silverpit area, and Zechstein evaporites in the north-east Netherlands and western Germany; some intraformational sealing is also found.

In the north-east Netherlands and neighbouring Germany, these reservoirs form traps in Carboniferous pop-up structures related to Variscan wrench-fault systems; they are also found in Variscan inversion anticlines in the North Sea. In each area, Late Cretaceous inversion has been the main controlling factor on the present-day shape of these structures. According to Hollmann et al. (1997), exploration potential in the Netherlands and Germany is limited to areas where there has been wrenching/faulting of this kind, as these movements probably caused the formation of fracture zones that significantly enhance the permeability. Field examples of this play are Coevorden, Husum Schneeren, Tyne, Boulton (40/21a), Trent (43/22a, structure) (see Section 6.3) and Schooner (44/26; **Figure 6.20b**).

Clastic-delta systems

The clastic-delta play concept (Fraser & Gawthorpe, 1990) applies to most of the UK onshore (**Figure 6.20a**). The reservoirs are both prodelta (turbidite) and delta-top (mouth-bar and channel) sandstones (**Figure 6.21**, play 2). The sandstones infilling the antecedent rift basins are generally the best reservoirs (Fraser & Gawthorpe, 1990). The predominantly oil-prone basinal Namurian mudstones are the most important source rock. The seals can be formed by the prodelta mudstones that overlie the marine bands in the deltaic cyclothems. These seals work for oil onshore and occasionally for gas offshore, but they do have to be unusually thick. Most reservoirs are found in gentle (hanging-wall) anticlines formed during the late Variscan inversion phase. This play concept also applies to the Lublin Basin in Poland, although the reservoirs in this basin are interpreted as fluvial sandstones. Field examples of this play are West Firsby and Welton (see Section 6.3.3).

Carbonate-shelf margins

The carbonate-shelf margin play concept was developed by Fraser & Gawthorpe (1990) for the UK, where it was found that rimmed shelves (e.g. carbonate shoals, buildups, debris flows and turbidites) that preferentially form around half-grabens are potentially good reservoirs (**Figure 6.21**, play 3). The rimmed-shelf carbonate platforms of the Netherlands (Kombrink, 2008) could also fall into this category (**Figure 6.22**). The most likely sources for these reservoirs are the Dinantian or Namurian basinal or prodelta mudstones that onlap the carbonate platforms (**Figure 6.5**). As the mudstones cover the entire carbonate platform, they can also form the top seal. The hydrocarbons in these reservoirs do not seem to be trapped by structural or fault-controlled closures; therefore, lateral changes in sedimentary facies must provide the trapping mechanism. Basinward, the reef carbonates are probably draped by basinal mudstones, whereas shelfward, tightly cemented carbonates are required to form a stratigraphic trap. Unfortunately this play concept is unproven, except for a small exhumed example at Windy Knoll in Derbyshire, England (**Figure 6.1**). The Loenhout gas-storage facility in the Campine Basin may be another example, although no hydrocarbons have been found (see Chapter 16).

6.3 Hydrocarbon field examples

6.3.1 Boulton gasfield, UK offshore

The Boulton gasfield is located in UKCS Block 44/21a, approximately 160 km off the Lincolnshire coast in the southern North Sea (**Figure 6.20b**). In 1965, the first well to drill Carboniferous rocks in this block was originally planned to test the Triassic Bunter Sandstone. When this was unsuccessful, it was decided to deepen the well to reach the Carboniferous, but no hydrocarbons were found. BP drilled a second well in this block in 1984 and gas was discovered in Bolsovian to Asturian sandstones and conglomerates. A second reservoir was found in Duckmantian sandstones in 1990. As such, the Boulton field comprises two structures, B and F, representing the Bolsovian (Lower Ketch 2 unit) and lower Duckmantian sandstones (Murdoch Sandstone) respectively (**Figure 6.23a**; Conway & Valvatne, 2003a).

The Boulton field is an anticlinal structure (**Figure 3.23b**) dissected by north-west–south-east and north-east–south-west-trending faults. It formed during the Late Carboniferous to Early Permian inversion phase when the entire NWECB was prone to uplift and folding (Fraser & Gawthorpe, 1990). Gas in the B-structure is trapped by a combination of up-dip seal against Permian shales and salts (**Table 6.1**), whereas side seal is formed by sealing faults and low-permeability Bolsovian sandstones. The F-structure gas is trapped in an anticlinal structure sealed by Duckmantian mudstones. Coals within the Westphalian Coal Measures are the main source of the gas in the Boulton field.

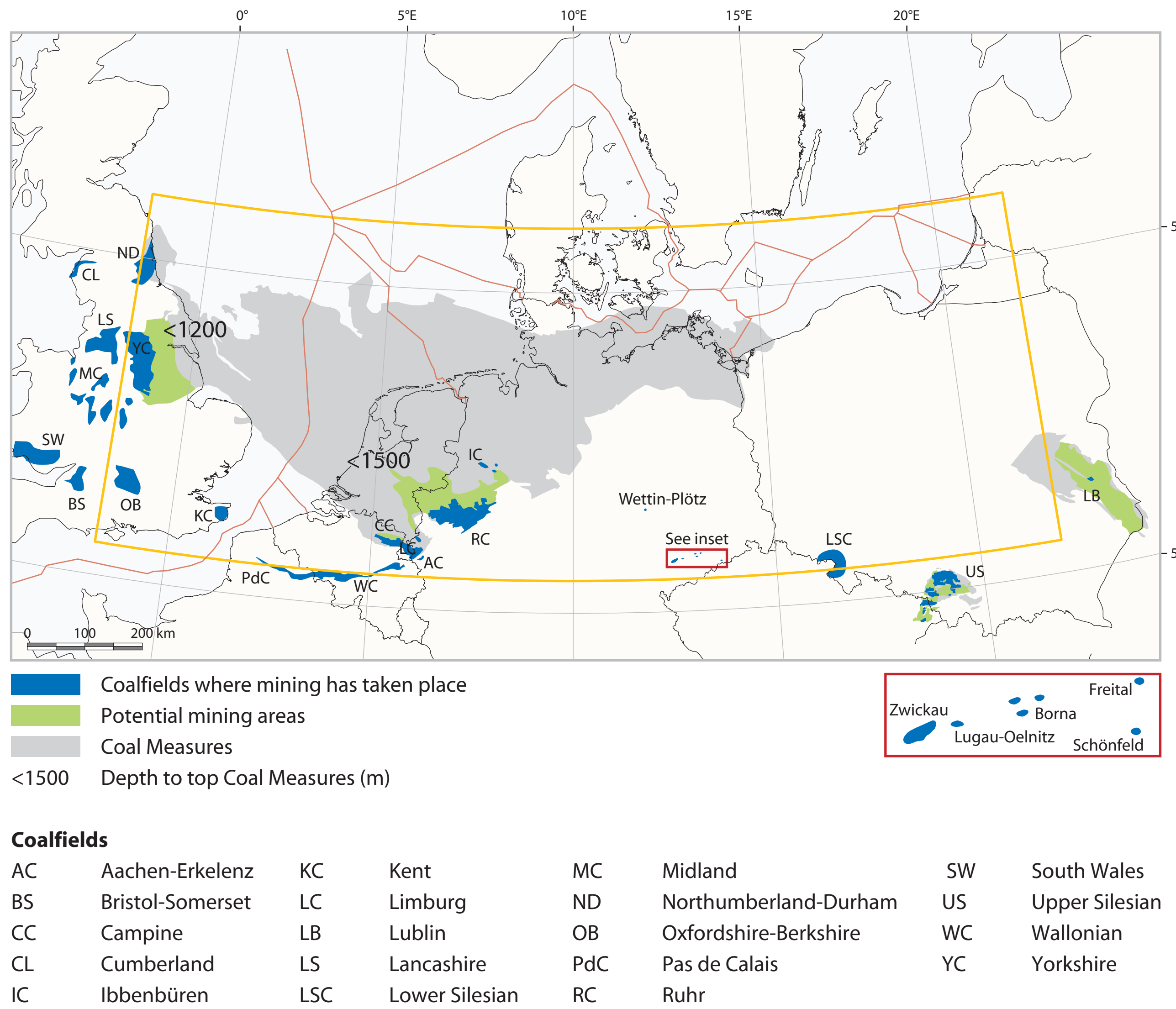


Figure 6.17 Carboniferous Coal Measures in the SPBA. The coal-mining areas are mainly located at the margins of the SPB. Potential mining areas are those where coal mining may be possible in the future because of the relatively shallow occurrence of coal seams.

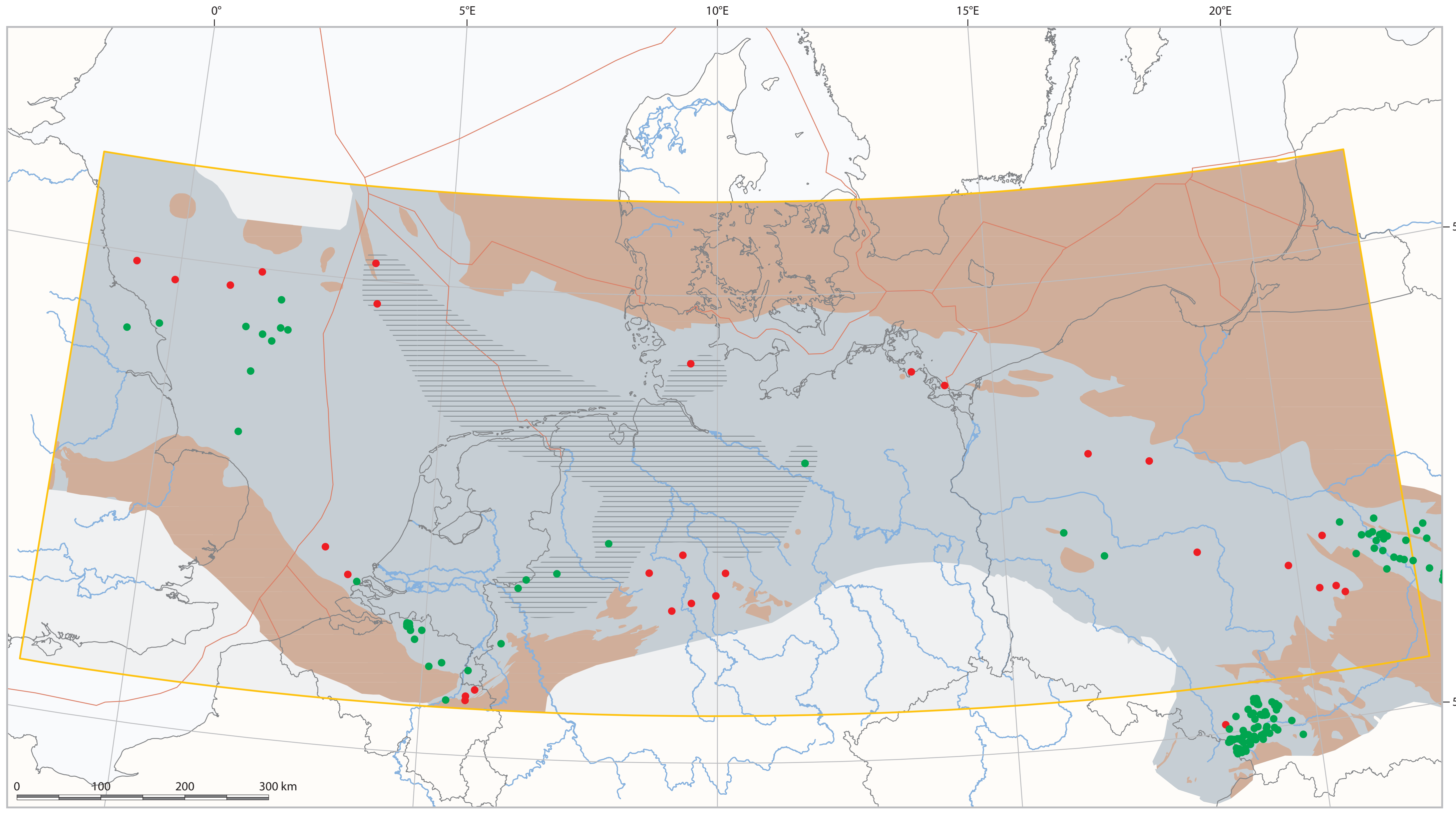


Figure 6.18 Namurian and partly Dinantian black shales in the NWECB. Based on well data and Gerling et al. (1999c) and Hoffmann et al. (2001).

Both reservoir units occur in fluvial sandstones (**Figures 6.23c** & **6.23d**). The Murdoch Sandstone was deposited in a humid, tropical, lower delta-plain environment, whereas the Lower Ketch Sandstone is characterised by deposition in a well-drained, upper delta-plain environment. The palaeoflow direction is interpreted to have been generally from north to south. The Murdoch Sandstone is mostly fine grained in the reservoir area, with the exception of one 3.5 m-thick, well-sorted, coarse-grained sandstone. Due to compaction, quartz overgrowth and carbonate-grain replacement, porosities are mostly moderate (8-10%), whereas permeabilities range from 0.5 to 1.0 mD. The Bolsovian to Asturian sandstones have better porosities (10-12%) and far better permeabilities (50-400 mD) because average grain sizes are coarser.

Table 6.1 Properties of the Boulton field.

Reservoir	Duckmantian sandstones
Lithology	Sandstone
Depth to top (m)	3868
Maximum column height (m)	128
Net reservoir thickness (m)	177
Net to gross ratio	0.37
Porosity (%)	10
Permeability (mD)	73
Fluid type	Gas
Initial pressure (bar)	448
Temperature (°C)	130
Source rock	Westphalian Coal Measures
Seal	Permian shales and salts

6.3.2 Trent gasfield, UK offshore

The Trent gasfield is located in the northern part of block 43/24, approximately 140 km off the Lincolnshire coast (**Figure 6.20b**). The Trent structure was first drilled in 1985, although the first significant discovery was made in 1990 when ARCO drilled well 43/24-1. The Trent field reservoir sandstones are late Namurian to early Langsettian in age (**Figure 6.24a**).

The fault trend in the positive inversion structure is mainly west-north-west (**Figure 6.24b**); antithetic faults run north-east and east–west. As found in the Boulton structure, these faults were active during the late Variscan compressional phase, when at least 900 m of Carboniferous sediments were eroded (O'Mara et al., 2003a). The present structure is probably the outcome of the Late Cretaceous inversion phase. The top seal of the Trent reservoirs is formed by Permian lacustrine shales and salts (Silverpit Formation) (**Table 6.2**). Coals from the Westphalian Coal Measures are the main source of gas, although Namurian carbonaceous mudstones also have source potential.

The Namurian (Marsdenian and Yeadonian) reservoir sands in the Trent field are part of the Millstone Grit Formation and are interpreted as delta-top sediments, although the main Marsdenian reservoir may be the fill of an incised palaeovalley (**Figure 6.24c**). The lower Langsettian sandstones were deposited in a lower delta-plain environment (O'Mara et al., 2003a). Reservoir thicknesses vary from less than 10 m for transgressive sandstones to about 30 m for incised-valley fills and distributary channels. The gas column has a maximum height of 366 m.

Table 6.2 Properties of the Trent field.

Reservoir	Lower Trent Sandstone, Namurian	Upper Trent Sandstone, Namurian	Westphalian A Sandstone
Lithology	Sandstone	Sandstone	Sandstone
Depth to top (m)	3225		
GWC/GOC.OWC (m)	3591		
Maximum column height (m)	366		
Net reservoir thickness (m)	10		9
Net to gross ratio	0.85	0.98	0.87
Porosity (%)	10.3	12.8	11
Permeability (mD)	0.30	247	38
Fluid type	Gas	Gas	Gas
Initial pressure (bar)	379.2	379.2	386.5
Temperature (°C)	112	112	116
Source rock	Westphalian Coal Measures		
Seal	Silverpit Formation		

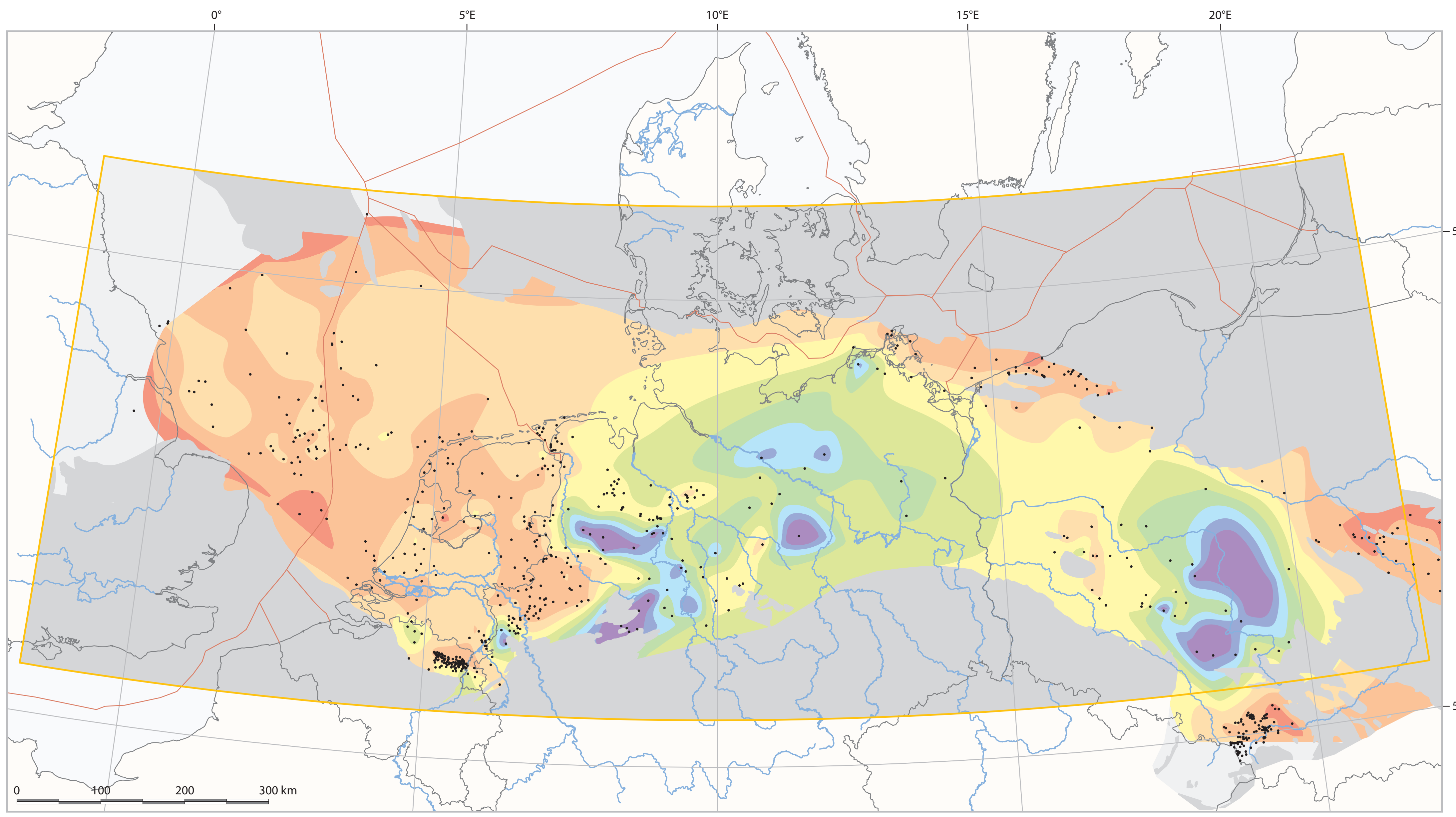


Figure 6.19 Maturity at the top of the Carboniferous.

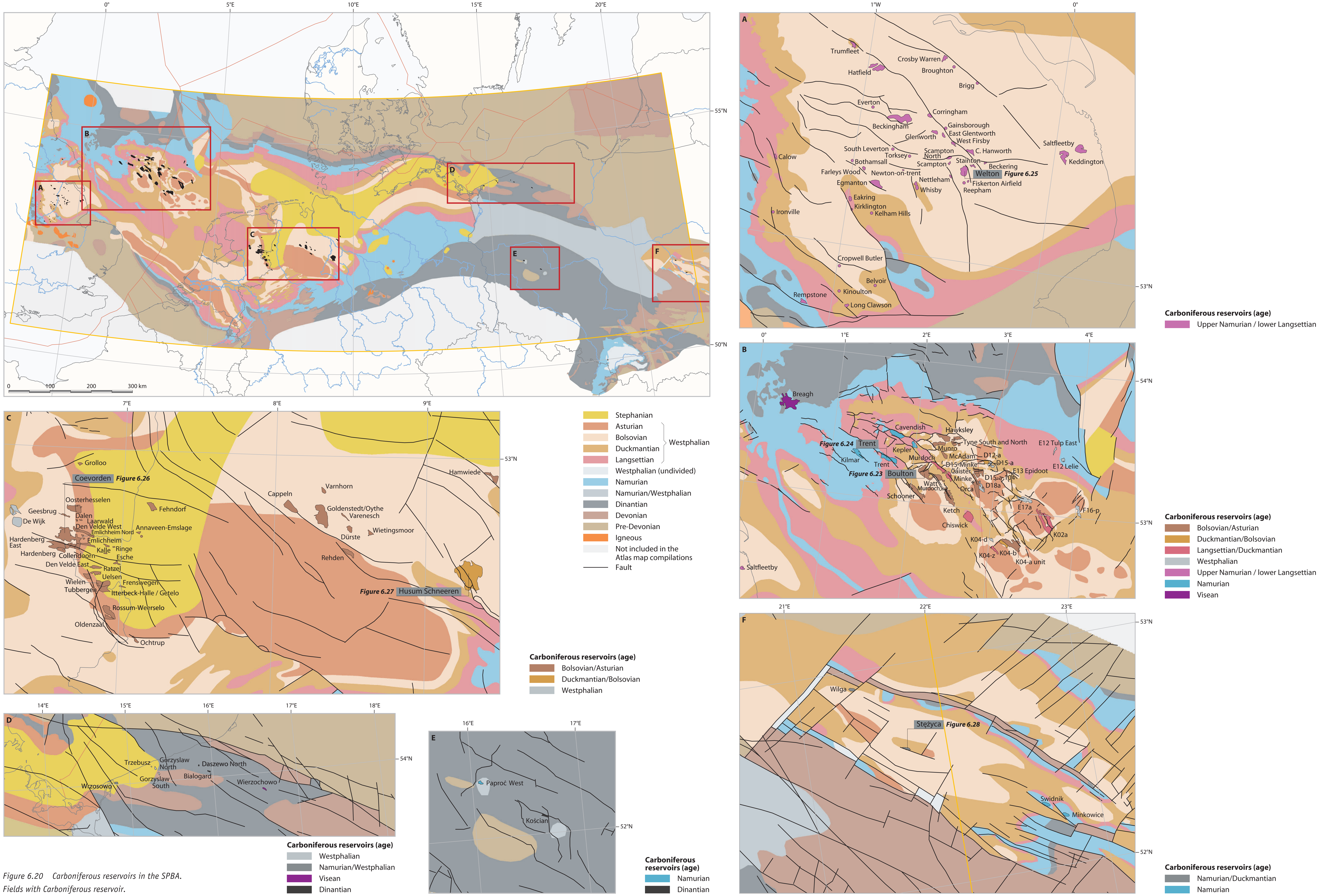


Figure 6.20 Carboniferous reservoirs in the SPBA. Fields with Carboniferous reservoir.

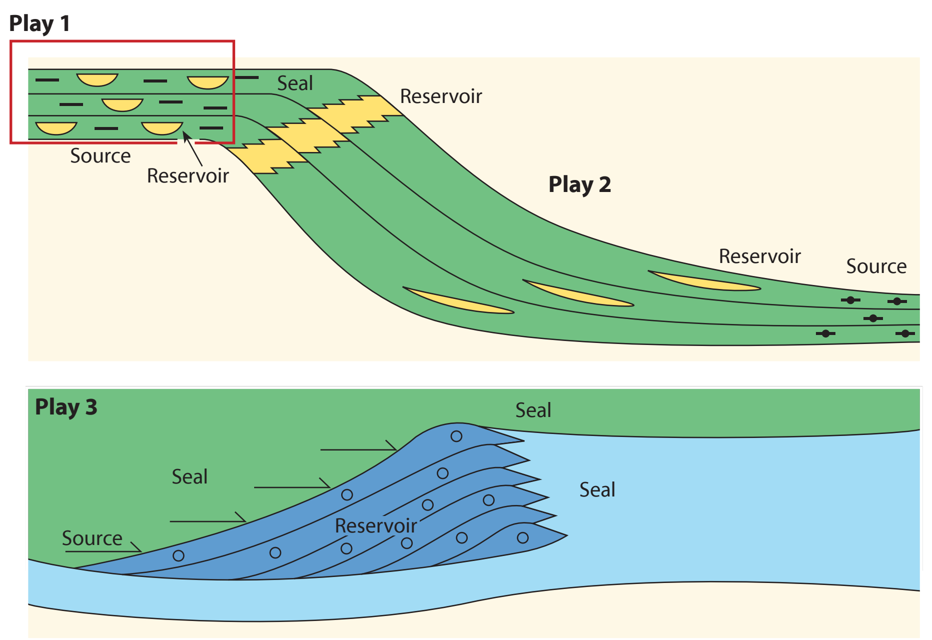


Figure 6.21 Illustration of play concepts for the Carboniferous in the SPBA.

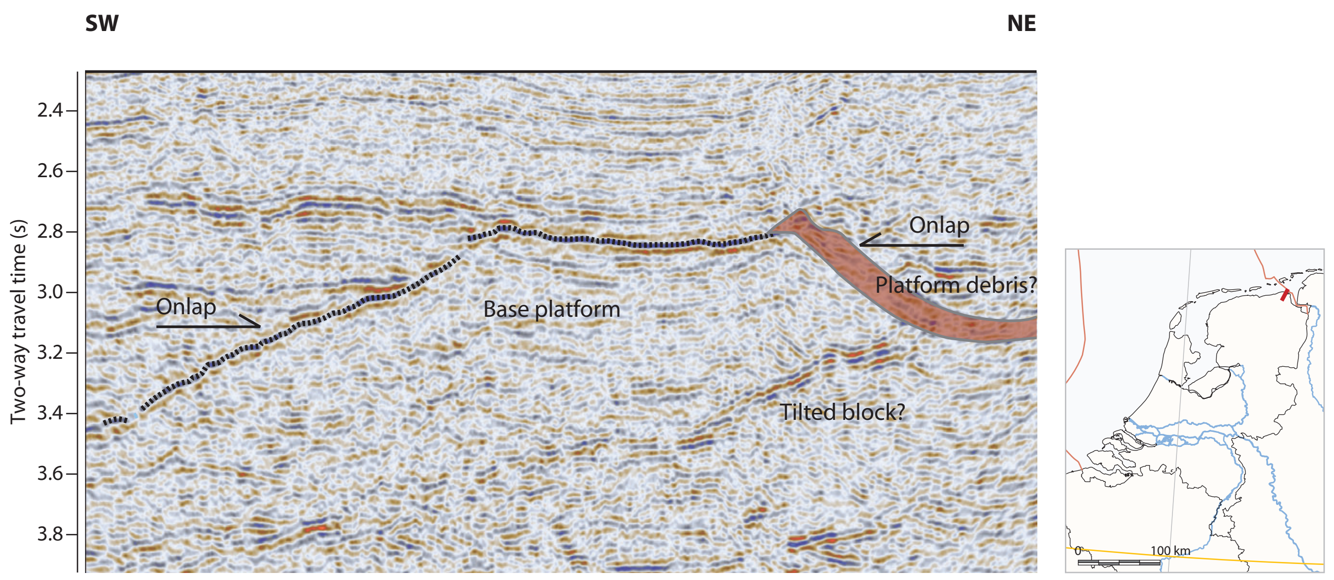
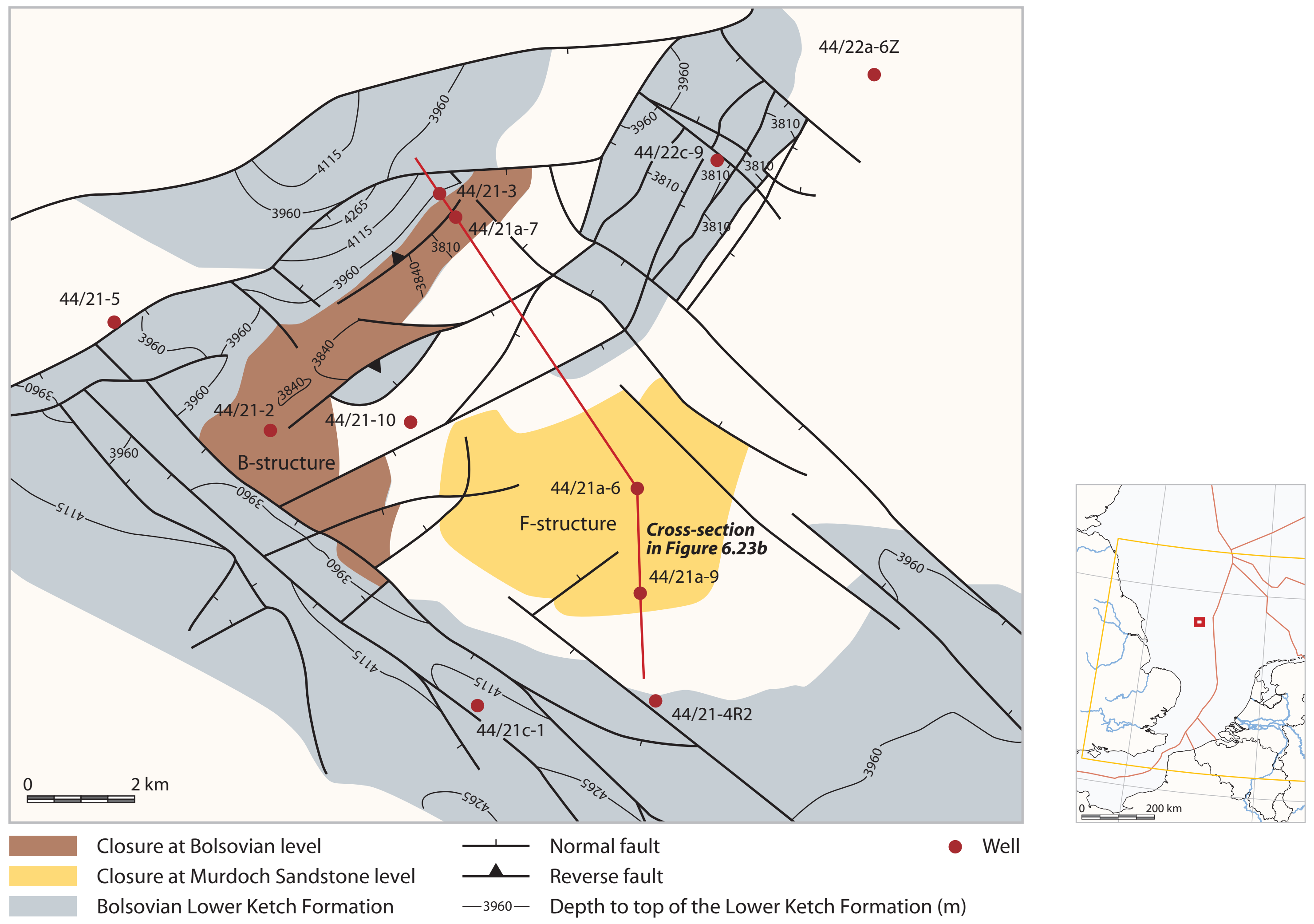


Figure 6.22 Seismic section showing the carbonate platform at Groningen.



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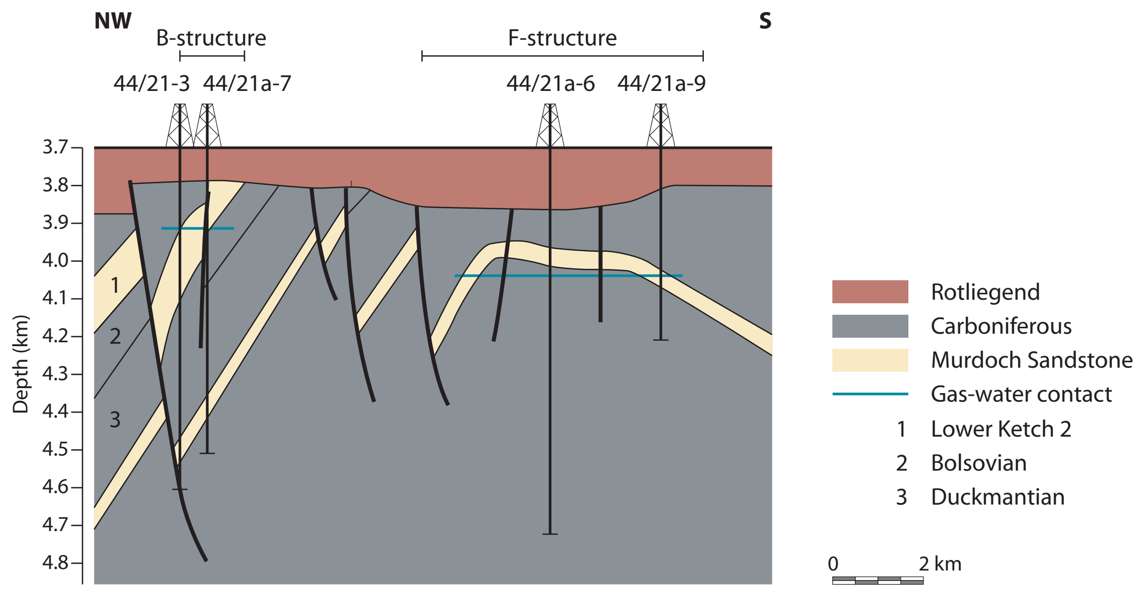

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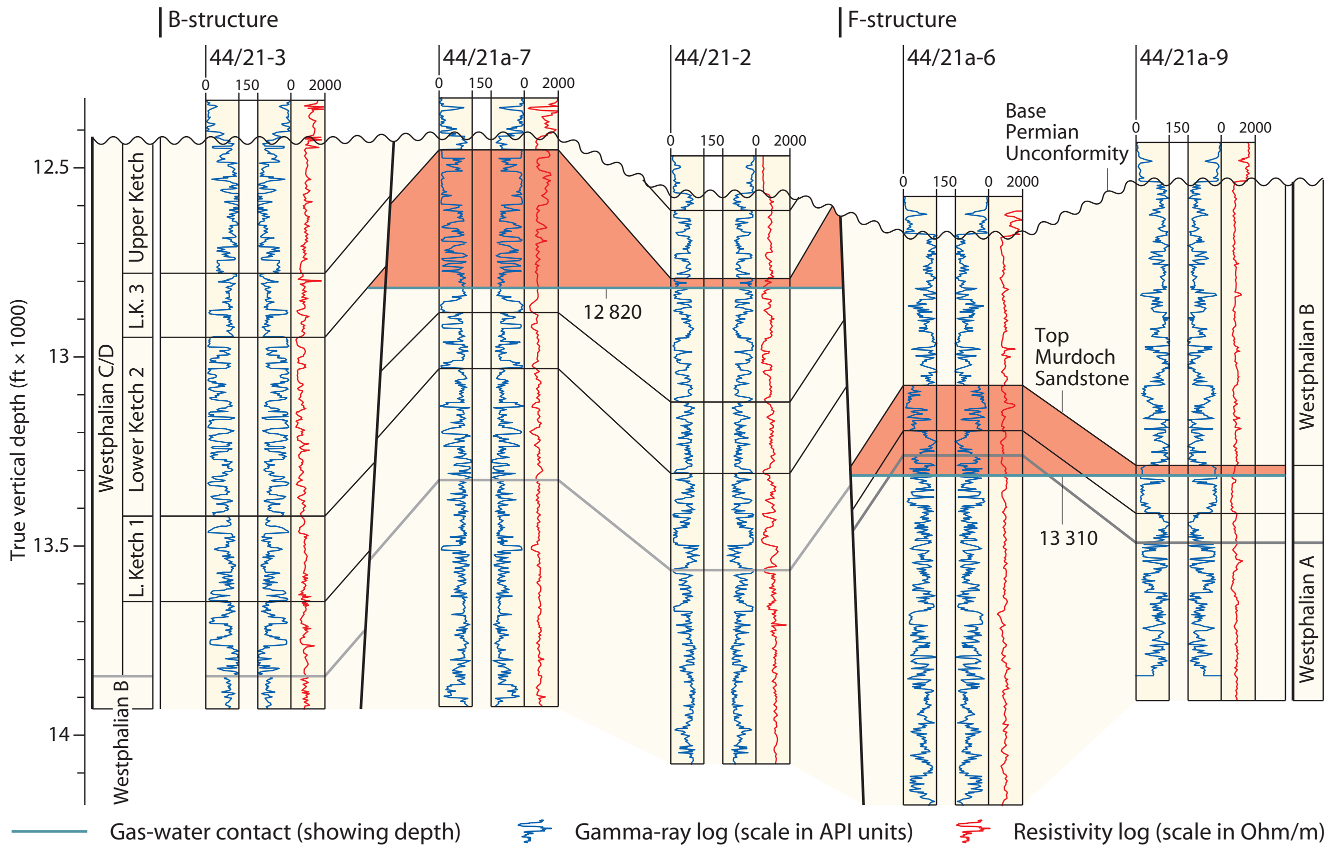

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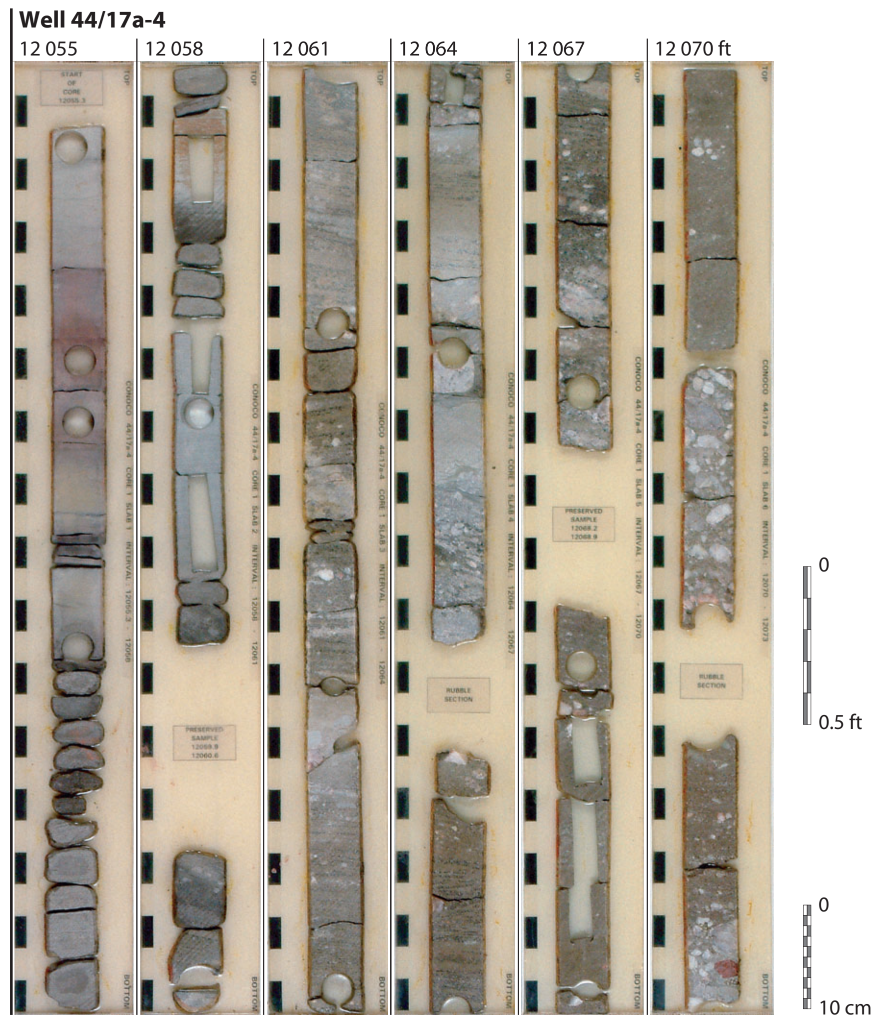
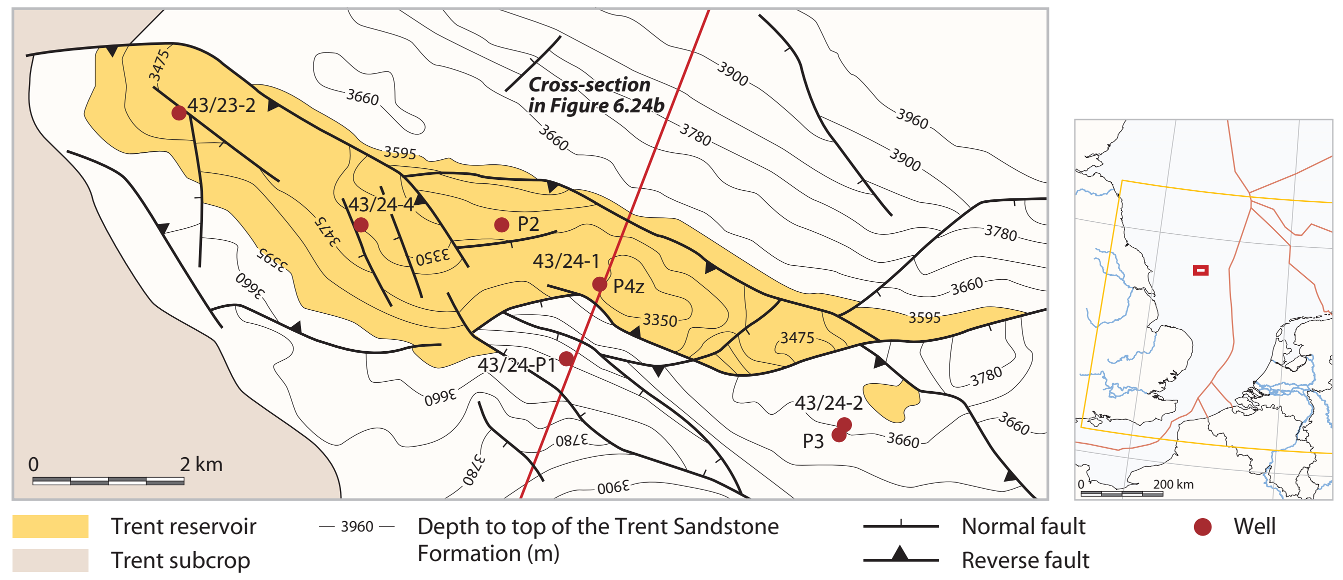
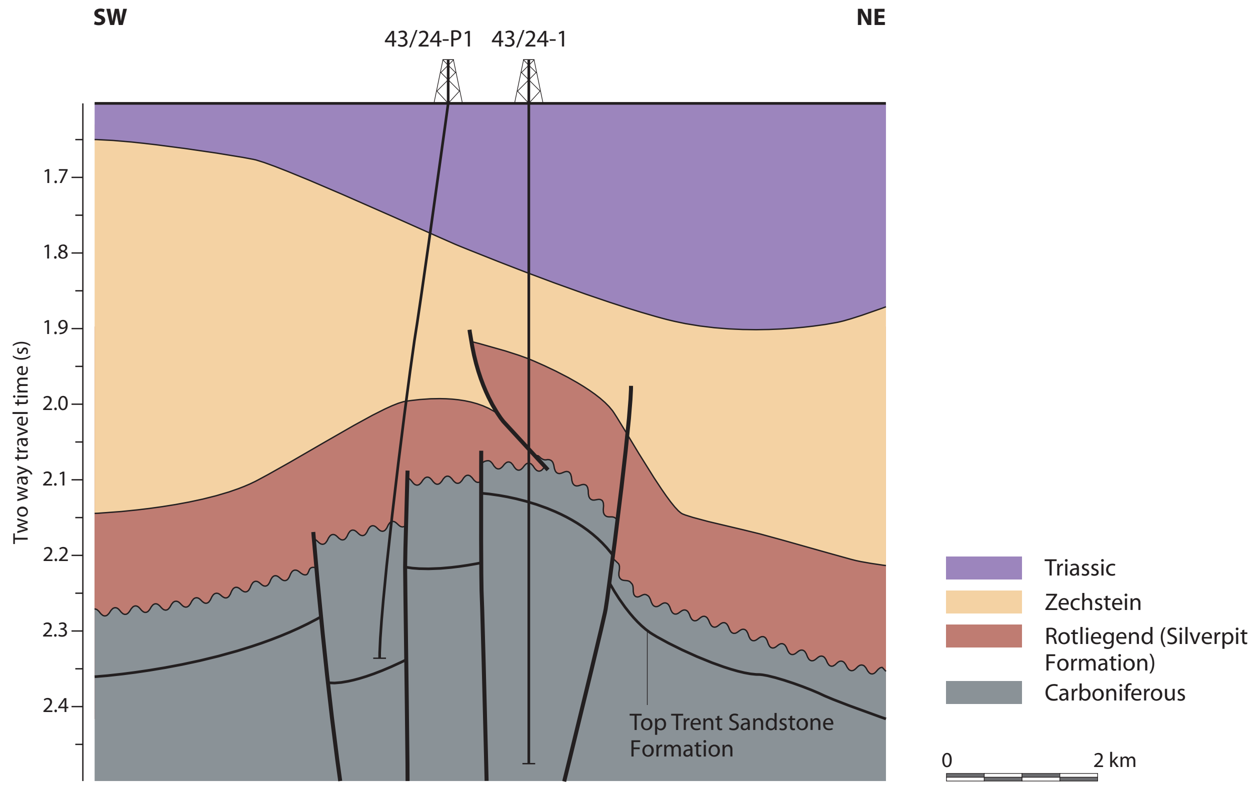


d.

Figure 6.23 Depth-structure map (a) and cross-section (b) across the Boulton field; c. Well-correlation panel across the Boulton B- and F-structures; d. Core photograph from well 44/17a-4. Although the core is not from the Boulton field but from the Hawksley field farther north-east, it provides an example of the Boulton B-structure reservoir facies. Parts a, b and c after Conway & Valvatne (2003a).



a.



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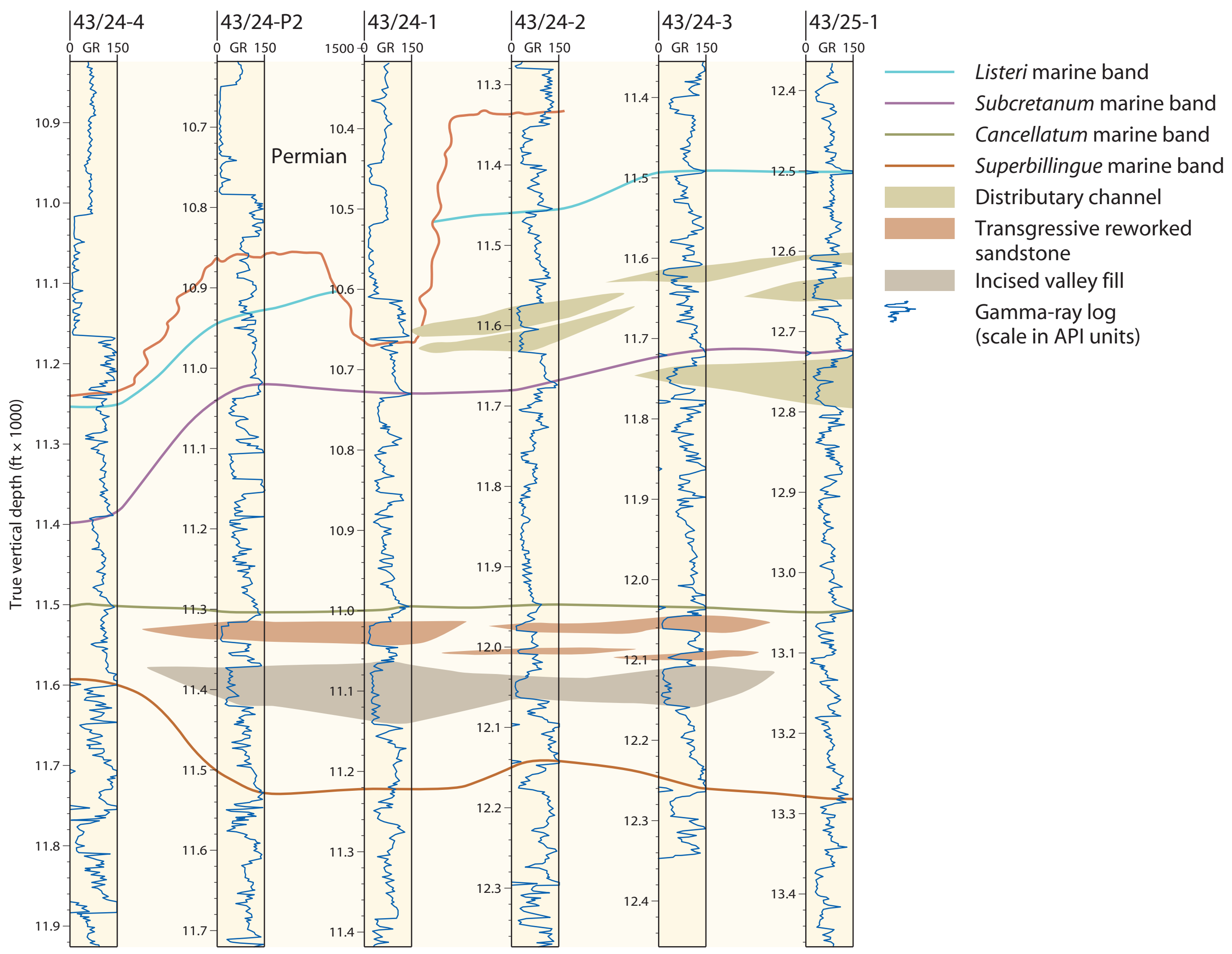


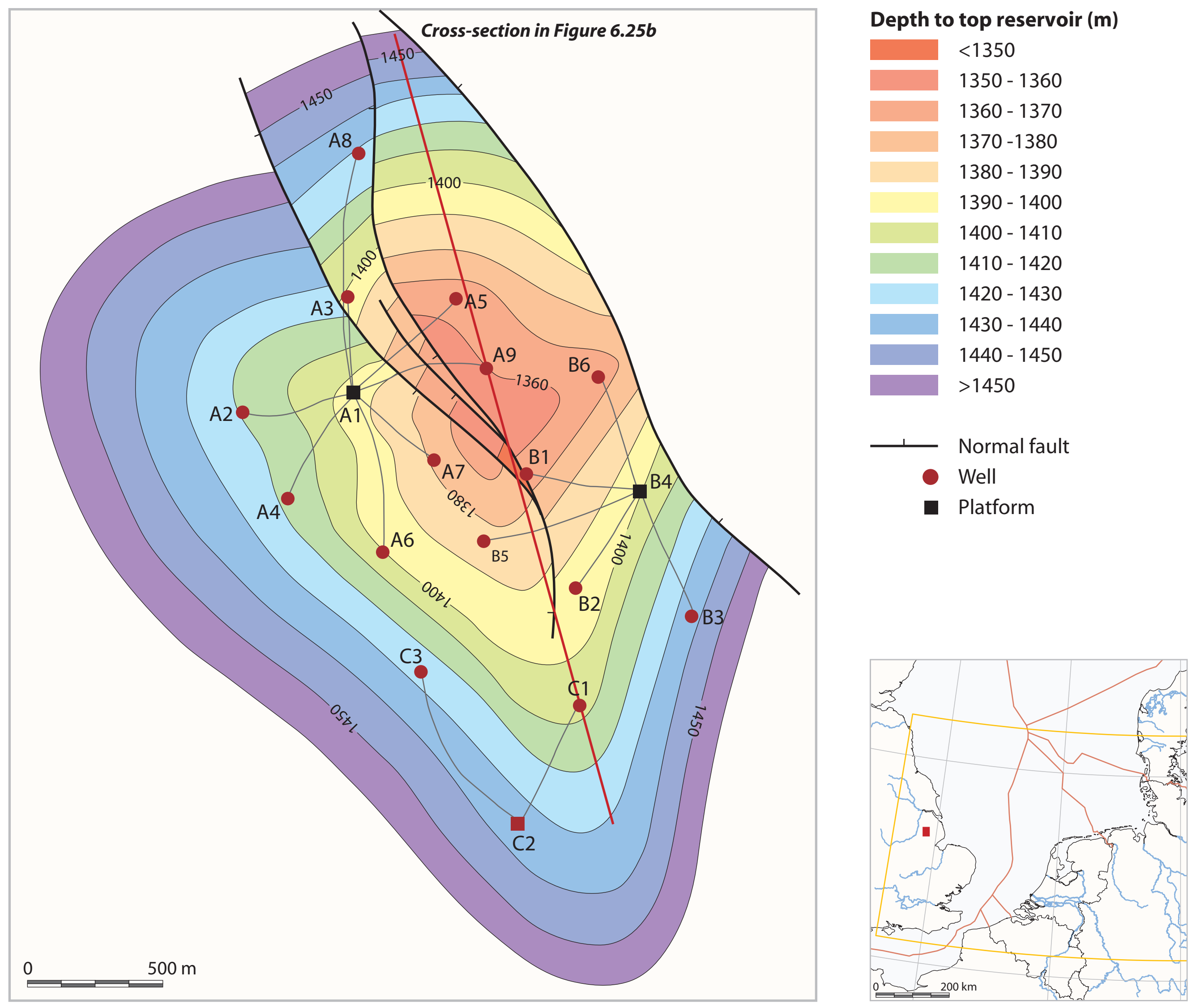
c.

Figure 6.24 Depth-structure map (a) and cross-section (b) across the Trent field; c. Cross-section of wells in the Trent structure. Figures after O'Mara et al. (2003a). See Figure 6.24a for locations of wells.

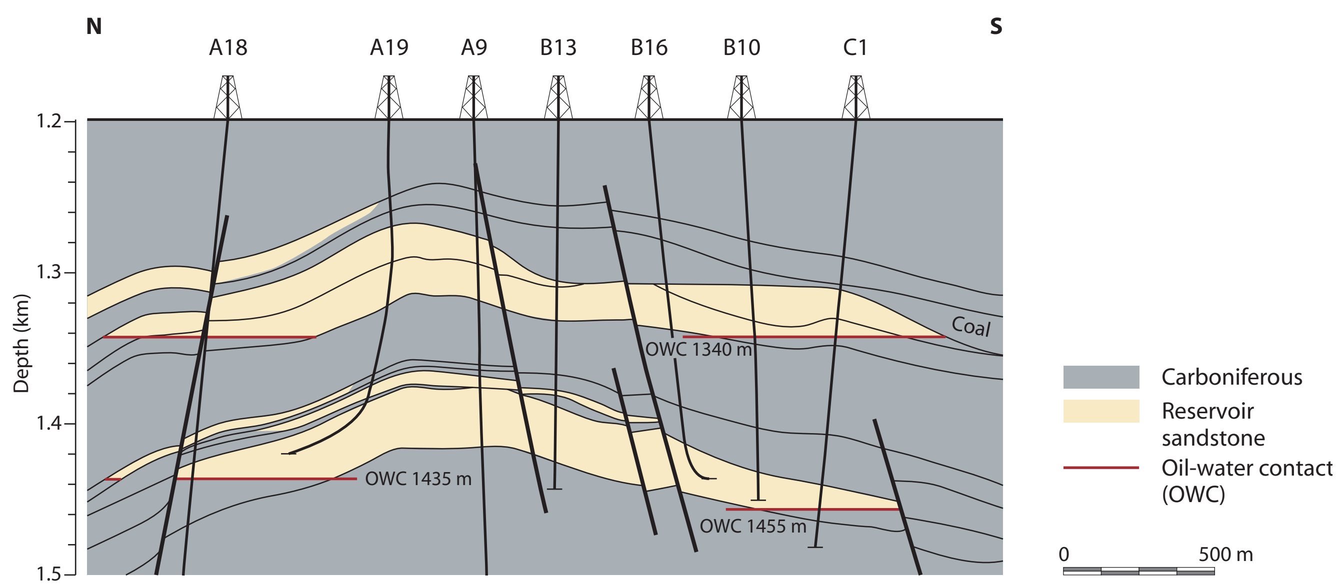
6.3.3 Welton oilfield, UK onshore

The Welton oilfield (with associated gas) is located about 10 km north-north-east of Lincoln, England (**Figure 6.20a**). The first oil discovery in 1981 was in Namurian sandstones resting unconformably on Dinantian limestones. The field was brought into production in 1985 and is still producing from two main reservoir sandstones with age-ranges from late Namurian to Duckmantian. The Welton field is the second largest UK onshore field after Wytch Farm (**Figure 6.1**).

The field lies at depths between 1188 and 1355 m in the south-eastern Gainsborough Trough to the south-east of the Askern-Spital Fault and directly adjacent to the East Midland Platform. The north-west–south-east-trending main fault was probably not inverted during the Variscan inversion phase as it strikes parallel to the main compression direction (Fraser & Gawthorpe, 1990). However, north-north-west-trending faults such as those found in the Welton field form closed Variscan inversion anticlines (**Figure 6.25a** & **b**). The source rock is the lower Namurian Edale Shale (Bowland Shale Formation) (**Figure 6.3** & **Table 6.3**), which is a bituminous black shale deposited in relatively deep water under sediment-starved conditions. Hydrocarbon generation occurred during the Mesozoic and ceased in the Tertiary due to regional uplift and erosion. The seal is formed by intra-Carboniferous prodeltaic mudstones. The highest reservoir sandstone in the Welton field (**Figure 6.25b**) has a Langsettian age and was deposited under fluvial conditions. The lower reservoir was deposited in a deltaic environment during the late Namurian.



a.



b.

Figure 6.25 Depth-structure map (a) and cross-section (b) across the Welton field.

Table 6.3 Properties of the Welton field.

Reservoir	Langsettian Carboniferous sandstone	Late Namurian sandstone
Lithology	Sandstone	Sandstone
Depth to top (m)	1188	1355
GWC/GOC.OWC (m)	1340	1455
Maximum column height (m)	152	100
Fluid type	Oil	Oil
Oil gravity	36	37
Initial pressure (bar)		154
Temperature (°C)		54
Source rock	Lower Namurian Edale (Bowland) Shale	Lower Namurian Edale (Bowland) Shale
Seal	Intra-Carboniferous prodeltaic mudstones	Intra-Carboniferous prodeltaic mudstones

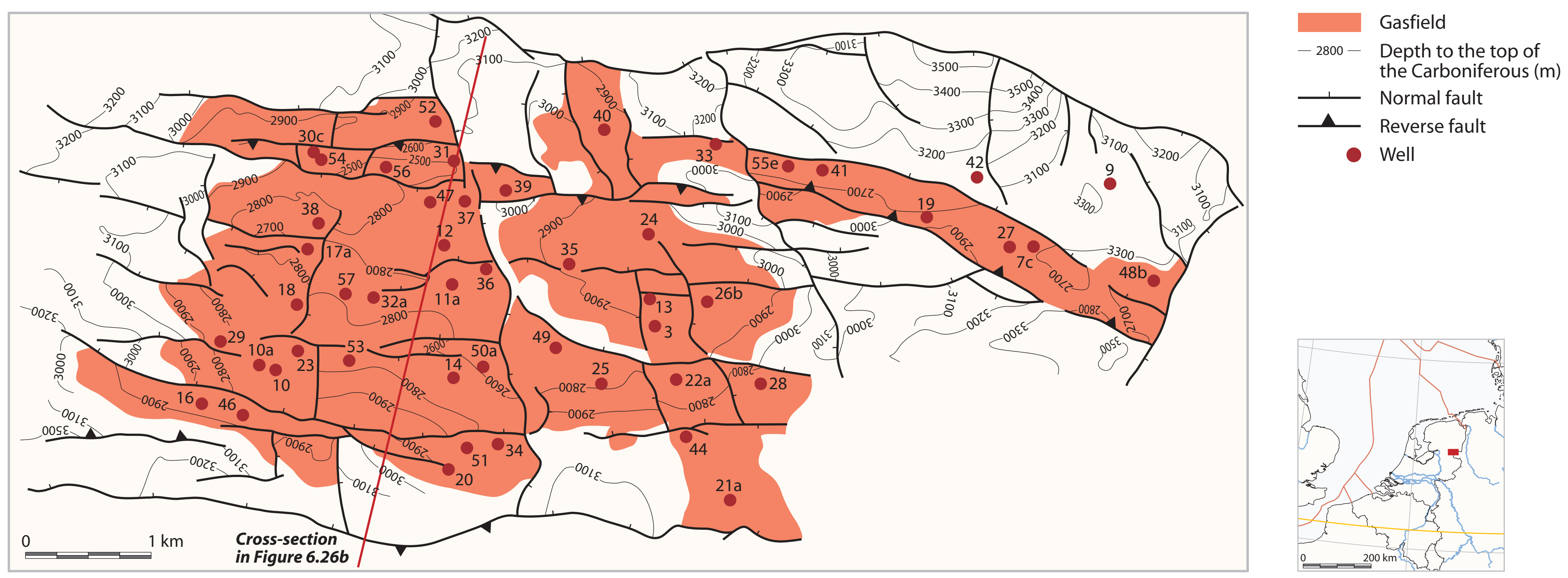
6.3.4 Coevorden gasfield, the Netherlands

The Coevorden field is located in the south-east of the province of Drenthe in the north-eastern Netherlands (**Figure 6.20c**). It was the first gasfield found in the Carboniferous rocks of the Netherlands. Although the field structure (**Figure 6.26a**) was already known during World War II, the first well to appraise Carboniferous gas was Coevorden-3 in 1951 (Van Buggenum & Den Hartog Jager, 2007). The field is still producing from two main reservoir sandstones of Bolsovian-Asturian age.

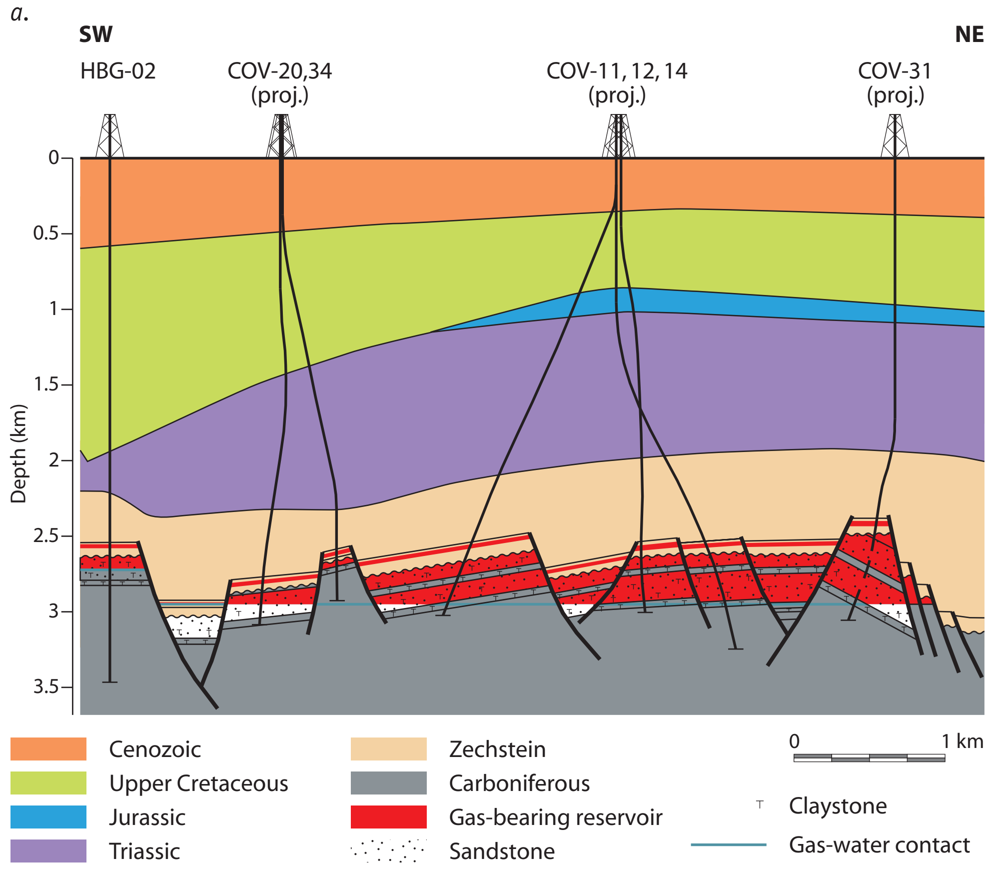
The Coevorden gasfield occurs at a depth of approximately 2850 m (**Figure 6.26a** & **b**). The field is dissected by east–west and north-north-west-trending faults of a wrench system that has been repeatedly activated. It is not clear if fault movements during the Bolsovian to Asturian played a major role in influencing depositional patterns (Kombrink et al., 2007), but it is likely that there was (re)activation during the late Asturian and Stephanian. The present tilted fault-block structure probably developed during the Late Cretaceous inversion phase. Westphalian Coal Measures are the source of gas in this field, as they are for the Zechstein and Triassic reservoirs higher up in the sequence (**Table 6.4**). Zechstein evaporites form the main seal, although intra-Carboniferous sealing can not be ruled out. The main Coevorden field reservoirs are two thick fluvial sandstones (40 and 20 m thick), each probably consisting of stacked channel belts (**Figure 6.26c** & **d**). The sandstones around these reservoirs are much thinner and have finer grain size.

Table 6.4 Properties of the Coevorden field.

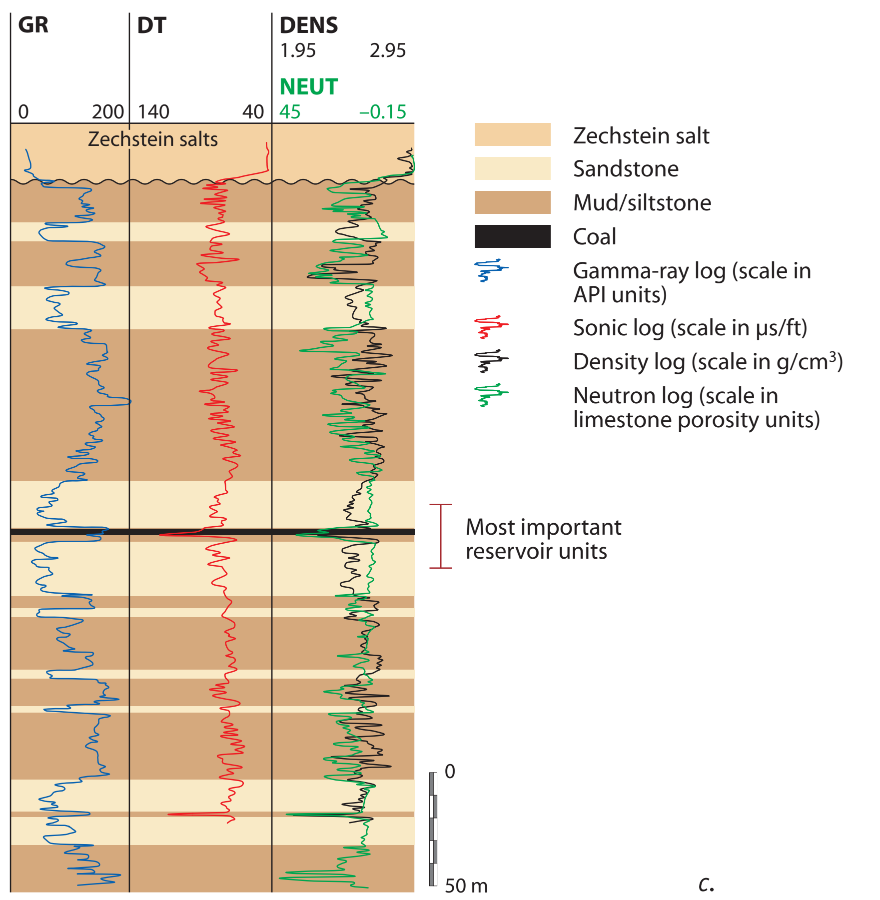
Reservoir	Bolsovian/Asturian sandstones
Lithology	Sandstone
Depth to top (m)	2850
Maximum column height (m)	350
Net to gross ratio	0.35
Porosity (%)	9
Permeability (mD)	1 (0.1-10)
Fluid type	Gas
Gas composition	C1 95%
Temperature (°C)	109
Source rock	Westphalian Coal Measures
Seal	Zechstein evaporites



a.



b.



c.

d.

Figure 6.26 Depth-structure map (a), cross-section (b), well-log (c) and core photographs (d) from the Coevorden field. Parts a, b and d are courtesy of the NAM.

6.3.5 Husum Schneeren gasfield, Germany

The Husum Schneeren gasfield is located about 40 km north-west of Hannover (**Figure 6.20c**). The first well to encounter Carboniferous rocks in the area around the field was drilled from 1961 to 1962, although it turned out to be unsuccessful (Hollmann et al., 1997). Following the acquisition of seismic data, the horst block containing the gasfield (**Figure 6.27a**) was discovered in 1986. Reservoir sands are mostly found in the Duckmantian succession, although there are also Langsettian and Bolsovian reservoirs.

The gasfield is situated at the intersection of two deformation zones (trending north-north-west and north-east–south-west; **Figure 6.27b**). The horst block at the northern Niedersachsen Basin margin, in which the Husum Schneeren gasfield was discovered, is comparable to that of the Coevorden field. However, in this case the major salt movements resulted in the salt subcropping against base-Tertiary strata. The seal is formed by lower Rotliegend anhydritic claystones (**Table 6.5**); the trap is formed by a tilted fault block. As found in the Coevorden field, coals of the Westphalian Coal Measures are the main source of the gas.

The fluvial to deltaic reservoir sandstones are Westphalian with thicknesses varying from 10 to 50 m (**Figure 6.27b**). Porosities range from 10 to 12%, but matrix permeabilities are relatively low. Due to open fractures, the overall permeability is rather high (Dietzel & Koeler, 1998; Luan et al., 1998). One phase of Late Jurassic fractures is mineralised; however, a second younger fracture system related to the Late Cretaceous inversion phase is generally open.

Table 6.5 Properties of the Husum Schneeren field.

Reservoir	Duckmantian sandstones
Lithology	Sandstone
Net reservoir thickness (m)	10-50
Porosity (%)	10-12
Fluid type	Gas
Source rock	Westphalian Coal Measures
Seal	Lower Rotliegend anhydritic clay

6.3.6 Stężyca oil and gasfield, Poland

The Stężyca field is located between the cities of Warsaw and Lublin in south-east Poland (**Figures 6.20f** & **6.28a**). The field's reservoir units were discovered between 1993 and 1998 and range from early Namurian A to Duckmantian age.

The field is located within the Stężyca Anticline in the north-western Lublin Basin and has six reservoir horizons (**Figure 6.28b**). The Stężyca Anticline formed during the Variscan inversion phase (late Westphalian to early Stephanian). The seals are mainly floodplain mudstones, estuarine claystones and stigmarian soils (**Table 6.6**). Visean to Namurian shales with dispersed humic-type organic matter form the main source rocks (Waksmundzka, 2005).

The field consists of a series of isolated reservoir sandstones, of which the deepest are fine- to coarse-grained fluvial sandstones of early Namurian A age (**Figure 6.28c**). The reservoir sands were all deposited by fluvial systems, some of which are interpreted to be incised-valley systems (Waksmundzka, 2005). The most important interval is a complex of three isolated Namurian C sandstones (geophysical horizon I_2) characterised by porosities ranging from ~8 to 17% and permeabilities up to 200 mD. The Namurian C sandstones tend to have low porosities (3-13%) whereas the Duckmantian reservoir is characterised by an average porosity of 20%. The sandstones are subarkosic and sublithic arenites mostly cemented by authigenic quartz, kaolinite and carbonates (**Figure 6.28d**).

Table 6.6 Properties of the Stężyca field.

Reservoir	Early Namurian to Duckmantian fluvial sandstones
Lithology	Sandstone
Depth to top (in m)	2334
Porosity (%)	7.83-16.79%
Permeability (mD)	1-200
Fluid type	Oil and gas
Source rock	Namurian/Visean Coal Measures
Seal	Fluviodeltaic mudstones

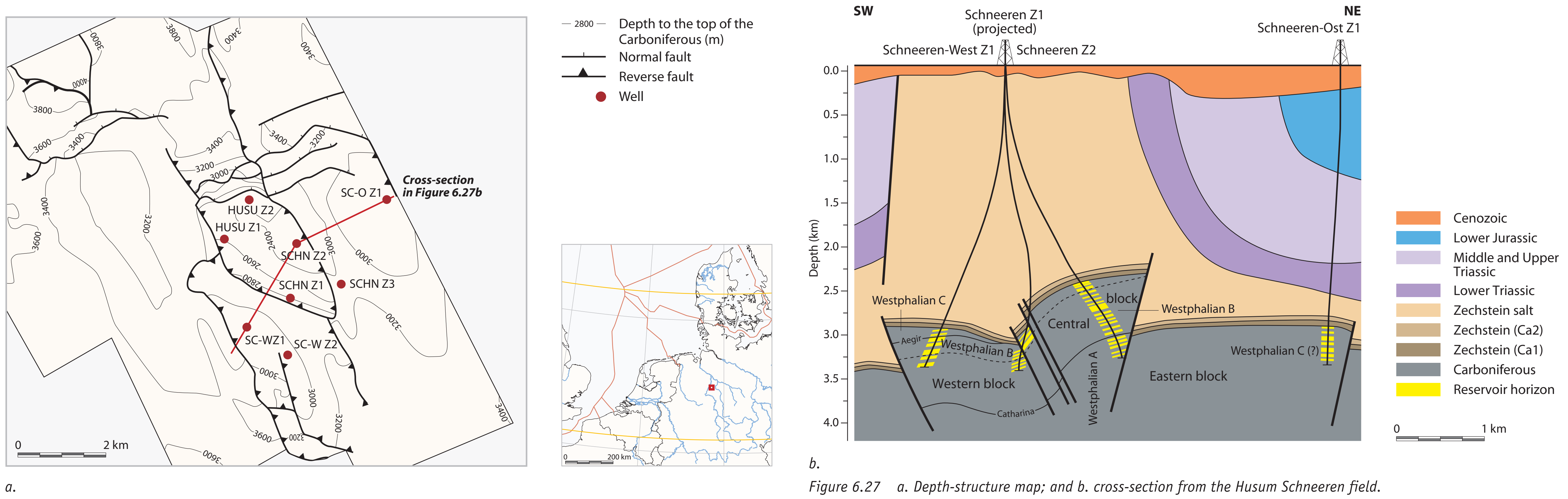
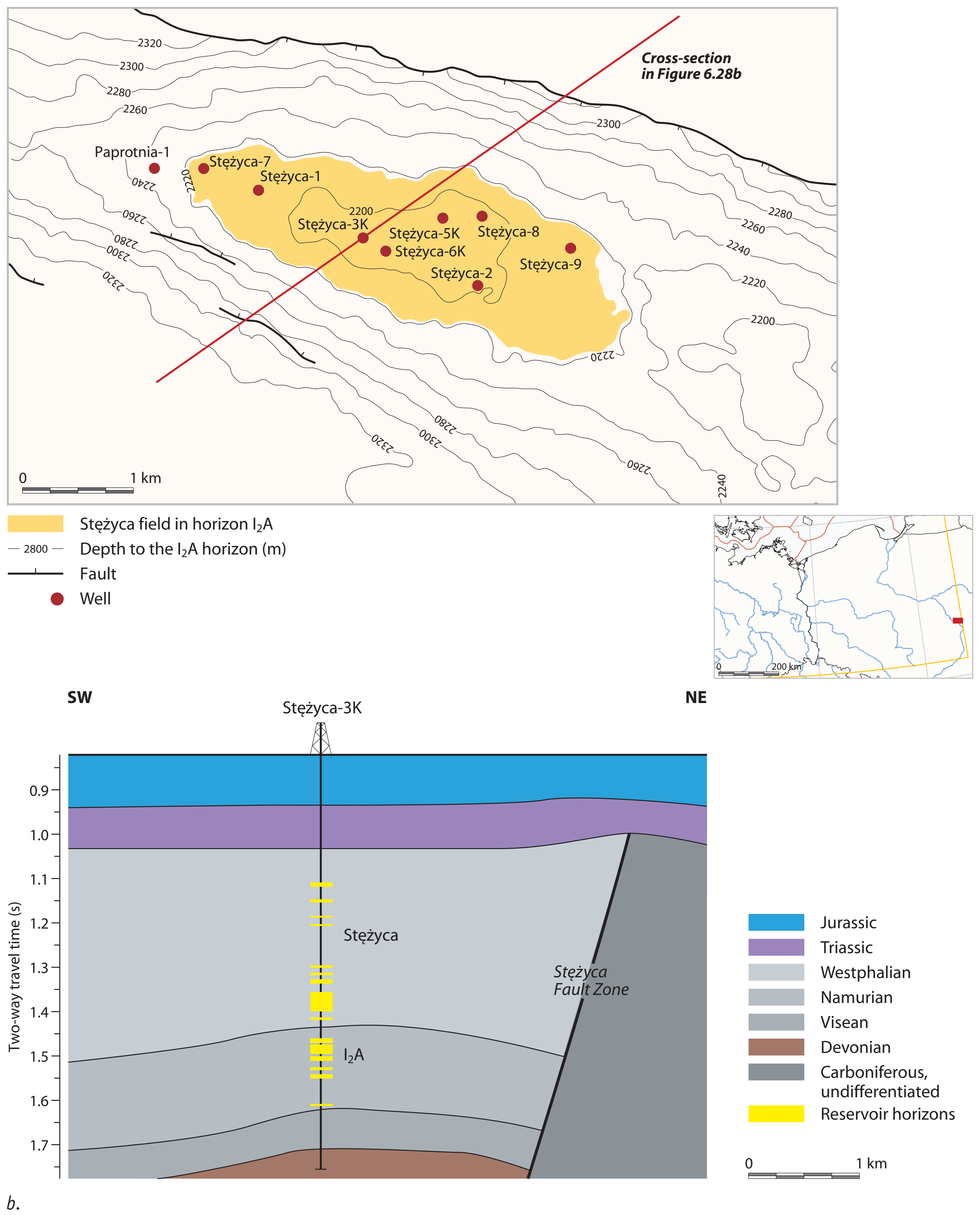


Figure 6.27 *a. Depth-structure map; and b. cross-section from the Husum Schneeren field.*



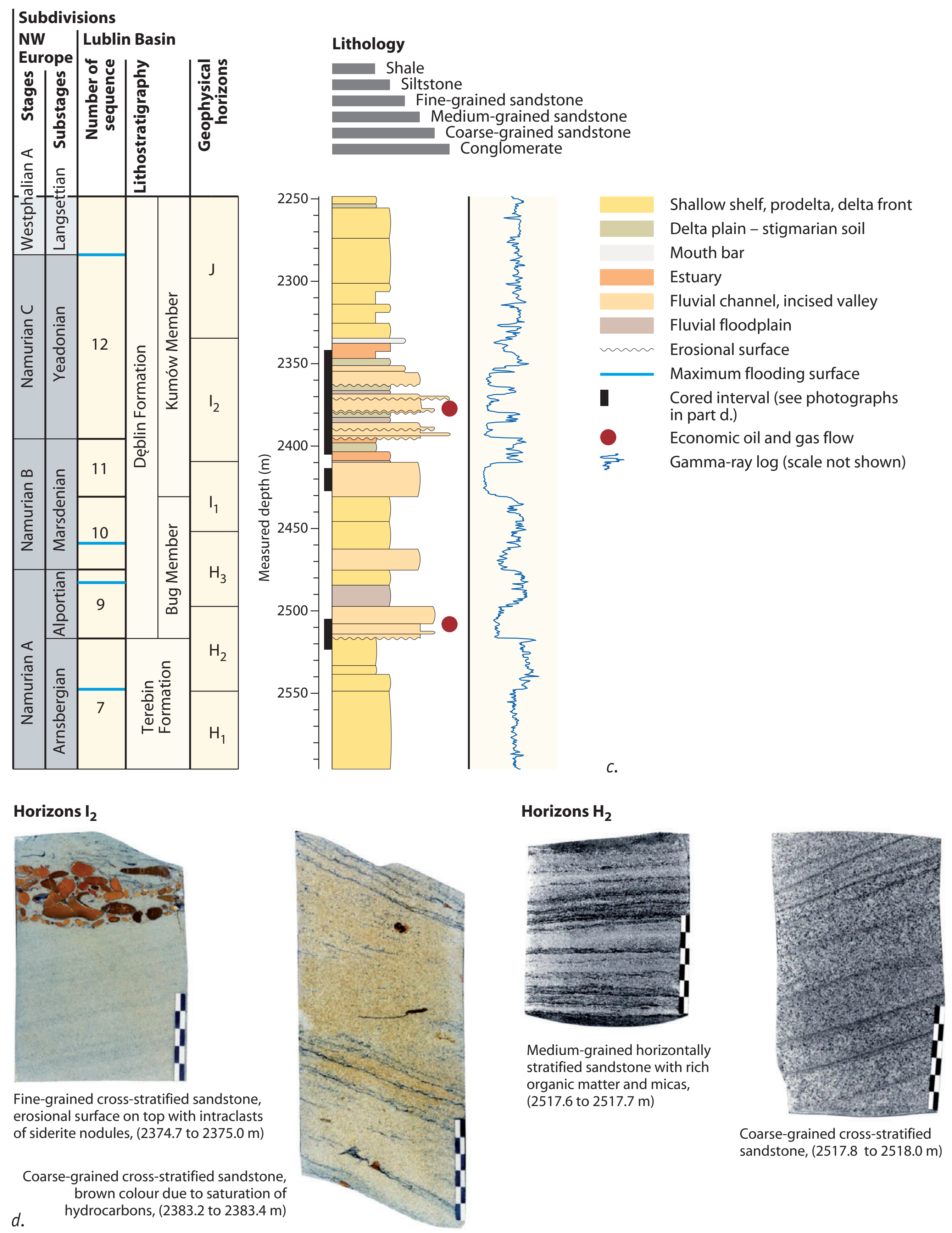


Figure 6.28 *a. Depth-structure map; b. cross-section; c. Carboniferous profile; and d. core photographs from the Stężyca field.*

Annex 1 Depositional cycles of the Southern Permian Basin
Gerhard H. Bachmann (Martin-Luther-Universitat Halle-Wittenberg)

The Southern Permian Basin (also referred to as the Central European Basin) is a typical intracontinental basin (Bachmann & Grosse, 1989; Bachmann & Hoffmann, 1997). The basin fill comprises a complete global transgressive-regressive sea-level cycle that lasted approximately 300 Ma (Figure 3.1). The unusually low initial global sea level generally rose with the breakup and disassembly of Pangea to reach its Phanerozoic maximum in Late Cretaceous times of some 250 m above the Permian (and present-day) level. This all-time sea-level high was followed by a general fall to its present low (e.g. Haq et al., 1988).

This type of global transgressive-regressive sea-level cycle has been referred to as a 1st Order Cycle and was the second in the Phanerozoic eon (Vail et al., 1977; Fischer, 1984; Duval et al., 1998). The cycle can be subdivided into a number of transgressive-regressive 2nd Order Cycles, each normally lasting between 3 and 50 Ma, which broadly correspond with the transgressive-regressive sequences of several authors, for example Sloss (1963), although they are often difficult to correlate; the 2nd Order Cycles were caused by changes in eustatic sea level and basin subsidence. 3rd Order Cycles (0.5 to 3 Ma) correspond to sequence-stratigraphic or base-level concepts (e.g. Vail et al., 1977; Haq et al., 1988) and were also caused by changes in eustatic sea level and basin subsidence. The 4th and 5th Order Cycles (0.01 to 0.5 Ma) correspond to parasequences, small base-level cycles or astronomically controlled Milankovitch Cycles in the order of approximately 20 000, 40 000, 100 000 and 400 000 years (Strasser et al., 2006).

This annex outlines the major trends in the SPB fill by defining and describing the 2nd Order Cycles, which are for practical reasons referred to as depositional cycles (DC). Special emphasis is placed on the central SPB in northern Germany and is based on a more detailed description by Bachmann et al. (2008b). Earlier definitions of major depositional cycles were given by Jacquin & Graciansky (1998) and Robin et al. (2000) in more marginal parts of the SPB.

A.1 Depositional cycles

Nine important depositional cycles (DC 1-9) have been observed in the central, German part of the SPB ranging from a few million years up to 75 Ma (Figure 3.1). Each cycle is bounded by major erosional unconformities. The first depositional cycle (DC 1) consists of volcanic and minor terrestrial clastic deposits. The second and third cycles (DC 2-3) are characterised by fining-upward terrestrial clastic sedimentation. Each of the succeeding six cycles (DC 4-9) has a transgressive phase, peak transgression and a regressive phase. The cycles can be described in terms of rising and falling base levels as well as by sea-level changes, which is especially appropriate for the continental DC 2 and 3 cycles. Such cycles were formed in a period when the SPB was not linked to the global sea-level. The short duration of the first depositional cycles is due to the fact that early stages of the evolution of the SPB were triggered by short-term tectonic events rather than by global sea level.

The early transgressive phase of cycles 4 to 9 consists of post-rift sediments that overlie the basal unconformity; in most cases they have relatively low subsidence rates and facies variations. Peak transgression is represented by deepest-marine environments occasionally characterised by euxinic sedimentation. The regressive phase mostly coincides with the strongest tectonic activity (rifting and inversion) and has relatively high subsidence rates and facies variations. It is terminated by a major erosional unconformity that forms the base of the succeeding DC. Halotectonic pulses that triggered Zechstein (and Rotliegend) salt diapirs commonly coincide with the rifting phases (Trusheim, 1957; Jaritz, 1973; Baldschuhn et al., 1996; Kockel, 1998; Mohr et al., 2005). The interval of Late Cretaceous compression and inversion caused salt-diapir deformation and the injection of salt wedges into adjacent salt-bearing Mesozoic strata.

A.1.1 Depositional Cycle 1: latest Carboniferous to Early Permian

Variscan compressional tectonics ended in Late Carboniferous times and were followed by regional uplift and erosion. Initiation of the SPB was accompanied by strong magmatism that can be related to strike-slip faulting and lithospheric thinning (Arthaud & Matte, 1977; Bachmann & Grosse, 1989; Ziegler, 1990a; Bachmann & Hoffmann, 1995a, 1997). Most faults trend north-east–south-west and west-north-westward. The SPB evolved on the former Variscan foreland although its southern parts also encroached into the successively peneplained Variscan Fold Belt (Maystrenko et al., 2008). The Altmark Subgroup and equivalents (Stephanian/Gzhelian-Asselian) overlying the Variscan Unconformity are here considered to be the oldest deposit of the SPB in the northern German area (Plein, 1995). The succession consists of up to 2000-3000 m-thick multiphase acidic and intermediate volcanics red beds (Geluk, 2005).

A.1.2 Depositional Cycle 2: Early Permian

The 'Saalian Unconformity' (Stille, 1924; Ziegler, 1990a) developed above the Altmark Subgroup and equivalents, and older rocks, and was interpreted to be the result of regional thermal uplift in the SPB area due to crustal heating (Bachmann & Hoffmann, 1997). The overlying Müritz Subgroup is an overall fining-upward succession of red and grey to black fluviolacustrine sediments. The Müritz Subgroup occurs mainly in a west-north-west trending area in north-east Germany with depocentres in several interconnected transtensional rift basins (Plein, 1995; Geluk, 2005).

A.1.3 Depositional Cycle 3: Middle Permian

The 'Altmark I Unconformity' (Hoffmann et al., 1989) represents another long period of erosion in parts of the SPB, lasting approximately 15 Ma. During mid-Permian times, the SPB was mainly west-north-west trending. Above the unconformity, the Havel Subgroup can be more than 1100 m thick in northern Germany (Plein, 1995) and consists of fining-upward predominantly red alluvial, fluvial, playa and salt-lake sediments. Initial deposition took place in rift basins between the area of the present-day German North Sea and Poland (Geluk, 2005). At the southern basin margin in Germany, the equivalents of DC 3 sediments are confined to a north–south-trending rift system (Gast, 1988). DC 3 shows rapid subsidence due to rifting and the beginning of thermal relaxation (thermal subsidence).

A.1.4 Depositional Cycle 4: Late Permian to Early Triassic

The base of DC 4 is marked by the 'Altmark III Unconformity'. DC 4 is characterised by rapid subsidence and the expansion of the SPB into the areas of eastern England and eastern Poland. The Elbe Subgroup, like the preceding Havel Subgroup, consists of fining-upward predominantly red alluvial, fluvial, aeolian, playa and salt-lake sediments that are up to 1500 m thick.

At the start of deposition of the Zechstein Group, the basin was flooded with sea water (peak transgression). This basinwide event led to the deposition of the euxinic, starved, thin 'Kupferschiefer' (Paul, 2006). The entire Zechstein succession has a generally regressive and hypersaline trend. The succeeding Lower Buntsandstein Subgroup is up to 400 m thick and was deposited in fluvial, lacustrine and playa environments. Short tectonic uplift pulses have been identified at particular structures within the Middle Buntsandstein (pre-Volpriehausen, pre-Detfurth, pre-Solling and intra-Solling). Of these, the pre-Solling pulse, which gave rise to the 'Hardegsen Unconformity', was the strongest (Röhling, 1991) and terminates DC 4.

A.1.5 Depositional Cycle 5: Early Triassic to Carnian

The base of DC 5 is formed by the prominent late Early Triassic (Olenekian) 'Hardegsen Unconformity'. DC 5 begins with mostly coarse-grained and thin fluvial sandstones of the uppermost Middle Buntsandstein (Solling Formation). The transgression began during the Anisian (depositing the evaporites and carbonates of the Röt Formation) and a shallow sea with carbonate sedimentation spread gradually from the area of Poland into eastern Germany (Kedzierski, 2000); this heralded the Muschelkalk transgression, which subsequently flooded most of the SPB. Renewed opening of the eastern gateways and the new Alemannic-Burgundy gateway to the Tethys Ocean allowed the establishment of large carbonate-ramp systems of the Muschelkalk Group (Anisian and early Ladinian). Peak transgression occurred in the latest Anisian (Meissner Formation of the Upper Muschelkalk). The upper part of the Upper Muschelkalk is generally regressive. During the late Ladinian, the marine conditions of the Muschelkalk Group were rapidly replaced by the successively continental environments of the Keuper Group. Three unconformities have been identified for the regressive phase. DC 5 terminates in large parts of the SPB with gypcretes, the Heldburg Gypsum Member, which is succeeded by the 'Early Cimmerian Unconformity'.

A.1.6 Depositional Cycle 6: Middle Keuper (Norian) to Dogger (Bajocian)

The base of DC 6 is the early Norian 'Early Cimmerian Unconformity'. The playa deposits of the upper Middle Keuper (Arnstadt Formation, Norian) cover the palaeorelief in a sheet-like manner and have the lowest subsidence rates of the Triassic.

The Upper Keuper (Exter Formation, Rhaetian) comprises the transition from late Triassic nonmarine environments through paralic systems to marine conditions in the Early Jurassic, which were caused by a generally rising sea level. The Lower Jurassic (Liassic) consists of dark grey, more-or-less marly marine shales with thin limestone beds that interfinger to the east with shallow-marine and paralic sandstones (Brand & Hoffmann, 1963).

The lower Toarcian Posidonia Shale Formation consists of dark grey, laminated, bituminous marlstones that were deposited in a euxinic starved environment. They represent peak transgression during a sea-level highstand and correspond with a global Oceanic Anoxic Event (Jenkyns, 1998). The formation contains some of the principal oil source rocks in the basin. The palaeogeography changed substantially during Mid-Jurassic times (Dogger) due to the development of the North Sea rift system and an associated large rift dome. In late Aalenian and early Bajocian times, sands were transported southwards from the eastern flank of the dome into the SPB area to form progradational paralic and deltaic units. There are two significant unconformities (the base upper Toarcian and base lower Bajocian), which are also referred to as 'Middle Cimmerian' unconformities (Ziegler, 1990a).

A.1.7 Depositional Cycle 7: Dogger (Bajocian) to Lower Cretaceous (Berriasian)

The widespread lower Bajocian unconformity, also referred to as the 'Late Cimmerian Unconformity', is thought to represent the basal unconformity of DC 7. Late Middle Jurassic (late Bajocian, Callovian) to early Late Jurassic (Oxfordian to Middle Kimmeridgian) times were characterised by a long-term eustatic sea-level rise that led to predominantly shallow- marine environments consisting of successions of shales, spiculitic sandy limestones, oolitic limestones and finally limestones and marls. Peak transgression occurred during deposition of the middle Kimmeridgian limestones and marls (Süntel Formation). These rapidly gave way to mixed marine, brackish and limnic limestones and shales. The latest Tithonian to earliest Berriasian Münder Formation consists mainly of grey marlstones with anhydrites and halites.

A.1.8 Depositional Cycle 8: Cretaceous

The widespread mid-Berriasian unconformity at the base of the continental Bückeberg Formation ('North German Wealden'), which is also referred to as the 'Late Cimmerian Unconformity' (Ziegler, 1990a), can be regarded as the basal unconformity of DC 8. The long-term eustatic sea-level rise during Valanginian to Albian times led to deposition of thick, relatively uniform dark grey marine shales that finally spread from present-day England to Poland. At the Cenomanian boundary, these shales passed into light grey pelagic coccolith marl- and limestones as a result of a major sea-level rise. Eustatic sea-level rise culminated either in Turonian (e.g. Vail et al., 1977) or Campanian times (Hancock 1989) at the worldwide Phanerozoic sea-level maximum (see above), which corresponds with the maximum landward extent of open-marine facies (Hancock & Kauffmann, 1979; Vail, 1979). Around the Cenomanian-Turonian boundary there are several layers of black, laminated, euxinic marlstones that are interbedded with light grey marl- and limestones and were caused by a global Oceanic Anoxic Event (Schlanger & Jenkyns, 1976). During the Late Cretaceous, the basin centre was generally characterised by deposition of widespread coccolithic marlstones and chalk that persisted into earliest Tertiary (Danian) times. The southern part and the northern boundary of the basin were particularly subjected to uplift ('inverted') in Late Cretaceous times (Ziegler, 1990a).

A.1.9 Depositional Cycle 9: Tertiary

DC 9 started with a Mid-Paleocene sea-level rise (Ziegler, 1990a). The erosional 'Laramide Unconformity' at its base was caused by earlier Late Cretaceous inversion and was possibly due also to a eustatic sea-level fall in latest Cretaceous and earliest Tertiary times. There was a generally transgressive trend from Late Paleocene (Thanetian) to Early Oligocene (Rupelian) times with deposition of shelf mudstones and shallow-marine sandstones. Broad coastal plains developed at the southern basin margin and gave way to the accumulation of thick lignite deposits. Sedimentation was frequently interrupted by sharp sea-level falls that caused erosional hiatuses, especially at the bases of the Lower, Middle and Upper Eocene (Ypresian, Lutetian, Priabonian; Vail et al. 1977). The Early Oligocene Rupelian Shale extends far to the south and marks the Tertiary peak transgression following which there was a strong regressive trend with sharp sea-level rise and fall and shifts in shorelines. Parts of north-eastern Germany, mainly in the lower Elbe area, are still subsiding, indicating that the SPB is still an active basin (Ziegler, 1990a; Reicherter, 2005; Sirocko et al., 2008).

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