Rotliegend dune-sandstones in the Sventesius quarry at Bebertal, Germany. The grainflow-layers are sold for use as flagstones.

Chapter 7 Rotliegend

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Bibliographic reference
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1 Summary and introduction

Rotliegend sediments and volcanics crop out across the entire SPBA area and have been drilled in all countries from the UK to Poland (**Figures 7.1**, **7.2** & **7.3**). The economic significance of the Rotliegend is demonstrated by the fact that more than 10 000 wells have been drilled in these rocks within the SPB. Rotliegend sandstones are the most important gas reservoirs in north-west Europe. Gas was sourced from the widespread Carboniferous Coal Measures and the top seal is formed by basal Zechstein anhydrites and salt, mainly the Zechstein Stassfurt Halite Formation in the North Sea.

The history of exploration and production of the Rotliegend gas reservoirs started with the discovery of Groningen in the Netherlands in 1959. When Nederlandse Aardolie Maatschappij (NAM) discovered a series of natural gasfields in Groningen, no-one could have predicted the far-reaching significance of this find. Oil and coal were then the most popular fuels. The Groningen field turned out to hold the world's largest gas reserves at that time, with a capacity of nearly 3000 bcm. Consequently, there was further exploration of the gas-prone Rotliegend sandstone trend to the east of Groningen, where another giant field, Salzwedel (2650 bcm), was discovered in 1968 in the former East Germany (see Section 6.3.2). To the west, large fields were drilled in the UK and Dutch offshore sectors and in 1966 the Leman gasfield was found. Leman is the largest UK gasfield (340 bcm) and the third largest gasfield in the North Sea after Groningen and Troll (see Section 6.2.1).

1.1 *Plate-tectonic setting*

The SPB developed in the area between the Variscan orogenic belt to the south and the Mid North Sea High, Ringkøbing-Fyn High and the Teisseyre-Tornquist Zone in the north (**Figure 7.2**; Chapter 3). The relative westward movement of the African plate during the late stages of Permian collision with the European plate initiated the formation of west-north-west to westerly trending, deep-seated, strike-slip faults (Ziegler, 1990a) during which a series of *en-echelon* basins developed across the SPBA area. The basins subsided in the area of the predecessors of the Variscan Foreland Basin after a phase of under-plating, crustal thinning and uplift from Stephanian time onwards, partly resuming deformation along pre-existing tectonic elements (Franke et al., 1996; Geluk, 2005; Gast & Gundlach, 2006). Smaller basins relative to the SPB developed south of the Variscan Deformation Front as so-called intramontane basins, such as the Saar-Nahe Basin in central Germany (e.g., Plein, 1995; Schäfer & Korsch, 1998; Schneider et al., 1995; Schneider, 1996).

Late Rotliegend thermal subsidence of the crust north of the Variscan Mountain belt led to the final development of the SPB (Bachmann & Hoffmann, 1995, 1997; Geluk, 2005). Crustal extension (stretching) appears to have been increasingly predominant over strike-slip movements at that time. Rotliegend volcanicity and sedimentation took place in central and north-west Europe. The SPB was affected by periodic marine ingressions during the late Rotliegend II, which were followed by a Zechstein transgression that completely flooded the basin and established fully marine conditions, (Gebhardt, 1994; Legler, 2005, 2006).

1.2 *Palaeogeography*

Towards the end of the Carboniferous, during deposition of the Westphalian Coal Measures, the SPB area was situated just north of the Equator, drifting northwards until it reached its Permian location in the northern hemisphere desert belt between about 10 and 30°N (Glennie, 2007). The SPB was entirely land-locked and terminal playa and saline lakes had developed in the central, deepest parts of the basin. Rotliegend sediments were deposited in a desert environment in which aridity increased throughout the Permian. South of the lakes, predominantly transverse dunes accumulated from fluvial sands transported by north-east trade winds, which were preserved in the geological record.

2 Stratigraphy

2.1 *Rotliegend stratigraphy*

A threefold subdivision of the Rotliegend that is closely related to different phases of structural development of the Rotliegend Basin can be applied to the entire SPB (**Figures 7.1**, **7.4**, **7.5** & **7.6**). The three groups are the lower Rotliegend sediments and volcanics, followed by the largely sedimentary rocks of the upper Rotliegend I and II (Schröder et al., 1995). Lower Rotliegend sediments are restricted mainly to present-day

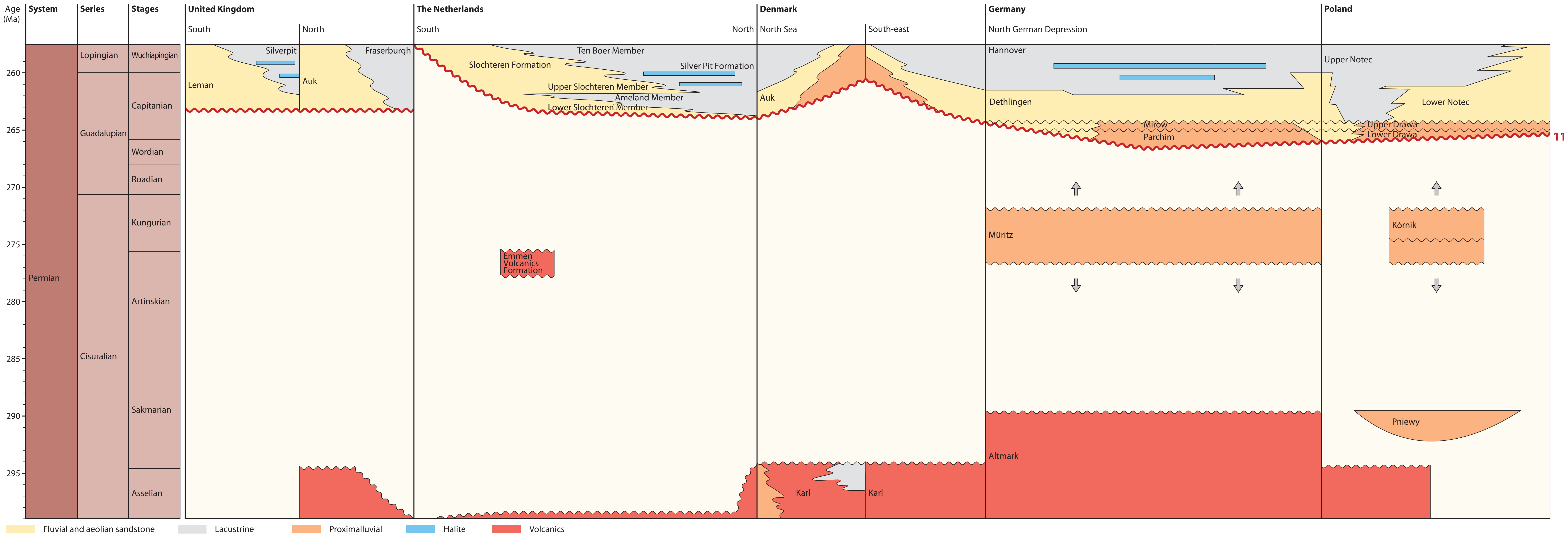


Figure 7.1 *Rotliegend tectonostratigraphic chart. Based partly on Glennie (2007). The red line at the base of the upper Rotliegend clastic succession (11) is the lithostratigraphic horizon used to compile the depth map in Figure 7.2 (see Figure 1.5).*

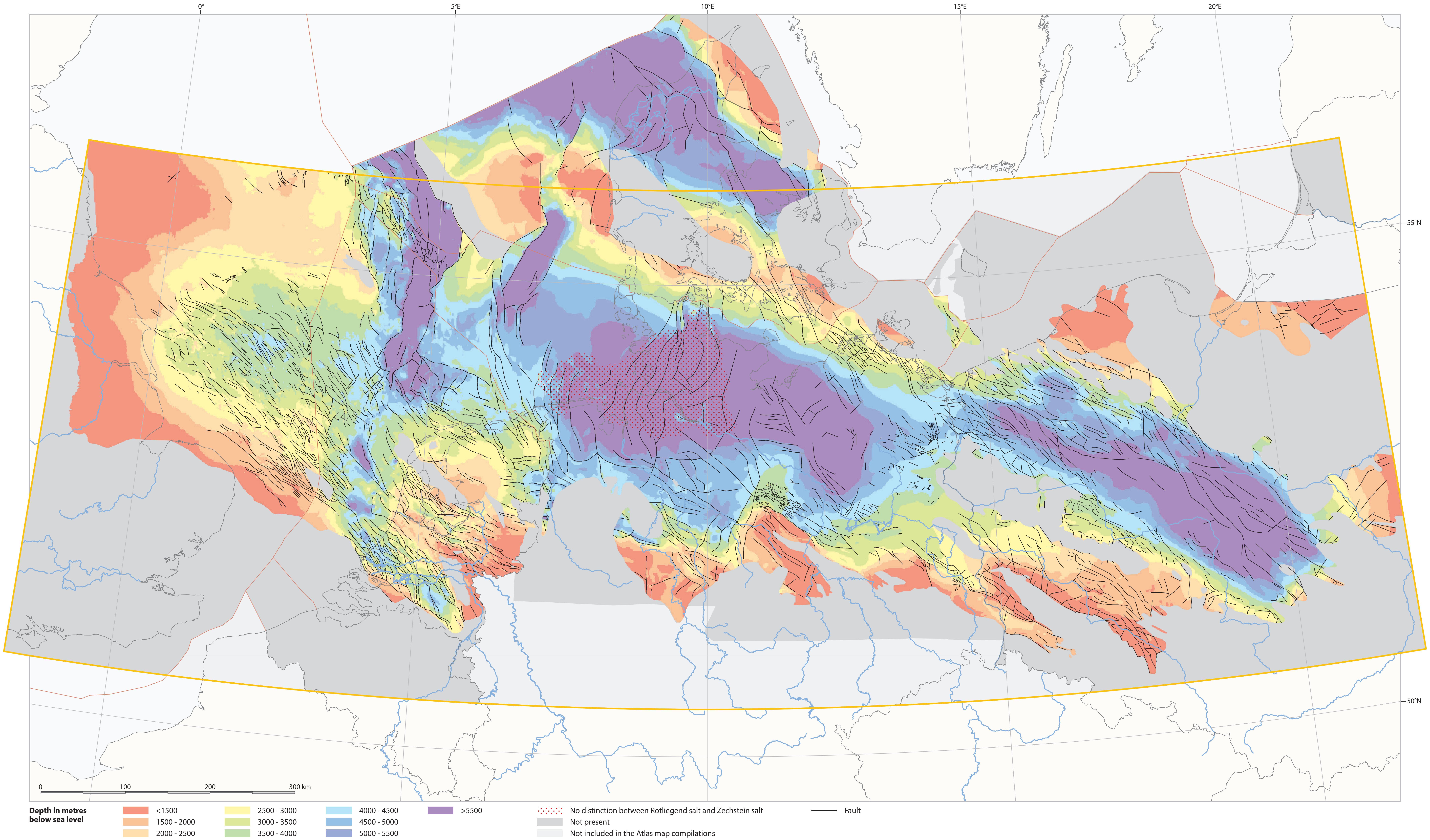


Figure 7.2 Depth to the base of the upper Rotliegend clastics. This lithostratigraphic horizon is shown as horizon 11 on Figures 1.5 and 7.1.

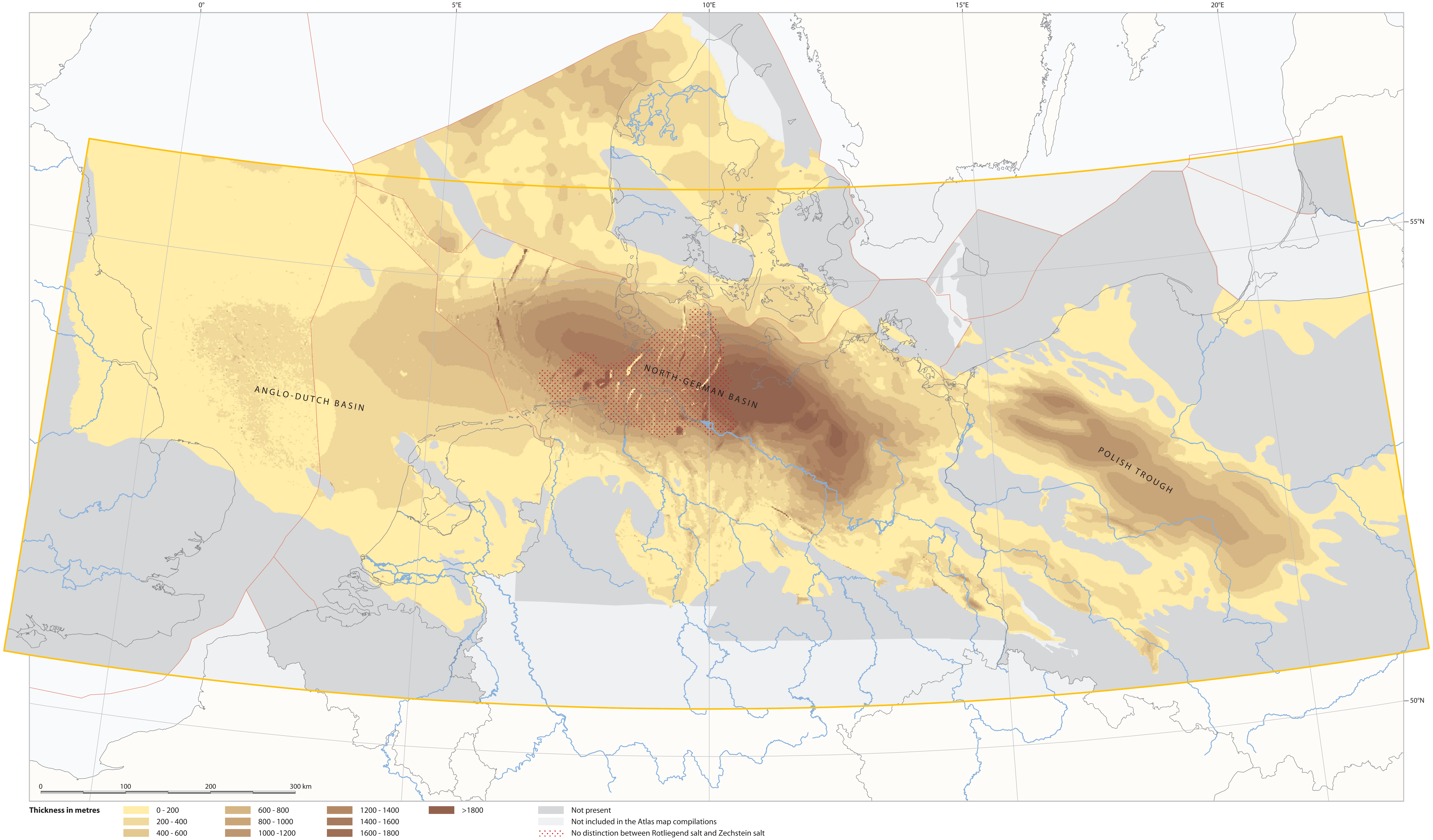


Figure 7.3 Thickness of the upper Rotliegend clastics.

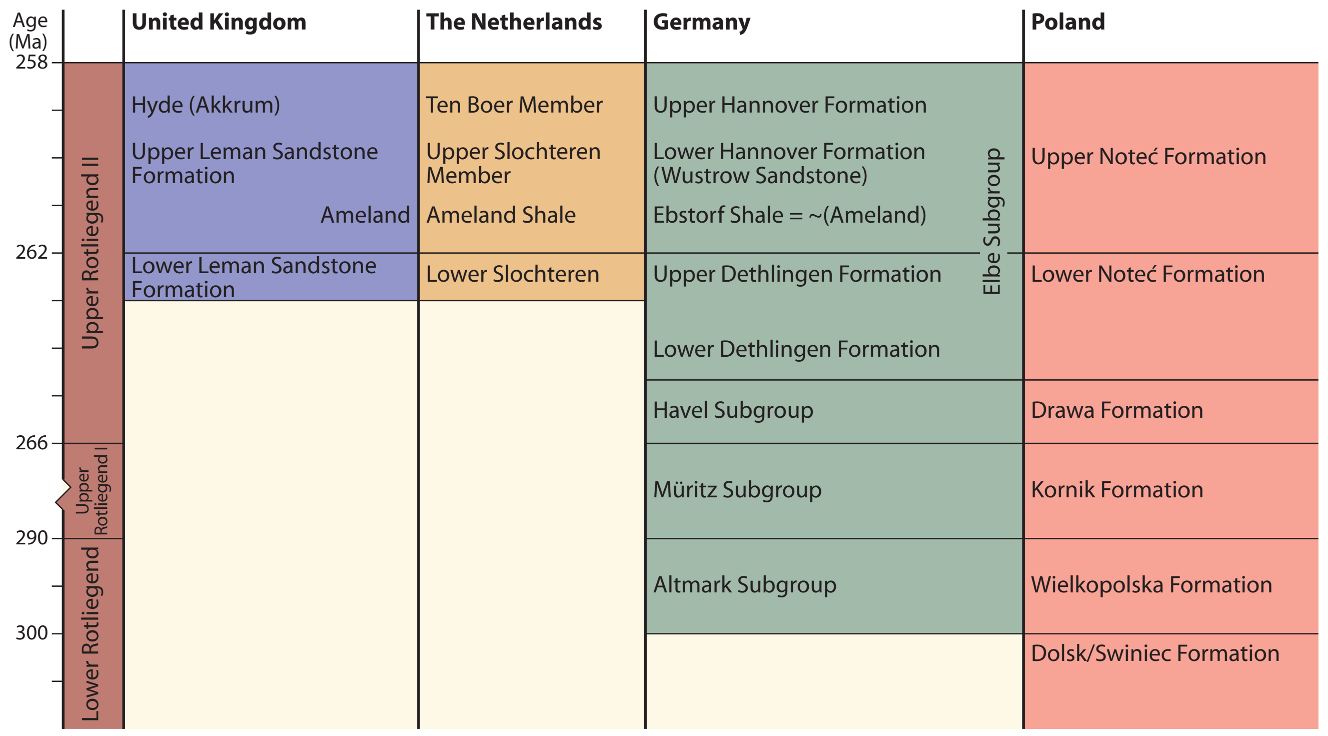


Figure 7.4 Rotliegend stratigraphic overview of the Southern Permian Basin. Dates from Table of Germany (Menning & German Stratigraphic Commission, 2002) .

Germany and Poland and are capped by the Saalian Unconformity. Upper Rotliegend I deposits are also restricted to rift basins and grabens in the German/Polish areas, whereas upper Rotliegend II strata, which were deposited during the following thermal sag phase, extend across the entire SPB area. The threefold subdivision forms a framework with which to tie various local stratigraphic schemes. Regional correlations of the upper Rotliegend I and II units have been made with some degree of confidence based on wireline logs (e.g. Schröder et al., 1995; Geluk, 2005; Kiersnowski & Buniak, 2006).

The Havel and Elbe subgroups (**Figures 7.4** & **7.5**) represent the development of the SPB following the major erosion that produced the Base Permian Unconformity. The subgroups record the major expansion in both sediment thickness and basin area. The four formations of these subgroups have a combined thickness of around 2500 m (Plein, 1995; McCann, 1998b), by far the thickest and most widespread upper Rotliegend II sequence in Europe, and were deposited within a period of some 5 to 10 Ma (Menning, 1995; Schneider, 1996). At their fullest development, Elbe Subgroup sediments and their lateral equivalents covered an area some 1500 km from east to west, and about 400 km from north to south (Glennie, 2007).

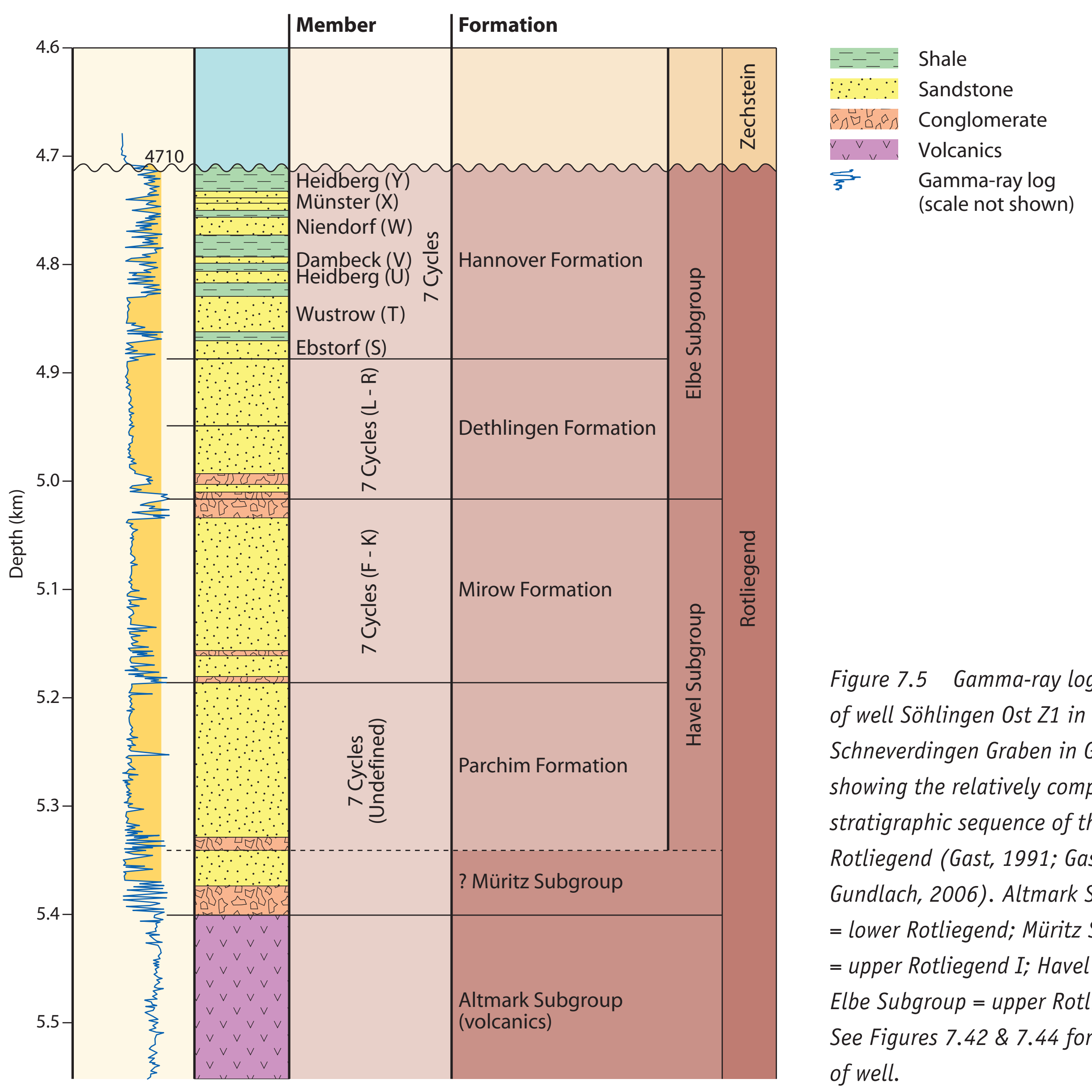


Figure 7.5 Gamma-ray log of well Söhlingen Ost Z1 in the Schneverdingen Graben in Germany showing the relatively complete stratigraphic sequence of the Rotliegend (Gast, 1991; Gast & Gundlach, 2006). Altmark Subgroup = lower Rotliegend; Müritz Subgroup = upper Rotliegend I; Havel Subgroup, Elbe Subgroup = upper Rotliegend II. See Figures 7.42 & 7.44 for location of well.

2.1.1 *Dating of Rotliegend strata*

Correlation of the nonmarine strata of northern Europe to the global Permian timescale is still at an early phase of development (e.g. Lucas et al., 2006) due to the lack of widespread macro- and microfloras in the Rotliegend succession combined with increasing floral provinciality during the Permian. Recent correlations between the Rotliegend succession and the global Permian timescale have relied on radiometric-age data from the lower Rotliegend volcanic succession (e.g. Stemmerik et al., 2000; Lützner et al., 2007) and recognition of the Illawara Magnetic Reversal event during the late Rotliegend (Menning, 1995; Roscher & Schneider, 2006).

Even when the dates of lower Rotliegend volcanics allow a general correlation across the SPB, they do not help to correlate the upper Rotliegend sedimentary sequences, partly because of the very large time-gap between the volcanics and overlying sediments. A potential solution to this problem is to correlate wells using climate-cycle analysis from the Zechstein transgression level downwards (see Section 2.1.2).

Dating of the silica-rich lower Rotliegend volcanics of the Altmark Subgroup (**Figure 7.5**) based on zircon SHRIMP U/Pb ages gives radiometric ages in the range 290 to 303 Ma with a prominent increase in magmatic activity between 295 and 299 Ma (Breitkreuz et al., 2007). The dataset implies that the Rotliegend volcanic event was synchronous across the entire basin. The 295-299 Ma radiometric ages place the main phase of volcanic activity within the Asselian according to the timescale of Ogg et al. (2004), whereas it is of latest Carboniferous age according to the timescale of Menning et al. (2006).

The older upper Rotliegend I Müritz Subgroup (Plein, 1995) is truncated by a low-angle unconformity that represents an unknown gap in Rotliegend sedimentation. The equivalents of this subgroup are best exposed in central Germany (e.g. the Hessian and Saar-Nahe basins) and comprises mostly fluviolacustrine and aeolian deposits, although it also contains some volcanic strata. Its lower boundary is also an unconformity above volcanic rocks.

The lower Rotliegend and upper Rotliegend I sediments include sporadic horizons rich in insects and amphibians, which have been used to develop an internal stratigraphy and a guide to the correlation of the nonmarine Permian basins in Europe (Roscher & Schneider, 2006; Schneider & Werneburg, 2006; Lützner et al., 2007). As mentioned above, the absence of marine sediments makes it difficult to correlate to the global Permian timescale (compare Menning & German Stratigraphic Commission, 2002, Menning et al. 2006 and Lützner et al., 2007). The early Rotliegend and late Rotliegend I are therefore relatively poorly defined intervals of latest Carboniferous to possibly mid-Permian age. Radiometric ages and insect biostratigraphy indicate that early Rotliegend volcanism started during the latest part of the Carboniferous (~300 Ma) and had culminated before the end of the Asselian. The overlying sediments were deposited during later, Early Permian times and could be as young as mid-Permian (Roadian) in age.

The recognition of the Illawara Magnetic Reversal in the basal part of the Parchim Formation (**Figures 7.1** & **7.5**) of the lowermost upper Rotliegend II sequence has been used to correlate this part of the succession to the global Permian timescale (Menning et al., 2006). The Illawara reversal has long been regarded as earliest Capitanian in age (265-266 Ma) according to both Ogg et al. (2004) and Menning et al. (2006). However, new palaeomagnetic data indicate that the mid-Permian polarity pattern is more complex and that the first normal polarity event may be of slightly older, mid-Wordian age (~267 Ma) (Steiner, 2006). The youngest age of the upper Rotliegend II is constrained by the early Wuchiapingian conodonts in the overlying Kupferschiefer of the Zechstein transgression (e.g. Legler et al., 2005). The upper Rotliegend II was therefore deposited during a fairly well-constrained stratigraphic interval of less than 10 Ma, spanning the latest Wordian to earliest Wuchiapingian with well-expressed climate cyclicity, especially in the younger part of the sequence (see Section 4.2).

2.1.2 *Cyclostratigraphic subdivision of younger Rotliegend*

Deposition of upper Rotliegend II sediments was characterised by climatically forced cycles (**Figures 7.5**, **7.7** & **7.8**). Cyclicity within the upper Rotliegend II sediments depends almost exclusively on base-level/lake-level fluctuations. Different orders of cyclicity have been recognised in upper Rotliegend II sediments in outcrops and boreholes. The frequencies of the cycles are 20, 100 and 400 ka and correspond to the Milankovitch frequency band. The most complete and readily interpreted cyclicity is found in lake and lake-margin deposits of the large perennial Rotliegend saline lake (see example from playa-lake margin deposits in Germany; **Figure 7.7**). The preservation and resolution of even small-scale 20 ka Milankovitch Cycles is well expressed, although the longer-term large-scale cycles of 100 ka and 400 ka are easier to identify. In densely drilled areas, the cyclicity can be identified even in landward aeolian sequences (Kocurek, 1988; Gast, 1993; Howell & Mountney, 1997; Sweet, 1999; Kocurek et al., 2001). The plausibility of selecting the right cycle-type can be checked with sedimentation rates. In an epicontinental area like the SPB, subsidence rates generally vary between 4 cm/ka and 20 cm/ka in central parts of the basin (e.g. Füchtbauer & Müller, 1977).

Even though the SPB was not connected to the ocean for most of the time, third-order eustatic cycles could also be postulated as having an influence on facies evolution during the late Rotliegend. The cyclicity of the Elbe Subgroup (upper Rotliegend II, lower Slochteren-Zechstein transgression), including marine ingressions proven by fossil evidence, is shown in **Figure 7.8** (Legler et al., 2005; Legler & Schneider, 2008).

During a time-series analysis of a gamma-ray log using a Fast-Fourier Transformation, Maynard & Gibson (2001) were able to identify twelve cycles within the area of the UK 'Rotliegend Feather Edge' (see Section 2.1.3). The six lower cycles are dominated by coarser-grained lithofacies, whereas the upper six are finer-grained, comprising facies of the Silverpit Formation. Cycle boundaries were taken at lake-flooding events and their correlative surfaces in the erg to the south. Detailed cycle analysis by Maynard & Gibson (2001) established that cycle-boundary surfaces were extensive. They also found that the cycles were fairly uniform in thickness and showed onlap and pinch-out onto the pre-Rotliegend Basin palaeotopography, and that coarser-grained lithofacies, particularly dune facies, were deposited in topographic lows. They concluded that the principal controls on Rotliegend deposition were topography and climate, with topography controlling the location of erg development and local facies development, and climate controlling the first-order effect of aridity and the second-order effect of groundwater and lake-water levels.

Glennie & Provan (1990) identified five units in many areas of the southern North Sea, although only three could be recognised in the Sole Pit area where subsidence is thought to have been less pronounced. These units were recognised on the basis of the presence of an interbedded wadi, interdune or playa sandflat succession. They can also be recognised across the UK and Dutch sectors of the southern North Sea (Yang & Baumfalk, 1994; Glennie, 1998b), although George & Berry (1993) could not recognise the cycles within the erg interior. The lack of accurate age constraints on the UK Rotliegend has hampered cycle analysis. However, George & Berry (1997) suggested a periodicity of 260 to 533 ka for each of the five drying-upward cycles that they recognised.

Two major sequences can be recognised in most wells drilled in the German Rotliegend Basin, each with seven 400 ka cycles (Schröder et al., 1995). In the Dutch part of the basin, seven cycles of similar thickness were also identified in the lower and upper Rotliegend sequences, which are comparable in time, but with an additional shaly sequence in between (**Figure 7.9**).

2.1.3 *Special stratigraphic features of the UK part of the basin*

In the UK sector of the southern North Sea, the Rotliegend comprises the Leman Sandstone Formation and the chronostratigraphically equivalent Silverpit Formation (Rhys, 1974; Cameron, 1993; Johnson et al., 1994) (**Figures 7.5** & **7.9**). These can be assigned to the upper Rotliegend II Unit, which is probably of Capitanian age (Glennie et al., 2003) (**Figure 7.1**). The upper ~50 m of the Leman Sandstone Formation comprises uncoloured sandstones known as the Weissliegend (Glennie, 1972, 1998b; Glennie & Buller, 1983; George & Berry, 1993).

The Silverpit Formation lies to the north of the Leman Sandstone Formation in a west-north-west-trending lenticular belt between 54°N and 55°N. The boundary between the two is gradational and diachronous and has been termed the 'Rotliegend Feather Edge'. The Silverpit Evaporite Member of the Silverpit Formation is recognised wherever halite occurs, of which up to five prominent beds can be present (George & Berry, 1993; Johnson et al., 1994) with many more in north-west Germany (Trusheim, 1971; Gast, 1991; Geluk, 2005).

Farther north in the Horn Graben between the Mid North Sea and Ringkøbing-Fyn highs, rhyolites and basalts of the Liva Member of the Karl Formation are overlain by Rotliegend sandstones (Deegan & Scull, 1977); both formations have been assigned to the upper Rotliegend II (Glennie et al., 2003). Similar volcanic rocks in the Danish Central Graben area have been dated at 265-267 Ma (Ineson, 1993a), which may indicate the initiation of rifting associated with upper Rotliegend II sedimentation (Glennie, 1998b). The Auk Formation comprises interbedded reddish brown and grey aeolian sandstones with minor water-lain sandstones and conglomerates (Heward, 1991; Cameron, 1993; Trewin et al., 2003). The formation is thought to be broadly similar to the Leman Sandstone Formation (Glennie, 1998b).

Onshore, the earliest Permian deposits are typically thin conglomerates with angular pebbly clasts of locally derived material, often referred to as the 'basal breccia of unknown age'. The conglomerates cover most of the East Midlands Shelf northwards to the Durham Shelf and are generally less than 10 m thick. In the Durham and Yorkshire areas, they are overlain by the Yellow Sands Formation. Around Durham, the Yellow Sands Formation comprises a number of west-south-west-trending linear ridges of sandstone (Steele, 1983; Smith, 1989; Chrintz & Clemmensen, 1993). The uppermost Rotliegend Weissliegend may also occur in the onshore succession (Glennie & Buller, 1983; Turner & Smith, 1997).

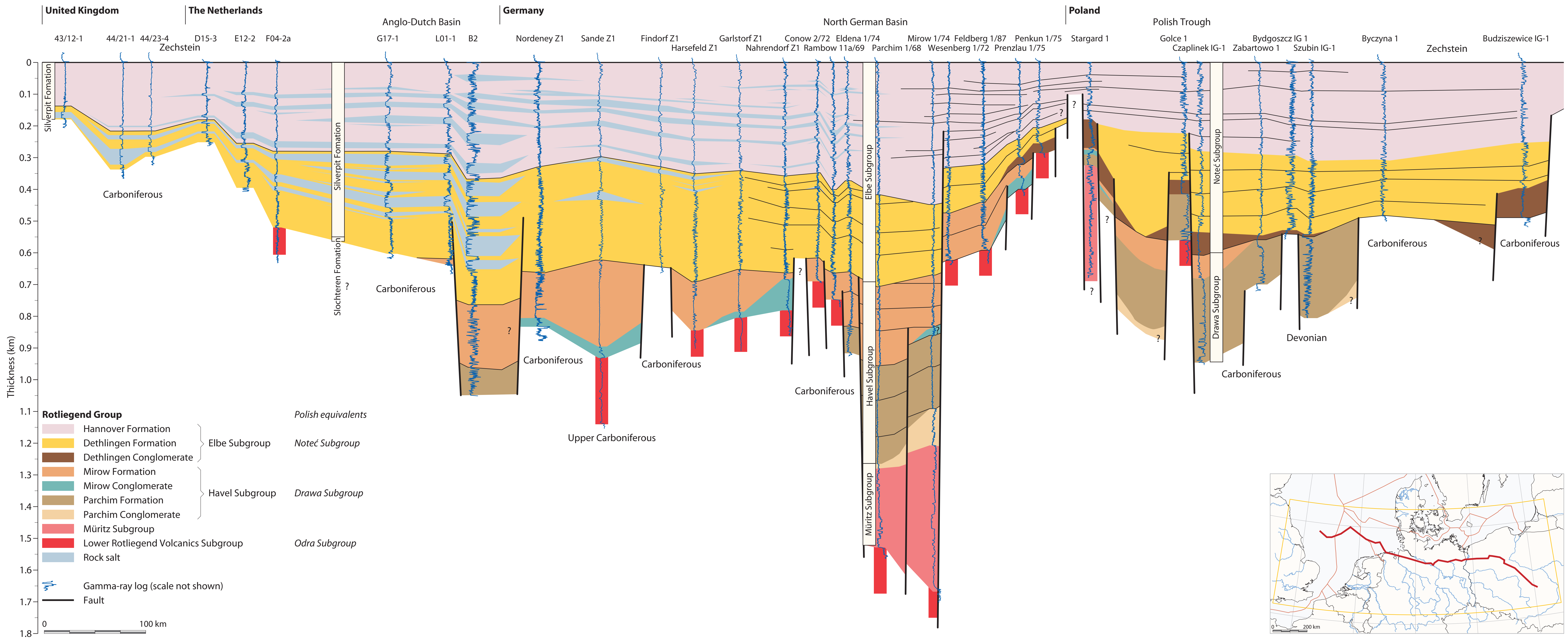


Figure 7.6 Stratigraphic cross-section through the Rotliegend Southern Permian Basin.

2.1.4 *Special stratigraphic features of the Polish part of the basin*

The stratigraphy of the upper units of the upper Rotliegend of the North German Basin (see correlations from Schröder et al., 1995) are not easily applied to the Polish Upper Rotliegend Basin (PURB), although some sedimentary layers appear to be traceable between basins, allowing lithofacies and sedimentary unification. The correlation of sedimentary units based simply on appearance is complicated by tectonic movements during the early stages of Rotliegend sedimentation, as well as by differentiation of the PURB into several sedimentary basins.

2.1.5 *The Base Permian Unconformity*

The boundary between Carboniferous and Rotliegend rocks is formed mainly by an important unconformity in the SPB (Ziegler, 1990a; Lokhorst et al., 1998). Above the middle to Upper Permian succession, Rotliegend strata may overlie Namurian to Stephanian deposits. This hiatus represents as much as 40 to 60 Ma (Geluk, 1999a) and in large parts of the basin it inhibits the amalgamation of several unconformities into a single mega-unconformity (Glennie, 1998b). The hiatus is commonly known as the Saalian Unconformity in the Netherlands and the North Sea area (e.g. Van Wijhe, 1987a; Glennie, 1998b). However, this name is not appropriate everywhere as it only refers to the Saalian Unconformity that separates the Lower Rotliegend from the Upper Rotliegend in the eastern parts of Germany (Stille, 1920; cf. Schneider, 2006). Other unconformities include the Franconian Unconformity (Katzung, 1972) between the Carboniferous and the lower Rotliegend, and the Altmark I-III unconformities in the Rotliegend (Hoffmann et al., 1989) (**Figures 7.1** & **7.9**). In Germany and Poland (Karnkowski, 1999c), the individual unconformities can be recognised in the sedimentary succession, but westwards they merge into a single mega-unconformity at the base of the upper Rotliegend II, for which the name Base Permian Unconformity is proposed (**Figure 7.1**). Despite the large time gap, the identification of the unconformity may prove to be very difficult in some areas because of a uniform red-bed lithology across the boundary and the general absence of fossils.

3 Tectonic evolution and basin fill

3.1 *Tectonic setting of the Southern Permian Basin*

Contrary to common understanding, the SPB of Rotliegend times was not a single basin (e.g. Ziegler, 1990a; Glennie, 1998b; Van Wees et al., 2000; Glennie et al., 2003), but an amalgamation of three different basins. These are from west to east the Anglo-Dutch Basin, North German Basin and Polish Trough (**Figures 7.3**, **7.6** & **7.10**). The basins differ both in origin and subsequent geological history, although their subsidence is essentially driven by thermal relaxation of the lithosphere (Ziegler, 1990a; Gast & Gundlach, 2006; Van Wees et al., 2008). The basins are separated by swells, which may be quite subtle. The location of the basins and their orientation parallel to the Tornquist Zone probably indicates a deeper structural control.

All three basins underwent structural modification during Permian and Triassic times, which had an impact on their outline and depocentres. The Central and Horn grabens and Brande Trough connect the SPB with the Northern Permian Basin (the Glückstadt Graben ends south of the Danish border). At the southern margin of the basin, some grabens terminate against west-north-west-trending transfer faults (Baldschuhn et al., 2001), whereas others continue farther south (e.g. the Hessian Depression). The Permian and Triassic fault patterns indicate dextral transtensional movements (Frikken, 1999).

3.1.1 *The western Anglo-Dutch Basin*

The Anglo-Dutch Basin developed entirely within the Variscan Foreland Basin. Permian subsidence started during late mid-Permian times (Capitanian?) following the youngest of the Altmark tectonic pulses; there was no volcanism during the Permian. The UK part of the Anglo-Dutch Basin is a west-north-west-trending basin bounded to the north by the Mid North Sea High, the London-Brabant Massif to the south and by the Pennines High, which was slowly rising to the west (van Hoorn, 1987). Prior to Permian basin development, a major Variscan transpressive deformation event gave rise to the development of the Base Permian Unconformity (see Section 2.1.5) and the initiation of extension during the Early Permian, which ultimately created the Proto-Atlantic and Viking-Central system of grabens (Glennie, 1998b). Two phases of extension or transtension are thought to have occurred immediately before and during deposition of the Rotliegend in the SPB (Glennie, 1998b). The first phase was associated with early Rotliegend volcanism during the final stages of the Variscan Orogeny (Glennie 1998b). Transtension was directed along north-west–south-east lines and resulted in a suite of north–south-trending graben developments across the present-day North Sea and Germany. To the west, the London-Brabant Massif seems to have acted as a rigid block and shows no evidence of volcanism or major extensional movements (Glennie, 1998b). During the long interval marked by the Saalian-Altmark Unconformity, the Carboniferous successions were considerably eroded, locally down to the Namurian, over areas such as the Market Weighton-Cleveland Hills Block and Sole Pit Trough, as a result of transpressional movements (Glennie & Boegner, 1981; Glennie & Provan, 1990; Glennie, 1998b).

A later phase of extension, postdating the formation of the Altmark Unconformity, was associated with volcanism in the Central Graben including extrusion of the Inge Volcanics Formation (Ineson, 1993a). It appears that rifting began later in the present-day offshore German area compared to onshore, as indicated by the volcanics in the Danish Central Graben (Glennie, 1998b). Dextral strike slip is believed to have led to the development of a number of sub-basins, including the Sole Pit, Silverpit and Broad Fourteens basins, and associated north-west–south-east and west-north-west-trending fault systems. The East Midlands Shelf, Cleaver Bank, Indefatigable and Sole Pit areas formed contemporary intrabasinal highs, and it has also been suggested that underlying buoyant granite bodies influenced the development of structural highs and fault systems (George & Berry, 1997). These sub-basins ultimately joined to form the Indefatigable and Cleaver Bank highs, which progressively collapsed during continued transtension (George & Berry, 1997). Synsedimentary tectonism during late Rotliegend II times has been invoked, with uplift along features such as the Dowsing Fault Zone, the London-Brabant Massif and the Texel-IJsselmeer High resulting in local alluvial-fan and fan-delta development (George & Berry, 1993, 1997).

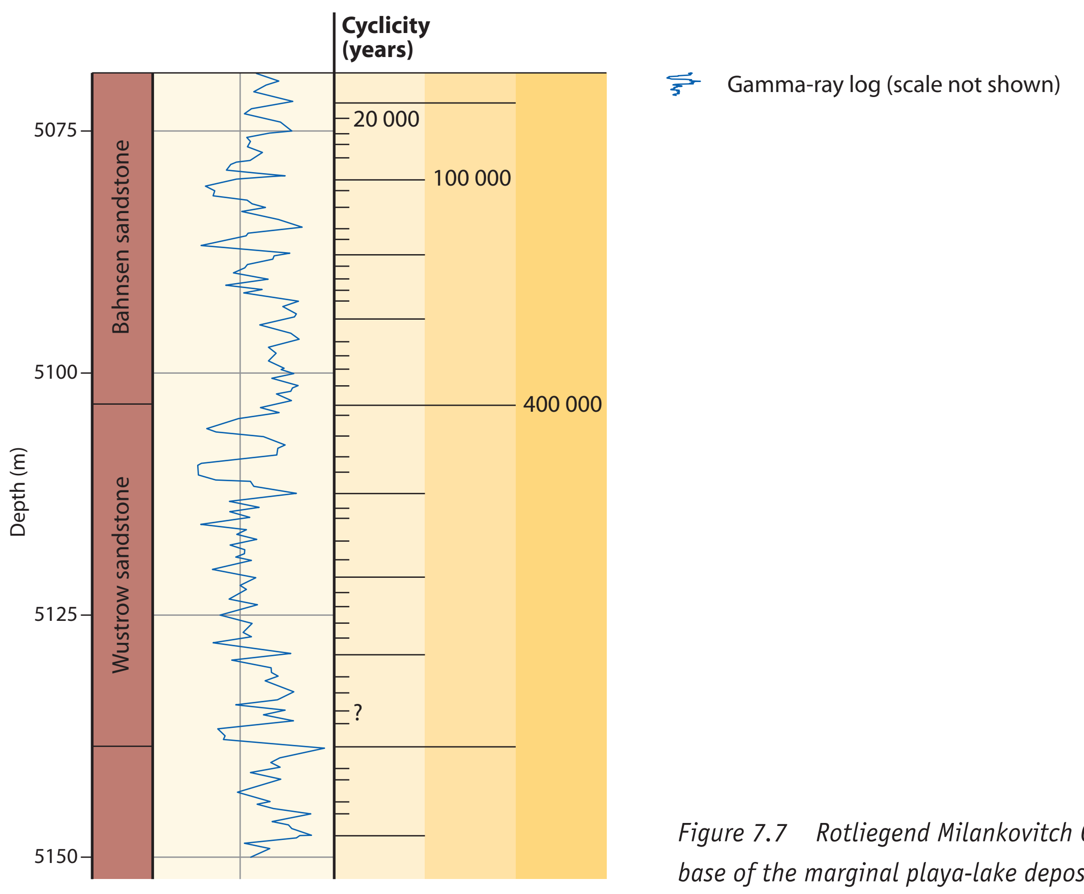


Figure 7.7 Rotliegend Milankovitch Cyclicity at the base of the marginal playa-lake deposits.

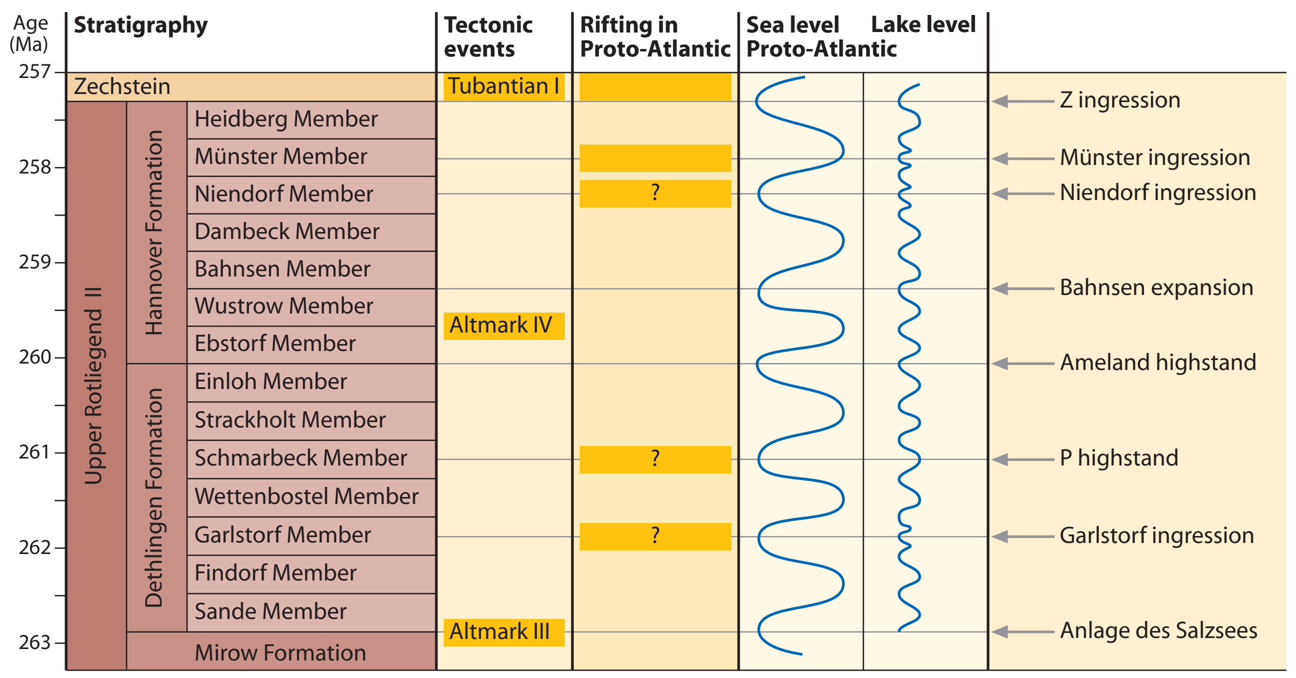


Figure 7.8 Cyclicity of the Elbe Subgroup (upper Rotliegend II, lower Slochteren to Zechstein transgression) (Legler, 2006).

3.1.2 North German Basin

The German part of the Rotliegend Basin is asymmetric in shape and is generally deepest in the north (e.g. Plein, 1993; McCann, 1998b) (**Figure 7.10**). The basin is superimposed upon the Variscan foreland and fold belt and the Avalonian crust to the north of the fold belt. The North German Basin was modified by intense Early Permian rifting and related extrusive volcanism, followed by mid-Permian extension.

Most of the strike-slip basins of the German part of the SPB were filled with thick volcanics (and also with lower Rotliegend sediments in eastern Germany), usually older types of Rotliegend volcanics, such as aphyritic to porphyritic andesites (Marx, 1994). Volcanic rocks drilled on highs were found to have reduced thicknesses relative to those in grabens. **Figure 7.13** shows a seismic line crossing the area in a north–south direction, which illustrates the geometric relationships between adjacent blocks and the steeply dipping strike-slip systems that separate them.

During early Rotliegend times, multiple deep-seated west-north-west-trending strike-slip systems formed within short distances parallel to each other. If the distance was small enough, they interacted to form a Riedel shear-dominated (R and R') strike-slip corridor with a complex pattern of small horst and graben segments between the through-going bounding principal displacement zones (PDZs).

Rifting took place mainly during early Rotliegend times, but also as rejuvenation of older lineaments in late Rotliegend and early Zechstein times. Such rifts include the Faroe-Rockall Rift and Greenland-Norway Rift (Ziegler, 1990a) to the north-west of the SPBA area. Together with the Viking and Central grabens of the North Sea (Glennie, 1995, 1997b), these rifts were reactivated to form the seaway for the Zechstein ingression as well as its late Rotliegend marine predecessors (Legler, 2006; Legler & Schneider, 2008) (see Chapter 8).

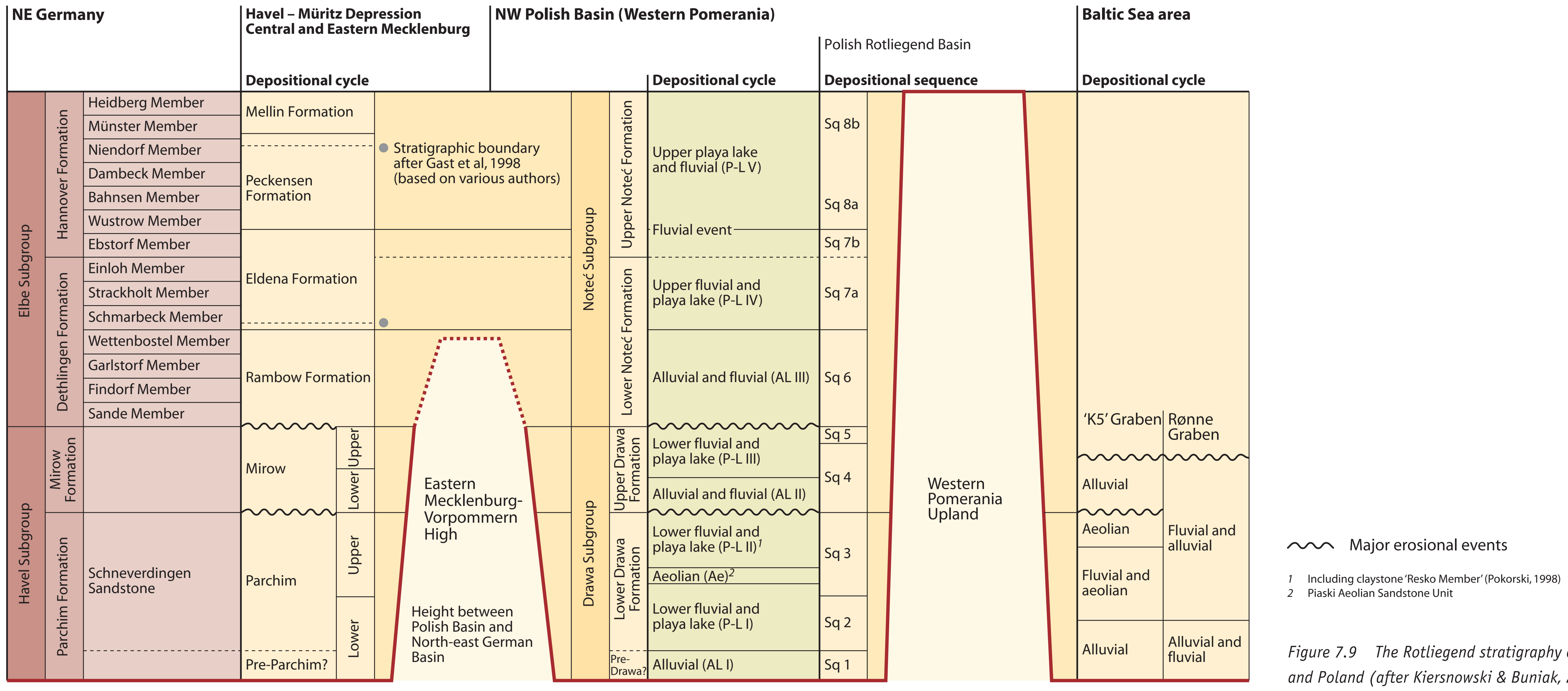


Figure 7.9 The Rotliegend stratigraphy of Germany and Poland (after Kiersnowski & Buniak, 2006).

The characteristic late Rotliegend deformation started during deposition of the Havel Subgroup (Schneverdingen), at about 267 Ma (Menning, 1995; Gast et al., 1998) and continued during early deposition of the Elbe Subgroup. Minor basalt flows are seen in the Havel Subgroup of eastern Germany and the Elbe Subgroup north of Hannover (the Soltau basalt of the Wustrow or upper Slochteren). A minor angular unconformity can be seen between the Havel and Elbe subgroups in some areas, indicating a short period of uplift along the southern basin margin. Graben subsidence continued during deposition of the Dethlingen Formation. Anomalous thicknesses in the overlying Hannover Formation are commonly related to differential compaction. The outcrops at Bebertal in the Flechtingen Hills north of the Harz Mountains are a famous analogue for early graben-fill sandstones (Ellenberg et al., 1976; Kulke et al., 1993; Legler, 2006) (**Figures 7.11** & **7.12**). Almost equally famous, because of their reptile tracks, are the Rotliegend graben-fill sandstones of Cornberg in Hessen (Gast, 1994). This graben of the 'Hessian Depression' is filled with more than 1000 m of clastic debris. In north-west Germany, the major grabens generally trend north-west– south-east, whereas in the east they change to a more north-east–south-west orientation. The same pattern of horsts and grabens continues westwards to the western border of the SPB in England (George & Berry, 1997).

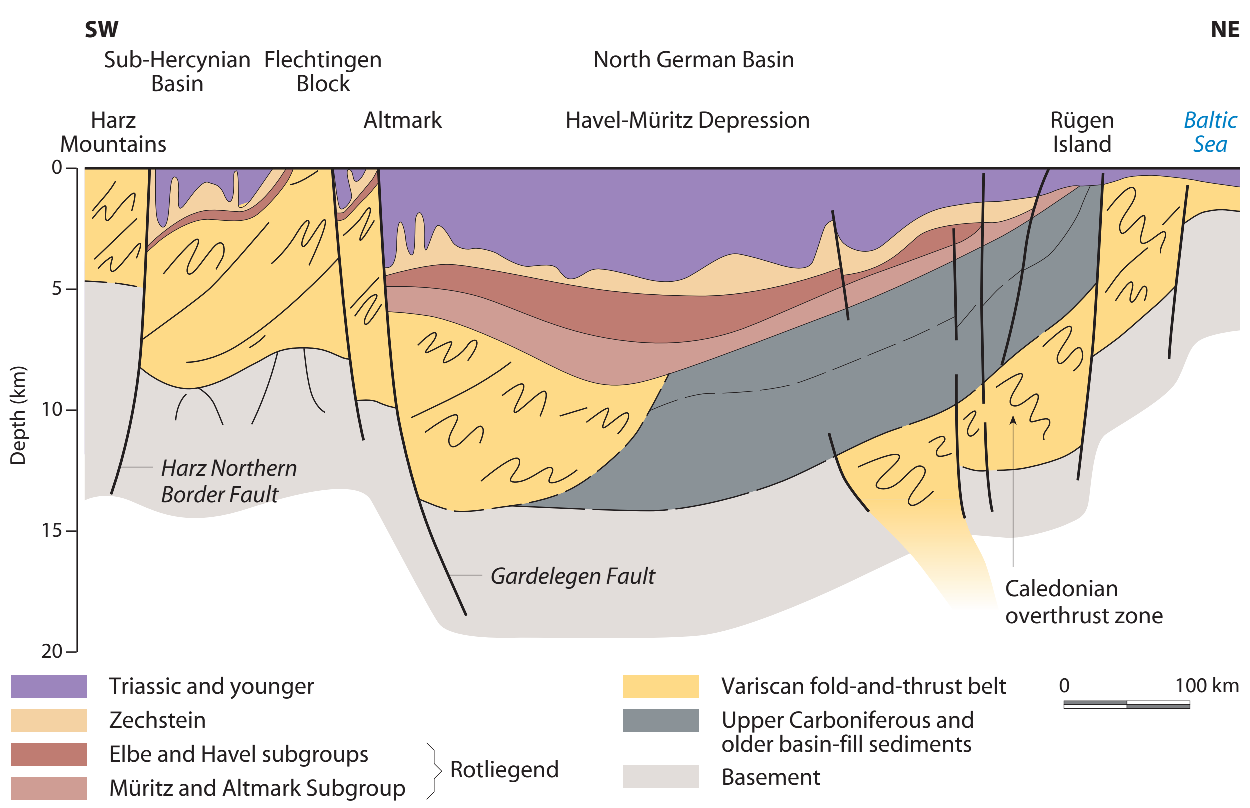


Figure 7.10 Schematic structural cross-section through the North German Basin.

Figure 7.11 Rotliegend dunes (Parchim Formation) in the Sventesius quarry at Bebertal, Germany. The sandstones have porosities of ~10-12% and permeabilities of ~10-30 mD. The grain-flow layers are used as flagstones (see photograph opposite page 101).

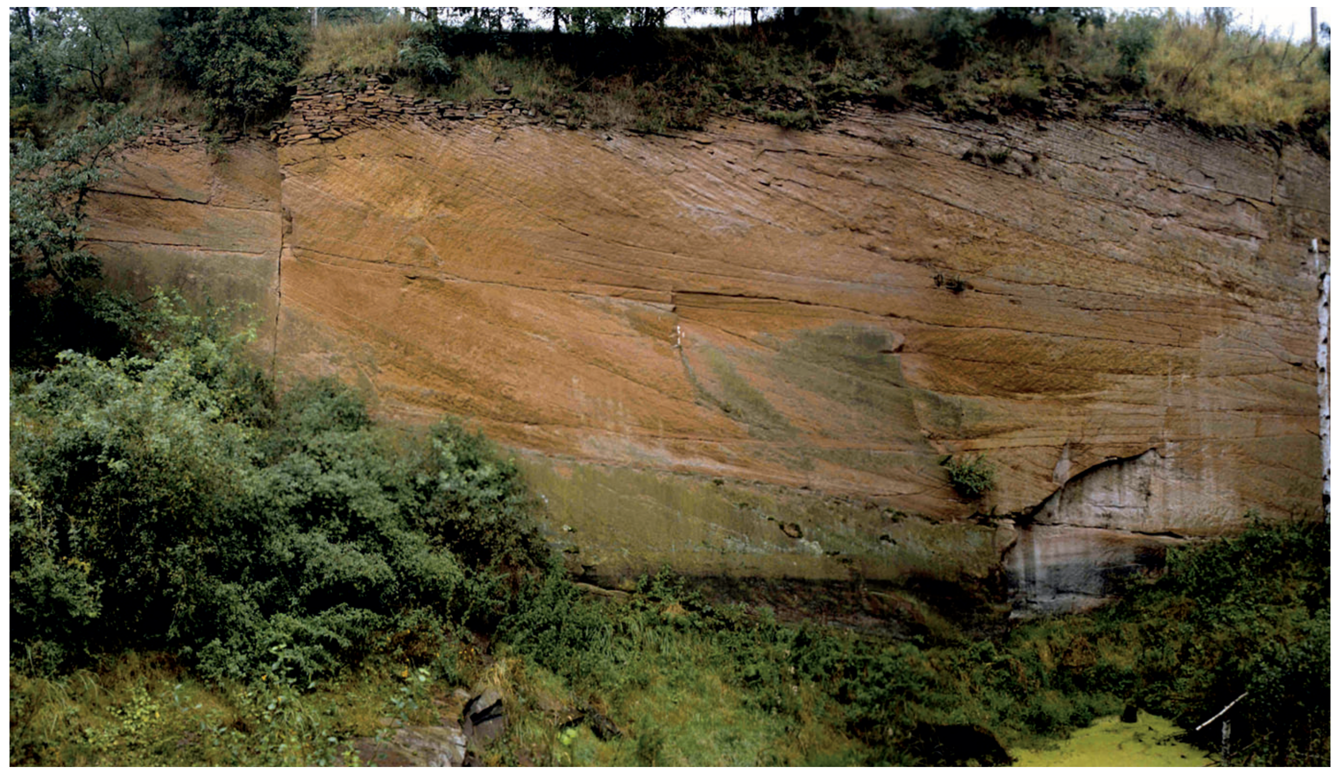


Figure 7.12 Rotliegend 'Bausandstein' (= building stone) dune sandstones of the Parchim Formation in the old quarry at Bebertal, Flechtingen Hills, Germany.

Only a few grabens in northern Germany can be regarded as being caused by 'real rifting', such as the Ems Trough, the Schneverdingen Graben, the Arsten/Bremen Graben, the Gifhorn Graben and the Havel-Müritz Depression. In the Schneverdingen Graben, a detachment plane can be seen on seismic sections (**Figure 7.13**) at a depth of about 9 to 11 km. At the western margin of this graben, Carboniferous sandstones in the footwall block are juxtaposed with Rotliegend sandstones in the hanging-wall block. However, the graben boundary faults have sealed, and there is a pressure difference of more than 200 bar across the faults.

To the north of Hannover, Rotliegend grabens, half-grabens and horsts, preferably activating R' (antithetic strike slip) to form graben-boundary faults, were mapped in detail using 3D-seismic data (**Figure 7.15**). The western part of the map shows the Schneverdingen Graben with its dog-leg boundary faults. An

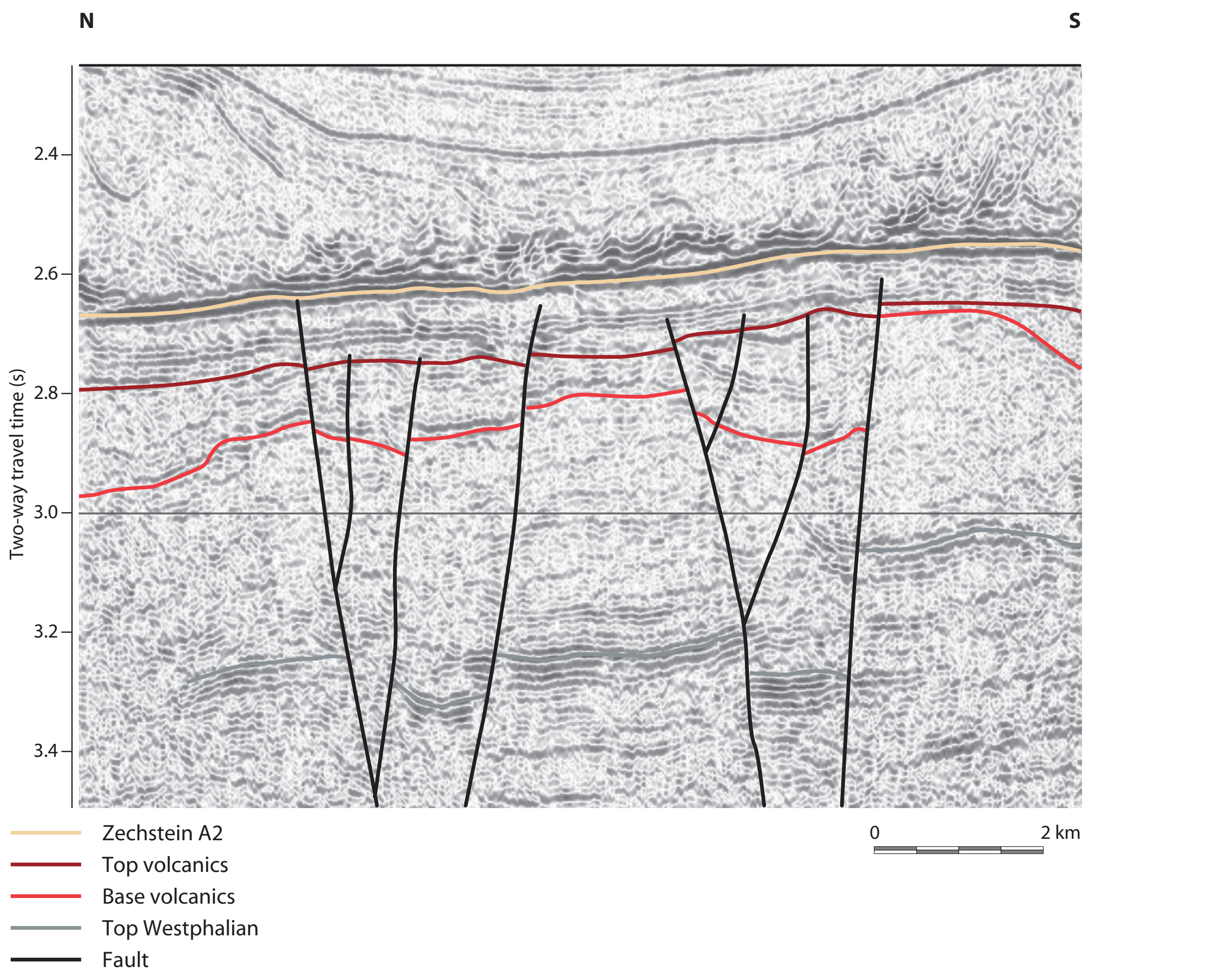


Figure 7.13 Seismic section across the strike-slip basins (negative flower structures). See Figure 7.15 for location.

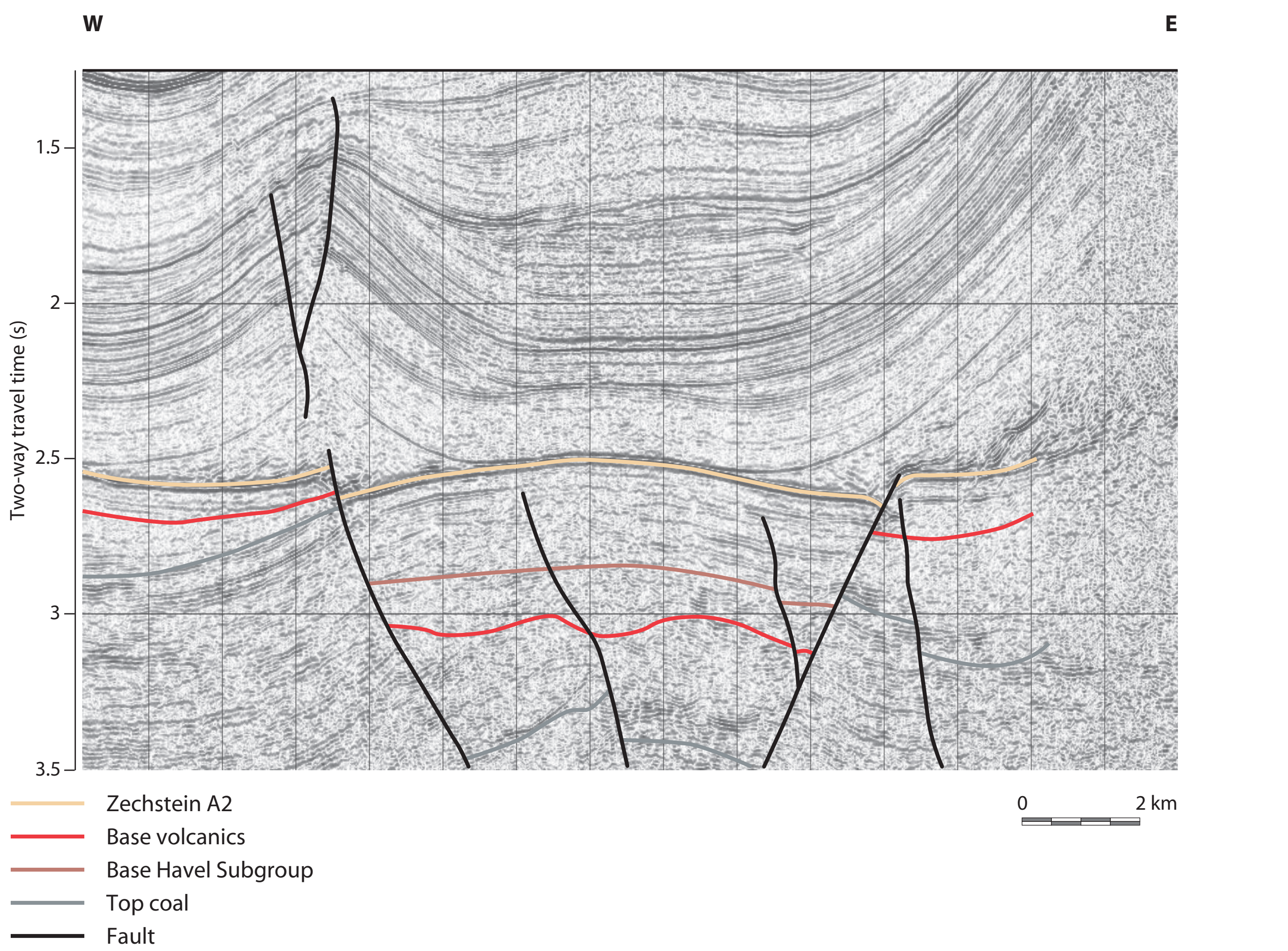


Figure 7.14 Seismic section showing late Rotliegend to Zechstein graben formation with normal faulting. See Figure 7.15 for location.

east–west-trending seismic profile (**Figure 7.14**) illustrates the ~250 m offset along the graben-boundary faults in the Schneverdingen Graben during Zechstein time. These major faults were rejuvenated during the Triassic, Jurassic and, as the salt movement above the western border fault shows, also during the Cretaceous.

In most of the SPB, the same stress regime that characterised the late Rotliegend was rejuvenated in very latest Rotliegend times and persisted until Zechstein 2 times (see Chapter 8). Geluk (1999a) observed that rifting set in during Zechstein 1 times ('Tubantian I') in the Netherlands area causing uplift, erosion and the formation of small pull-apart basins. The axes of these basins follow a north-west–south-east trend comparable to the orientation of Rotliegend basins in parts of northern Germany.

The base-Zechstein illumination map of the Söhlingen-Soltau area (**Figure 7.15**) shows that the late Rotliegend extensional deformation style was still predominant during the early Zechstein. The early Rotliegend strike-slip lineament (PDZ II) is still faintly apparent in the central part of the map. A north-west–south-east-oriented, *en-echelon* fault system is associated with this tectonic element, suggesting there was also minor continuous dextral movement (see annotation on **Figure 7.15**) during the early Zechstein.

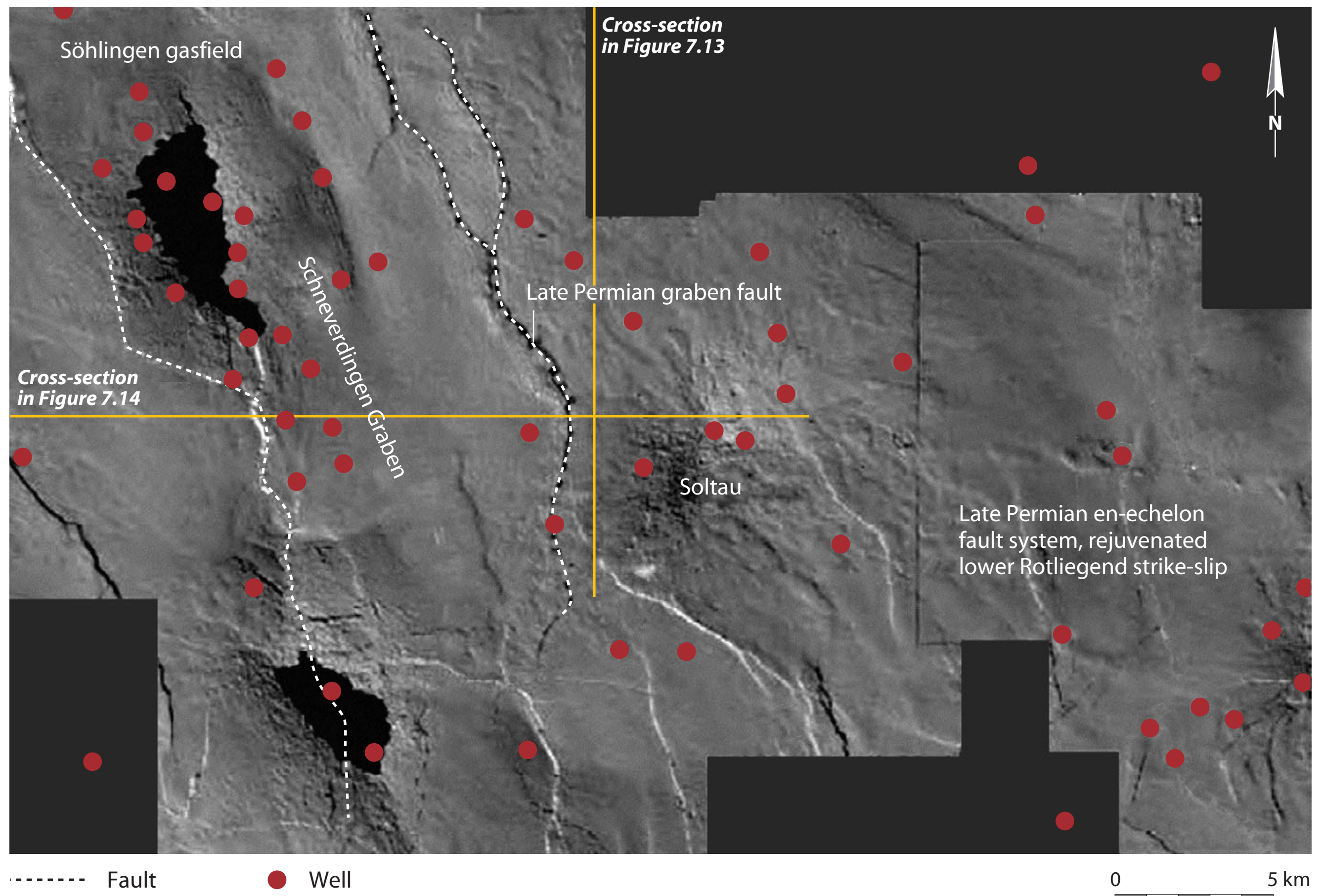


Figure 7.15 Late Rotliegend to Zechstein graben formation illustrated by seismic illumination of a base-Zechstein anhydrite reflector. See Figure 1.4 for location of the Söhlingen field.

3.1.3 Polish Basin

The Rotliegend Basin of north-west Poland is characterised by a complex structure that reflects syndepositional reactivation of fault systems related to the Teisseyre-Tornquist and Sorgenfrei-Tornquist zones. The basin is superimposed on the Caledonian Trans-European Suture Zone and encroaches eastwards onto the East European Craton and south-westwards onto the Variscan Externides (Kiersnowski & Buniak, 2006). Early Permian volcanism took place in the Variscan Fold Belt, (i.e. Wolsztyn High). The structural differentiation and tectonic reactivation of the pre-Permian basement had a strong influence on the distribution and thickness of the upper Rotliegend series, as is evident on **Figure 7.3**. In the Pomerania area, the Rotliegend series was deposited over horsts, tilted fault blocks, grabens and half-grabens that contain Carboniferous, Devonian and, locally to the east, Silurian sediments (Tomczyk, 1987). The structure of the upper Rotliegend substrate was the result of intense latest Carboniferous to Early Permian dextral strike-slip deformation along the Teisseyre-Tornquist and Sorgenfrei-Tornquist zones and associated uplift and erosion of the Variscan Foreland Basin and the external parts of the Variscan thrust-and-fold belt. The northern parts of the Polish Rotliegend Basin are fringed by, and superimposed upon, major crustal boundaries. The oldest of these crustal boundaries corresponds to the margin of the East European Craton, which coincides with the Teisseyre-Tornquist Zone in the Pomerania region.

The late Rotliegend depocentres of north-west Poland and north-east Germany are separated by a regional palaeohigh consisting of a volcanic depocentre (a large shield volcano; see Section 3.2) and the Wolsztyn High, which extends along the Polish-German border. South of the Variscan Deformation Front, the Polish Rotliegend Basin is fringed by palaeohighs that were formed by the strongly folded Lower Carboniferous sediments of the Variscan Externides, which are capped by Lower Permian volcanic rocks. To the north, the Rotliegend Basin is clearly delineated by a system of palaeohighs (here referred to as the Western Pomerania Upland; **Figure 7.9**) that consists of Carboniferous sediments and Lower Permian volcanic rocks. The tectonic origin of these palaeohighs has not been documented.

3.2 Basal Rotliegend volcanic rocks in the Netherlands, Denmark, Germany and Poland, including offshore areas

One of the special characteristics of the SPB area is the intense volcanic activity during its initial stages, i.e. during the Carboniferous-Permian transition (Breitkreuz et al., 2008). Later Rotliegend volcanic centres were active only locally in, for example, the present-day eastern Netherlands, the Soltau area between Hamburg and Hannover, and the Kotzen area north-east of Magdeburg (**Figure 7.16**). After this initial phase, volcanic activity was rare in the SPB during the Mesozoic to Cenozoic.

Numerous attempts at K-Ar dating of rocks from the North Sea area, the Netherlands, Lower Saxony and Poland led to ambiguous, rather young ages (Lippolt et al., 1982), presumably due to thermal overprinting during the Triassic to Jurassic (Gaupp et al., 1993; Wolfgramm et al., 1998). Heeremans et al. (2004) gave an Ar-Ar age of 299±3 Ma for basaltic lava from the North Sea Central Graben. Breitkreuz & Kennedy (1999) and Breitkreuz et al. (2007) provided reliable emplacement ages between 290 and 302 Ma with a focus between 295 and 299 Ma (**Figure 7.16**). These ages were obtained by SHRIMP dating of zircons separated from silica-rich volcanic rocks drilled in Denmark, Germany and Poland. The climax of volcanic activity in the SPB therefore took place at the time of the Carboniferous-Permian transition. Silica-rich pumice fragments found in sediments of the Süplingen Basin (Flechtingen-Rosslau Block; **Figure 7.16**) point to minor explosive volcanic activity already during the Stephanian (Egenhoff & Breitkreuz, 2001). Local alkali-basaltic and tholeiitic volcanic centres developed late in the Permian (Parchim to Dethlingen formations), for example, in the Kotzen and Soltau areas (**Figure 7.16**).

Apart from outcrops in the Flechtingen-Rosslau Block north of Magdeburg, knowledge of volcanism in the SPB is derived mainly from hundreds of wells, some as deep as 8000 m, although only a few penetrated the complete volcanic succession (Hoth et al., 1993a, 1993b). Data on thickness and volcanic evolution are therefore limited in many parts of the SPB area. In most areas, the thickness of the volcanic succession in wells does not exceed more than a few tens or few hundreds of metres at most. However, wells in the volcanic Mecklenburg-Vorpommern Sub-Province (MVSP) north of Berlin (**Figure 7.16**) have encountered thick volcanic piles. For example, the well Friedland 1/71 terminated after 2249 m of volcanic rocks had been drilled, without reaching their base. The spatial distribution of volcanic rocks in the SPB area is well established with the exception of the area north and north-west of Hamburg, where Upper Paleozoic rocks are deeply buried beyond the reach of hydrocarbon exploration wells (Benek et al., 1973; Korich, 1992; Jackowicz, 1994; Marx et al., 1995; Benek et al., 1996; Maliszewska et al., 2003). Isolated subcrops are known from the southern North Sea (Central and Horn grabens, grabens in J-Blocks; Marx et al., 1995; Börmann et al., 2006). Isolated occurrences of volcanic rocks are also found in the eastern Netherlands and Lower Saxony in Germany (Marx, 1995; Verdier, 1996). The centre of volcanic activity was certainly in the area of north-east Germany and western Poland (**Figure 7.16**). Here, intrabasinal structural highs such as the West Brandenburg High and the North-east Brandenburg-Wolsztyn High caused local thickness variations and the absence of volcanic rocks. By integrating lithostratigraphic information from the Flechtingen-Rosslau Block and hydrocarbon wells in north-east Germany, Benek et al. (1996) calculated a minimum volcanic volume of about 50 000 km³ for this area. The total volume of volcanics in the SPB is therefore about 80 000 km³.

The SPB volcanic zone comprises basaltic lava fields, Mg-andesite shield volcanoes, extended ignimbrite sheets and other pyroclastic deposits, and silica-rich lava flows and domes (both as small isolated bodies and as voluminous complexes). Subvolcanic andesitic complexes (Awdankiewicz et al., 2004) and silica-rich laccoliths have also been recognised (Paulick & Breitkreuz, 2005; Geißler et al., 2006a). Three sub-provinces can be identified in north-east Germany (**Figure 7.16**): a) an ignimbrite-dominated province in the Altmark region (FASP, north of Magdeburg), b) a shield volcano complex in the Berlin area (EBSP, see also Huebscher, 1989) and c) an area dominated by voluminous lava domes in eastern Mecklenburg-Vorpommern (MVSP, see also Paulick & Breitkreuz, 2005). In the latter two regions, weathering-resistant, topography-forming structures developed that resulted in a substantial volcano-topography throughout much of the Rotliegend (Geißler et al., 2006a). In parts of Germany and western Poland, this volcanic topography was not completely covered by sediments until Zechstein times (e.g. Katzung, 1995; **Figure 7.17**).

Volcanic rocks in the SPB area are mainly intermediate to silica-rich calc-alkaline types with subordinate, Mg-andesitic, tholeiitic and alkali-basaltic domains (Marx et al., 1995; Benek et al., 1996). Magma generation is believed to have occurred in an intracontinental extensional regime involving wrench tectonics, post-orogenic extension (Marx et al., 1995; Benek et al., 1996), the effects of late Variscan slab delamination in the south (Schott & Schmeling, 1998), and mantle plume-related magmatism mainly in northern Europe (Neumann et al., 2004).

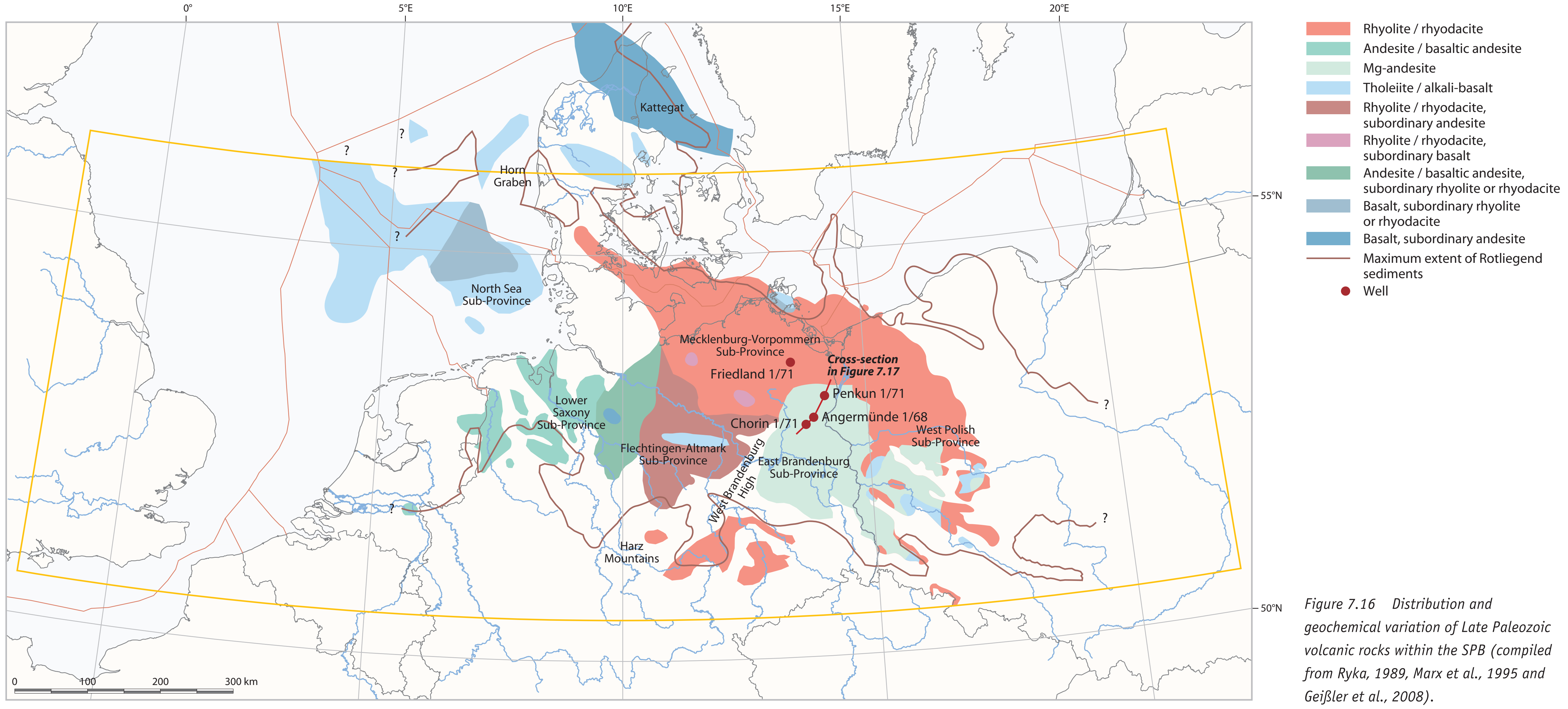


Figure 7.16 Distribution and geochemical variation of Late Paleozoic volcanic rocks within the SPB (compiled from Ryka, 1989, Marx et al., 1995 and Geißler et al., 2008).

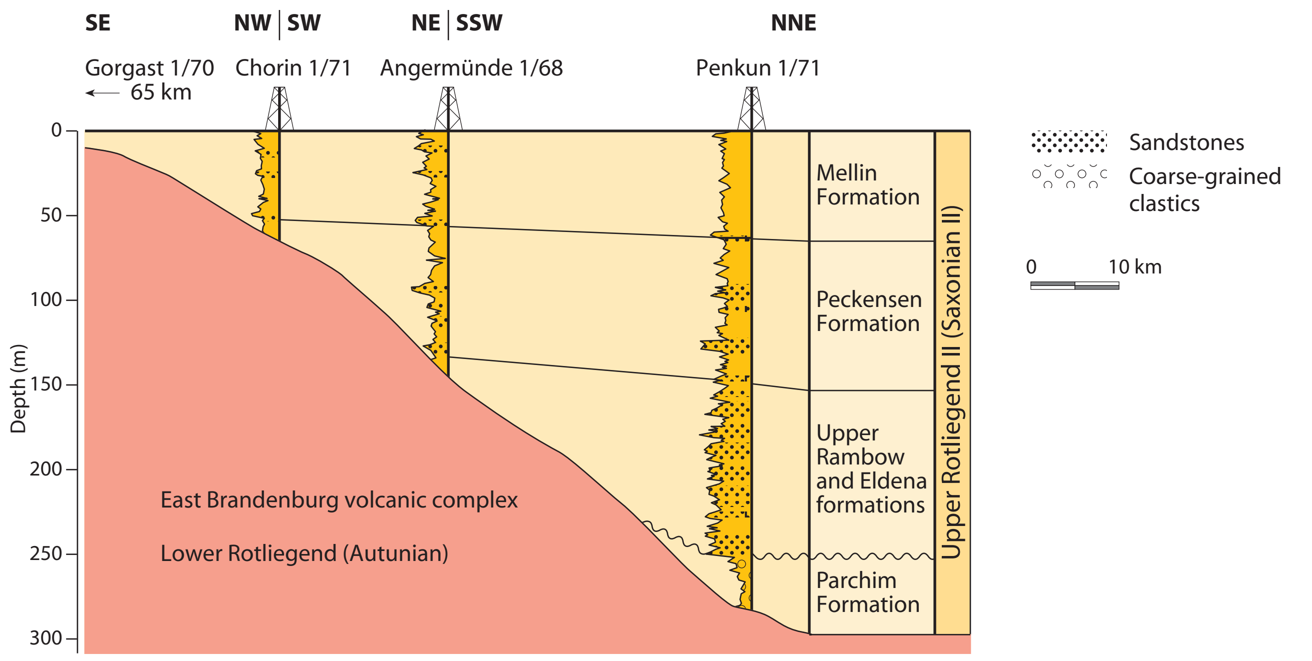


Figure 7.17 'Inundation' of shield volcano topography by playa sediments during late Rotliegend II times (after Katzung, 1995). See Figure 7.16 for location.

4 Depositional evolution of the Rotliegend Basin

4.1 Development of the sedimentary basin fill

The three stratigraphic subgroups of the Rotliegend described in Section 2.1 represent different stages of basin development. During the deposition of the Havel and Elbe subgroups (lower and upper Slochteren to base Zechstein), sedimentation extended from the eastern SPB westwards into shallower parts in the area of the Netherlands and England.

As the SPB was entirely land-locked, terminal playa- or saline-lake environments developed in its deepest parts, where rock-salt (halite) was deposited. The playas gradually built out across the entire North German Basin merging into one large saline playa lake during late Rotliegend times (Gralla, 1988; Gast, 1991; Plein, 1993). During dry periods, halite was deposited over huge areas of the basin centre as seen in northern Germany and the southern North Sea, whereas during more humid periods the lake expanded and clays and silts were deposited over the desert area to the south of the lake. Maximum flooding events took place during deposition of the middle Dethlingen Schmarbeck Member or P-Ingression (**Figure 7.8**) (Gast, 1991; Legler, 2006), early Hannover or Ameland highstands and finally upper Hannover or Ten Boer formations. The outline of the playa lake at the end of Rotliegend deposition was similar to the area of the Z2 Carbonate and Triassic early Buntsandstein basin (see Chapters 8 & 9), underlining the relative tectonic quiescence and prevalence of thermal subsidence during the Late Permian to earliest Triassic.

During late Westphalian B times, sediments deposited in the southern Netherlands area were already being sourced from the south (Besly, 1998). Glennie (1990b), Plein (1993) and Verdier (1996) postulated that the sediment source for the SPB lay to the south due to the erosion of the Variscan hinterland. However, wells close to the Ringkøbing-Fyn High (e.g. Flensburg Z1) penetrated upper Rotliegend sands and fanglomerates that were derived from the north and north-east, proving that a sediment source existed between the Southern and Northern Permian basins. The sediments were probably eroded from Devonian rocks on the Ringkøbing-Fyn High and transported via fluvial channels and trade winds into the SPB area. Rieke et al. (2001) also showed that sediment had been transported into the eastern part of the North German Basin from both northerly and easterly directions. In Poland, the fill of the northern part of the SPB is derived mainly from the Baltic Shield to the north.

Müritz Subgroup (upper Rotliegend I)
The oldest Rotliegend sediments (known as upper Rotliegend I) were deposited in a series of local fault-bounded basins in the North German Basin and Polish Trough (Plein, 1993; Hoffmann et al., 1997). The North German Basin was connected with intra-Variscan basins, such as the Saar-Nahe Basin and the Kraichgau Trough, along north-north-east-trending faults. In the Polish Trough, the Rotliegend deposits were more isolated. Movements along the Tornquist Zone also played an important role. The upper Rotliegend I sediments are volcanic fanglomerates, fluvial sandstones and playa deposits up to 600 m thick. Radiometric ages indicate that there was contemporaneous extrusive volcanic activity in the Central North Sea and Horn grabens.

Havel Subgroup (upper Rotliegend II, lower graben-fill sequence)
Following the Altmark tectonic pulse, Rotliegend deposition resumed in the North German Basin and the Polish Trough after a long hiatus during mid-Permian times (Bachmann & Hoffmann, 1997). The subgroup is more than 1100 m thick in the North German Basin and comprises a variety of mostly aeolian and fluvial-desert sediments (**Figure 7.6**). Deposition initially took place in fault-bounded depressions, where thick breccia was deposited (Parchim Formation). Interbedded basalts record intense tectonic movements (Hoffmann et al., 1997). In contrast to the earlier Müritz Subgroup, the North German Basin expanded westwards during Rotliegend II times. A north–south-trending graben system developed in the area of north-west Germany (Gast, 1988; Gast & Gundlach, 2006). Differential subsidence of the North German Basin ceased (Bachmann & Hoffmann, 1997) and, during deposition of the upper part of the subgroup (Mirow Formation), sedimentation extended from the grabens over larger areas. Playa lakes occupied the deepest parts of the North German Basin, bordered to the south by a system of alluvial plains and aeolian dunes. The Polish equivalent of the Havel Subgroup is the Drawa Subgroup (Kiersnowski, 1997; Kiersnowski & Buniak, 2006), which is up to 600 m thick in the basin and more than 750 m in some tectonic grabens (**Figure 7.6**).

Elbe Subgroup (Rotliegend II thermal subsidence stage; approximate time equivalent to the lower Slochteren up to the base of the Zechstein (Late Permian))
Thermal subsidence really set in during deposition of the Elbe Subgroup, when the sedimentation area extended south and westwards. The subgroup is up to ~1500 m thick in the saline lake at the centre of the North German Basin and 800 m in the Polish Basin, but only 300 m in the Anglo-Dutch Basin. The subgroup comprises basal sheetflood deposits, dry desert-dune sands and cyclic salt and shale deposits, reflecting a generally wetting-upward sedimentary sequence.

At the beginning of Elbe Subgroup deposition, the rate of basin subsidence exceeded that of sediment infill, causing the surface of the basin to intersect the regional water table (Glennie, 1997b). There were two minor extensional pulses (Plein, 1993), which caused limited differential subsidence in the eastern and northern Netherlands area (Geluk, 2005). Sedimentation also extended across the Tornquist Fault Zone onto the East European Platform. The North German Basin formed a closed playa system, with terminal playa lakes with thick halites in the deepest parts of the basin. In contrast, the Polish Trough is characterised by the absence of halite. Very thick aeolian sands (up to 700 m) were deposited north of the Wolsztyn High (Hoffmann et al., 1997), suggesting that the prevalence of dry conditions explains the absence of evaporites, rather than higher humidity as suggested by Karnkowski, (1999c). Large dune fields also occupied the western part of the SPB.

Only at the end of Elbe Subgroup deposition, during the early Late Permian, did the basin extend to the limits shown in many publications (e.g. Ziegler, 1990a; Glennie, 1997b, 1998b). The Southern and Northern Permian basins were connected via the Central and Horn grabens and the Bamble Trough. The Noteć Subgroup is the stratigraphic equivalent of the Elbe Subgroup (Kiersnowski, 1997; Kiersnowski & Buniak, 2006) and thicknesses reach more than 750 m.

The SPB was flooded very rapidly during the Zechstein transgression (see Chapter 8). Estimated water depths in the basin centre range up to several hundreds of metres (Glennie & Buller, 1983; Gast, 1994; Van Wees et al., 2000). The rapid flooding implies that the floor of the sediment-starved Rotliegend Basin was significantly below sea level, comparable to the present-day Dead Sea. The distribution of carbonate-facies sediments of the first Zechstein cycle outlines the pre-existing Rotliegend relief, which appears to have been very pronounced (see Chapter 8). Locally high gradients are shown by ooidal shoals on former volcanic and Carboniferous highs (which form the gas reservoirs of the Oldenburg area), the slope facies along the old escarpments, and nearby basin shales. The total relief of the Rotliegend Basin at the time of the Zechstein ingression is estimated to be 300 m (Bitzer, 1996) or 600 m below sea level (Van Wees et al., 2000).

4.2 Facies development of the upper Rotliegend II in the sub-basins of England, Belgium/Netherlands, Denmark, Germany and Poland

4.2.1 Facies development overview

Economically, the most important Rotliegend units of the SPB are the sandstones of the upper Rotliegend II Havel and Elbe subgroups (Lower and Upper Slochteren members). The older Havel Subgroup is dominated by aeolian and the less fluvial sandstone sequences of the Parchim and Mirow formations. The Dethlingen and Hannover formations of the overlying Elbe Subgroup are characterised by cyclic deposition of aeolian and fluvial sands during regressive stages of a huge basin-centre saline lake, and by salts, shales and marginal playa-sandflat sequences during highstands. There are also coarser-grained clastics, especially towards the southern basin edge, where increased water supply to the basin was via wadis flowing from the Variscan Mountains, the rising Pennine Range of England, and westward from the area of Russia. The paleogeographical location was similar to that of the present-day southern Sahara Desert (10 to 20°N). Aeolian sediments were best-developed in the south-west of the basin where their transport was influenced by north-easterly trade winds. The aeolian facies provides the most economic gas reservoirs in the basin (the Leman Sandstone of the UK, Slochteren Sandstone in the Netherlands and Wustrow Sandstone in Germany) (Glennie, 2007).

There were highlands to the south and east of the saline lake and no Wustrow / upper Slochteren sediments were deposited in these areas. The highlands were the source of alluvial-fan deposits shed into the valleys and across the saline-lake margin. The hill slopes were surrounded by dune fields or aeolian sandflats, which graded downslope into erg-margin facies and farther to the sandflats on the shoreline of the saline lake. Beyond these were saline-lake playa sandflats (upper playa), playa mudflats (lower playa), and finally lake areas with permanent salt deposition. The upper Rotliegend depositional sequences therefore include a variety of upper-playa sandflats, strandlines of the saline-lake shoreline belt (main reservoir), erg-margin sandflats with small dunes and erg-dune, sandstones farther inland (**Figures 7.18**, **7.19**, **7.20** & **7.21**).

Table 7.1 Facies types of the different sedimentary environments with potential reservoirs highlighted (reservoir quality data from Germany onshore).

Lithofacies	Sedimentary structures, characteristics	Environments (mapping units) with porosity (%) and permeability (D) values
Halite, sulphates, clays	Clays often laminated, salt is recrystallised	Saline lake (playa lake), salt flats
Clay and siltstones	Flaser bedding, halo-turbation, anhydrite nodules	Playa mudflat (lower playa)
Sandstone/siltstone with clay layers	Flaser bedding, anhydrite, desiccation cracks, halo-turbation	Playa sandflat (upper playa)
Fine- to medium-grained, well-sorted sandstones	Laminated to low-angle cross-bedding, dune-bedding, often reworked, grey	Playa margin (coastal sandbelt of playa lake) 10-20%, <~1 D
Fine- to medium-grained, poorly sorted sandstones	Small dunes and sheetsands with intercalated wet interdune	Erg margin (sandflats) 8-12%, <~50 mD
Fine- to coarse-grained sandstones, well- to moderately sorted	Stacked dunes or sheetsands, rarely interdune	Erg (dunes) 10-18%, <~500 mD
		Fluvial plain/fluvial dominance:
Fine-grained, moderately sorted sandstone/siltstone	Fining-upward sequences, current-ripples	– Low-gradient terminal fans or clastic aprons
Fine-grained, moderately sorted sandstone/siltstone	Fining-upward sequences, current-ripples, clay chips (rip-up clasts)	– Mid-fan to distal-alluvial fan 8-15%, <~10 mD
Fine- to coarse-grained, sandstone, clay-layers	Fining-upwards, erosive base, cross-bedding, current-ripple	– Alluvial plain (fluvial channel) (mid-fan) 8-18%, <~10 mD
Fanglomerates and conglomerates	Structureless (fanglomeratic), cross-bedding in sheetflood deposits	– Proximal alluvial fan

The upper and lower Slochteren facies shown in **Figures 7.20** & **7.21** have been generalised. The frequent changes in base level of the playa-lake environment caused different facies to interfinger at a 0.1 to 1 m scale. To reconstruct the palaeotopography that controlled the sedimentary facies distribution, the topographic contours of a time slice (at maximum regression level or sequence boundary) have been compiled and are used to represent the facies transitions.

Erg and proximal alluvial fans
The term 'erg' was introduced by Wilson (1971) and describes the accumulation of aeolian sand in the central parts of deserts. Aeolian dunes are only preserved in the geological record if sediment input is greater than, or in balance with, the subsidence of the area (e.g. Ahlbrandt & Fryberger, 1982).

Large areas of the basin hinterland were covered by alluvial fans shed from the remnants of the Variscan Mountains and early Rotliegend volcanic highs. The prevailing winds were predominantly easterly. Local variations were probably due to the palaeotopography and the occasional preservation of dunes deposited during summer months with southerly migration directions (Loope et al., 2004). Dry aeolian facies of an erg environment are thought to have developed about 8 m or more above groundwater (e.g. the Great Erg of southern Tunisia) (James, 1985). The fourth facies group comprises proximal alluvial fans and highlands above ~20 m elevation.

Erg-margin and mid-fan alluvial sediments
Erg-margin sediments are implied either by their proximity to the water table or base level, with capillary forces leading to gypsum and salt formation in the pore spaces of the mostly aeolian sandstones, or uphill by lack of sand due to deflation or fluvial erosion (Hunter, 1990; Fryberger, 1993; Langford & Chan 1993; Kocurek et al., 2001). Erg-margin facies, normally with poorly sorted sandstones, are found about 3 to 8 m above base level, a zone that is most strongly influenced by capillary evaporation and therefore early gypsum cementation. In many basin-margin areas, the middle parts of alluvial fans are associated with these facies types and there is a good chance of finding reservoir-quality sandstones provided the diagenesis is favourable, but mainly depending on the depth of burial (illite growth is unfavourable below ~3000 m). This facies type is shown on **Figure 7.18** (wadis and parts of wet sandflats); in **Figures 7.20** and **7.21**, it is the transition between dune and sabkha facies.

Playa-lake shoreline sandbelt
This term describes sand-prone areas along the shoreline of the playa lake in the area of the SPB. It may consist of large sandflats (wet and dry) sloping very gently towards the basin centre, especially in the western Anglo-Dutch parts of the basin (George & Berry, 1993). It can also include alluvial fans comparable to those seen in arid areas all over the world, which end in playas. In areas with steeper basin gradients, relatively narrow sandbelts of palaeo-strandlines developed on the flanks of the hilly to mountainous terrain. Good examples can be seen along the palaeo-shoreline of the Salton Sea (Lake Cahuilla) in California (Noris & Norris, 1961) (see **Figure 7.24**) and in the recent Lake Eyre of Australia (King, 1956).

The best Rotliegend reservoir qualities in Wustrow / upper Slochteren deposits of northern Germany are found in sediments that accumulated along the shoreline sandbelt. These are aeolian and water-lain sandstones with intercalated thin playa shales, indicating an environment with slightly fewer sands compared to the erg areas farther inland. The transition from the lake-margin sandbelt reservoir sandstones into the playa-sandflat realm is subtle and difficult to define. The quality of the lake-margin dune sands, which have better sorting than inland erg dunes (Ahlbrandt, 1979), categorises them as shoreline dunes that underwent aquatic sorting prior to their preservation; this has been confirmed by grain-size analysis (Gast et al., 1998). A palaeotopographic height of up to 3 m above base level or lake level was assumed. The sandstones deposited in this zone are also characterised by their special saline-lake influenced chlorite diagenesis, preserving porosities up to 20%.

Upper-playa and distal or terminal alluvial fans
The marginal playa-sandflat or upper-playa facies with wavy (adhesion ripples) and halo-turbated bedding can be mapped up to 2 m below base level. The facies was flooded only irregularly during winter highstands.

Lower playa
The lower playa consists of muddy sediments with wavy and/or halo-turbated bedding and common anhydrite nodules. The lower-playa mud-flats or lower playa extend to an estimated depth of about 6 m below lake-level highstand, depending very much on the local palaeomorphological situation and fluvial input. Below ~6 m, salt could have been preserved in the geological record due to the limited disturbance of saline-brine layering by wave action at this water depth, and also because of the rare complete desiccation of the deeper saline-lake areas at certain times of the basin's development.

Saline lake
a. *Ephemeral* — Large areas were subject to ephemeral salt-pan conditions, especially in the western Anglo-Dutch parts of the basin, but also in embayments in the east German area. The Polish part of the basin was dominated by regular freshwater input via rivers at the start of deposition of the Mirow Formation and then the Dethlingen Formation. It is also assumed that freshwater input from the western and northern slopes of the Brandenburg-Wolsztyn High had an influence on the eastward expansion of the salt lake.
b. *Perennial* — A prerequisite of a perennial saline lake is continuous freshwater input by rivers, which in the SPB was provided by the large river system in the area of the present-day Dutch-German border and numerous smaller rivers that flowed from the mountain range dividing the German and Polish areas. There was also regular freshwater input via rivers in the Polish part of the basin.

The fluvial input can be estimated directly from analysis of cores and indirectly by the larger distance of salt-layers from the shoreline in such areas, due to the dilution of saline brines (compare **Figures 7.18**, **7.19**, **7.20** & **7.21**). Glennie (1998b) described lacustrine-facies sediments deposited in the basin centre lacking mud-desiccation cracks. The generation of the Rotliegend lake systems is discussed by Gast (1991) and Legler (2006).

No extensive halite deposits have been found in the Polish part of the SPB, although traces of former thin salt layers have been observed in the form of sediment deformation caused by halite-crystal growth.

4.2.2 Rotliegend reservoir facies in the Anglo-Dutch areas

In the Leman Sandstone Formation, the main facies associations are aeolian, fluvial, sabkha and lacustrine, which were deposited during alternating wet and dry phases. The aeolian associations are mainly dune deposits with dune-top, high-angle foresets (22-34°; 25-30° is commonly the maximum angle) and

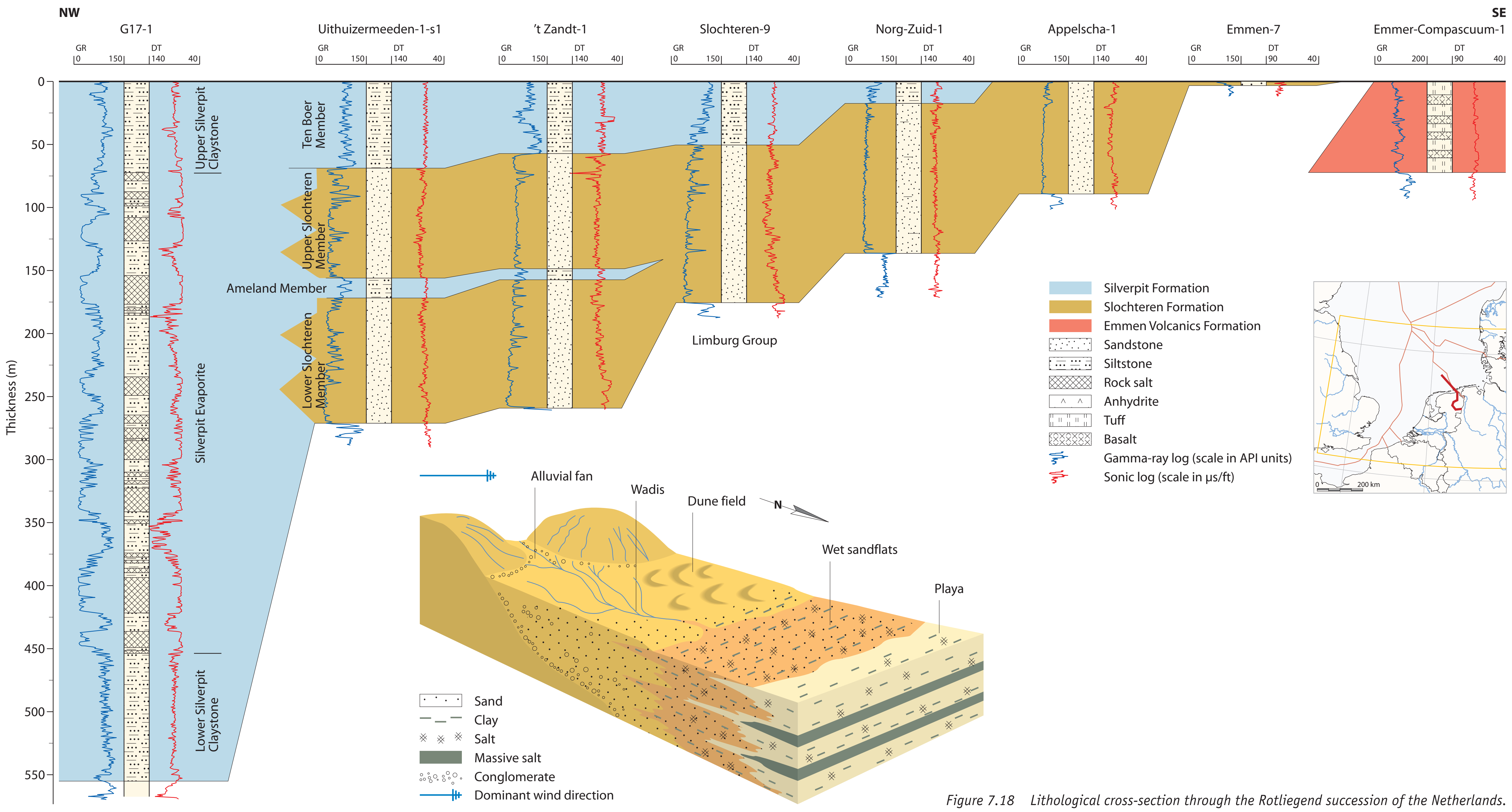
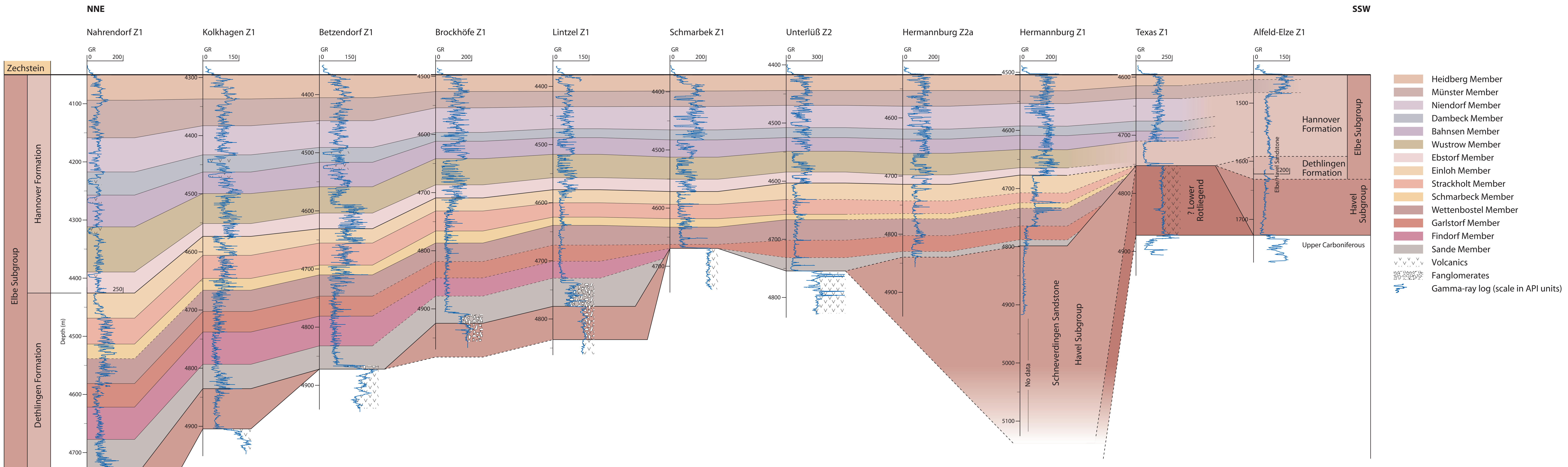


Figure 7.18 Lithological cross-section through the Rotliegend succession of the Netherlands.



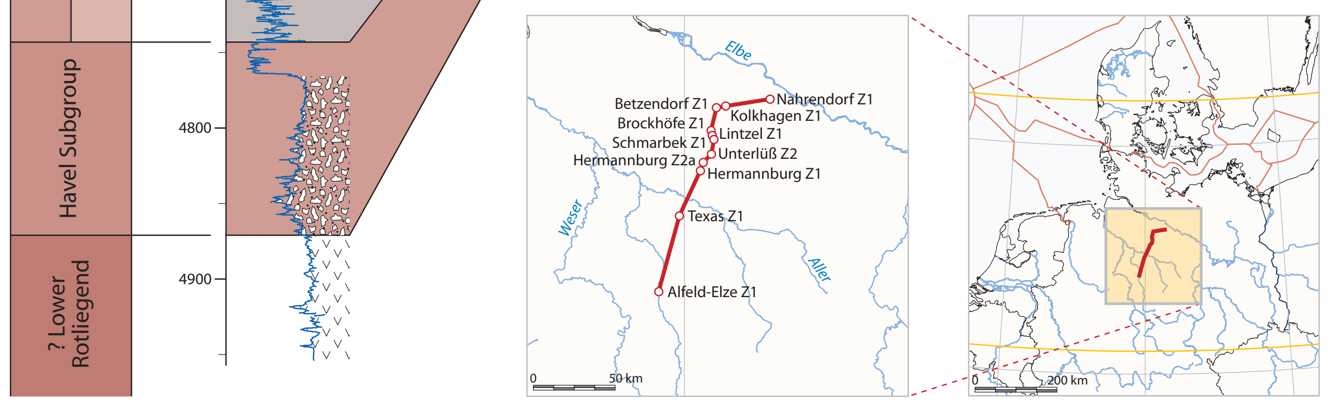


Figure 7.19 Stratigraphic cross-section through the Rotliegend succession of northern Germany.

commonly preserved toe-sets. The thickest development of aeolian-dune facies is interpreted as being erg deposits. In the Sole Pit area, individual preserved dune sets are up to 30 m thick in successions that total between 100 and 200 m in thickness (Arthur et al., 1986; Glennie, 1998b). Interdune and sandsheet successions are also preserved and include dry, damp and wet facies types. Offshore, the dunes are barchan or transverse types, whereas on land they are variably described as longitudinal, seif or complex-transverse in form (Glennie, 1970, 1983, 1998b; Steele, 1983; Yardley, 1984; Chrintz & Clemmensen, 1993). Dipmeter data and cross-bedding information from outcrop areas suggest that the prevailing wind direction was from the east or north-east, with sediment supplied from the Variscan Mountains to the south-east (Glennie, 1972, 1998b; Van Veen, 1975; Glennie et al., 1978), although this was disputed by Sneh (1988) who proposed that the Permian wind blew from the north.

The fluvial facies are cross-bedded, cross-laminated and massive fine- to coarse-grained sandstones with sporadic basal conglomeratic lags. They originated mainly as sheetflood and ephemeral-stream deposits in an arid or semi-arid environment. They tend to be more common in the lower parts of the succession. In the UK, they are more prevalent in the west where they were transported into the basin from the East Midlands and South Hewett shelves (George & Berry, 1993; Glennie, 1998b).

The playa-sandflat association has a variety of lithologies including very fine-grained sandstones, silty sandstones and claystones. These are characterised by irregular to wavy bedding forms from adhesion-ripple development, sandstone dykes, anhydrite nodules and desiccation cracks (Glennie, 1998b), which are interpreted to have formed on a low-relief playa sandflat bordering a desert lake (George & Berry, 1993). The main depositional processes operating on the playa sandflat were the adhesion of wind-blown detritus onto a damp sediment surface and periodic sheetflooding (George & Berry, 1993; Howell & Mountney, 1997). Complex interactions between fluvial, lake-flooding and aeolian reworking events were characteristic of this playa-sandflat setting (Glennie, 1998b).

The lacustrine-facies association is typically reddish brown to greenish grey, micaceous claystones and siltstones, commonly with desiccation cracks (George & Berry, 1993). Bioturbated mudstones, anhydrite and halites are also found in places (George & Berry, 1993; Glennie, 1998b; Maynard & Gibson, 2001) and rain-drop impressions are often seen (George & Berry, 1993). The Silverpit Formation is mainly lacustrine facies flanked by playa-sandflat and aeolian sandsheets (George & Berry, 1993). The lacustrine facies have no reservoir potential and can form permeability barriers (Glennie, 1998b; Lawton & Roberson, 2003). Glauconite and marine foraminifera (*Spirillina*) have been recorded in the Leman Sandstone Formation of the West Sole field, indicating a possible marine influence (compare Butler, 1975 and Legler, 2006).

The sedimentology of the Yellow Sands Formation of north-east England has been discussed by Steele (1983), Yardley (1984), Clemmensen (1989) and Chrintz & Clemmensen (1993). In the Durham area, the formation comprises a series of north-east-trending sand ridges up to 60 m high and 1.5 to 3.5 km wide (Glennie, 1983; Steele, 1983) separated by zones up to 1-2 km wide that are largely lacking in sand (Steele, 1983; Chrintz & Clemmensen, 1993). These ridges are sinuous-crested dunes that form the cross-beds exposed at outcrop, and show good examples of aeolian foreset stratification types, including grainfall, grainflow and wind-ripple (pinstripe) lamination. Cross-bedding measurements indicate a strong bimodality, with a vector mean to the south-west, parallel to the draa orientation (Chrintz & Clemmensen, 1993).

4.2.3 Rotliegend reservoir facies in the Polish area

The area and volume of aeolian sandstones is of great importance for hydrocarbon exploration in the Polish Upper Rotliegend Basin (PURB), especially within the uppermost Rotliegend units. Deep aeolian units may also be of reservoir significance where there are local seals such as playa-lake claystones and evaporites (not yet found in the PURB). In the northern part of the PURB, freshwater lacustrine claystones may also form seals. The maximum extent of some aeolian dune fields within the PURB is still unknown. Undiscovered gas potential is therefore largely dependent on the identification of aeolian sands.

The Rotliegend fluvial sandstones also have good reservoir potential. They are widespread along the basin margins and, during wet periods, were sporadically introduced into the basin centre as fluvial-channel systems supplying the playa lakes. Fluvial-deltaic facies also developed during playa-lake highstands. In the north-western PURB (Pomerania), within the axis of a north–south-oriented local drainage system, stacked fluvial channels formed sand bodies within which gasfields have been discovered. The sandy channel deposits of the basin source areas should also be considered as reservoir rocks.

The southern part of the PURB (Silesia) lies above the Carboniferous to Early Permian Variscan basement horst and graben complex, which gave rise to minor subsidence (compared to the northern part of the PURB) and the deposition of predominantly aeolian and fluvial deposits. The reservoir importance of the aeolian sandstones is locally improved by significant reworking of Weissliegend aeolian sandstone deposits during the Zechstein transgression. The rapidity of the Zechstein transgression probably prevented the reddening of these sandstones, whether still aeolian or newly marine.

During the evolution of the PURB, the north-west part of the basin had tectonic subsidence rates two to three times higher than the southern area. Moreover, the zone of maximum subsidence changed over time, although the maximum subsidence rates were linked to the tectonic margin of the East European Craton (the north-eastern flank of the PURB). Tectonic grabens with rapid subsidence are seen on the south-west flank of the PURB within the Variscan domain area.

A recent study of the northern (Pomerania) part of the PURB (Kiersnowski & Buniak, 2006) demonstrated the importance of erosional events during the evolution of the basin. For example, a significant erosional event affected even the central part of the basin with low-angle discordances on the basin margins (**Figures 7.6** & **7.25**).

The north-western area of the basin is better known than the area to the south-east. Here, there are nine successive depositional cycles characterised by their heterogeneity and lateral extent. These cycles partly correspond to the depositional sequences defined by Kiersnowski (1997) (**Table 7.1**) and include, alternating ephemeral streams and alluvial fans representing arid and more humid climatic conditions, sandy and muddy alluvial plains, muddy playa lakes with a marginal admixture of sulphates, and ephemeral freshwater lakes and aeolian deposits. The cycles also contain numerous conglomerate horizons that represent alluvial-fan/plain depositional systems. The recurrence of the conglomerates in individual profiles is interpreted as reflecting diastrophic events associated with palaeorelief rejuvenations and/or palaeoclimate changes. The conglomerates periodically advanced far southwards from source areas in the north and north-east to form conspicuous correlative marker horizons of stratigraphic significance. In contrast, the southern basin area (Czaplinek and Piła sub-basins) had relatively stable subsidence rates leading to the accumulation of fine-grained playa-lake deposits that reached considerable thicknesses.

These were temporarily, and sometimes cyclically, interrupted by fluvial sands and, during drier periods, by aeolian sheet and dune sands. The cycles form widespread sedimentary units, each of which relates to a genetically coherent depositional system bounded by isochronous surfaces. These surfaces record important

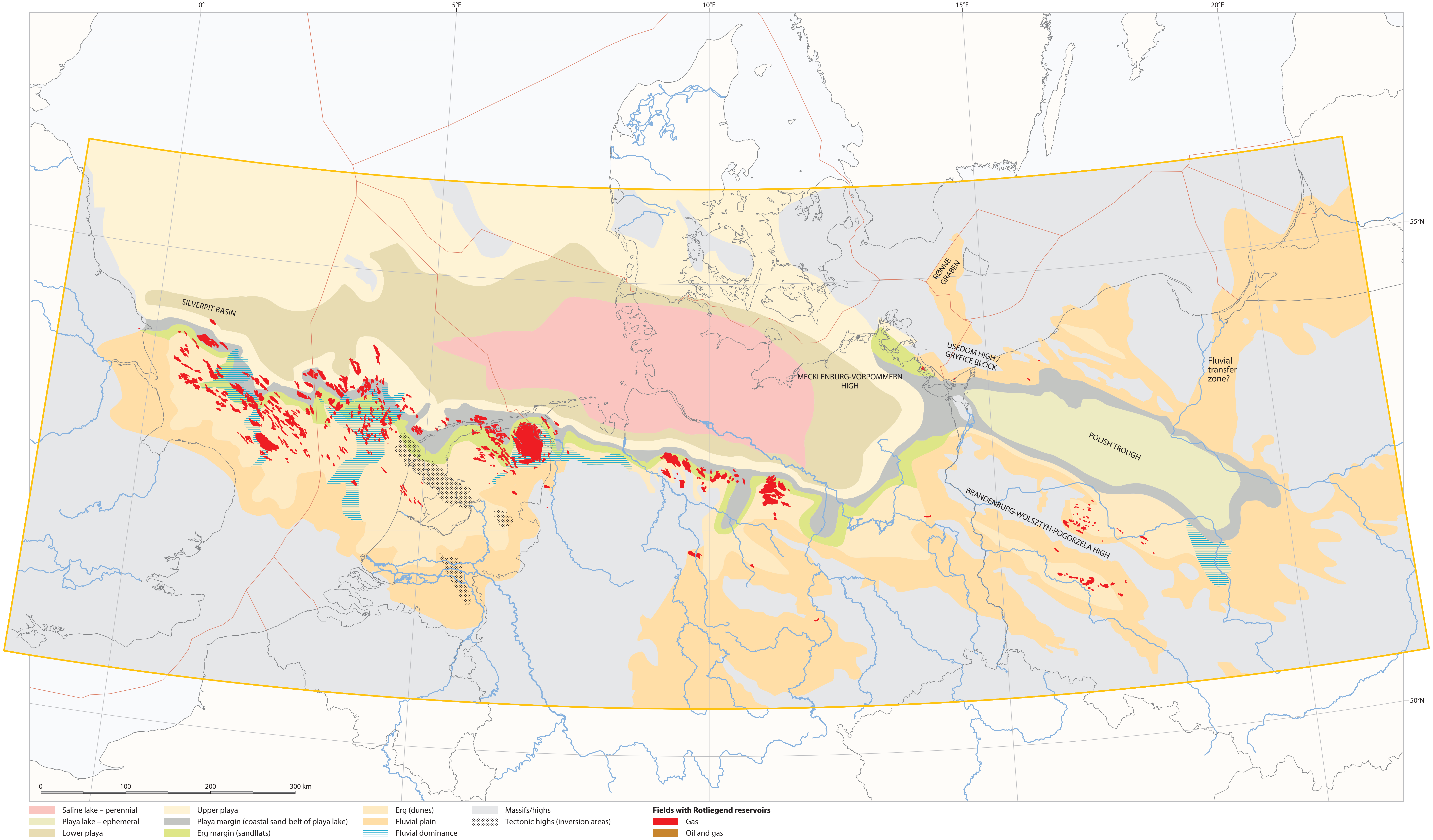


Figure 7.20 Reservoir facies distribution of the lower part of the Slochteren Formation and its equivalents. Fields with Rotliegend reservoir.

changes in the sedimentary regime, which had a significant impact on the architecture of the evolving basin. The changes can be attributed to tectonic movements and/or conspicuous palaeoclimatic changes.

Alluvial depositional cycle (AL I) (as stratigraphic equivalent of the lower part of the Parchim Formation or pre-Parchim beds)
Conglomerates and sandstones of the AL I cycle accumulated during the initial stage of the PURB development (**Figure 7.9**). They form the lowermost sediments of the Drawa Formation (Pokorski, 1981b), also referred to as the Polwica Conglomerate Member (Karnkowski, 1994), and may be equivalent to conglomerates in the lowermost part of the Parchim Formation in Germany (**Table 7.1**; Schröder et al., 1995). The conglomerates are possibly attributed to the lower Rotliegend, as suggested by Kiersnowski (1997) and Maliszewska et al. (2003).

In the SPBA area, basal Rotliegend clastics were deposited in a system of north-west–south-east-oriented tectonically controlled troughs that follow the trend of the main tectonic zones in the region. The sediments that accumulated in these depressions reflect the earliest development of rapidly subsiding zones such as the Resko-Czaplinek, Ślepce and Świna grabens, the latter of which possibly extends north-westwards in the Strelasund Trough and south-eastwards in the Piła Sub-Basin (Hoffmann et al., 1997). At the same time, the vast system of the K5 and Rønne grabens may have developed to the south-west and south of Bornholm (Vejbæk et al., 1994) as may have the 'initial Phase 1' dry conglomerates been deposited in the Strelasund Trough (Reike et al., 2001). Lower Rotliegend volcanic rocks covered the areas surrounding these troughs, except the Czaplinek Tectonic Step on which Early Carboniferous rocks were exposed.

Lower fluvial and playa-lake depositional cycle (P-L I) (equivalent to the lower part of the Parchim Formation)
The clastic source area for the alluvial fans was to the north and probably south-west of the PURB. Overall, alluvial fans advanced south-eastwards into the area of maximum subsidence, with conglomerates gradually giving way to sandstones (Resko 1, Resko 3, Berkanowo 1) and ultimately to fine-grained playa-lake deposits (Czaplinek IG-1, Czaplinek IG-2, Golce 1, Piła IG-1; **Figure 7.6**). Aeolian sandstones occur as intercalations in playa-lake deposits (e.g. Piła IG-1 and probably Golce 1, and upper part of the Czaplinek IG-2 profiles; **Figure 7.6**). There is a sharp contact between these fine-grained sediments and the underlying coarse-grained, alluvial-plain deposits of the AL I cycle. The contact is evident in areas of highest subsidence rates (e.g. boreholes Czaplinek IG-1, Czaplinek IG-2, Golce 1 and Piła IG-1) and may point to a conspicuous palaeoclimatic change.

The conglomerates, sandstones and mudstones of the P-L I cycle are more widespread than the AL I cycle, particularly in the south-east of the PURB (**Figure 7.9**). Deposition of the P-L I sediments was accompanied by further tectonic activity in the Ślepce, Resko-Czaplinek and Świna grabens, and by increased subsidence rates in the Czaplinek and Piła sub-basins. Conglomerates were also deposited in the K5 Trough (Lindert et al., 1993) and the Strelasund system of tectonic troughs.

Aeolian depositional cycle (Ae) (equivalent to the upper part of the Parchim Formation)
Aeolian sandstones were identified in cores or inferred from log characteristics in several boreholes located far to the north of the main area of aeolian deposits, the Eastern Erg in the Poznań region (Kiersnowski, 1997). Their sedimentology suggests that these stratigraphically condensed sandstones represent dune and interdune deposits (sandsheets). The Ae cycle forms part of the Drawa Formation (Pokorski, 1981b) or the Siekierki Sandstone Formation (Karnkowski, 1994), which may equate to the aeolian sandstones of the Parchim Formation (**Figure 7.9**) (**Table 7.1**; Drong et al., 1982; Schröder et al., 1995).

The development of these extensive aeolian sandstones is interpreted as reflecting a unique and rapid palaeoclimatic shift to extremely arid conditions, allowing for long-range dune-migration. During the deposition of the Ae cycle, aeolian sands migrated northwards across the central playa lake of the PURB and covered a vast area along its margin, here referred to as the 'Northern Erg' The source areas for the aeolian sandstones lay to the south, for example the Eastern Erg (Kiersnowski, 1997, 1998) and Brandenburg-Wolsztyn High (**Figure 7.20**). Aeolian sands in the north-western tectonic grabens, such as the Świnoujście and Międzyzdroje grabens, were partly derived from the Mecklenburg-Vorpommern High and Usedom High / Gryfice Block areas respectively. Aeolian sands in the Rønne Graben (borehole K5, Lindert et al., 1993 and Pernille 1; Vejbæk et al., 1994) were derived mainly from the Mecklenburg-Vorpommern High. Aeolian sands interfinger with fluvial deposits in the Rønne Graben to the north (borehole Pernille 1; Vejbæk et al., 1994).

Lower fluvial and playa-lake depositional cycle (P-L II) (equivalent to the upper part the Parchim Formation)
The sediments of the Ae cycle are overlain by claystones, mudstones and sandstones deposited in lacustrine, playa-lake and fluvial environments (**Figure 7.9**). These deposits reflect a rapid return to more humid conditions at the onset of the P-L II cycle. During deposition of this cycle, a freshwater lake occupied the northern part of the PURB, where clays were the main deposit. There are more clays in the lower lacustrine deposits than in the upper sediments (Resko 1 and Resko 3 boreholes), presumably due to an early period of maximum flooding and bathymetric stability of the freshwater lake.

Alluvial and fluvial depositional cycle (AL II) (equivalent to the basal part of the Mirow Formation)
The deposits of the AL II cycle (**Figure 7.9**) are conglomeratic, alluvial and sandy fluvial fans that advanced from the north into the PURB, filling the Świna, Samlino-Resko, Słowieńsko and Ślepce grabens. The cycle is interpreted to be the result of tectonic rejuvenation of the palaeorelief and associated erosion in the source areas, as well as reactivation of fault systems bounding the individual grabens. Conglomeratic alluvial fans prograded into these grabens, giving way basinward to sand-dominated fluvial fans and possibly playa deposits. Sediments of the AL II cycle are assigned to the upper Drawa Formation (**Figure 7.9**) and probably equate to the basal parts of the Mirow Formation in the North German Basin (Schröder et al., 1995).

Lower fluvial and playa-lake depositional cycle (P-L III) (equivalent to the upper part of the Mirow Formation)
The sediments of the P-L III cycle were deposited in continuity with those of the preceding cycle and represent the topmost member of the Polish Drawa Formation, which equates to the upper part of the Mirow Formation of the North German Basin (**Figure 7.9**). P-L III cycle deposits were only preserved in areas of highest subsidence rates.

Alluvial and fluvial depositional cycle (AL III) (equivalent to the lower part of the Dethlingen Formation)
Deposits of the AL III cycle are widespread in the Polish Basin where they form the basal part of the Noteć Formation, the equivalent to the lower part of the Dethlingen Formation of the North German Basin (**Figure 7.9**) (**Table 7.1**; Schröder et al., 1995). Progradation of fluvial systems reached a peak during this cycle, spreading across almost the entire PURB. Following erosion of older deposits across actively rising fault blocks such as the Moracz High and the Czaplinek Tectonic Step, these were progressively onlapped and overstepped by the AL III conglomerates. The widespread extent of the AL III deposits points to the development of an ever-expanding alluvial plain with a relatively smooth palaeorelief, and to the coalescence of the Czaplinek and Piła sub-basins. The vast area covered by sediments of this cycle reflects long-term erosion of the source areas to the north (West Pomerania Upland), north-east and south-west. At the end of the cycle, the Polish and north German parts of the upper Rotliegend Basin were still partly separated by a vast palaeohigh (**Figure 7.9**).

Upper fluvial and playa-lake depositional cycle (P-L IV) (equivalent to the upper part of the Dethlingen Formation to lower parts of the Hannover Formation)
Deposits of the P-L IV cycle form the middle part of the Noteć Formation of the PURB and are essentially equivalent to the upper parts of the Dethlingen and basal parts of the Hannover formations of the North German Basin (**Figure 7.9**). Although clastic influx into the PURB, mainly from northern sources, gradually abated during this depositional cycle, basin margins and intrabasinal highs (e.g. Moracz High) were gradually overstepped as subsidence of the Czaplinek sub-basin increased (see **Figure 7.25).** At the same time, there was a decrease in activity along basin- and block-bounding faults. Thin alluvial conglomerates were deposited in the northern basin, passing southwards into fluvial sandstones and mudstones up to 30 m-thick in the Piaski region. By the end of the P-L IV cycle, the Trzebież-Stargard area had been largely overstepped, which led to a broad connection between the Polish and North German basins.

Upper playa-lake and fluvial depositional cycle (P-L V) (equivalent to the upper part of the Hannover Formation)
This cycle represents the end of upper Rotliegend deposition and is capped by the marine sediments of the basal Zechstein Kupferschiefer. The cycle corresponds to the top part of the Polish Noteć Formation and the North German Hannover Formation (**Figure 7.9** & **Table 7.1**).

The P-L V depositional cycle can be divided into at least two sub-cycles. The beginning of the depositional cycle is marked by the Wustrow fluvial event. P-L V sediments are found throughout the PURB and are mostly playa-lake and fluvial deposits, the latter occurring along the northern margin of the basin becoming more widespread north-eastwards. Regional subsidence of the PURB took place during this cycle in response to lithospheric cooling and contraction, with no evidence for further reactivation of its fault systems (**Figure 7.6**). At the same time, there was a decrease in clastic supply to the basin, mainly from northern and north-eastern sources, which accounted for the development and wide lateral extent of a playa lake that was connected to the North German Basin. Towards the end of Rotliegend sedimentation and prior to the transgression of the Zechstein Sea, playa deposits extended far to the north, almost to the depositional limit of Rotliegend sediments.

5 Reservoir development/evolution

5.1 Reservoir quality of the Southern Permian Basin

5.1.1 Reservoirs

The most important factors controlling reservoir quality are sedimentary environment and diagenetic history. In Germany, most of the recoverable reserves in Rotliegend strata are found in the Wustrow Member (upper Slochteren) of the Elbe Subgroup. According to a cluster analysis of the grain-size parameters of the Wustrow Sandstone (based on 1888 samples), the facies types used for mapping are clearly distinguishable (Gast et al., 1999). The Wustrow Member / upper Slochteren Sandstone is a 35 to 40 m-thick third-order cycle sandstone embedded in saline-lake shales. This third-order cycle sandstone can be subdivided into five climate-controlled sub-cycles, probably representing ±100 ka periods. In areas where playa sediments are the predominant facies, a Milankovich Cyclicity of ±20 ka is distinguishable.

Rotliegend fields in the UK sector are mainly north-west–south-east trending and the reservoir is typically the main part of the Leman Sandstone Formation. Reservoir quality can vary considerably across fields due to changes in depositional and/or diagenetic environment. There are two main reservoir facies in the Rotliegend; aeolian sandstones and fluvial (wadi) sandstones and conglomerates (Glennie & Provan, 1990). The aeolian sandstones form the best reservoirs regardless of the overall level of diagenesis in an area (Turner et al., 1993; Glennie, 1998b). The high-angle dune-foreset facies has typically higher porosities and permeabilities. For example, in the Leman field, porosities vary from 10 to 20% and permeabilities from 4 mD to 1 D (Van Veen, 1975). The different aeolian lamination types (grainfall, grainflow and wind-ripple lamination) have notable differences in porosity and permeability values (Glennie, 1998b). Dune toe-sets can have a higher proportion of carbonate cement and clay, which reduces their quality (Van Veen, 1975). Grain size and sorting also control the reservoir properties, with better sorted and coarser-grained sandstones normally having the better porosity and/or permeability characteristics (Leveille et al., 1997a; McCrone, 2003; Gaupp et al., 2005).

The fluvial-facies types are commonly concentrated along the basin margins, and in most fields the fluvial facies tend to be more tightly cemented and form poor reservoir zones (Glennie, 1998b; Hillier, 2003a). However, in the Rough field on the western edge of the basin, the reservoir comprises both proximal fluvial sandstones and conglomerates (alluvial-fan facies) and interbedded aeolian-dune facies (**Figure 7.22**) with porosities ranging from 5 to 17% (maximum 23%) and permeabilities from 0.07 to 78 (maximum 200) mD (James, 1985; Goodchild & Bryant, 1986; Ellis, 1993; Platt, 1994; Ziegler et al., 1997). Increased quantities of fine-grained sediments such as interstitial muds or muddy interbeds tend to lower the reservoir quality.

Diagenesis provides an important control on reservoir quality and typically reduces characteristics such as porosity and permeability; it can vary significantly across fields (Glennie et al., 1978; Gaupp et al., 1993, 2005; Turner et al., 1993; Leveille et al., 1997a). This is particularly the case where there are clay minerals, especially fibrous illite. Abundant illite can reduce reservoir permeability by two orders of magnitude (Deutrich, 1993; Leveille et al., 1997a; Zwingmann et al., 1998); the degree of compaction also seems to be important. Work in the Jupiter field has shown that structurally high blocks underwent less compaction and therefore had better reservoir properties (Leveille et al., 1997a).

The other factor that controls reservoir quality is the degree and type of faulting and fracturing and associated depth of burial. The presence of synsedimentary extensional faults is important as they resulted in thicker Rotliegend successions in footwall blocks. These were subsequently deeply buried and therefore more altered by diagenesis (Leveille et al., 1997a; Cooke-Yarborough & Smith, 2003). This is particularly evident in the Sole Pit area (Glennie & Boegner, 1981; references in Ziegler et al., 1997). In the Barque, Clipper and West Sole fields, Late Cretaceous and Tertiary shear or extensional fractures cross-cut the reservoir and, where not mineralised, remain as open fractures that enhance well productivity (Winter & King, 1991; Glennie, 1998b; Sarginson, 2003a, 2003b). Production from these fields is still possible, even with permeability values that would normally preclude economic recovery of gas. In the Jupiter and Hewett fields, and the Rotliegend fields in the North German Basin, a number of normal faults act as lateral seals and therefore compartmentalise the reservoirs (Leveille et al., 1997b; Cooke-Yarborough & Smith, 2003; Gaupp et al., 2005).

5.1.2 Source rocks to the Rotliegend hydrocarbon reservoirs

It is widely accepted that coal-bearing Upper Carboniferous sediments, predominantly the Westphalian Coal Measures underlying the Rotliegend deposits, are the most important source rocks for natural gas in the SPB. This is evident from the paleogeographical distribution, thickness and lithology of the Carboniferous rocks as well as from isotopic studies (e.g. Faber et al., 1979). Nevertheless, pre- or post-Westphalian source rocks may also have contributed to local gas accumulations in Rotliegend reservoirs (Gerling et al., 1999c; Hoffmann et al., 2001). The Westphalian Coal Measures are up to 2500 m thick in the southern Central

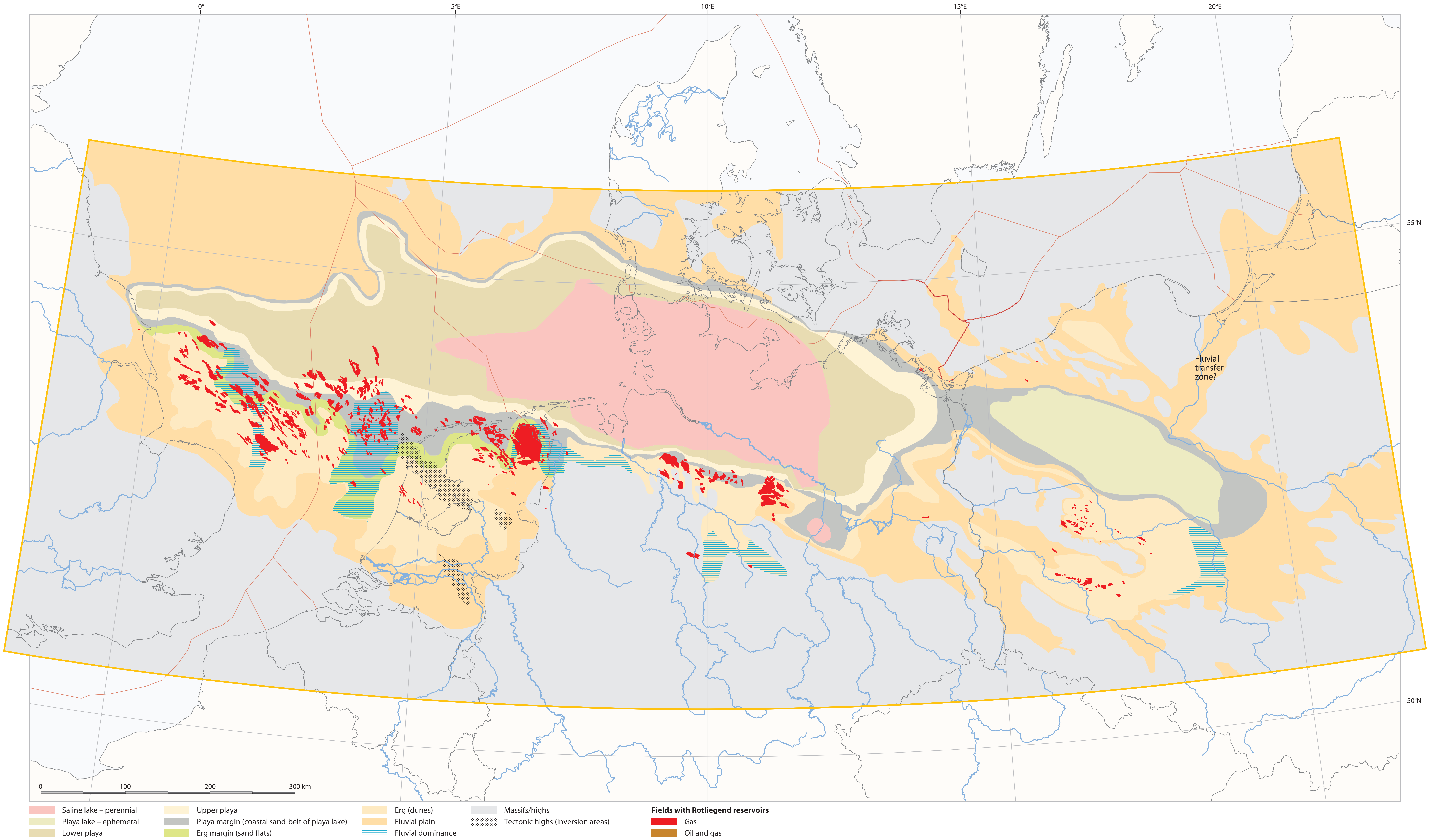


Figure 7.21 Reservoir facies distribution of the upper part of the Slochteren Formation and its equivalents. Fields with Rotliegend reservoir.

Figure 7.22 Rotliegend outcrops with dune and proximal-fan sediments (example from Devon, England).

European Basin (Hedemann et al., 1984; Katzung & Krull, 1984; Stancu-Kristoff & Stehn, 1984). Coal seams are common in the Westphalian A-C, but rapidly decrease in number and thickness towards the top (upper Westphalian C, Westphalian D). Dispersed organic matter is also found in shales and sandy sediments. The Westphalian A to C succession comprises 3 to 5% coal on average, with a maximum of more than 6% in the lower Westphalian of the Ruhr area in Germany.

In the Sole Pit Trough, Westphalian rocks were buried to depths of up to 4000 m, reaching maturity during the Jurassic and continuing to generate gas from coals and organic-rich shales during the Cretaceous (Lutz et al., 1975; Cornford, 1990, 1998; Sarginson, 2003b). In some areas, hydrocarbon generation was terminated by Late Cretaceous basin inversion, which allowed remigration of gas from former basin-margin areas (e.g. the Indefatigable High) into Rotliegend reservoirs that had already undergone reservoir damage (e.g. West Sole, north-west Leman Bank) (Cornford, 1990, 1998). The gas in the western parts of the SPB has low nitrogen content (typically <1.5%), indicating a short and direct migration path (Lutz et al., 1975). This is not the case in the Netherlands, where the older Jurassic charge has a relatively high N_2 content, whereas the Tertiary charge top-up has gas with low N_2 (mixing of high and low N_2 gas in many fields). Vitrinite-reflectance values of up to 2.8% are recorded in the Sole Pit area (Cornford, 1990). In the central SPB (North German Basin), Westphalian coals were buried to depths of more than 8000 m with maturation histories different from the shallower western parts of the basin (Neunzert et al., 1996). In eastern Germany, Namurian and Visean marine shales directly underlie the Rotliegend reservoirs and are responsible for high nitrogen contents in the gas (Plessen et al., 2006).

5.1.3 Rotliegend trap types

Most Rotliegend traps have broad north-west–south-east-trending fault-dip closures. The closures were formed by Alpine orogenic transpression during Late Cretaceous and Tertiary inversion (Glennie & Provan, 1990). In the Netherlands area, most traps formed during Late Jurassic rifting and survived later Alpine tectonic compression. The Leman Sandstone Formation and most fields in the Netherlands are commonly filled to spill point in these closures, which in Holland is related to Tertiary charge top-up. In some fields, there is evidence of gas leakage along faults due to fault reactivation and charging of the overlying Zechstein carbonate and Triassic sandstone reservoirs. Traps in German Rotliegend gasfields are usually combined fault and structural traps. Their fill depends mainly on source quality and length of migration pathways, but top-seal integrity as well as fault-seal quality is an issue in some fields.

Fault sealing plays a dominant role in graben fields such as Söhlingen (see Section 6.3.1). The sealing has a positive effect as it extends the closures. Formation of downthrown traps was observed, often with several tens of metres of additional gas column. There are other types of stratigraphic traps in the Polish part of the basin (see Section 6.4).

5.1.4 Regional seal

The regional top seal to the Rotliegend reservoirs is formed by Zechstein evaporites, especially halite, which re-anneals if fractured during faulting, and tight carbonates that directly overlie the Rotliegend strata. Intra-Rotliegend seals (shales) are known in only a few fields, for example gas in the Schneverdingen sandstone of the Havel Subgroup in the Söhlingen field (see Section 6.3.1).

5.1.5 Diagenesis

5.1.5.1 General description of Rotliegend sandstone diagenesis

The diagenetic evolution of sandstones is the result of complex fluid-rock interactions following deposition and during burial within a sedimentary basin. The major controls on diagenetic processes include (1) the mineralogical and granulometric composition of the rock, (2) the type of fluids interacting with the host rock, and (3) the timing of fluid migration and the concurrent temperature of the system. Rotliegend deposits, which are the most important clastic reservoirs of the Central European Basin, have been explored by the hydrocarbon industry for many decades (e.g. Bender & Hedemann, 1983; Glennie, 2001). The reservoirs were buried to depths of 3500 to 5200 m and may contain gas that in most cases was sourced from coal-bearing Carboniferous strata. Prior to methane filling, a complex suite of dissolution and precipitation reactions altered the primary composition and physical properties of red-bed sandstones. There have been many attempts to understand porosity and permeability evolution in these sandstone reservoirs, mostly based on petrographic studies, and important diagenetic processes and their controls have already been identified (e.g. Glennie et al., 1978; Drong, 1979; Almon, 1981; Seemann, 1982; Gaupp et al., 1993; Lanson et al., 1996; Leveille et al., 1997a). However, the reasons for contrasting diagenetic evolution in different basin compartments are still not well understood and prediction of diagenesis therefore remains very limited. Hydrocarbon fluids from organic-rich source rocks are a major control on red-bed sandstone diagenesis. Case studies clearly indicate that sandstone diagenesis may be influenced by organic-rich fluids if hydrocarbon source rocks are close by. Traces of bitumen, which provide evidence for the former presence of liquid hydrocarbons, are widespread in many Rotliegend sandstones even if there is no well-defined structural and hydraulic connection between source and reservoir rocks. The role of organic-maturation products in clastic diagenesis has been the subject of intense debate, often focussing on the generation of secondary porosity and metal-organic interactions. Nevertheless, only a few detailed studies have demonstrated that red-bed diagenesis may actually evolve very differently in different basin compartments depending on the availability of organic-rich rocks and the timing of organic maturation and migration (e.g. Burley, 1986; Gaupp et al., 2005; Schöner & Gaupp, 2005).

5.1.5.2 Diagenesis in UK fields

Sandstones of the Leman Sandstone Formation are typically fine- to medium-grained and moderately to well-sorted. They are generally quartz arenites and sublithic to subarkosic arenites. Monocrystalline quartz forms the predominant framework mineral, with common polycrystalline quartz and minor rock fragments and alkali feldspars (Turner et al., 1993; Leveille et al. 1997a). The diagenetic stages can be grouped as early, intermediate and late events. The early shallow-burial stage includes the mechanical infiltration of grain-coating clays, the dissolution of ferromagnesian minerals and the precipitation of hematite (Glennie & Provan, 1990). Early framework-supporting quartz and dolomite cements have also been recorded and early anhydrite is found locally (Turner et al., 1993). Compaction also occurs during the early and intermediate stages.

As the depth of burial increases, clay-mineral transformations and feldspar dissolution take place and pressure solution becomes increasingly important (Glennie & Provan, 1990; Glennie, 1998b). Authigenic chlorite precipitation and the formation of blocky and fibrous illite also become important diagenetic phases (Glennie & Provan, 1990; Turner et al., 1993). Abundant illite is more common in reservoir sections that have undergone deeper burial, where the illite severely impairs permeability by clogging grain-pore throats (Figures 2 & 4 in Glennie et al., 1978). This is commonly observed in the Sole Pit area (e.g. Ravenspurn North and Jupiter fields); other areas that were not buried to great depths, such as the Indefatigable Shelf, have less illitisation and therefore the sandstones have better reservoir quality (Glennie & Boegner, 1981; Conway, 1986; Turner et al., 1993; Glennie, 1997b). Ages given by K-Ar dating of authigenic illite from the Leman Sandstone Formation in the Jupiter field typically lie within the range 177-122 Ma (Mid-Jurassic to Early Cretaceous), and those from Ravenspurn North give a mean illite age of 173 Ma (Turner et al., 1993; Leveille et al., 1997a). Thermal-history modelling using fission-track data indicates that this is broadly coincident with the maximum burial phase, interpreted to have occurred during the Late Jurassic to Early Cretaceous, with temperatures reaching around 120°C (Leveille et al., 1997a).

Later-stage diagenetic features postdate the authigenic illite and include common blocky cement phases, including quartz, gypsum/anhydrite and dolomite, although non-ferroan dolomite and microcrystalline dolomite can also occur at an intermediate stage (Glennie & Provan, 1990; Leveille et al., 1997a). These blocky cements tend to be volumetrically unimportant (Leveille et al., 1997a). The gypsum/anhydrite and dolomite cements appear to be more prevalent towards the top of the Rotliegend and suggest an origin linked to percolating Zechstein brines (Glennie & Provan, 1990). Siderite can also be present and locally quite abundant (Turner et al., 1993).

Onshore, the Yellow Sands Formation comprises fine- to medium-grained subarkosic sandstones. Well-rounded monocrystalline and polycrystalline quartz forms more than 85% of the detrital mineralogy, with minor amounts of feldspar, rock fragments and heavy minerals (Hodge, 1932; Smith, 1994). The sandstones are generally weakly cemented, although there are carbonate and gypsum cements in places (Krinsley & Smith, 1981; Smith, 1994). The carbonate concretions (nodules) weather out where the Yellow Sands Formation is exposed on quarry faces (**Figure 7.23**). The yellow colour is caused by a thin grain coating of limonite and the colour has led some authors to suggest that the sandstone was never red coloured (Hodge, 1932; Magraw, 1975). Interestingly, the Yellow Sands from offshore boreholes are red and it is likely that the onshore deposits were also originally red, but were subsequently weathered as a result of oxidation of ferrous oxides and pyrite.

Figure 7.23 Yellow Sands Quarry near Durham, England.

5.1.5.3 Diagenesis in German fields

The reservoirs in the German sector of the SPB (North German Basin) were buried to depths of 3500 to 5200 m. This implies more advanced diagenetic alterations compared to other parts of the SPB. The influence of primary depositional control on reservoir properties diminishes with increasing depth. Even so, in the deepest reservoirs the best porosities and permeabilities are found in dry aeolian sandstones. Despite many diagenesis studies, there are several alternative models of diagenesis related to reservoir evolution, and the reasons for contrasting diagenetic evolution in different compartments of the Rotliegend gasfields are still a matter of investigation. (Glennie et al., 1978; Drong, 1979; Almon, 1981; Seemann, 1982; Gaupp et al., 1993, 2005; Lanson et al., 1996; Leveille et al., 1997a; Zwingmann et al., 1998, 1999). Gas-bearing Rotliegend reservoirs have been found only at the southern North German Basin margin.

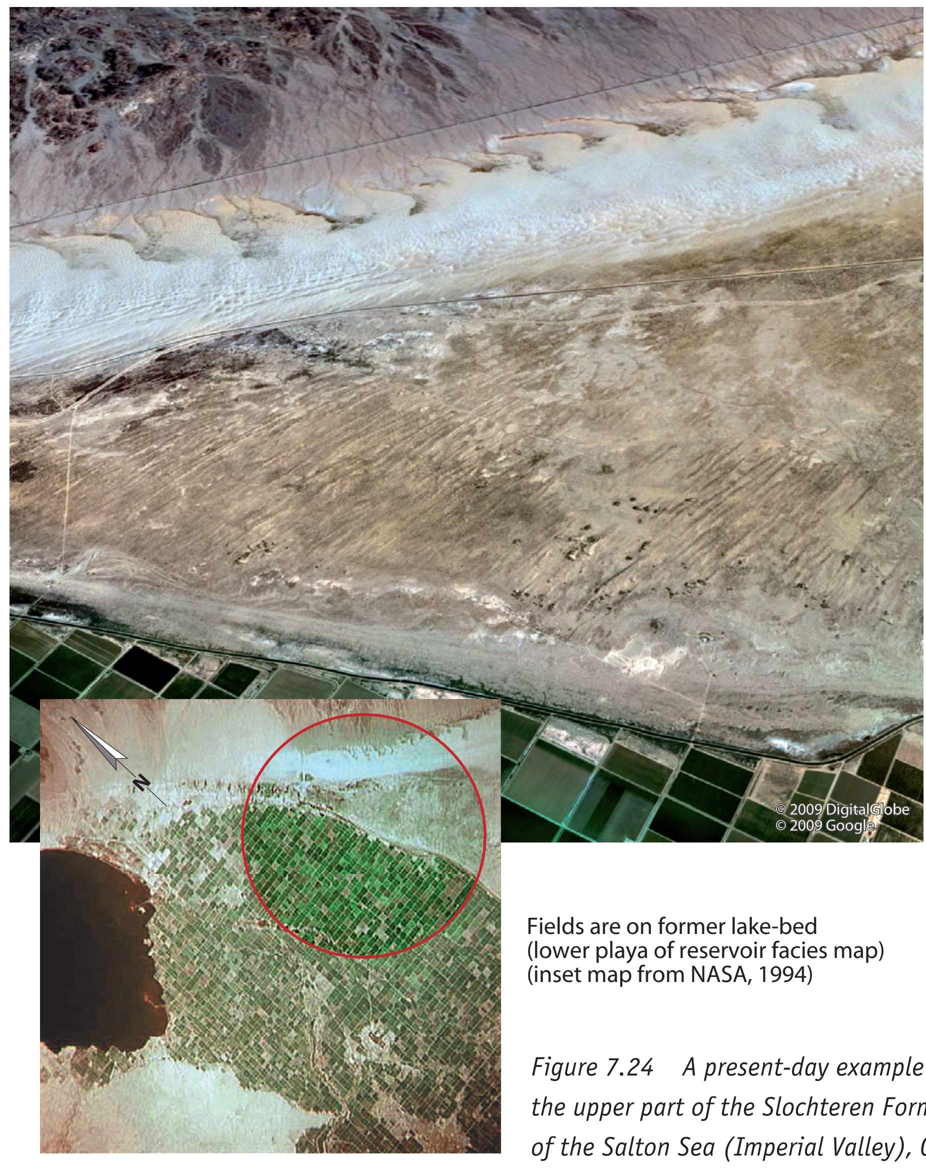


Figure 7.24 A present-day example of an erg system similar to that of the upper part of the Slochteren Formation. The image shows a precursor of the Salton Sea (Imperial Valley), California, USA. Courtesy of Google.

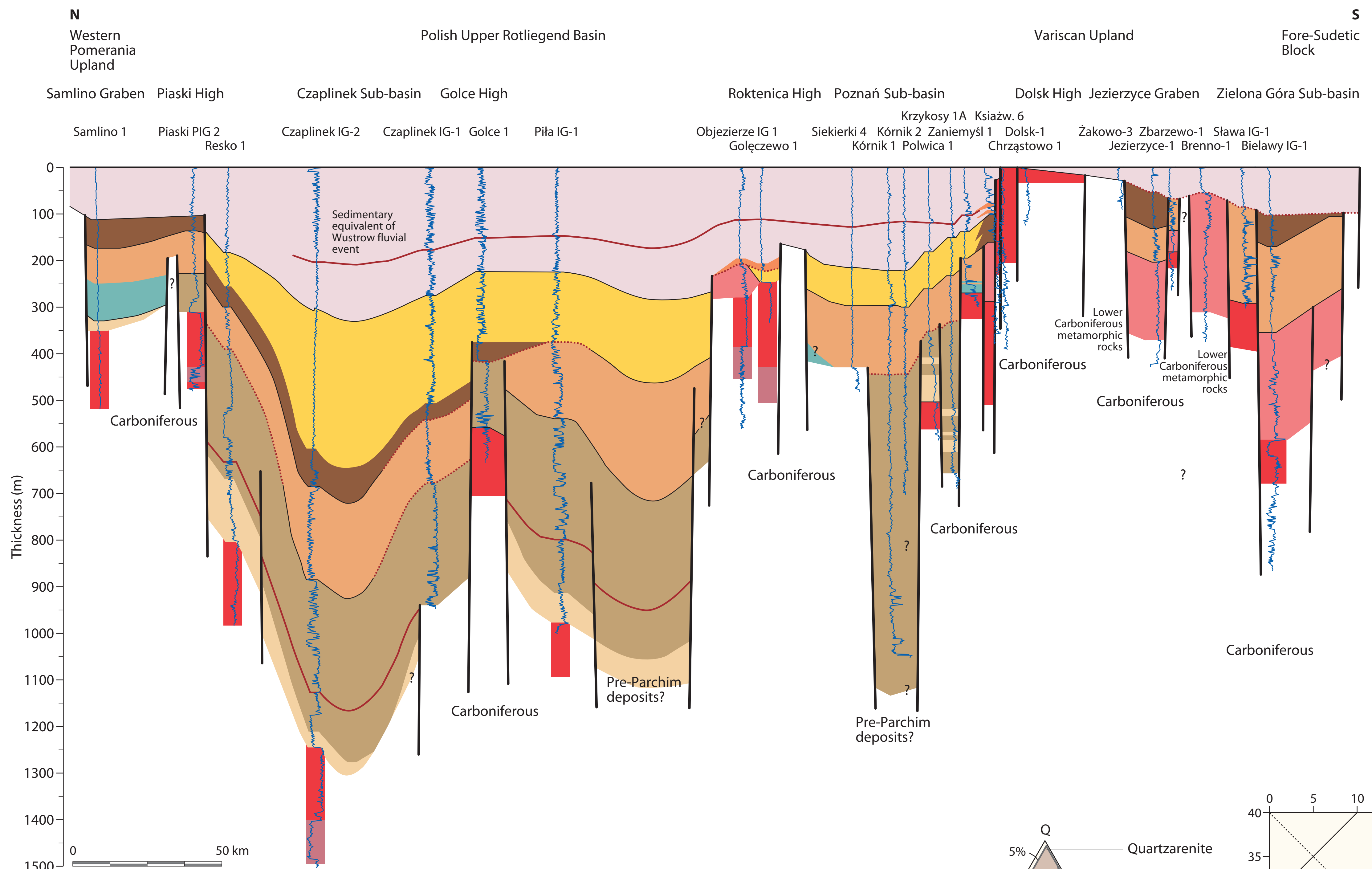
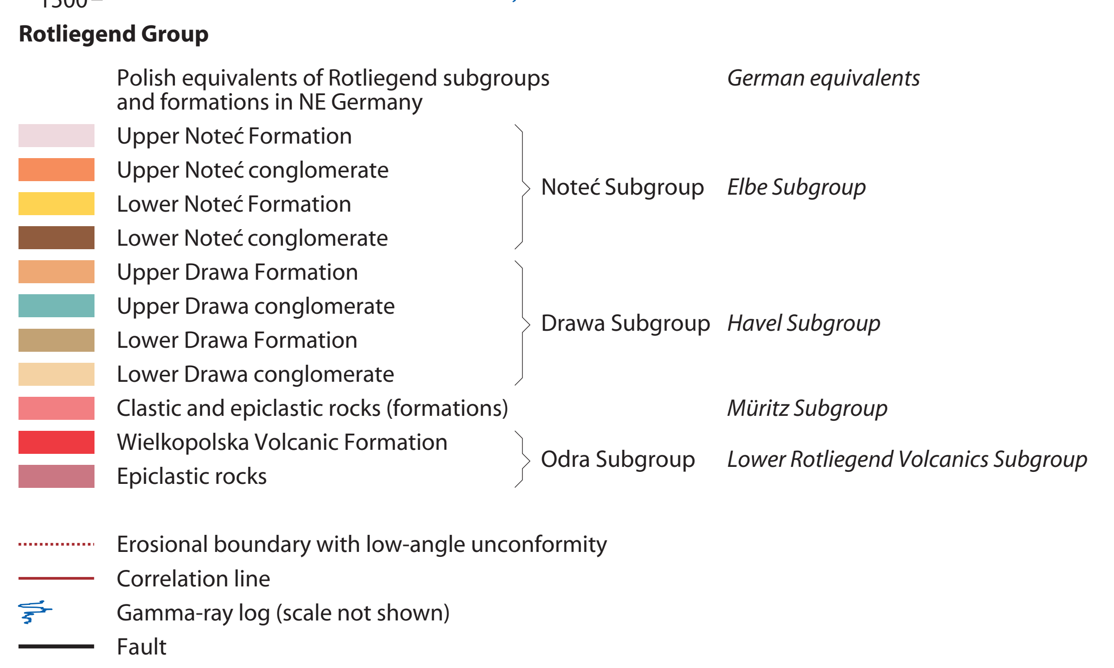
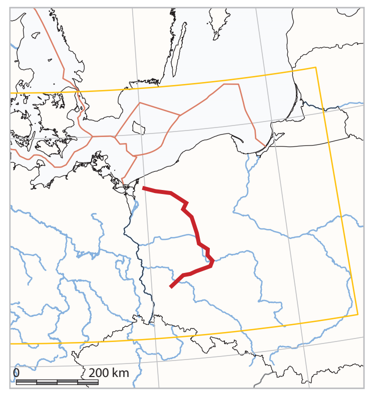



Figure 7.25 Cross-section through the Polish Rotliegend basins.



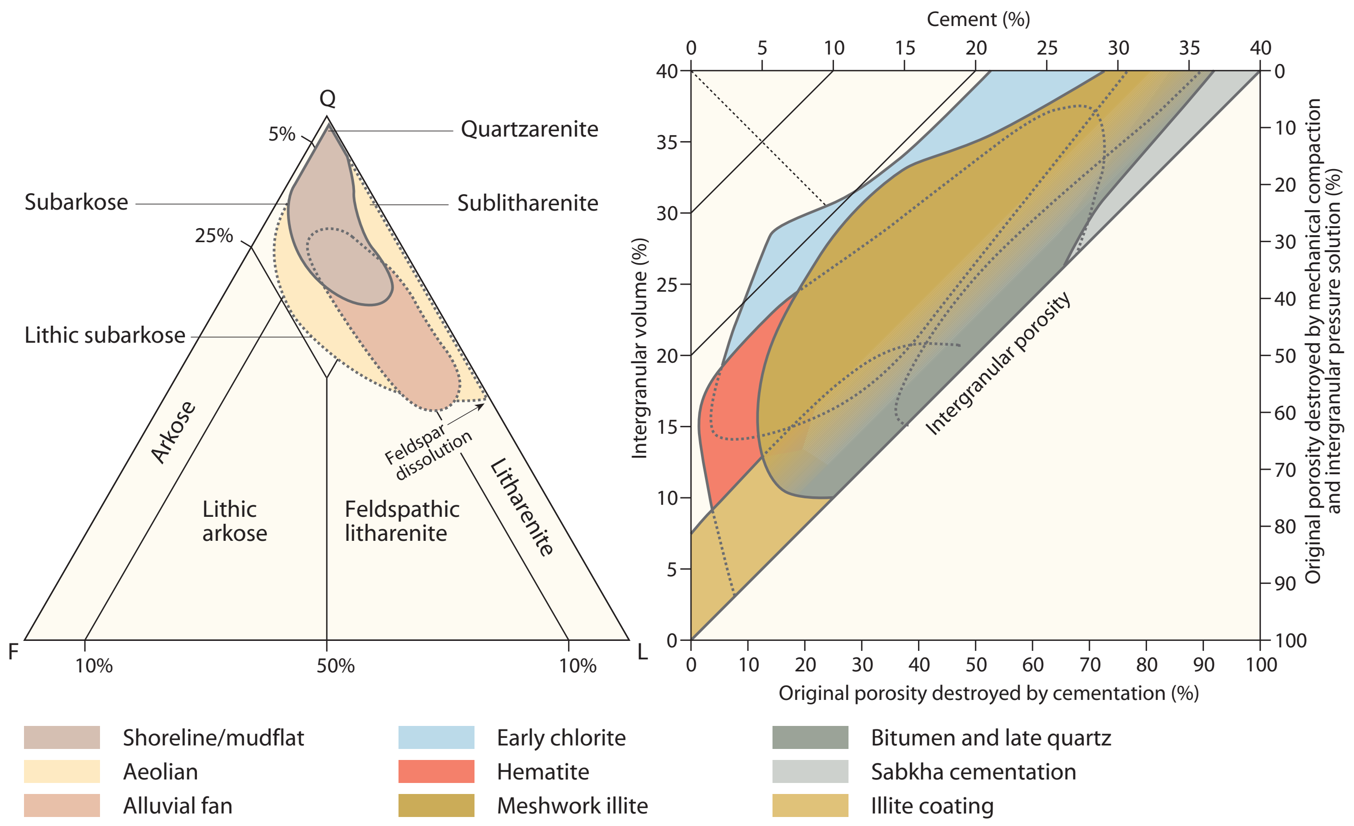


Figure 7.26 Sandstone petrography and diagenesis from the southern margin of the SPB.

The diagenetic processes and products resemble those of, for example, the UK offshore and the Netherlands both onshore and offshore. Only some aspects of diagenetic evolution are different, such as the absence of inversion-related meteoric (telodiagenetic) influence or the more pronounced transformations of the initial detrital composition, and advanced mechanical compaction due to extended residence times in deep burial regimes.

The most abundant authigenic minerals in Rotliegend sandstones at the southern basin margin are quartz, various carbonates, sulphates, clay minerals (illite, chlorite and rare kaolinite), and ferric oxide, similar to those in other parts of the play from the UK to southern Poland. The relative succession of diagenetic processes is shown in **Figure 7.26**. Samples cemented by meshwork-illite have moderate to low porosities and varying intergranular volume, but largely reduced permeabilities. Authigenic illite is widespread and not limited to any particular sedimentary facies, but is especially abundant near major fault zones (Gaupp et al., 1993, 2005) in close hydraulic contact with Carboniferous Coal Measures. Dense, coarse-grained plates of kaolin minerals, mainly dickite, occur close to the Carboniferous Coal Measures and are strongly related to feldspar leaching preceding or synchronous with the time of illitisation (Gaupp et al., 1993). Bleaching of red beds, illitisation, bitumen impregnation and late-stage porosity enhancement (intragranular pores) are a successive set of diagenetic features often found in Rotliegend gas reservoirs. The best permeabilities appear to be present in parts of the fields that were not accessible to illitising fluids during Late Triassic to Mid-Jurassic times.

6 Hydrocarbon field examples

6.1 UK Rotliegend fields

6.1.1 Leman field

The Leman gasfield is located in the UK part of the southern North Sea, about 50 km from the Norfolk coast. It occupies five licence blocks: 49/26, 49/27, 49/28, 53/1 and 53/2. Discovered in 1966 and starting production in 1968, Leman was the second gasfield to come into production in the UK sector of the North Sea. It is classified as a giant field with an estimated ultimate recovery of 328 bcm of gas in the aeolian dune sands of the Rotliegend Group. The field is being developed by two groups, with Shell and Amoco as the operators. Despite being an old field, development drilling was still being carried out during the 1990s with the development of the less permeable north-west area (Hillier & Williams, 1991).

The Leman field is located in the southern part of the Sole Pit Basin between two major fault zones, the Dowsing-South Hewett Fault Zone and the Swarte Bank Hinge (**Figure 7.27**). Gas is trapped in one dip-closed and periclinal reservoir (**Figure 7.28**). The maximum closure is approximately 335 m. Trap formation is probably related to the late Cimmerian and Late Cretaceous to Early Tertiary inversion phases of the Sole Pit Basin. Gas in the Leman field is derived from Westphalian coal seams (**Table 7.2**). As Namurian rocks subcrop the Rotliegend in the field area, migration from a source kitchen to the south is envisaged.

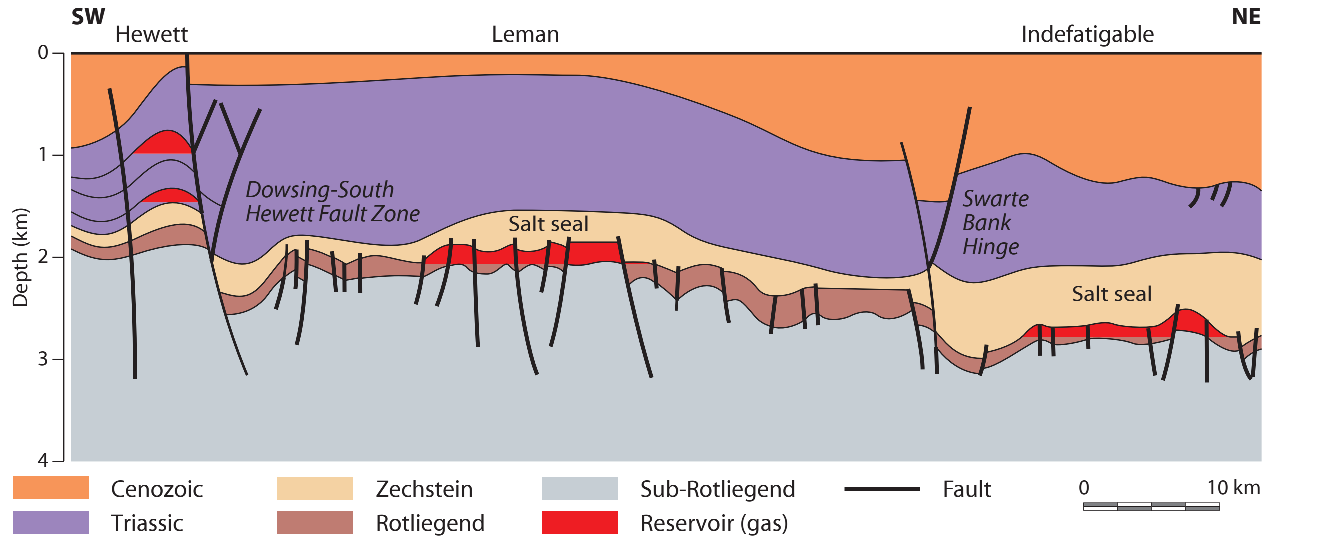


Figure 7.27 Schematic cross-section through the Hewett, Leman and Indefatigable fields.

The Rotliegend sediments in the Leman field area consist entirely of sand facies; there are no sediments of the clay-dominated Silverpit Formation. The sediments are up to 300 m thick and contain a record of the interaction between desert fluvial systems and adjacent aeolian and playa environments. A tripartite division can be made according to the depositional environment of the reservoir sands (**Figure 7.29** & **7.30**). Sands were deposited in a wadi environment at the onset of Rotliegend sedimentation, followed by a period of dominantly aeolian-dune formation. The uppermost unit reflects sedimentation in a waterlogged environment. The division into the units A and B (aeolian dunes) has been made on the basis of porosity/permeability. Unit C represents the wadi deposits.

Table 7.2 Properties of the Leman field.

Reservoir	Leman Sandstone Formation
Lithology	Sandstone and conglomerate
Depth to top (m)	1803
GWC/GOC.OWC (m)	2047
Maximum column height (m)	280
Net reservoir thickness (m)	245
Net to gross ratio	100
Porosity (%)	12.9% (A), 14.3% (B), 11% (C)
Gas saturation (%)	59
Permeability (mD)	0.5-15
Fluid type	Gas and condensate
Gas composition	C1 95%, C2 2.86%
Initial pressure (bar)	208.4
Temperature (°C)	52
Source rock	Westphalian Coal Measures
Seal	Zechstein Group

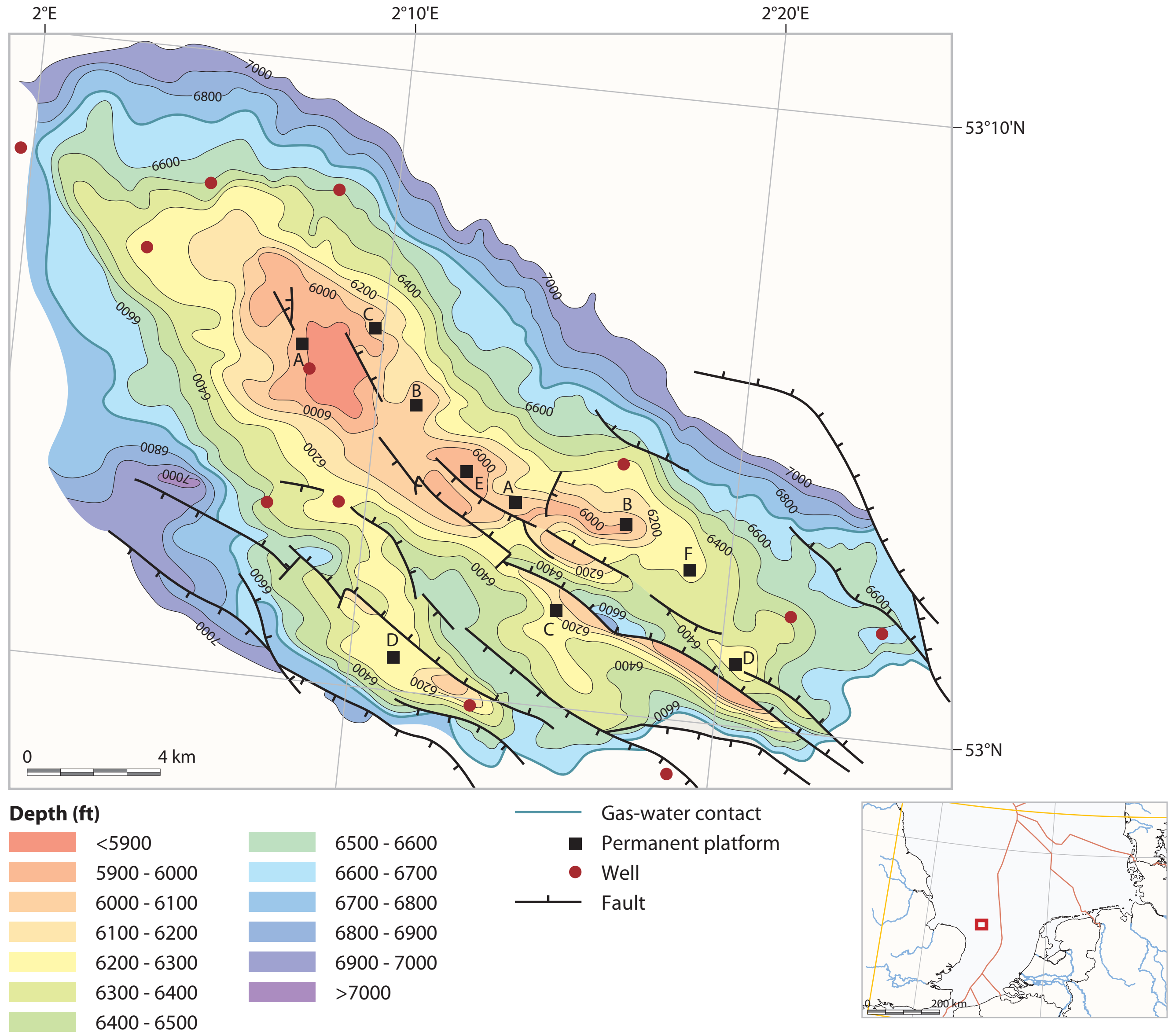


Figure 7.28 Depth-structure to the top of the Leman Sandstone Formation in the Leman field (based on mid-field development in 1974) (source: IHS; modified after Hillier & Williams, 1991).

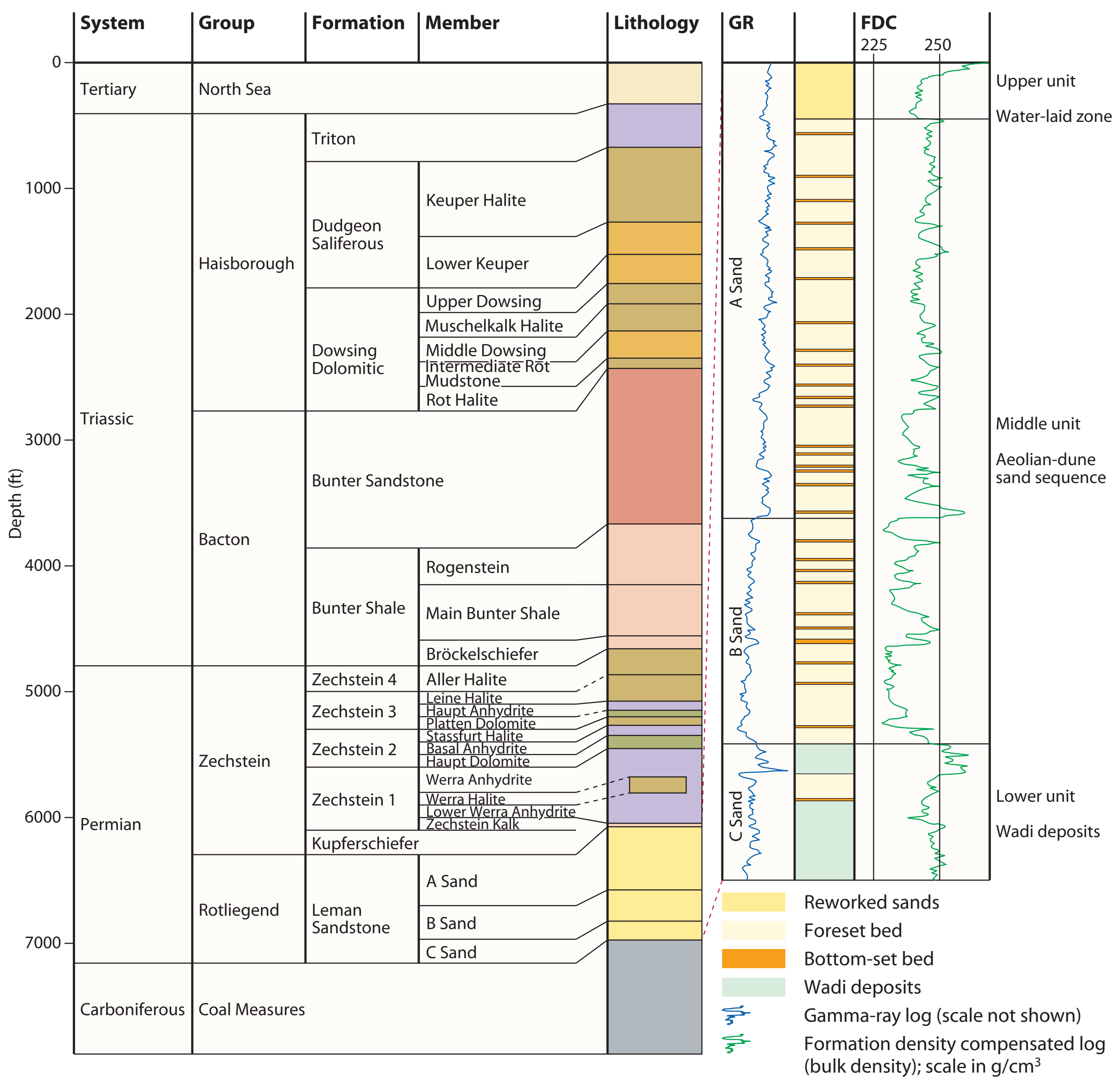


Figure 7.29 General stratigraphy of the Leman field and detailed lithostratigraphy of the Rotliegend sandstone reservoir sequences (source: IHS; modified after Hillier & Williams, 1991).

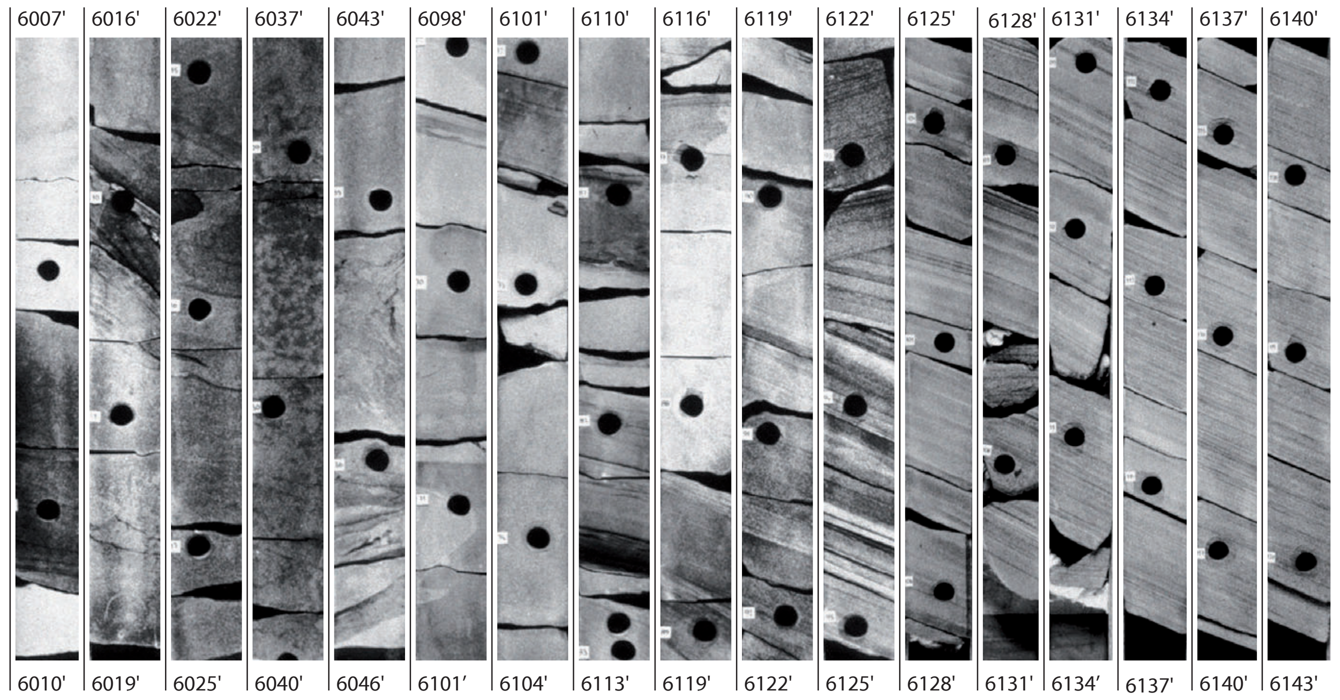


Figure 7.30 Core photographs of Leman reservoir sandstones. Note that the depths shown at the top and base of each section are given in feet (source: Glennie, 2008).

6.1.2 Johnston field

The Johnston gasfield is located in UKCS blocks 43/26a and 43/27a, approximately 75 km off the coast of Lincolnshire in the southern North Sea. It is a medium-sized Permian Rotliegend dry-gas accumulation, developed as a satellite to Ravenspurn North. The discovery well was drilled in 1990. Current mapped gas initially-in-place (GIIP) estimates for the field are between 10.2 and 11.4 bcm, with an estimated recovery factor of between 60 and 75% (Lawton & Roberson, 2003). Two development wells were drilled initially from a four-slot sub-sea template, with commercial production commencing in October 1994. Following the acquisition of a 3D-seismic survey, a high deliverability 869 m horizontal well was drilled in 1997. The well tested at a rate of up to 1.55 mln m^3 of gas per day.

The field has a structural trap, fault-bounded to the south-west and dip-closed to the north, east and south (**Figures 7.31** & **7.32**). The south-west bounding fault can have a throw of up to 300 m. The top seal and fault-bounding side seal are formed by the overlying claystone of the Silverpit Shale Formation and the evaporite-dominated Zechstein Supergroup (**Table 7.3**). Westphalian Coal Measures form the source rock.

The sandstone reservoir interval consists of the Middle Permian lower Leman Sandstone Formation of the upper Rotliegend II. The reservoir is a series of interbedded aeolian dune, fluvial, and clastic playa-sandflat lithofacies (**Figure 7.33**). The aeolian sediments can be subdivided into fine- to coarse-grained, high-angle sandstones and fine- to medium-grained, low-angle sandstones. Fluvial associations have both massive and structured sandstones, the latter characterised by basal-conglomerate lags. A mixture of very fine-grained sandstones, silty sandstones and claystones is found in the playa-sandflat sediments. The aeolian sandstones have the highest reservoir quality (**Figure 7.34**).

Table 7.3 Properties of the Johnston field.

Reservoir	Lower Leman Sandstone Formation
Lithology	Sandstone
Depth to top (m)	3125
GWC/GOC.OWC (m)	3244
Maximum column height (m)	120
Net reservoir thickness (m)	85
Net to gross ratio	100
Porosity (%)	11
Gas saturation (%)	75
Permeability (mD)	1-800
Fluid type	Gas and condensate
Gas composition	C1 95.5%, C2 2.4%, N 3.9%
Initial pressure (bar)	326
Temperature (°C)	108
Source rock	Westphalian Coal Measures
Seal	Silverpit shale and Zechstein evaporite

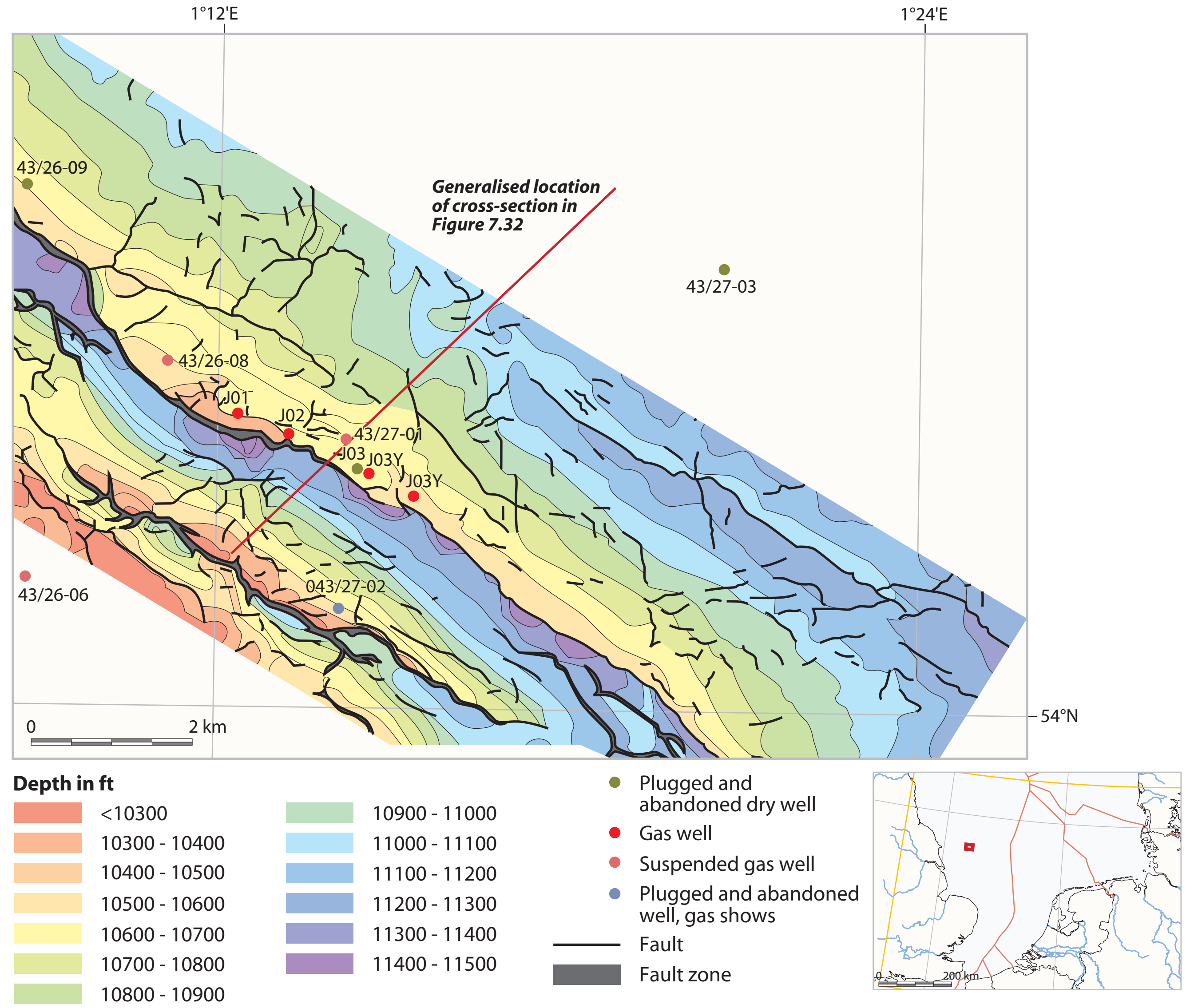


Figure 7.31 Depth-structure to the top of the Leman Sandstone Formation in the Johnston field (source: IHS; modified after Lawton & Roberson, 2003).

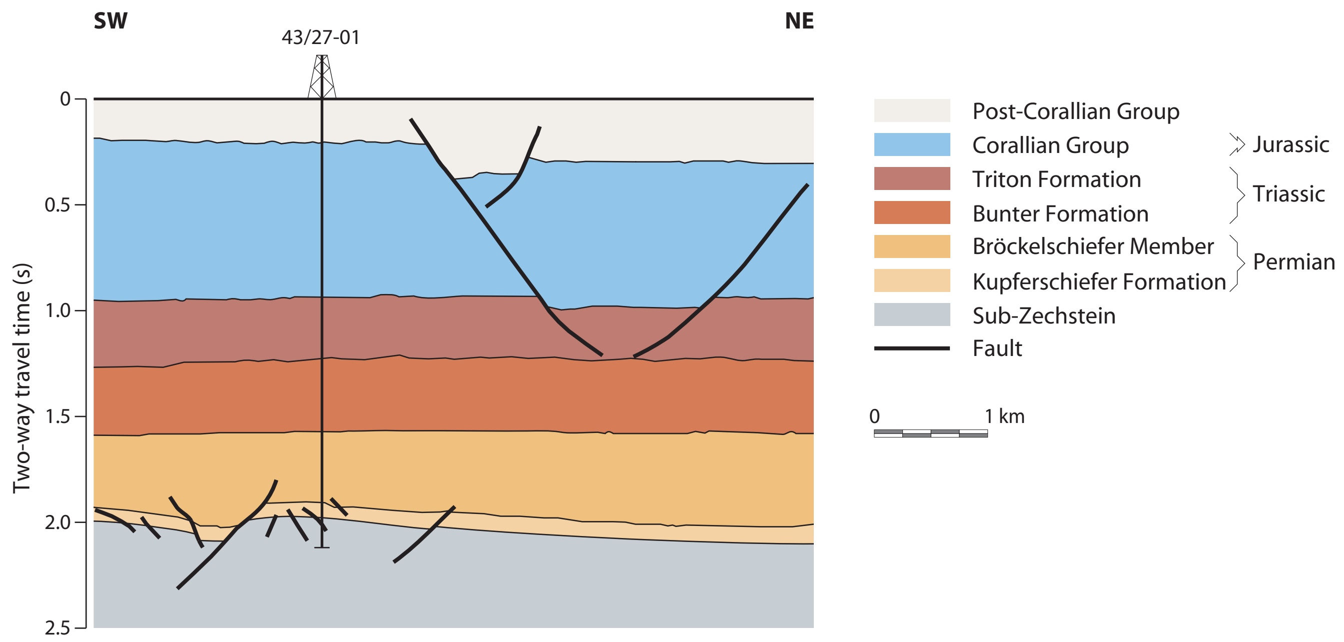


Figure 7.32 Interpreted 3D dip-line across the Johnston field (source: IHS; modified after Lawton & Roberson, 2003). See Figure 7.31 for location.

6.1.3 West Sole field

The West Sole gasfield is located in UKCS block 48/6, approximately 65 km off the Yorkshire coast in the southern North Sea and has an area of 19 × 5 km. The field was discovered in September 1965 in acreage licensed to BP Amoco in the first UK licensing round. The find marked the beginning of gasfield development in the southern North Sea, which within a decade supplied almost all of the UK's gas demand. Like the Leman and Johnston fields, West Sole is located in the Sole Pit Basin. Both the Rotliegend lower and upper Leman Sandstone are producing, but the lower Leman Sandstone is the most important. The field has been in production since 1967 and has 21 production wells producing to three platforms. Conventional drilling of the reservoir has been marginally economic due to the low permeability caused by pervasive illite cementation (Winter & King, 1991).

The West Sole field occurs in a north-north-west-trending fault-bounded inversion anticline underlying a Zechstein salt dome (**Figures 7.35** & **7.36**). The anticline formed during Late Cretaceous and Cenozoic inversion, although the timing is not very well constrained. Zechstein evaporites form the sealing units (Barr, 2007) (**Table 7.4**).

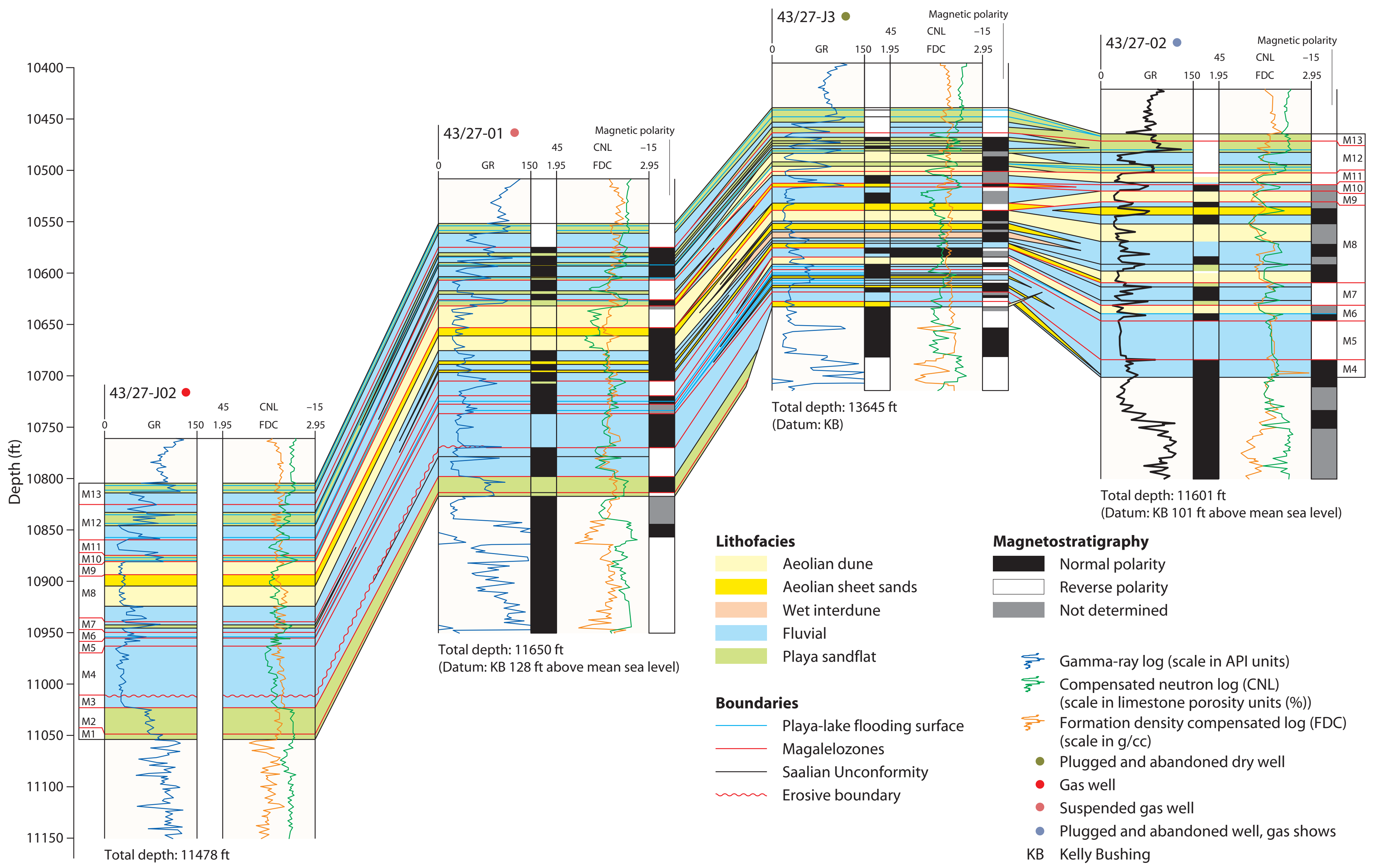


Figure 7.33 Magnetostratigraphic cross-section across the Johnston field (source IHS; modified after Lawton & Roberson, 2003). See Figure 7.31 for location of wells.

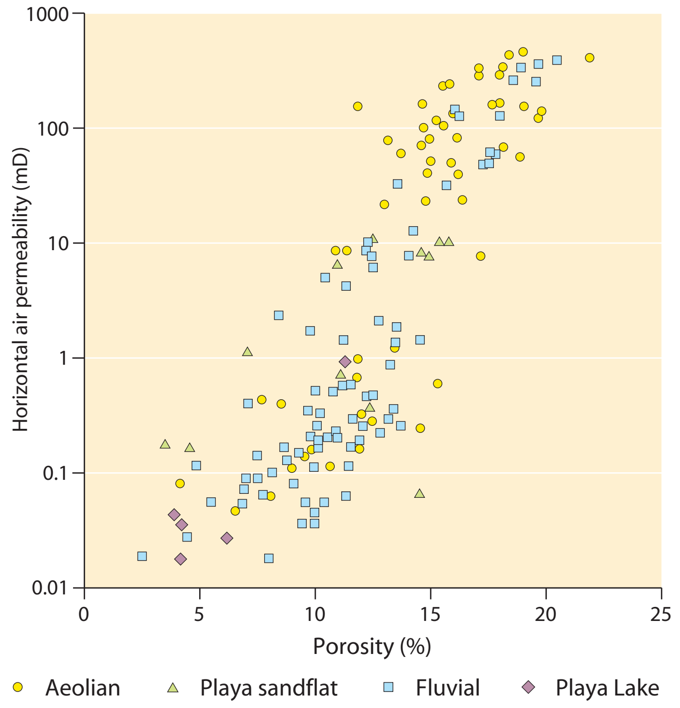


Figure 7.34 Reservoir zonation in the Johnston field showing the superior reservoir quality of aeolian sandstones (source: IHS; modified after Lawton & Roberson, 2003).

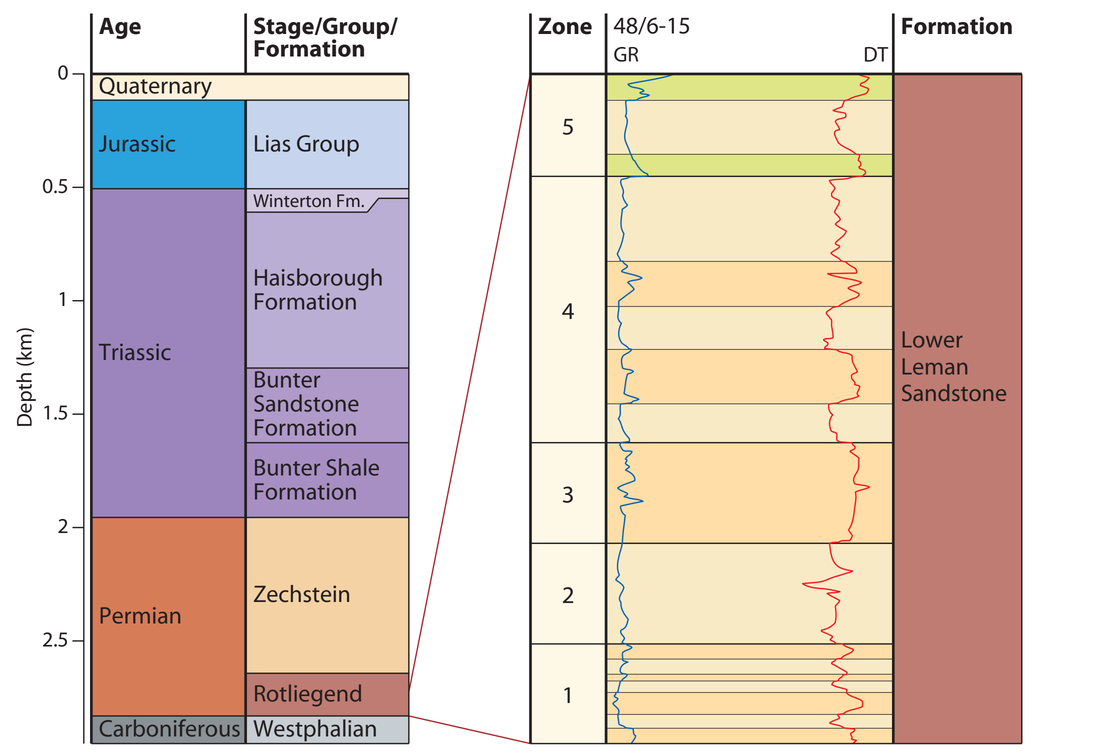


Figure 7.37 Stratigraphy and gamma-ray log of the lower Leman Sandstone Formation in the West Sole field (source: IHS; modified after Winter & King, 1991). See Figure 7.35 for location of well.

Table 7.4 Properties of the West Sole field.

Reservoir	Lower and upper Leman Sandstone Formation
Lithology	Sandstone and siltstone
Depth to top (m)	2700
GWC/GOC.OWC (m)	2950
Net reservoir thickness (m)	97
Porosity (%)	12
Permeability (mD)	1
Fluid type	Gas and condensate
Initial pressure (bar)	29
Temperature (°C)	85
Source rock	Westphalian Coal Measures
Seal	Zechstein Group

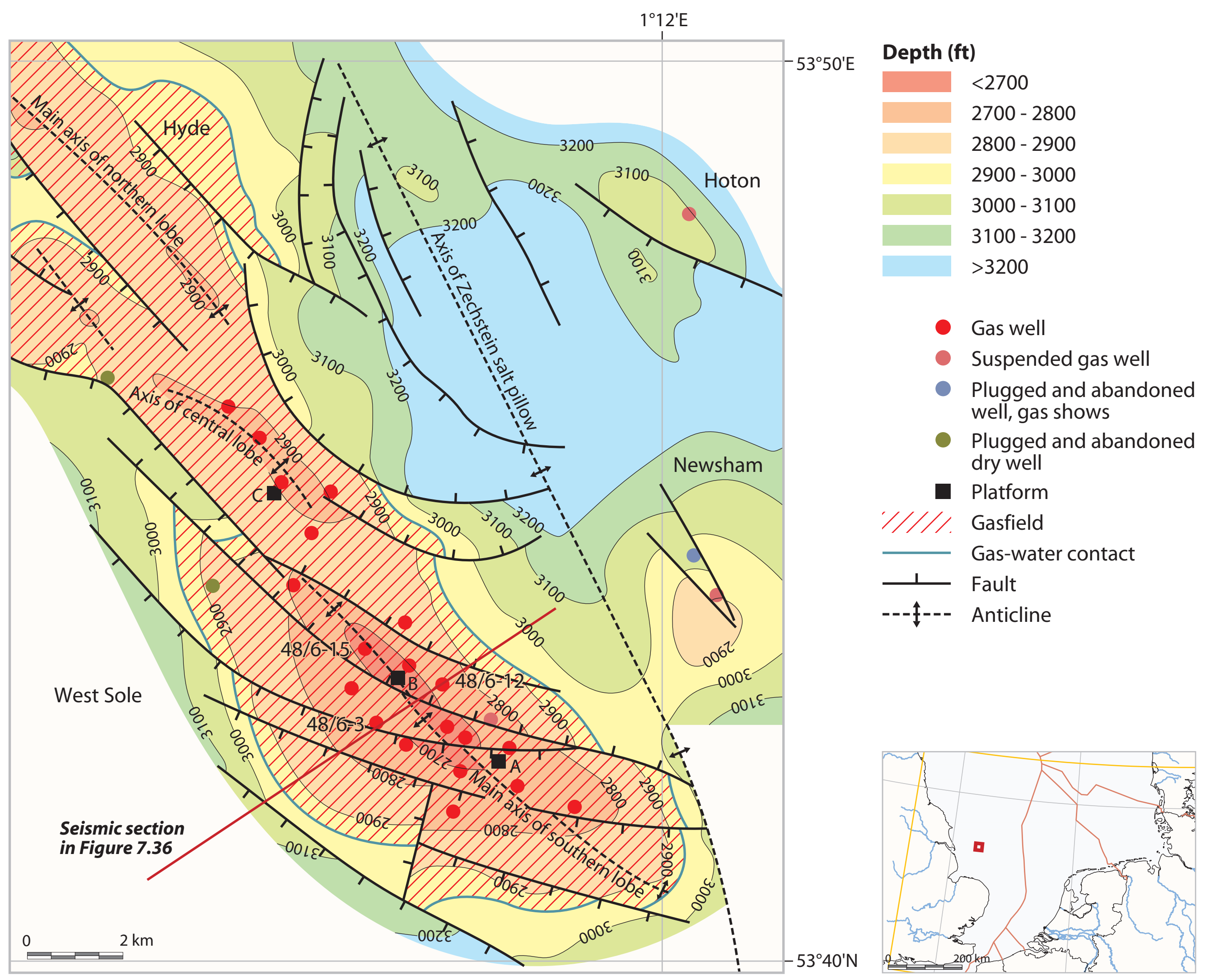


Figure 7.35 Depth structure map of the West Sole field (based on interpretation during the 1970s) (source: IHS).

The reservoir sandstones of the lower Leman Sandstone (125 m thick) consist of a basal fluvial interval, whereas most of the sandstones are interpreted as aeolian in origin (Barr, 2007; **Figure 7.37**). The 45-m thick clay-rich Silverpit Formation overlies the lower Leman Sandstone, which in turn is overlain by the thin (15 m thick) upper Leman Sandstone of relatively poor reservoir quality.

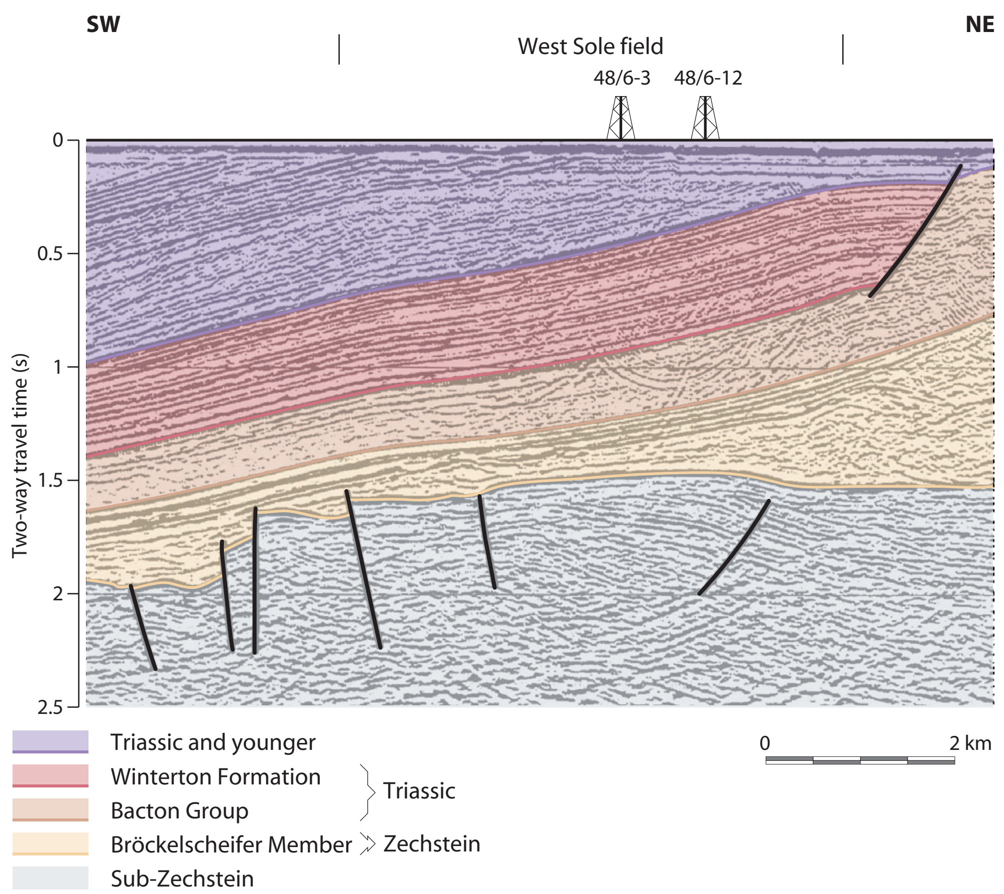


Figure 7.36 Seismic section across the West Sole field (source: IHS; modified after Winter & King, 1991). See Figure 7.35 for location.

6.2 Dutch Rotliegend fields

6.2.1 Groningen gasfield

The Groningen gasfield is located in the north-east of the Netherlands. A small part of the field is located under the Ems Estuary in Germany. The field is the largest gas accumulation in western Europe with initial recoverable reserves of close to 2800 bcm of gas. It holds two thirds of the total recoverable proven gas volumes in the Netherlands. To date, approximately 1750 bcm of gas has been produced. The field was discovered in 1959 by well Slochteren-1. The sheer size of the field (862 km^2) was not initially recognised (**Figure 7.38**). The well's target was the basal Zechstein carbonates in a relatively small structural closure, which had been mapped using 2D seismic; however, the underlying Rotliegend sandstones also turned out to be gas bearing. Only after several further wells had been drilled was it realised that the original target formed part of a much larger structure. Gas production started in 1963 and the field has been operated since then by the NAM (50% Shell, 50% Exxon Mobil).

The Groningen gasfield is situated on the regional Groningen High, which is bound to the west by the Lauwerszee Trough and to the east by the Ems Graben (**Figure 7.39**). The Groningen High is a prominent stable structural high that originated during the Carboniferous, but which was largely shaped by the late Cimmerian tectonic phase during the Jurassic. The high has strongly faulted east, south and west flanks, and a gently dipping north flank (**Figure 7.39**). The throws of the boundary faults range from several tens of metres to more than 300 m. The Groningen field is subdivided into a number of fault compartments with slightly different free water levels (FWL), reservoir pressure and gas composition. None of the faults within the central part of the field appear to act as significant barriers to gas flow, although they might hold a pressure differential. The field is fairly flat with a culmination in the south at approximately 2600 m depth below mean sea level. The field FWL ranges from 2971 to 3017 m true vertical depth subsea. In the southern part of the field, truncated and strongly faulted Carboniferous sands, shales and coals of

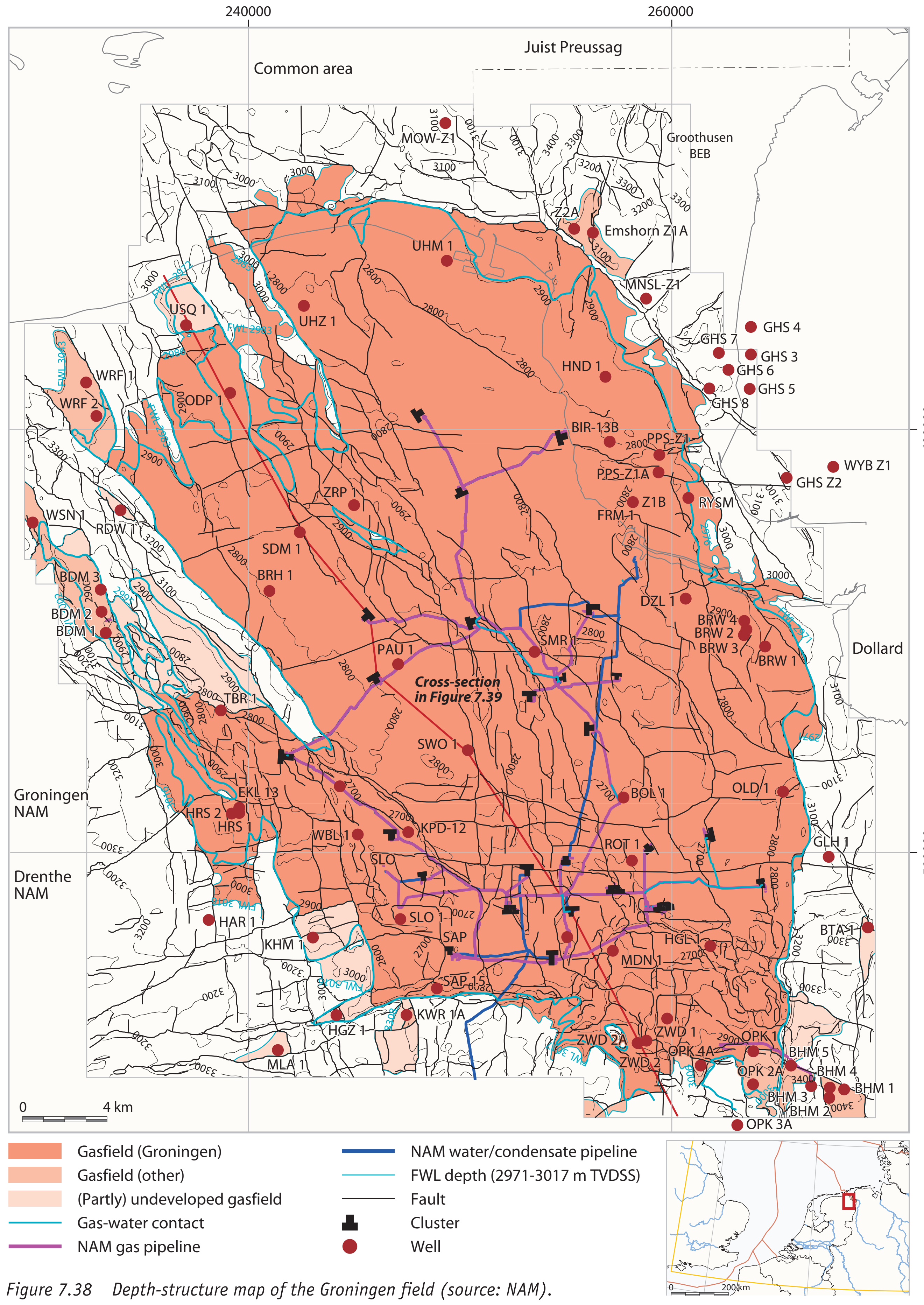


Figure 7.38 Depth-structure map of the Groningen field (source: NAM).

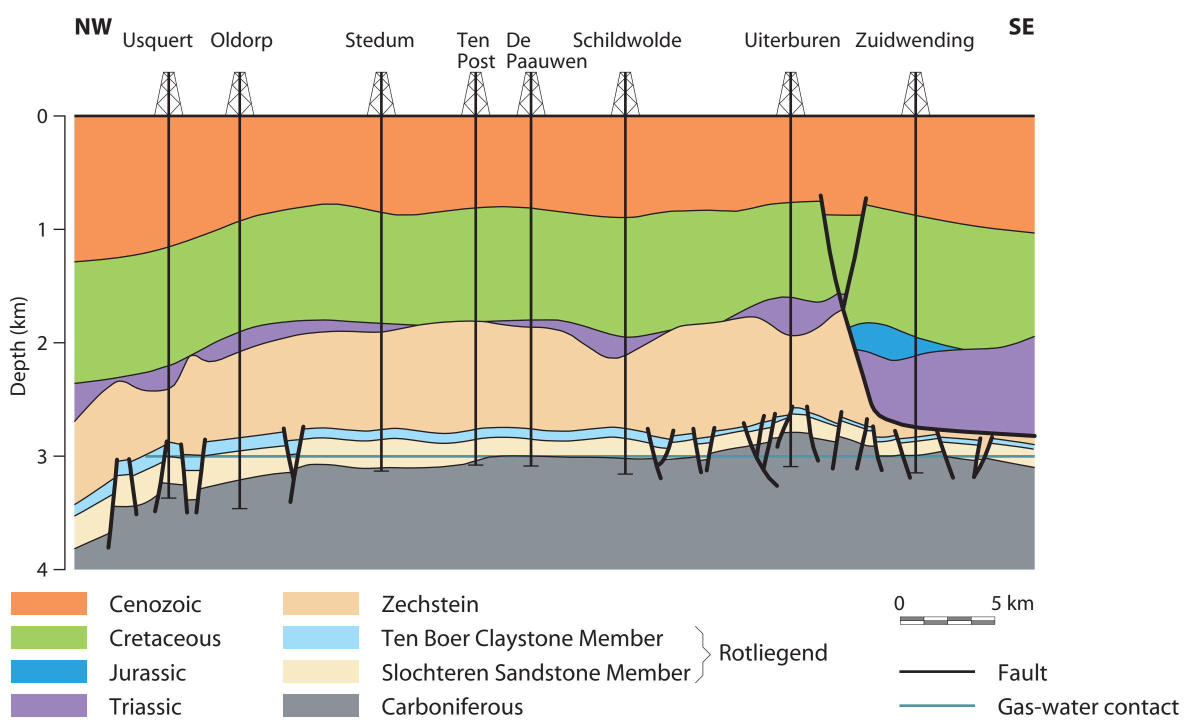


Figure 7.39 Schematic geological section across the Groningen field. See Figure 7.38 for location.

fluviodeltaic origin (the Westphalian Limburg Group) are situated above the field's FWL, and form a secondary reservoir. However, the distribution of sands is still poorly understood and the N:G ratio is generally low (**Table 7.5**). The gas is mainly sourced from Westphalian coals. The seals to the gas are Zechstein salts, anhydrites and dolomites.

The main reservoir is formed by the fluvial and aeolian sandstones of the upper Rotliegend Slochteren Formation. The Slochteren gross reservoir thickness increases from some 70 m in the south-east of the field to 240 m in the north-west (**Figure 7.40**). The Slochteren Formation comprises a fairly homogeneous mixture of fluvial and aeolian sandstones (**Figure 7.41**). The average porosities per well range from 10% to 25%, with the highest values in the central part of the field, and have an average field value of 17%. The average permeability of the field is 240 mD (**Table 7.5**). A continuous shale-dominated succession (25 to 75 m thick), the Ten Boer Claystone Member, overlies the Slochteren Formation. In the northern part of the field, another shale layer, the Ameland Claystone Member, divides the Slochteren Formation into an upper and lower unit and locally acts as a flow barrier (**Figures 7.1** & **7.40**).

The Groningen gasfield plays an important role in the supply of gas to western European. For strategic reasons it is operated as a swing producer with a low load factor and a high maximum production capacity. Peak daily production was 324 mln m^3 of gas. Peak yearly production was 88 bcm gas in 1976, while yearly production in 2006 was 33 bcm. The field's GIIP is approximately 2900 bcm (93% in the Rotliegend, 7% in the Carboniferous) and initial recoverable reserves are expected to be close to 2800 bcm. The gas composition is fairly uniform across the field with average 81.2% methane, 2.9% ethane, 19.2% N_2 and 0.9% CO_2. The production mechanism is gas-depletion drive.

The Groningen field surface facilities comprise 296 active producing wells and a number of observation wells. The producing wells were drilled from 29 clusters, with each cluster carrying on average 10 wells (**Figure 7.38**). The clusters are currently being renovated and compressors are being installed. The gas is treated at the cluster facilities and fed into a ring pipeline, which is connected via transfer points to the main pipeline system for distribution to customers. Produced liquids are routed by pipeline to Delfzijl harbour where water and condensate are separated. Condensates are shipped to refineries in the Rotterdam area, whereas water is re-injected into the field's reservoir below the FWL. Maximum subsidence caused by gas production is 26 cm.

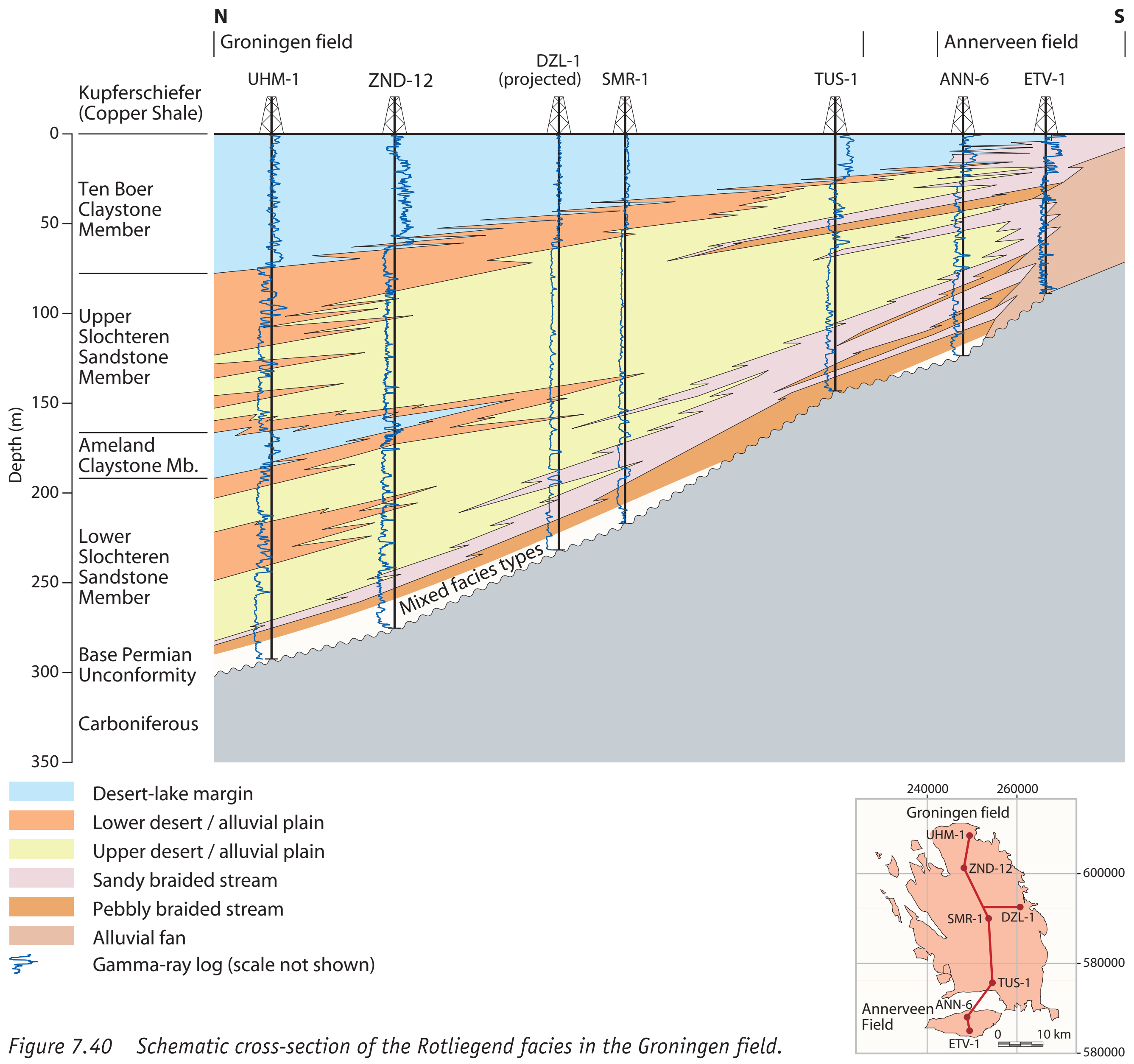


Figure 7.40 Schematic cross-section of the Rotliegend facies in the Groningen field.

Figure 7.41 Core photographs from well Slochteren-4. The 6 core sections on the right show fine-grained aeolian sandstones (grey) alternating with shales (brown) from the upper Slochteren Member. The cores to the left of the photograph (beneath 2832.3 m) show conglomerates from the lower Slochteren Member. Depths at the top and base of each section are in metres.

Table 7.5 Properties of the Groningen field.

Reservoir	Slochteren Formation
Lithology	Sandstone
Depth to top (m)	2600
GWC/GOC.OWC (m)	2971-3016
Maximum column height (m)	200
Net reservoir thickness (m)	70-240
Net to gross ratio	0.87
Porosity (%)	17
Permeability (mD)	240
Fluid type	Gas and condensate
Gas composition	C1 81.24%, N_2 19.2%, C3 0.41%, C5 0.04%, C2 2.89%, C6 0.07%, C4 0.15%
Initial pressure (bar)	346.8
Temperature (°C)	110
Source rock	Westphalian Coal Measures
Seal	Zechstein Group

6.3 German Rotliegend fields

6.3.1 Söhlingen gasfield

The Rotliegend gasfield of Söhlingen is situated in Lower Saxony, approximately half-way between Hamburg and Hannover. The field is the largest in the Lower Saxony region with initial recoverable reserves of 57 bcm gas. The field was discovered in 1979 when the Söhlingen-Z1 well was drilled through the core of a salt dome and proved reservoir sandstones. In 1992, a consortium consisting of Mobil, BEB, RWE-Dea and Wintershall drilled the first horizontal well (Söhlingen-Z10) with multiple fracs at a depth of 4783 m. This resulted in a stable production rate of 20 000 m^3/hour, which is three to five times the rate of a fraced vertical well (Schuler & Santos 1993).

The structure of the Söhlingen field consists of an anticlinal rise in the Rotliegend Schneverdingen Graben complex (**Figures 7.42** & **7.43**). The lowermost reservoir unit, the lower Rotliegend Schneverdingen Sandstone (Havel Subgroup), is confined to this graben complex. The general outlines of the Schneverdingen Graben were published by Drong et al. (1982) and as a 3D-seismic interpretation by Gast & Gundlach (2006).

The Söhlingen field is the only Rotliegend gas accumulation with three major producing reservoir sections (**Figure 7.44**). It probably has the highest gas column in the SPB, consisting from top to base of the Wustrow Sandstone (upper Slochteren), Dethlingen Sandstone (lower Slochteren) and Schneverdingen

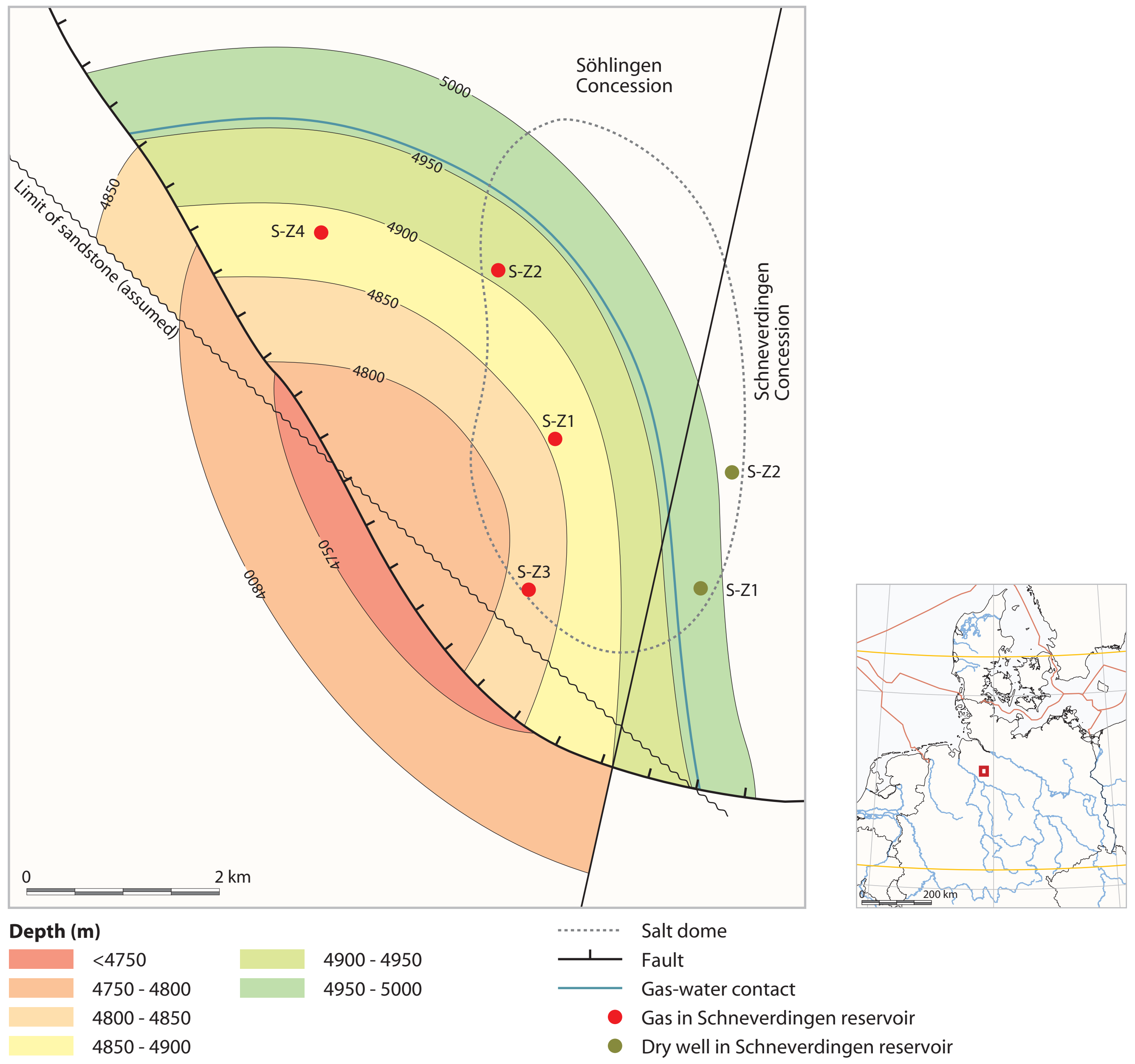


Figure 7.42 Simplified very early depth-structure map of the Söhlingen field at the top Schneverdingen Sandstone (Havel Subgroup) level (source: IHS). Only one fault-block of the much larger Söhlingen field is shown, where the Schneverdingen Sandstones are in the gas column (source: IHS; modified after Klose & Krömer, 1983).

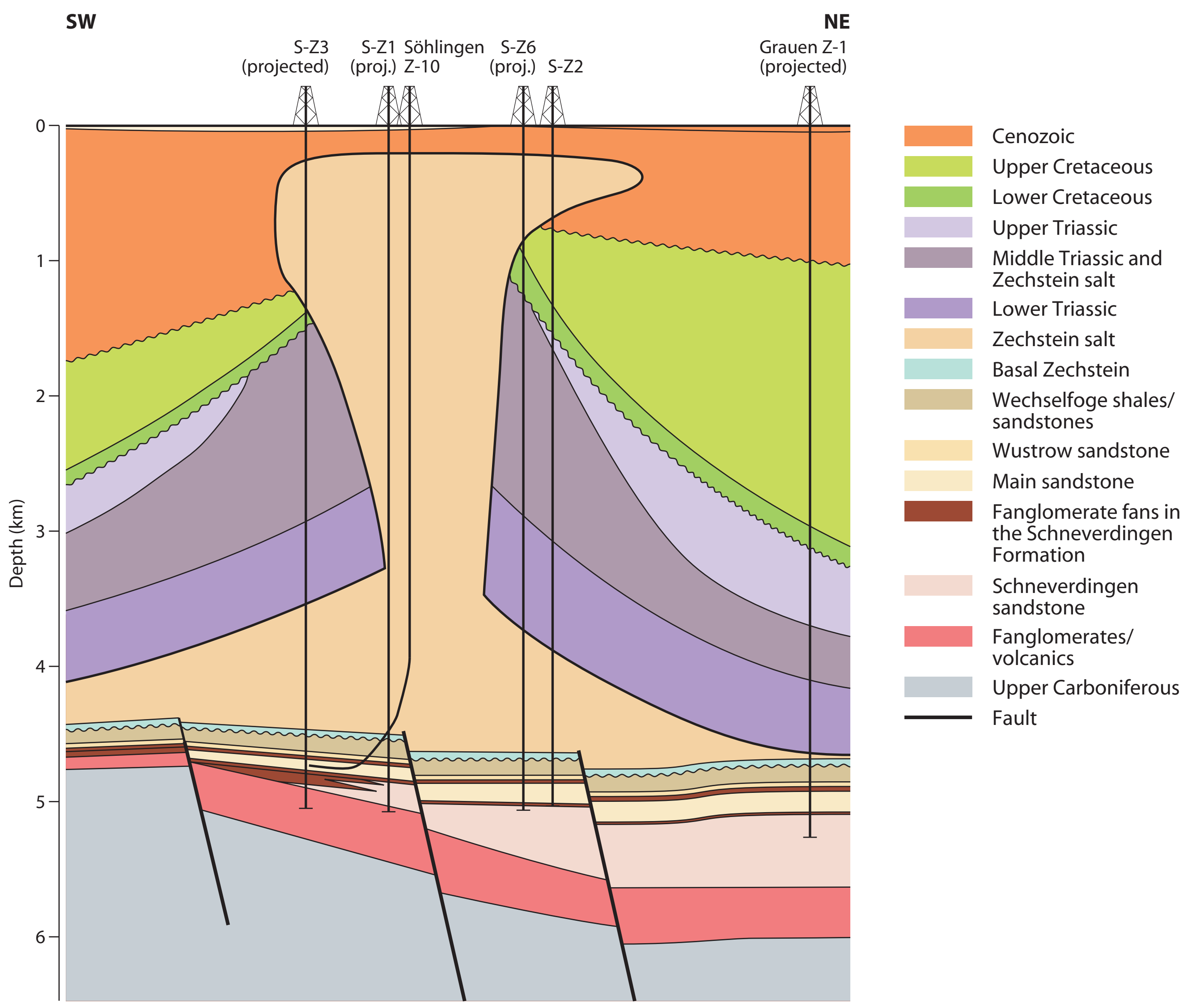


Figure 7.43 Simplified cross-section across the Söhlingen field (source: IHS; modified after Schuler & Santos, 1996). See Figure 7.42 for locations of wells.

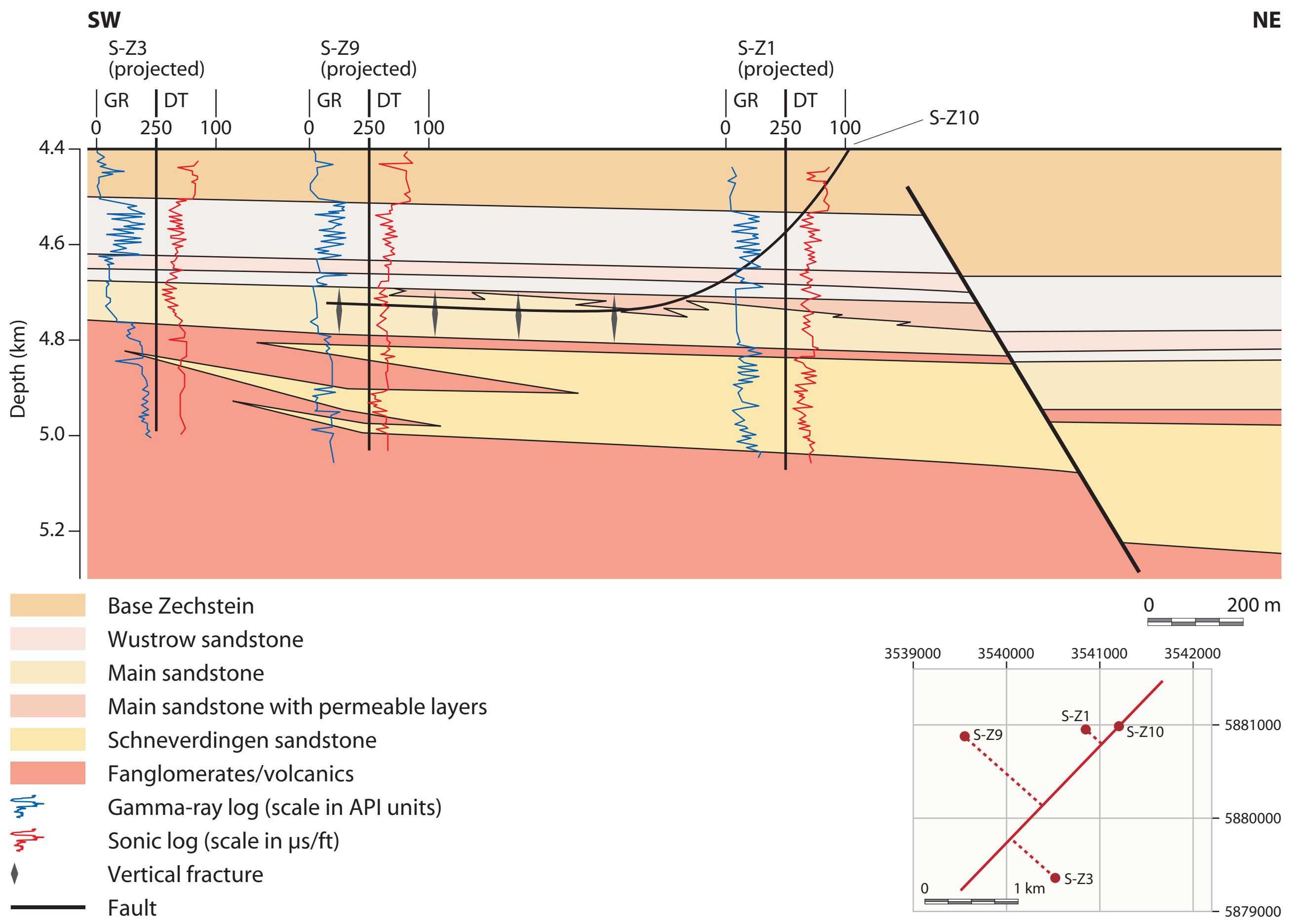


Figure 7.44 Cross-section through the Söhlingen field showing the Lower Slochteren Dethlingen Sandstones. Multiple frac-operations were carried out to improve gas recovery from the ultra-tight aeolian sandstones (source: IHS; modified after Schuler & Santos, 1996). See also Figure 7.42 for locations of wells S-Z1 and S-Z3.

Sandstone (Havel Subgroup) (**Figure 7.5**). The Wustrow and Schneverdingen sandstones yield high production rates, whereas the Dethlingen Sandstone is characterised by low permeabilities (<10 mD) with an average *in situ* (or effective) permeability of 0.01 to 0.02 mD (**Table 7.6**) (Schuler & Santos, 1993).

Table 7.6. Properties of the Söhlingen field.

Reservoir	Wustrow (upper Slochteren)	Dethlingen (lower Slochteren)	Schneverdingen Sandstone
Lithology	Sandstone	Sandstone	Sandstone
Depth to top (m)	4590		
GWC/GOC.OWC (m)	max. 4958		
Net reservoir thickness (m)	20	50	40
Porosity (%)	12	10	12
Permeability (mD)	50	<10	50
Fluid type	Gas		
Initial pressure (bar)	620.5		
Temperature (°C)	110	144	140
Source rock	Westphalian Coal Measures	Westphalian Coal Measures	Westphalian Coal Measures
Seal	Zechstein evaporites	Zechstein evaporites	Zechstein evaporites

6.3.2 Salzwedel gasfield

The natural gas reservoirs of the Salzwedel gasfield are part of the Altmark region of the Federal State of Sachsen-Anhalt, approximately 120 km south-east of Hamburg. The gasfield is licensed to GDF SUEZ E&P Deutschland GmbH, a subsidiary of Gaz de France, and ranks amongst the largest fields in Europe (**Figure 7.45**). The Salzwedel gasfield is at the eastern limit of a suite of gas reservoirs stretching from the Groningen gasfield in the west. The Salzwedel gasfield was discovered in 1968 and has been in production ever since. The field's peak was in 1984 and it has been declining steadily since 1996. The current cumulative production amounts to 265 bcm of gas; 78% of the original gas on site has now been recovered and economically viable gas production is slowly coming to an end. Nitrogen contents in the Salzwedel gasfield are high: methane represents no more than 40% (Glennie, 1998b).

The Salzwedel gasfield occurs at a depth of 3200 to 3500 m (**Figures 7.45** & **7.47** & **Table 7.7**). In total, 475 wells have been drilled over an area of approximately 30 × 40 km; about 150 wells are still in production. A recovery rate of 70 to 80% is expected for this type of gasfield. In gasfields such as Salzwedel, which is at the end of its production period, it is necessary to look at alternative options to increase production beyond the 80% recovery limit. The present option to extend the field's life, and consequently the reserves, is to inject CO_2 into the gas-bearing layers of the reservoir to displace the remaining gas towards the production wells. The selected sub-reservoir for the pilot phase is Altensalzwedel, a depleted natural gas reservoir with a limited area, which is isolated from other compartments and has good reservoir quality. The infrastructure is already in place and there are wells for injection, observation and production. Experience gained during the Altensalzwedel pilot will be of great value in the future, as this small field is representative of Altmark conditions in general. The total injection volume of the pilot phase amounts to 100 000 tonnes of CO_2. The first CO_2 could be injected at the earliest in December 2010 after 15 months of planning, pre-engineering and preparations. Selected core photographs are shown in **Figure 7.48**.

Table 7.7 Properties of the Salzwedel gasfield.

Reservoir	Slochteren Formation
Lithology	Sandstone (Figure 7.47)
Depth to top (m)	3200-3500
Net reservoir thickness (m)	70-240
Net to gross ratio	0.87
Porosity (%)	15
Permeability (mD)	20
Fluid type	Gas
Initial pressure (bar)	346
Temperature (°C)	110
Source rock	Westphalian Coal Measures
Seal	Zechstein evaporites

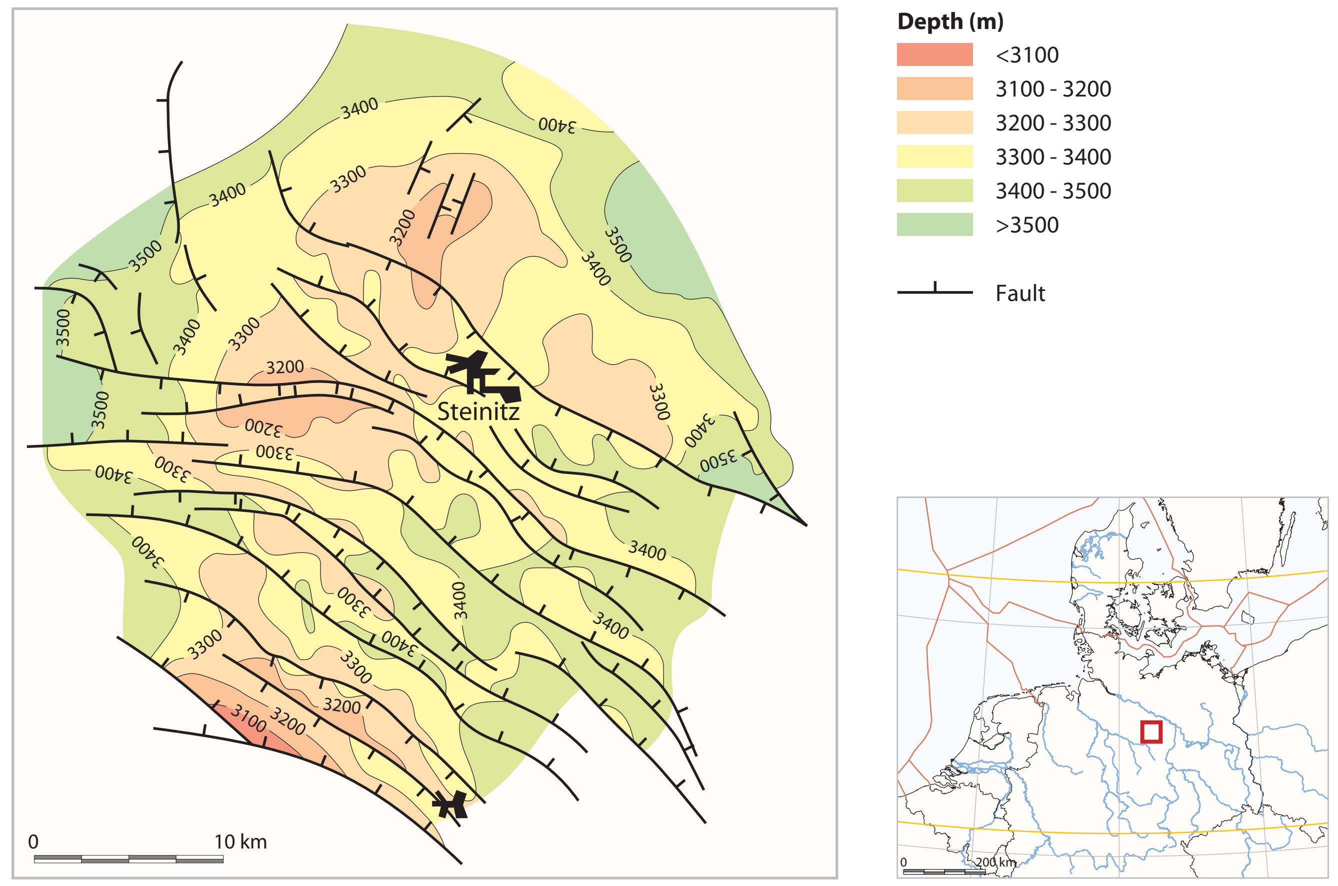


Figure 7.45 Depth-structure map of the Salzwedel gasfield.

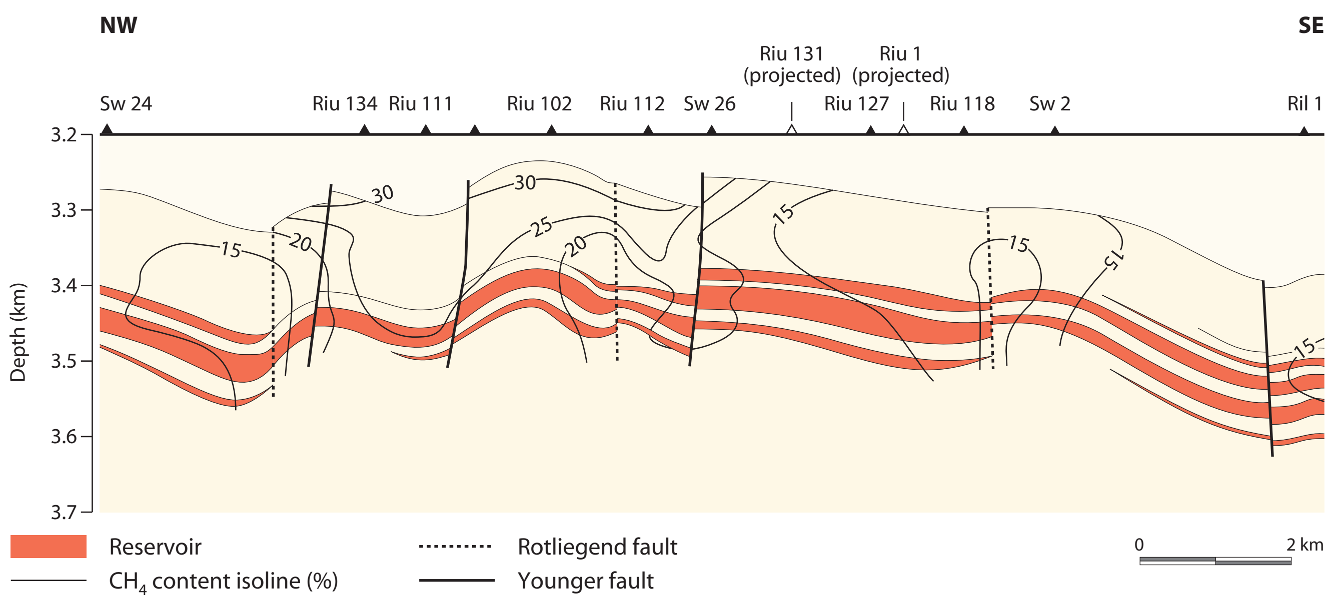


Figure 7.46 Structural cross-section through the Riebau part of the Salzwedel gasfield showing the distribution of methane in the field. The lowest percentages prove late-stage migration of nitrogen into reservoirs (source: IHS; modified after Schuhmacher & May, 1991).

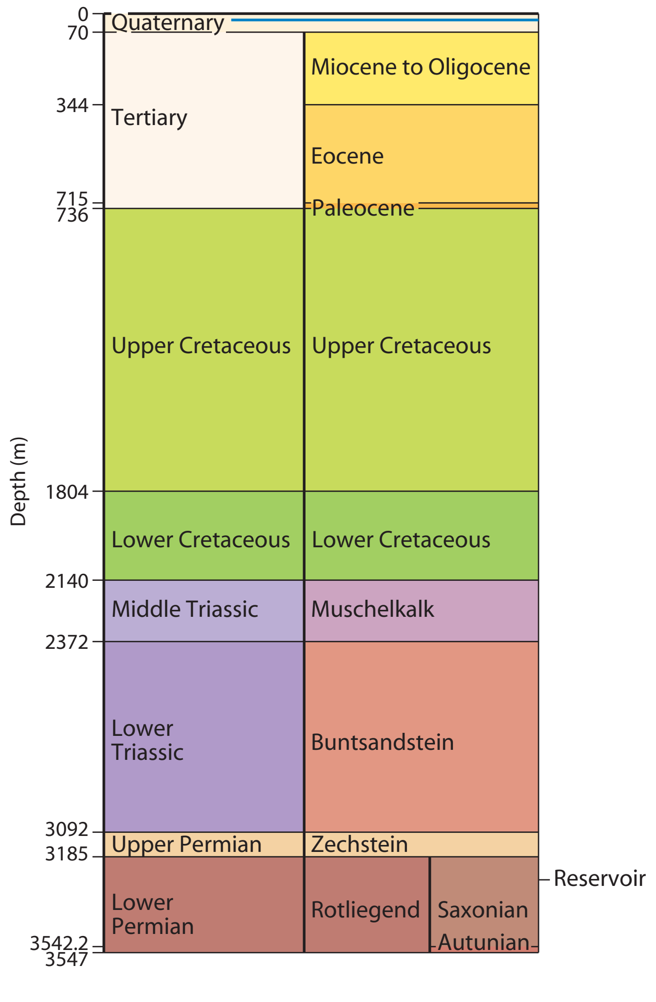


Figure 7.47 Stratigraphy of the Salzwedel field discovery wells showing the stratigraphic level of the reservoir. The well on the left drilled through the 'normal' sedimentary sequence of the Southern Permian Basin; the well on the right penetrated a salt-dome sequence (source: IHS).

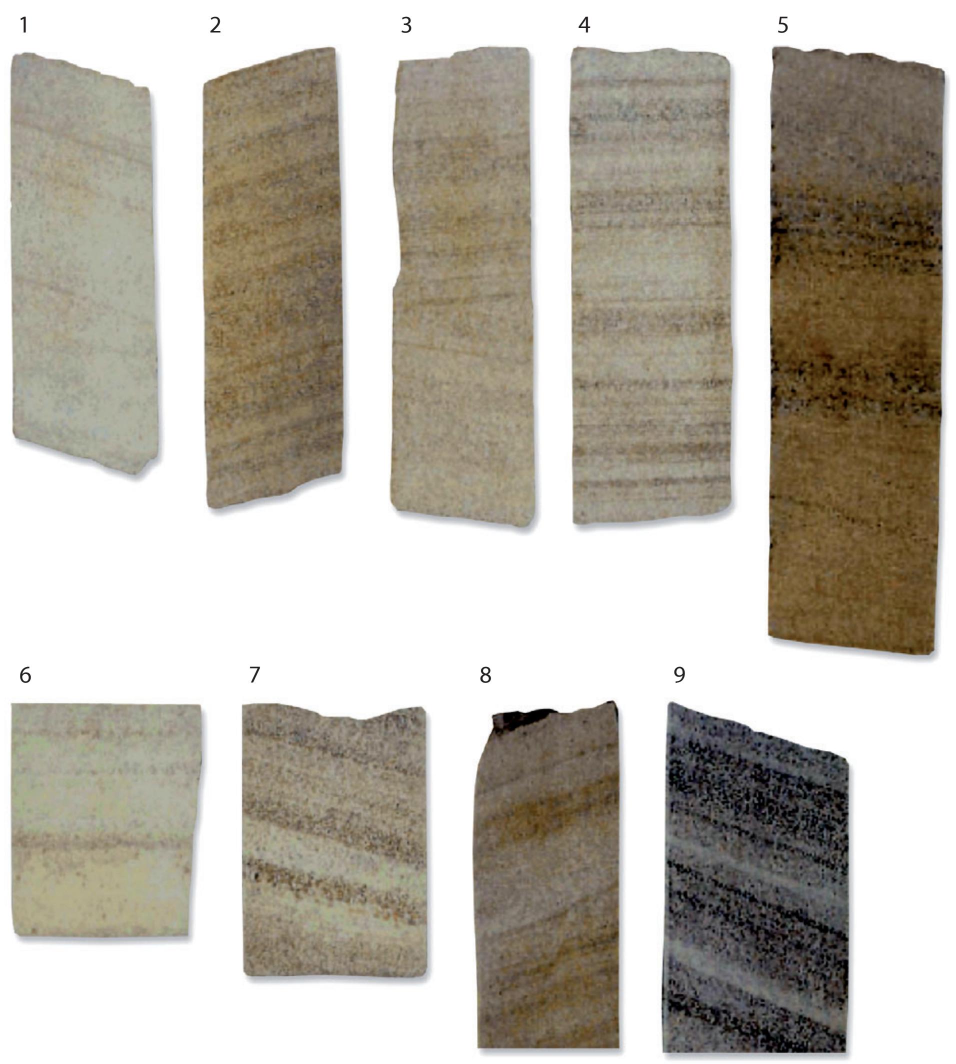


Figure 7.48 Core photographs showing aeolian dune sets from the Salzwedel field. The dark clasts are of volcanic origin (from Kleditzsch, 2003).

6.4 Polish Rotliegend fields

Siliciclastic sediments of the Rotliegend Group include the most important gas reservoirs in the western Polish Lowlands. To date, about 45 gas deposits have been discovered comprising more than 85% of the regions gas reserves. The Wolsztyn High is the source area for the Rotliegend siliciclastics (**Figure 7.21**) and is situated along the southern boundary of the Polish Trough. The first gasfield in the region, Bogdaj-Uciechów was discovered in 1964 (Karnkowski, 1966).

The gas deposits developed mainly in aeolian sandstones although they are also found in mixed fluvio-aeolian facies. The traps are partly tectonic (mostly in the north-eastern gas-bearing area); however the larger Rotliegend gasfields in the south-west of the gas-bearing zone have stratigraphic traps. These originated from large dune fields preserved during transgression of the Zechstein Sea. In places the preserved dunes allow gasfields to form more than 125 m of maximum gas-column height (e.g. Załęcze-Wiewierz and Żuchlów). Rotliegend gasfields in this gas-bearing zone are rare, the main reason being the limited distribution of sandstone facies in the main dune area. As described above, large areas of the Polish Rotliegend Basin were filled by playa-lake deposits. Fluvial sandstones are only found at the northern basin margin. An example of a gasfield in a fluvial sandstone reservoir is given below (Ciechnowo and Sławoborze). In the southern part of the gas-bearing zone, the Rotliegend gasfields are coeval with traps (fractured carbonate rocks) in Zechstein Limestone (Ca1). Southwards, gas is only trapped in Zechstein Limestone as the Rotliegend sandstones are water filled due to the inclination of the top Rotliegend palaeoslope.

In contrast to most of the classic Rotliegend gasfields discovered within lower and upper Slochteren Formation sandstones in the western part of SPB, the Polish gasfields have so far been discovered only in the topmost Rotliegend sands (the upper Noteć Formation, equivalent to the upper Hannover Formation). Most of the gasfields are located in large dune forms that were deposited just before inundation by the Zechstein Sea.

The discovery of the Radlin gasfield (see below) at depths below 3200 m led to further exploration in the deeper parts of the Polish Rotliegend Basin where structural and stratigraphic traps are expected to be found at the top of Rotliegend succession and deeper, sealed by playa claystones. In 2008, the discovery of a tight-gas trap in Rotliegend aeolian reservoir sands (e.g. the Trzek 1 well east of Poznań) suggested a new play with unconventional traps.

Upper Carboniferous (Westphalian) coal-bearing sediments are probably the source rocks for the gases in the Rotliegend reservoirs in the north-eastern gas-bearing zone. Most of the gas derived from Lower Carboniferous rocks (Culm facies) belong to the Variscan fold-and-thrust belt. The gas contains 50 to 80% methane, and nitrogen contents range from 20 to more than 50%. The high nitrogen content is due to Late Cretaceous to Early Tertiary basin inversion (Maastrichtian-Danian) as inversion-related movements resulted in the primary filling of the reservoirs (i.e. methane-rich gas) being replaced by nitrogen-rich gases formed during late catagenesis of humic kerogen. Basin modelling shows that the rate of inversion increases southwards to the Wolsztyn High.

6.4.1 Ciechnowo gasfield

The Ciechnowo gasfield is located in north-east Poland between Szczecin and Koszalin. The structure forms an asymmetrical anticline (**Figures 7.49** & **7.50**). Trapping is partly stratigraphic due to depositional pinch-out of the reservoir. Late Carboniferous (Westphalian) coal-bearing sequences are the source rocks for the gases in the Rotliegend reservoirs (**Table 7.8**). The gas has 50 to 80% volume of methane and nitrogen content ranges from 20 to 50%. The Rotliegend section in the Ciechnowo area consists (from the base to the top) of Autunian effusive rocks with a thickness of 61 m and upper Rotliegend II clastic rocks with a thickness of 149 m. The Saxonian clastic rocks (upper Artinskian) are orthoconglomerates in the lower part and quartz arenites in the upper section. The gas deposits are developed mainly in fluvial sandstones, but also occur in mixed fluvio-aeolian facies.

Table 7.8 Properties of the Ciechnowo gasfield.

Reservoir	Upper Noteć fluvial sandstone
Lithology	Sandstone
Depth to top (m)	3720.3
GWC/GOC.OWC (m)	3743.43
Maximum column height (m)	82.5
Net reservoir thickness (m)	34.65
Porosity (%)	4.85 (average)
Permeability (mD)	<0.001-480.342
Fluid type	Gas, condensate and helium
Initial pressure (bar)	462.5
Temperature (°C)	87.45
Source rock	Carboniferous bituminous shales
Seal	Zechstein halites and anhydrites

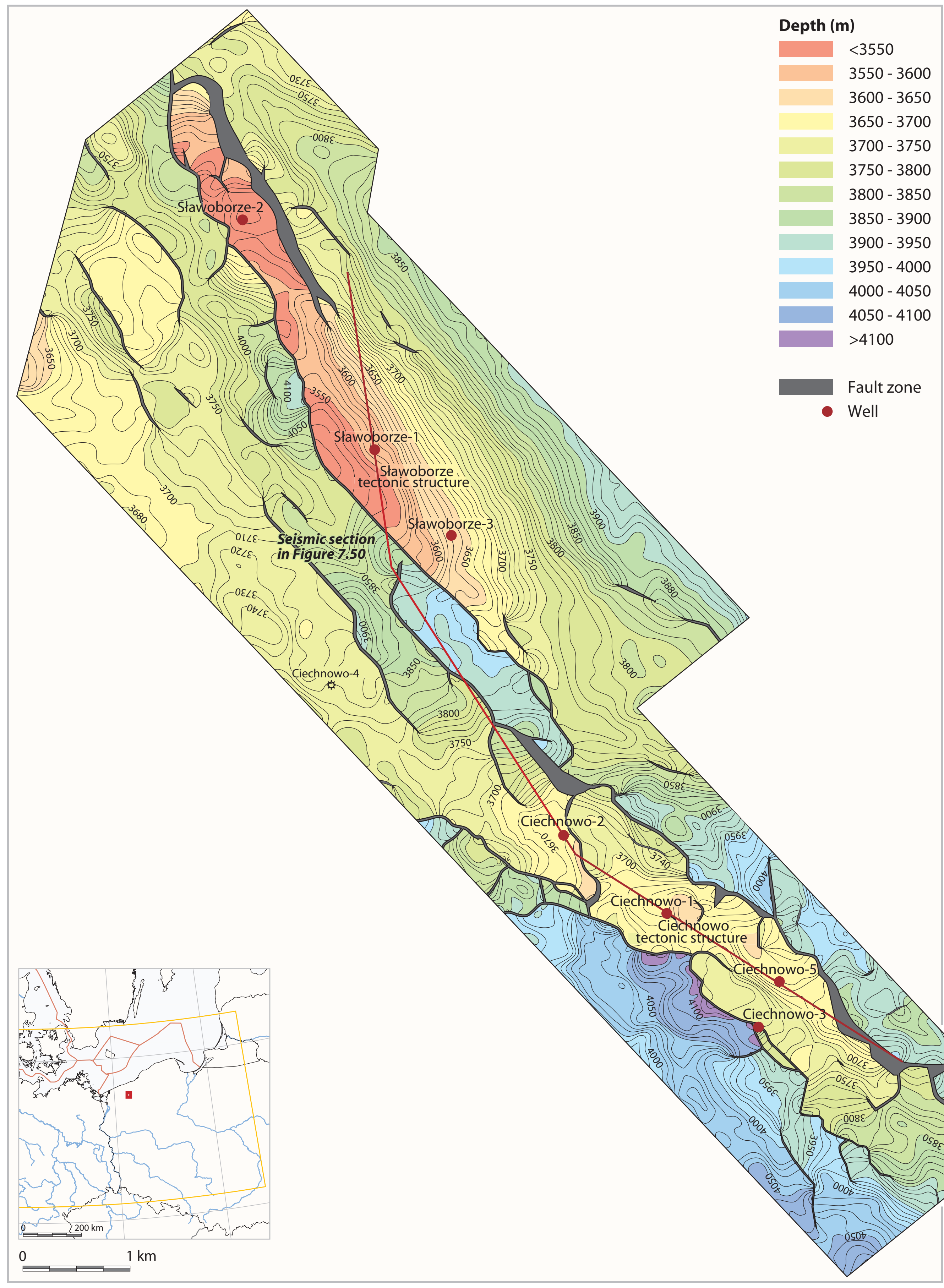


Figure 7.49 Depth-structure to the top of the Rotliegend reservoir in the Sławoborze and Ciechnowo fields.

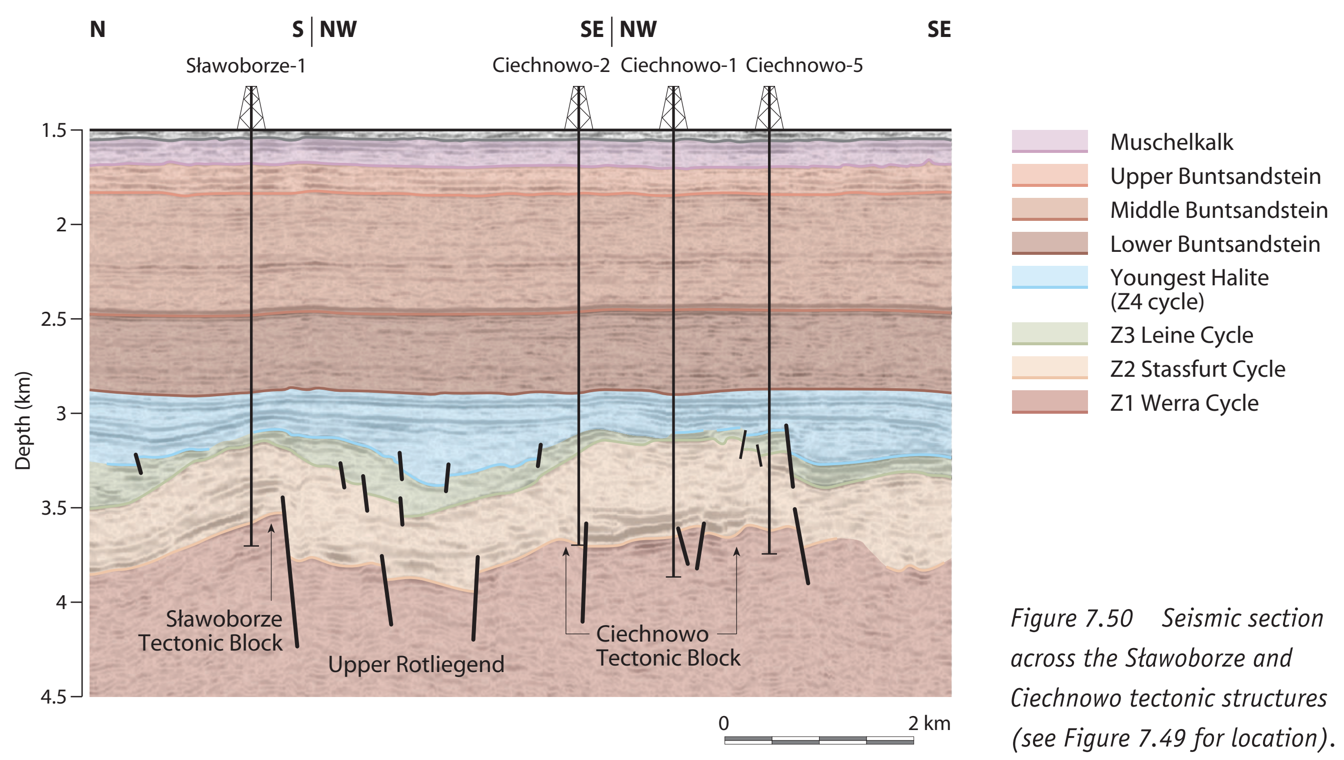


Figure 7.50 Seismic section across the Sławoborze and Ciechnowo tectonic structures (see Figure 7.49 for location).

6.4.2 Radlin gasfield

The Radlin gasfield is located in south-west Poland, approximately 60 km south-west of Poznań (**Figures 7.51** & **7.52**). The field was discovered in 1982 in the topmost upper Rotliegend sandstones at a depth of more than 3000 m (**Table 7.9**). The present-day field area exceeds almost 15 km^2 and has 33 producing wells. The field has been in operation since 1992. The Radlin gasfield is hosted in a tilted tectonic block bounded by a fault zone. The trap is sealed by Zechstein halites and anhydrites (Kwolek & Buniak, 2004).

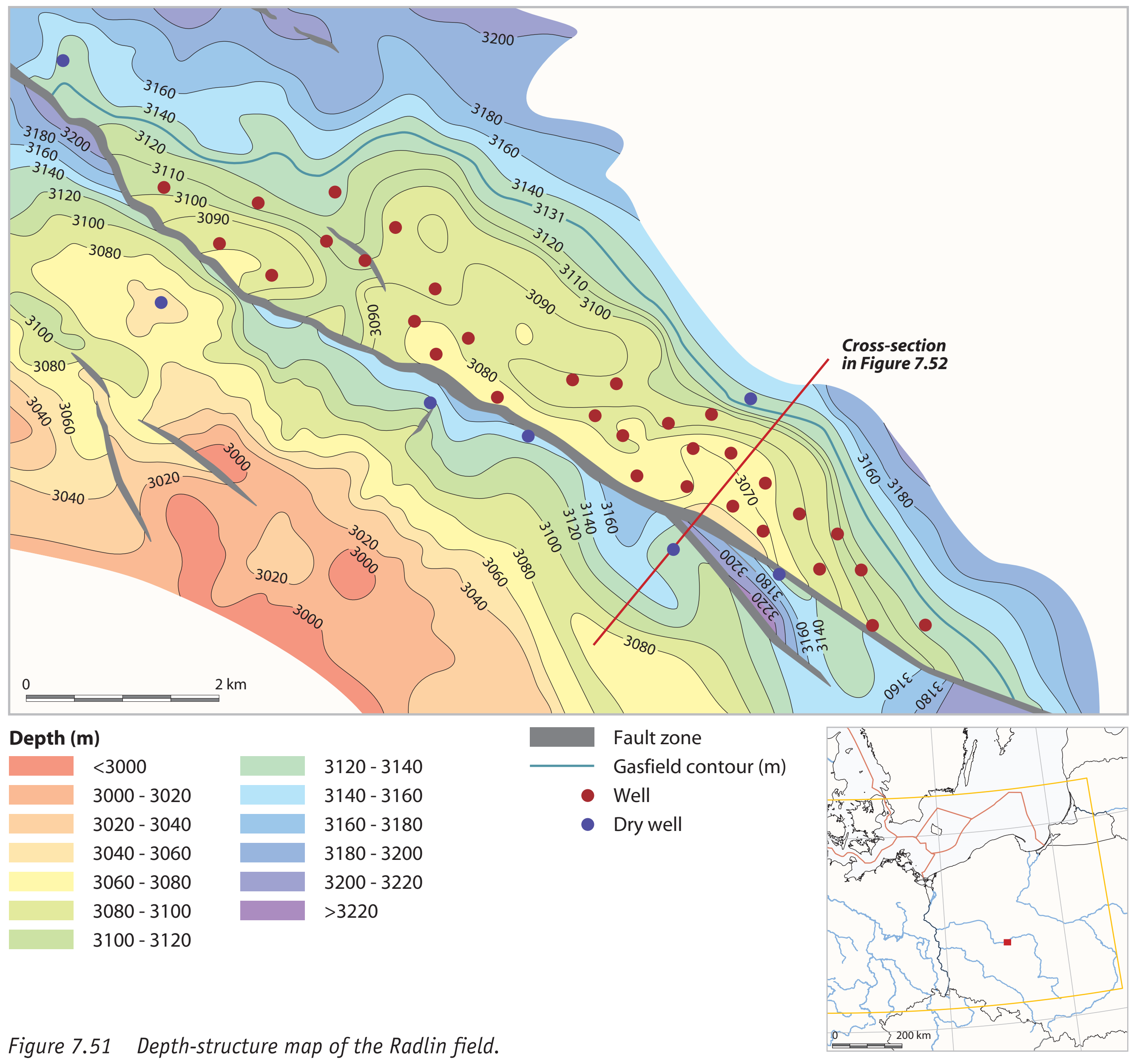


Figure 7.51 Depth-structure map of the Radlin field.

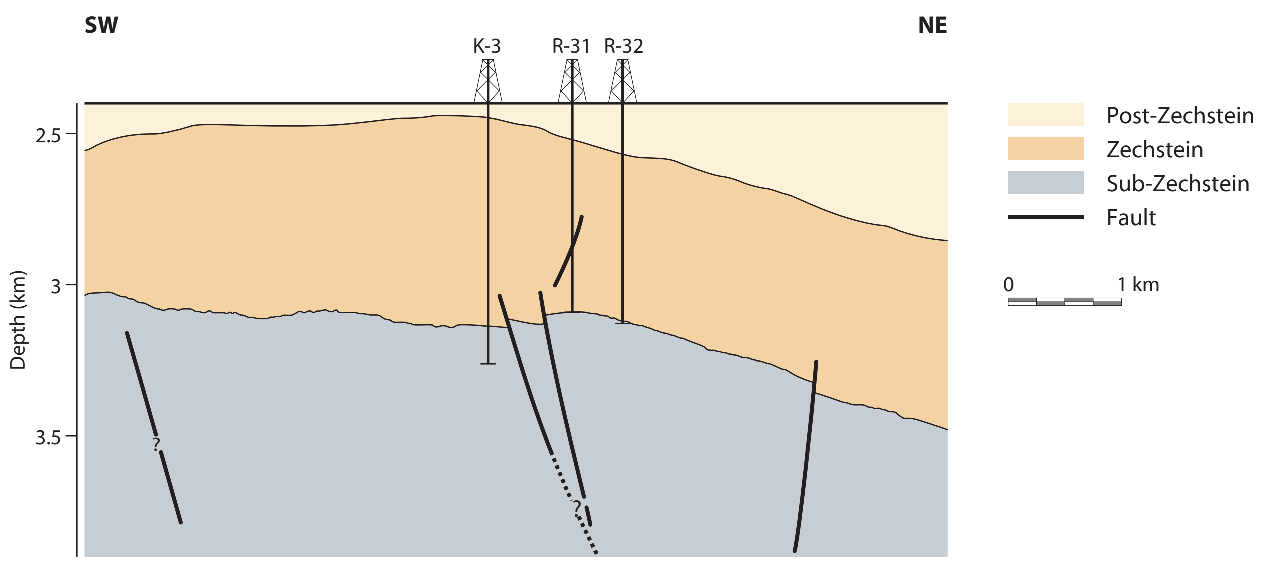


Figure 7.52 Schematic section across the Radlin field (see Figure 7.51 for location).

Table 7.9 Properties of the Radlin gasfield.

Reservoir	Upper Noteć Formation aeolian sandstone
Lithology	Sandstone
Depth to top (m)	3060.23
GWC/GOC.OWC (m)	3131 (primary depth)
Maximum column height (m)	70.77
Net reservoir thickness (m)	32.25
Porosity (%)	17.6 (average)
Permeability (mD)	0.1-740.53
Fluid type	Gas
Initial pressure (bar)	352.17
Temperature (°C)	112.36
Source rock	Lower Namurian and upper Westphalian (?) bituminous shales
Seal	Zechstein halites and anhydrites