Helgoland, German North Sea. The Volpriehausen and Detfurth formations (Middle Buntsandstein Subgroup). The formation boundary is at the base of the thick interval of white aeolian 'Katersande', which is also present near the top of the 'Lange Anna' sea stack (see Binot & Röhling, 1988). Photo courtesy of Prof. Dr H. Ibbeken, Berlin.

Chapter 9 Triassic

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Bachmann, G.H., Geluk, M.C., Warrington, G., Becker-Roman, A., Beutler, G., Hagdorn, H., Hounslow, M.W., Nitsch, E., Röhling, H.-G., Simon, T. & Szulc, A., 2010. Triassic. *In:* Doornenbal, J.C. and Stevenson, A.G. (editors): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 149-173.

1 Introduction

Triassic rocks extend across the SPB area from the UK to eastern Poland and Lithuania. They also extend beyond the area, northwards into northern Denmark and the central and northern North Sea, and southwards into southern Germany, northern Switzerland and eastern France (see **Figures 9.2** to **9.7**). An understanding of the Triassic in terms of basin development and depositional history can be obtained only by taking a regional view. Early work by Ricour (1963), Wurster (1964, 1968), Wolburg (1969), Warrington (1970), Schröder (1982), Ziegler (1982b, 1988, 1990a) and Jubitz et al. (1987, 1988) gives a general impression of the basin boundaries, main depocentres and depositional systems. However these publications were based mainly on outcrop data and onshore wells, and pre-dated the release of much commercial well and seismic data from areas such as the southern North Sea. In addition, the time intervals depicted on maps such as those of Schröder (1982) and Ziegler (1982b, 1990a) presented only a generalised picture.

New maps are now available for several parts of the SPB and adjacent areas. Lokhorst et al. (1998), Dercourt et al. (2000) and Gaetani (2000) published basinwide maps; maps of the United Kingdom and the UK southern North Sea sector were published by Warrington & Ivimey-Cook (1992) and Cameron et al. (1992) respectively, and of the central North Sea by Goldsmith et al. (2003). Wagner (1994), Kockel (1995), Baldschuhn et al. (1996, 2001), Dadlez et al. (1998) Szulc (2000) and DSK (2005) published maps of Germany and Poland. The maps of Kockel (1995), Baldschuhn et al. (1996), Dadlez et al. (1998) and Goldsmith et al. (2003) are based on extensive seismic and well data; those of Cameron et al. (1992) are based largely on well data and those of Warrington & Ivimey-Cook (1992) on outcrop and well data. A subcrop map and revised lithostratigraphic scale for the Belgian part of the Roer Valley Graben (Dusar et al., 2002) are compatible with those of the adjoining Dutch sector. Geluk (2005) combined this wealth of information with the regional stratigraphic framework to produce maps with a higher stratigraphic resolution. The maps shown in this chapter are based largely on those of Geluk (2005) and present a more detailed pan-European reconstruction of the Triassic depositional systems and basin development. Most of the data are derived from boreholes as Triassic outcrops are only found in parts of eastern England, northern Germany, southern Poland and on the island of Bornholm in the Baltic Sea (see Figure 1.6; Chapter 1). The main Triassic outcrops are outside the SPBA area in the central and western UK, eastern France and southern Germany.

The regional tectonostratigraphic correlation diagram (**Figure 9.1**) calibrates the stratigraphic intervals of the countries within the SPBA area. The maps presented show the main Triassic lithostratigraphic units, rather than time intervals, to avoid relating successions with insufficient biostratigraphic data to a chronostratigraphic framework. Log-correlation diagrams and thickness, structure and facies maps have been prepared for selected intervals, as it was not possible to do this for all (e.g. part of the Keuper Group and its equivalents) because of structural complexity and lack of data. The maps show the present-day distribution of individual stratigraphic units and the interpreted position of the basin margin during the deposition of each unit, taken mainly from published information (e.g. Ziegler, 1990a; Warrington & Ivimey-Cook, 1992; Beutler, 1998; Dadlez et al., 1998; DSK, 2005). Recent summaries of the SPB area in Triassic times are given by Feist-Burkhardt et al. (2008) and Stollhofen et al. (2008).

2 Stratigraphy

Friedrich von Alberti (1834) introduced the name 'Trias' for the tripartite succession in southern Germany, which he defined as a composite 'formation' consisting of:

- the predominantly continental 'Bunter Sandstein' (Buntsandstein, i.e. variegated sandstone), named by Abraham G. Werner (1786).
- the marine and hypersaline 'Muschelkalk' (i.e. bivalve limestone), named by G. C. Füchsel (1761).
- the continental, brackish and hypersaline 'Keuper' (a Franconian dialect term referring to brittle shales), named by Friedrich Hoffmann (1823) and Christian Keferstein (1824; cf. Hagdorn & Nitsch, 1999; DSK, 2005).

This classic tripartite succession is also referred to as the 'Germanic Triassic', and its depositional area as the 'Germanic Basin'. The German Triassic is now ranked as a lithostratigraphic supergroup consisting of three groups, the Buntsandstein, Muschelkalk and Keuper (e.g. Bachmann et al., 1999; DSK, 2002; **Figure 9.1**), each of which is divided into three subgroups (e.g. Lower, Middle and Upper Buntsandstein), which in turn consist of formations, most of which are subdivided into members.

The tripartite Triassic of Germany can be correlated across large parts of the SPB area, therefore the lithostratigraphic subdivisions and nomenclatures in neighbouring countries are similar to those used in Germany. However, in most cases the lithostratigraphic boundaries and names differ for historical reasons or because of facies changes. The major facies changes, and consequent changes in boundaries and nomenclature, are found towards the basin margins (e.g. in the UK southern North Sea sector, the eastern UK and northern Denmark). The UK lithostratigraphy developed independently in the onshore and offshore areas, giving rise to problems of spatial continuity of units; the onshore lithostratigraphy was based on mappable units (formations) (Warrington et al., 1980) whereas the offshore lithostratigraphy was derived from borehole geophysical logs (Rhys, 1974; Johnson et al., 1994).

As the German lithostratigraphic scheme is valid for large parts of the SPBA area, it is used as a reference to which other schemes are related in the correlation chart (**Figure 9.1**) and the chapter is also subdivided according to the German lithostratigraphy (e.g. Buntsandstein Group and equivalents). Recently, the Deutsche Stratigraphische Kommission (DSK, German Stratigraphic Commission) replaced many of the mostly ill-defined and sometimes confusing traditional German Triassic formation names with a simplified formal nomenclature (e.g. the name 'Unterer Gipskeuper' was replaced by Grabfeld Formation; DSK, 2005; Hagdorn & Simon, 2005; Nitsch, 2005). In **Figure 9.1** the former names are given in brackets. A combination of log correlations and, particularly in onshore areas, biostratigraphy has been used to compile the UK successions. It is important to note that some lithostratigraphic units, despite having the same name, may have different lithostratigraphic ranks and ranges in different countries, for example the Keuper Group of Germany and the Keuper Formation of the Netherlands.

Early attempts to correlate the Germanic Triassic with the open-marine Tethyan Triassic were somewhat imprecise regarding the stage boundaries (e.g. Salomon, 1926). The Germanic Triassic succession was correlated with the stages and substages of the international chronostratigraphic scale by Kozur (1972, 1974a, 1974b, 1975, 1984, 1993a, 1993b, 1998, 1999, 2003), Dockter et al. (1980), Kozur & Mock (1993) and Kozur & Seidel (1983a, 1983b). This was first achieved in the partly marine or marine Upper Buntsandstein, Muschelkalk and Lower Keuper successions and subsequently in the mostly continental Lower and Middle Buntsandstein subgroups and the Middle Keuper Subgroup. Most of these correlations have been confirmed or modified by ammonoid, bivalve, crinoid, conodont, conchostracan and palynological data (e.g. Warrington, 1970, 1996; Urlichs, 1978; Hagdorn & Gluchowski, 1993; Visscher et al., 1993; Urlichs & Kurzweil, 1997; Brack et al., 1999; Urlichs & Tichy, 1998, 2000; Bachmann & Kozur, 2004; Menning et al., 2005). As correlation with the Tethyan Triassic is best established in Germany and Poland, the German Triassic succession is again used as a reference in **Figure 9.1**.

Several intra-Triassic unconformities were noted by Trusheim (1961, 1963), Wolburg (1968, 1969), Beutler & Schüler (1978) and others. Most unconformities are especially obvious on swells (i.e. areas of reduced subsidence or episodic uplift) such as the Eichsfeld-Altmark Swell or East Netherlands Swell (see **Figure 9.10**) or towards the basin margins, as in north-eastern Poland. Substantial hiatuses are associated with the unconformities, especially in the Upper Triassic (**Figure 9.1**). There is uncertainty about some of these unconformities as they are largely undocumented in the UK and Denmark; however to present a consistent basin-centre to basin-margin correlation scheme their occurrence is projected in these areas and discussed in the text.

The newest and most reliable age data were used for the numerical calibration of the stage boundaries in **Figure 9.1**. Attempts to improve the numerical ages by astronomical calibration were also considered (Geluk & Röhling, 1997; Bachmann & Kozur, 2004; Hagdorn & Simon, 2005; Menning et al., 2005; Nitsch et al., 2005; Kozur & Bachmann, 2008). The Germanic Triassic is especially appropriate for such calibration as it has a well-developed cyclicity, both at outcrop and in well logs. Most cycles are between a few metres and more than 25 m thick. The cycles are mostly asymmetrical 'fining-upward', 'coarsening-upward' or 'shallowing-upward' cycles, similar to the 'parasequences' of sequence stratigraphy concepts, although they can sometimes be interpreted as more-or-less symmetrical 'transgressive-regressive cycles', 'base-level cycles' or 'high-frequency sequences'. The cycles are not all Milankovitch Cycles, but many of them seem to be well pronounced ~100 ka eccentricity cycles and ~20 ka precession cycles.

Sequence-stratigraphic methodology was first applied to the Germanic Triassic by Aigner & Bachmann (1992) and Van der Zwan & Spaak (1992). Later interpretations have preferred considering the cycles in terms of base-level changes (e.g. Köppen, 1997; Aigner et al., 1998). More than 12 third-order sequences or base-level cycles have been recognised, each bounded by more or less prominent unconformities (sequence boundaries). However, Szulc (2000) established 10 third-order sequences in the Anisian to Ladinian interval alone (Röt Formation to Grabfeld Formation). Major second-order depositional cycles (DC) have been described by Bachmann et al. (2008) in the uppermost Carboniferous to Recent fill of the SPB area, in which the Triassic comprises the upper part of DC 4, DC 5, and the lower part of DC 6 (Figure 3.1 and Annex 1 in Chapter 6).

There have been detailed magnetostratigraphic investigations in Poland (Nawrocki, 1997, 2004; Nawrocki & Szulc, 2000), Germany (Szurlies et al., 2003; Szurlies, 2004, 2007), and in the UK beyond the SPBA area (Hounslow & McIntosh, 2003; Hounslow et al., 2004). The magnetostratigraphy has consolidated the biostratigraphic correlation of the pan-European Triassic as it clarifies the relationships with Tethyan conodont-dated sections.

Some Triassic intervals have large differences in acoustic impedance and provide good seismic reflectors in some areas. In large parts of the basin, reflectors at the bases of the Buntsandstein Group and the Röt, Middle Muschelkalk and Middle Keuper evaporites are especially prominent, although most do not correspond with group or subgroup boundaries.

2.1 Buntsandstein Group and equivalents

In latest Permian to Anisian times, the evaporitic sabkha sedimentation of the uppermost Zechstein Group was replaced by predominantly fluvial, lacustrine and playa deposits of the Buntsandstein Group (Bachmann & Kozur, 2004). The group comprises three subgroups (**Figures 9.1** & **9.8**): the Lower Buntsandstein consisting of fine-grained clastics with prominent oolitic carbonate beds; the Middle Buntsandstein with coarser-grained clastic units alternating with oolites, oolitic sandstones and claystones; and the Upper Buntsandstein, or Röt Formation, composed of fine-grained clastics, evaporites and carbonates. This tripartite subdivision is recognisable throughout the SPB area.

The Permian-Triassic boundary (PTB) is placed in the lower part of the Lower Buntsandstein Subgroup, based on conchostracan biostratigraphy, C-isotopes and magnetostratigraphy (**Figure 9.1**; Ecke, 1986; Kozur, 1993a, 1993b, 1999; Szurlies et al., 2003; Bachmann & Kozur, 2004; Korte & Kozur, 2005; Hiete et al., 2006). PTB successions span the period of the largest mass extinction in Earth's history (Wignall, 1992), an event possibly caused by a combination of a fall in global temperature due to widespread volcanism in Siberia and China and a bolide (meteoric fireball) impact, followed by intense warming (Nikishin et al., 2002; Kozur, 2007). The event seems to correspond with the German Zechstein/Buntsandstein Group boundary where there was a rapid influx of sands, reflecting wetter conditions, and the occurrence of cosmic and volcanic microspherules (Bachmann & Kozur, 2003, 2004; Bachmann et al., 2004). However, the Permian/Triassic extinction is not easily recognised in the SPB area because the uppermost Zechstein sabkha deposits have very few fossils and the main extinctions in freshwater conchostracan and ostracod fauna occurred during the earlier Changhsingian (Late Permian), prior to deposition of the basal Buntsandstein Group sediments (Kozur, 1998). As seen elsewhere, stromatolites occur as 'disaster elements' above the PTB (Bachmann & Kozur, 2004).

During deposition of the Buntsandstein Group, the SPB area lay between 20° and 30°N (Feist-Burkhardt et al., 2008). The climate was semi-arid and sedimentation in the almost completely land-locked SPB was largely controlled by orbitally-driven Milankovitch wet-dry cycles with a periodicity of about 100 ka (Röhling, 1991, 1993; Geluk & Röhling, 1997, 1999; Bachmann & Kozur, 2004; Roman, 2004; Becker, 2005; DSK, 2005).

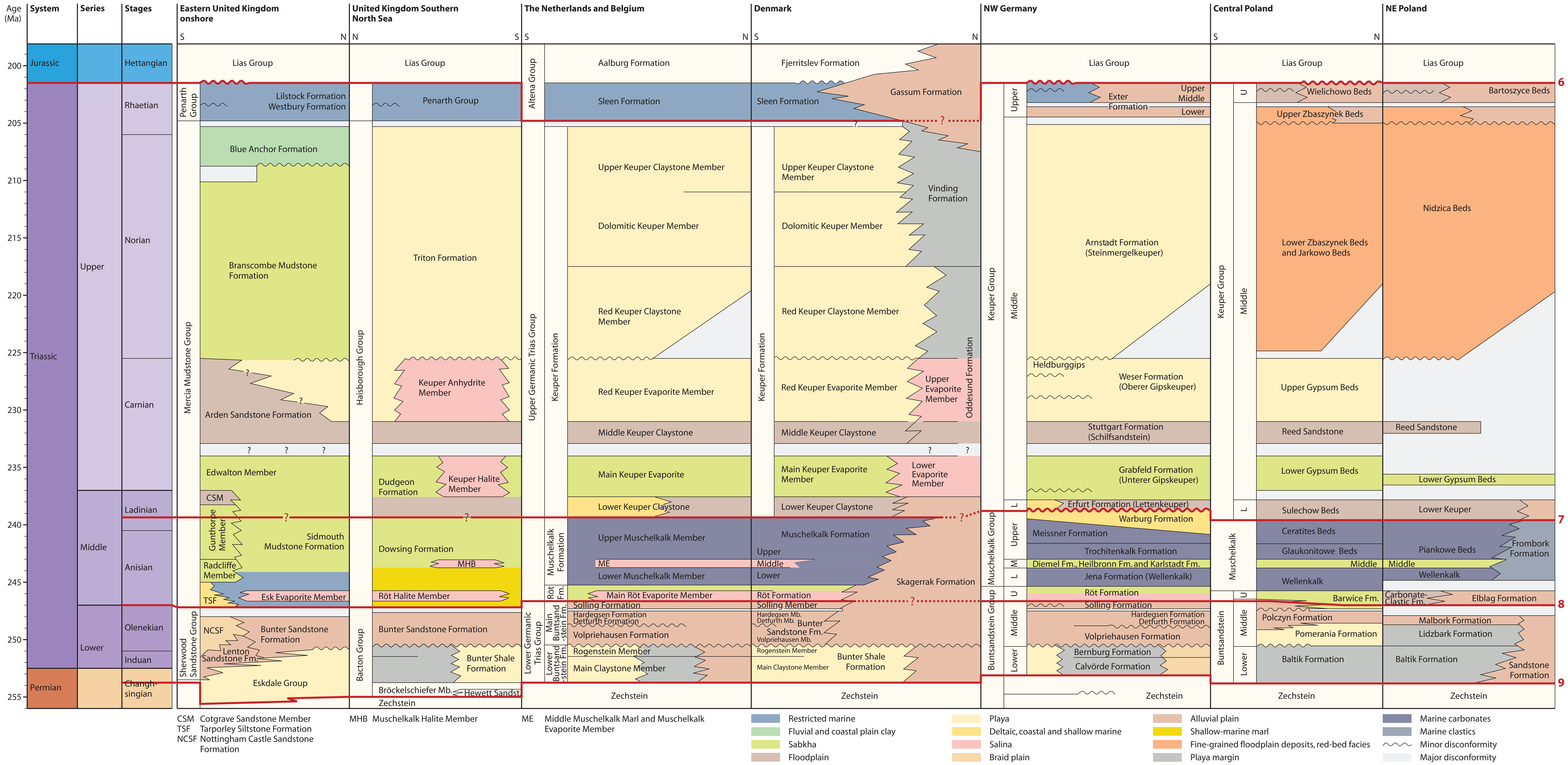


Figure 9.1 Triassic correlation chart. The red lines near the base of the Lower Jurassic (6), near the base of the Upper Triassic (7), near the base of the Middle Triassic (8) and at the base of the Buntsandstein Group and equivalents (9) are the lithostratigraphic horizons used in the depth maps in Figures 9.2, 9.4, 9.6 and 10.2 (see Figure 1.5).

Buntsandstein Group sedimentation began under gradually subsiding conditions; however this progressively changed with the development of swells and highs during deposition of the Middle Buntsandstein Subgroup. During deposition of the Upper Buntsandstein succession, subsidence occurred mainly in the North German Basin and a connection with Tethys was established in the eastern (Polish) SPB area (see **Figure 9.14**).

2.1.1 Lower Buntsandstein Subgroup and equivalents

The Lower Buntsandstein succession reflects gradual subsidence of the entire SPB area (**Figures 9.8, 9.10** & **9.11**). Minor synsedimentary fault movement took place in the Glückstadt Graben and possibly in the Horn Graben in north-west Germany (Frisch & Kockel, 2003). Elsewhere, broad undulating swells and lows resulted in a pattern of minor thinning and thickening.

In the western SPB area, the Lower Buntsandstein Subgroup is essentially a continental, fluviatile to lacustrine unit (Warrington, 1974; Ziegler, 1990a; Röhling, 1991; Cameron et al., 1992; Geluk, 1999b). However, in the eastern and central parts, microfossils (acritarchs, ostracods and foraminifers) indicate a marine influence that gave rise to brackish conditions (see below; Pieńkowski, 1991; summarised in Becker, 2005). The Lower Buntsandstein Subgroup and its equivalents form a distinctive succession with a high, blocky, gamma-ray signature (**Figure 9.8**). The subgroup comprises two fining-upward formations (**Figure 9.1**), which in turn consist of higher-order, wet-dry cycles (Brüning, 1986; Röhling, 1991, 1993; Geluk & Röhling, 1997, 1999; Szurlies, 1999; Szurlies et al., 2003; Roman, 2004).

During Induan times, the SPB area was not connected to the Tethys Ocean. Alluvial and fluvial deposits derived from the surrounding Variscan and older massifs (the London-Brabant, Rhenish and Bohemian massifs and the Fennoscandian Shield) accumulated in marginal areas and passed distally into finer-grained mud-flat and playa-lake margin sediments; an extensive playa lake developed in the most distal areas (**Figure 9.9**). More than 400 m of sediments accumulated in depocentres in the North German Basin and the Mid-Polish Trough (**Figures 9.2** & **9.10**).

In the German area, the main clastic input of the Lower Buntsandstein Subgroup came from the south via the Hessian and Thüringia-West Brandenburg depressions. The Ardennes-Eifel fluvial system transported clastics through the Roer Valley Graben into the Anglo-Dutch Basin and through the Ems Low into the North German Basin (Sindowski, 1957; Wolburg, 1961, 1962, 1968; Geluk et al., 1996; Geluk & Röhling, 1997, 1999). The main clastic input into the Polish region was from the southern and south-eastern margins of the SPB area (Marek & Pajchlowa, 1997). In the Netherlands, northern Germany and Poland, sands were confined to the basin margins (Wolburg, 1961; Szyperko-Teller & Moryc, 1988). To the west, arenaceous sediments transported by fluvial and aeolian processes from the Pennine High and the London-Brabant Massif prograded towards the Anglo-Dutch Basin depocentre (Warrington, 1974; Warrington et al., 1980; Cameron et al., 1992).

The Lower Buntsandstein Subgroup thins towards the bordering highs (**Figure 9.10**). A topography of subtle lows and swells developed during deposition of the upper part of the Lower Buntsandstein (Bernburg Formation). Carbonate oolites, the so-called 'Rogensteine' (roestones), formed in lakes on these swells, but were redeposited over larger areas during storms (Voigt & Gaupp, 2000). On the

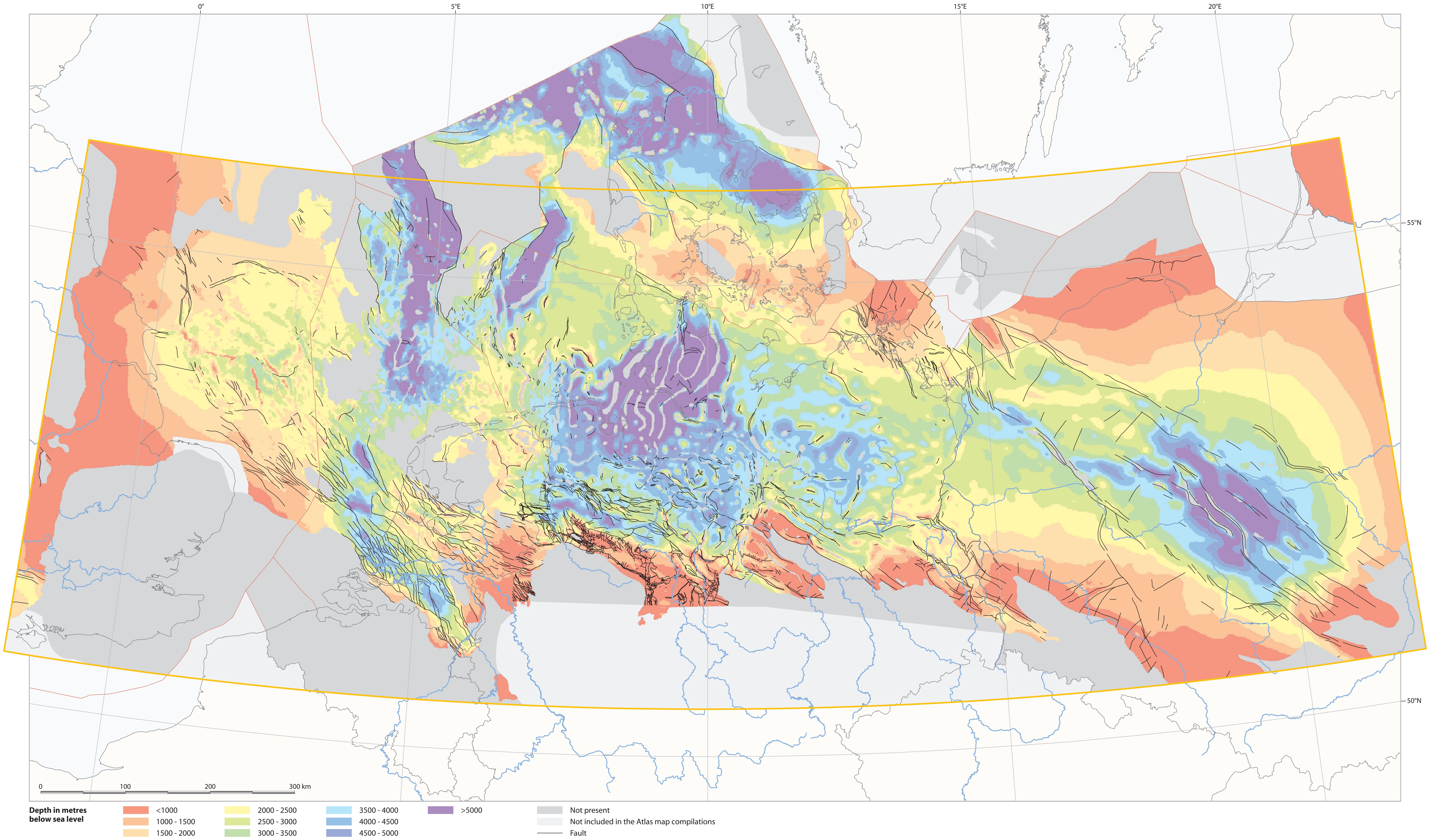


Figure 9.2 Depth to near base of the Lower Triassic (base of the Buntsandstein). This lithostratigraphic horizon is shown as Horizon 9 on Figures 1.5 and 9.1.

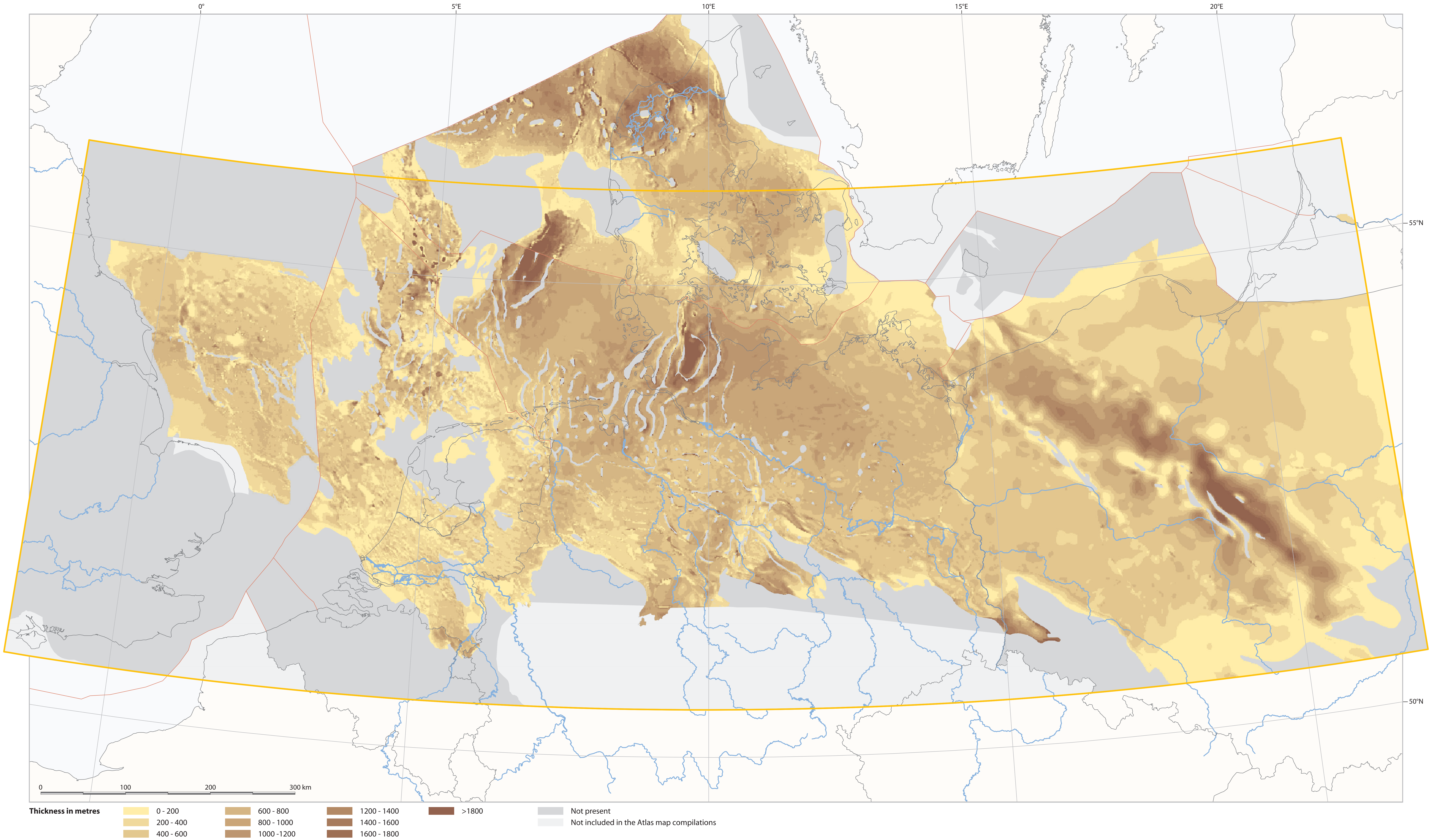


Figure 9.3 Thickness of the Lower Triassic.

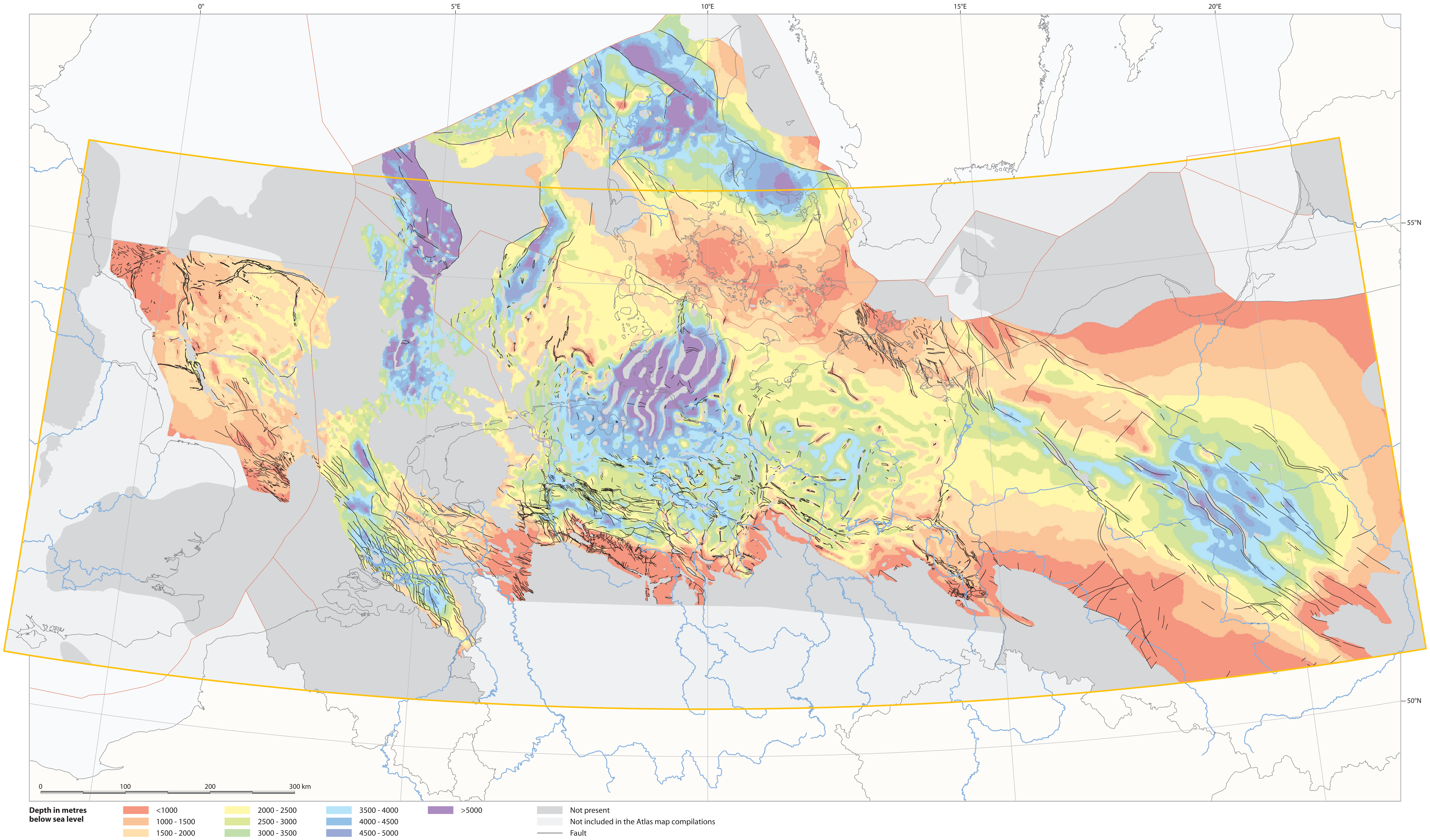


Figure 9.4 Depth to near base of the Middle Triassic (base of the Röt evaporites). This lithostratigraphic horizon is shown as Horizon 8 on Figures 1.5 and 9.1.

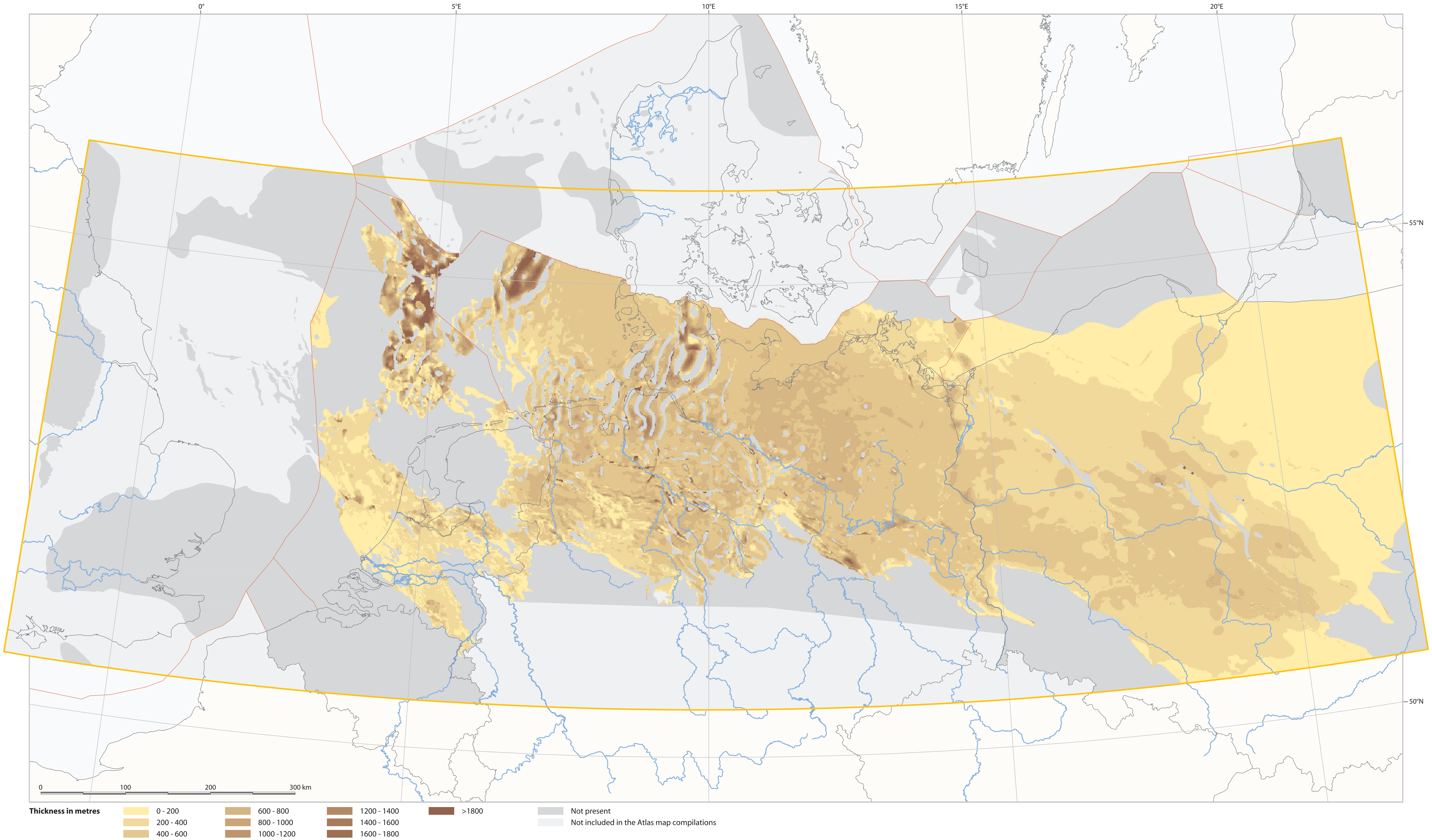


Figure 9.5 Thickness of the Middle Triassic.

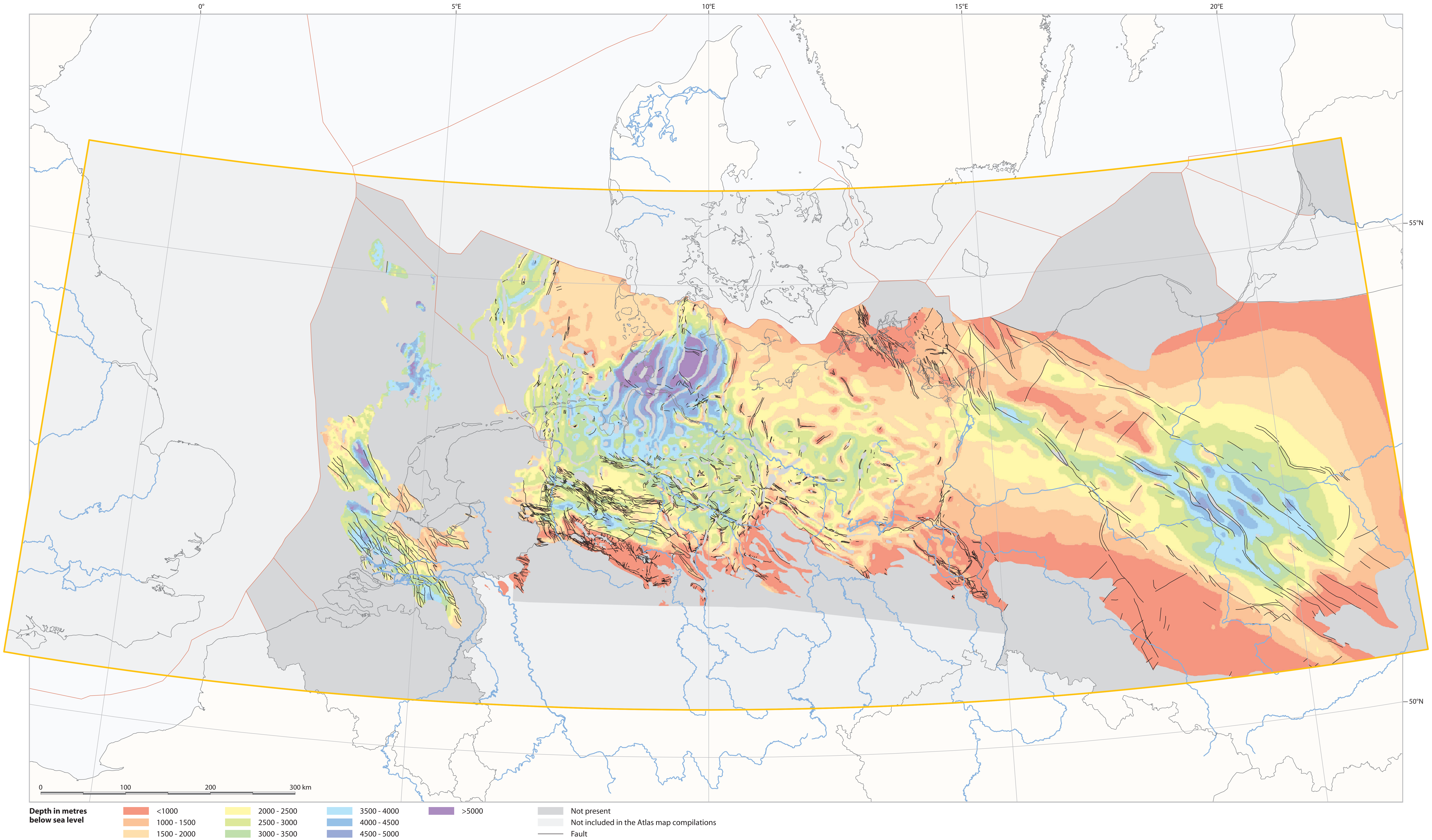
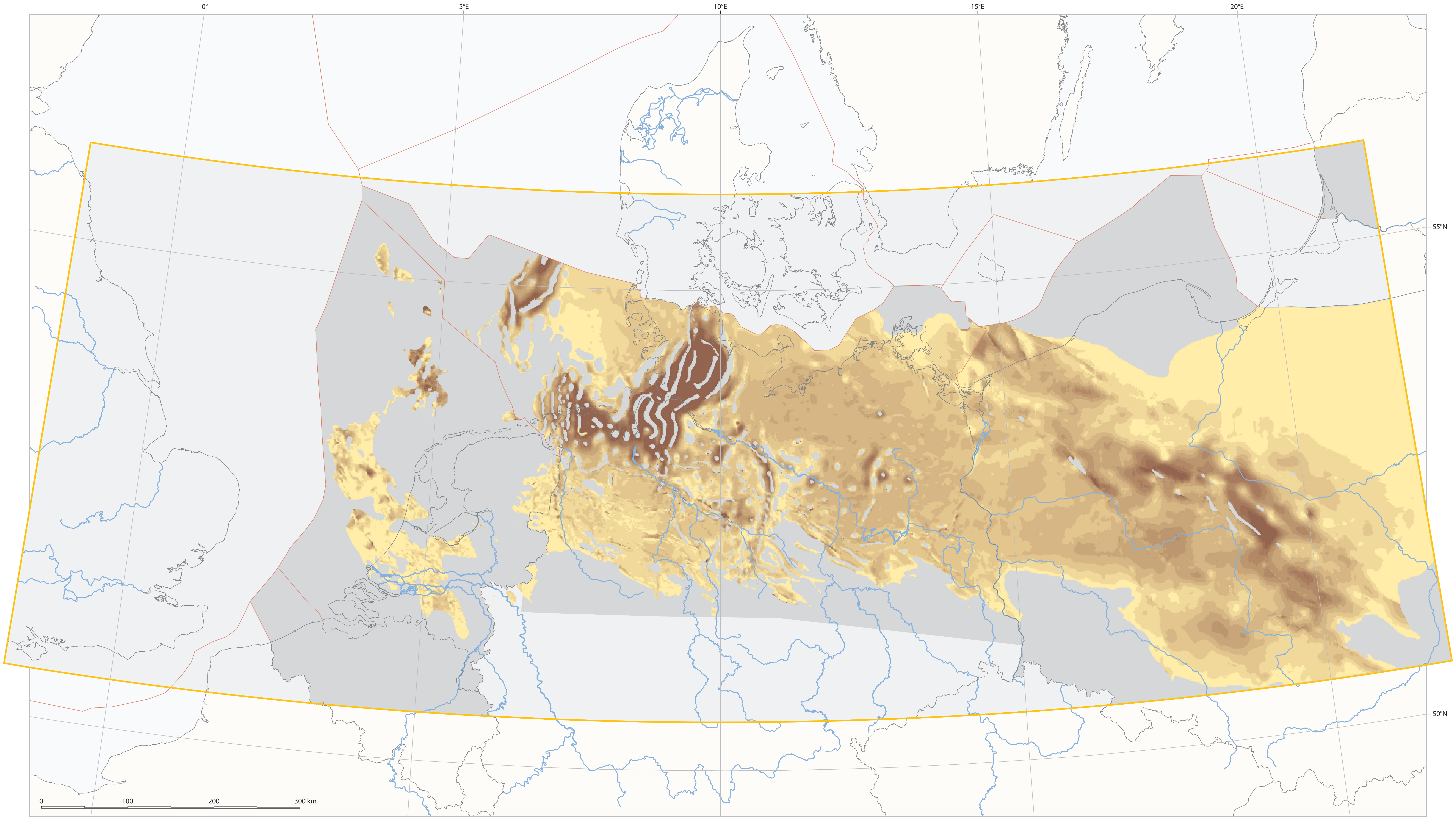


Figure 9.6 Depth to near base of the Upper Triassic. This lithostratigraphic horizon is shown as Horizon 7 on Figures 1.5 and 9.1.



Thickness in metres

0 - 200
200 - 400
400 - 600
600 - 800
800 - 1000
1000 -1200
1200 - 1400
1400 - 1600
1600 - 1800
>1800
Not present
Not included in the Atlas map compilations

Figure 9.7 Tickness of the Upper Triassic.

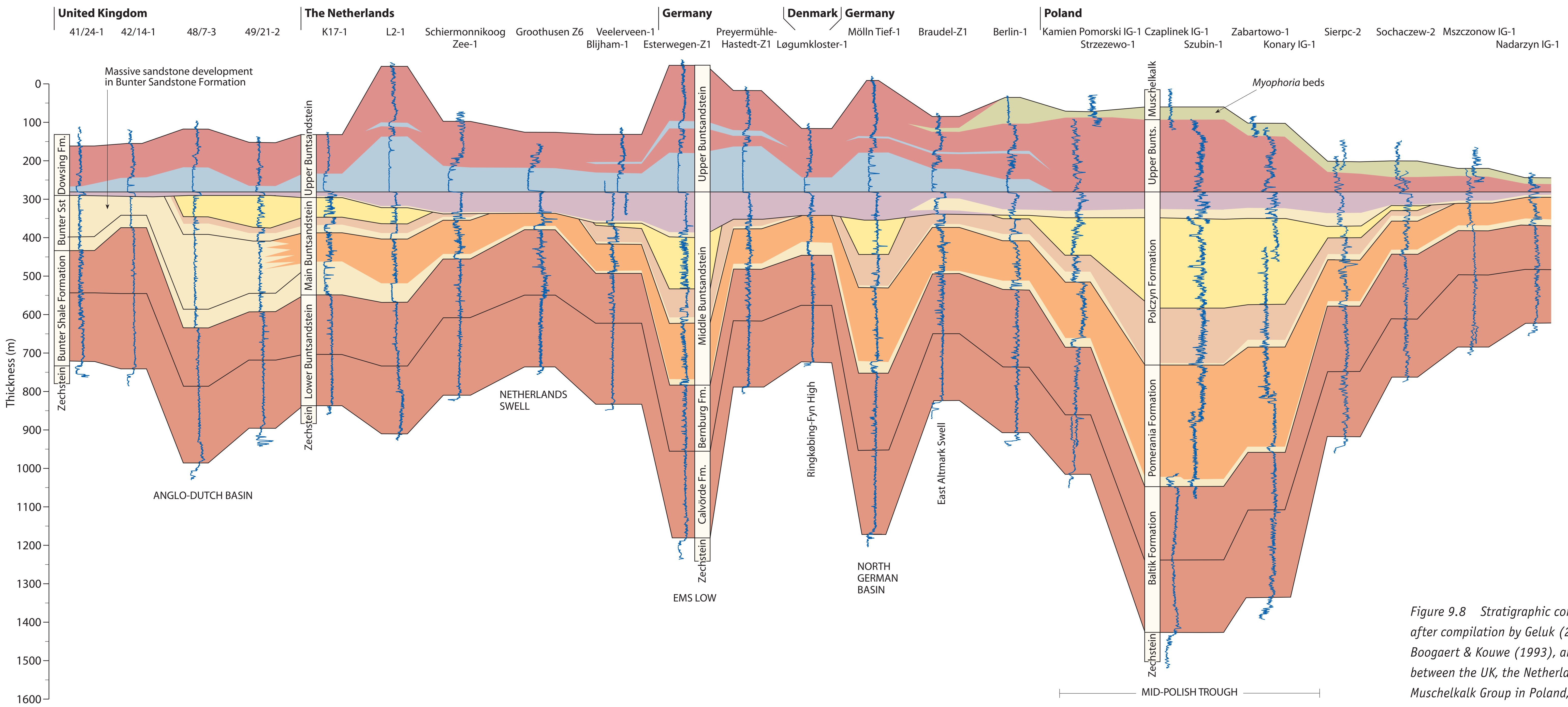


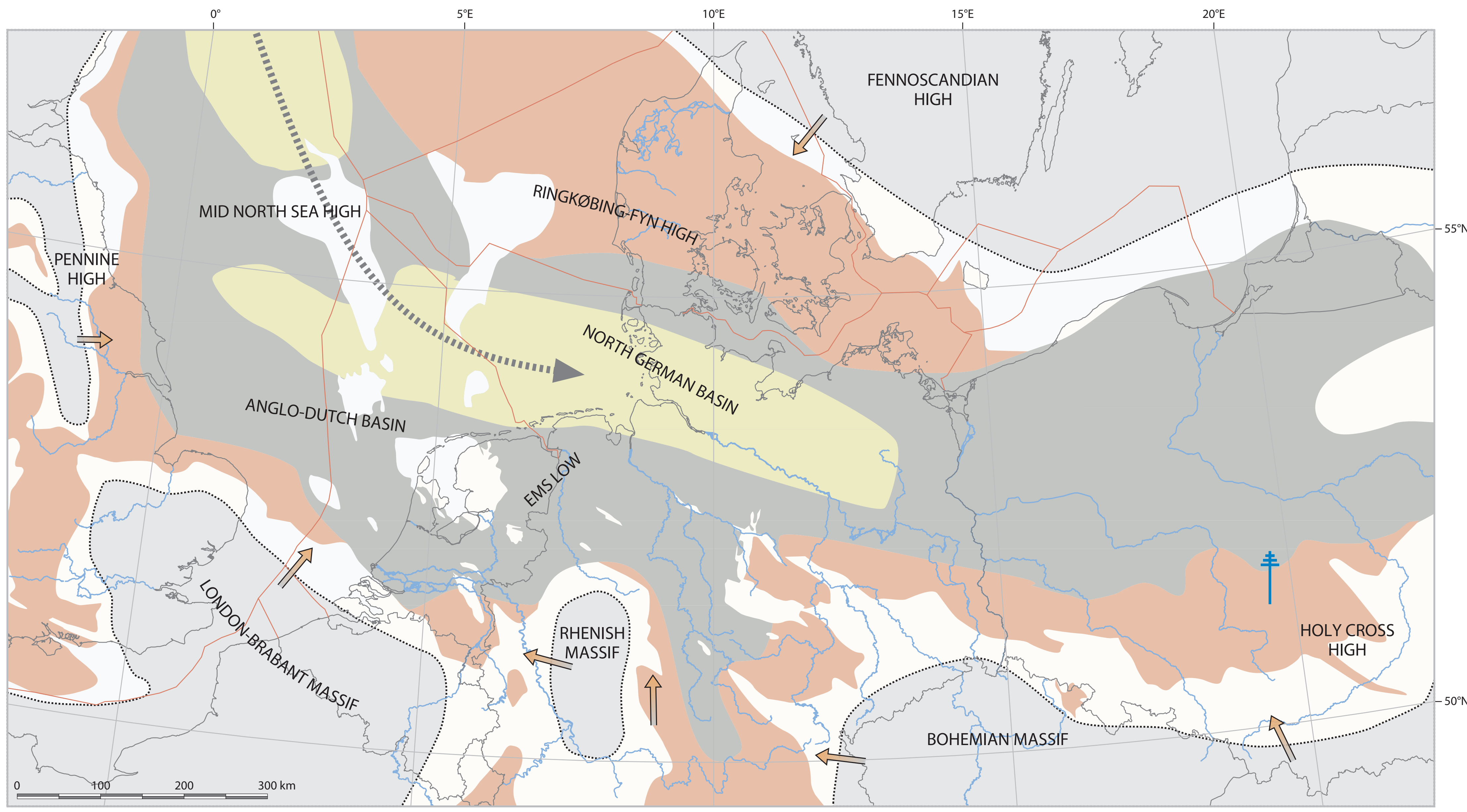
Figure 9.8 Stratigraphic correlation (gamma-ray logs) of the Buntsandstein Group between the UK and Poland. Modified after compilation by Geluk (2005) from Dadlez (1976), Bertelsen (1980), Marek (1983), Röhling (1991), Van Adrichem Boogaert & Kouwe (1993), and Johnson et al. (1994). Note the differences in the position of the base of the Triassic between the UK, the Netherlands and Germany. Also note the position of the Myophoria beds, which are included in the Muschelkalk Group in Poland, but in the upper part of the Röt Formation in Germany.

Eichsfeld-Altmark Swell (**Figure 9.10**), there are massive oolite beds up to 10 m thick, with ooids up to several millimetres in diameter associated with stromatolites up to 1 m thick (Paul & Peryt, 2000; Röber et al., 2006). The term 'oolite' was first used by Brückmann (1721), and the terms 'ooid' and 'stromatolite' by Kalkowsky (1908) in the Lower Buntsandstein of northern Germany (Burne & Paul, 2008).

In northern Poland, the Lower Buntsandstein Subgroup (Baltik Formation) comprises fine-grained clastics with a high oolitic carbonate content, similar to those in northern Germany. At the same time, predominantly coarse-grained, fluvial sediments, with some aeolian deposits, accumulated in southern Poland (Szyperko-Teller & Moryc, 1988). Aeolian dune bedding at the north-western margin of the Holy Cross Mountains indicates wind directions to the north (Gradziński et al., 1979) (**Figure 9.9**).

In the eastern UK, deposits interpreted as correlatives of the Lower Buntsandstein Subgroup form the unfossiliferous lower part of the Sherwood Sandstone Group and laterally equivalent parts of the Eskdale Group; the boundary is diachronous as the former prograded eastwards over the latter (Warrington, 1974a; Warrington et al., 1980; Warrington & Ivimey-Cook, 1992). In the UK southern North Sea sector, equivalent beds are termed the Bunter Shale Formation and include the Amethyst Member, a correlative of the rogenstein-bearing Bernburg Formation (Cameron et al., 1992; Johnson et al., 1994).

The degree of marine influence in the Lower Buntsandstein is debateable. Facies and isopach patterns seem to indicate that, contrary to the reconstructions of Goldsmith et al. (2003), there was a marine influx from the Boreal Sea to the north of the SPB area, through the North Sea rift system (Roberts et al., 1995; Beutler & Szulc, 1999). Some authors (e.g. Peryt, 1975) proposed a marine origin for the oolites and stromatolites, whereas others (e.g. Paul 1982a; Korte & Kozur, 2005; Korte et al., 2007) suggested that they are nonmarine. Foraminifera, acritarchs and sponges found in central Germany and Poland suggest a marine influence in these areas (Becker, 2005; Szulc, 2007); Pieńkowski (1991) related this to a global transgression at the beginning of the Triassic.



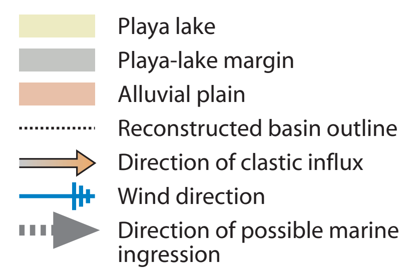


Figure 9.9 Present-day distribution and facies map of the Lower Buntsandstein Subgroup and equivalents (latest Permian to earliest Triassic). After Jubitz et al. (1987), Ziegler (1990a), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Tietze (1997), Dadlez et al. (1998), Geluk (1999b, 2005), Baldschuhn et al. (2001) and Goldsmith et al. (2003). Wind directions in Poland from Gradziński et al. (1979).

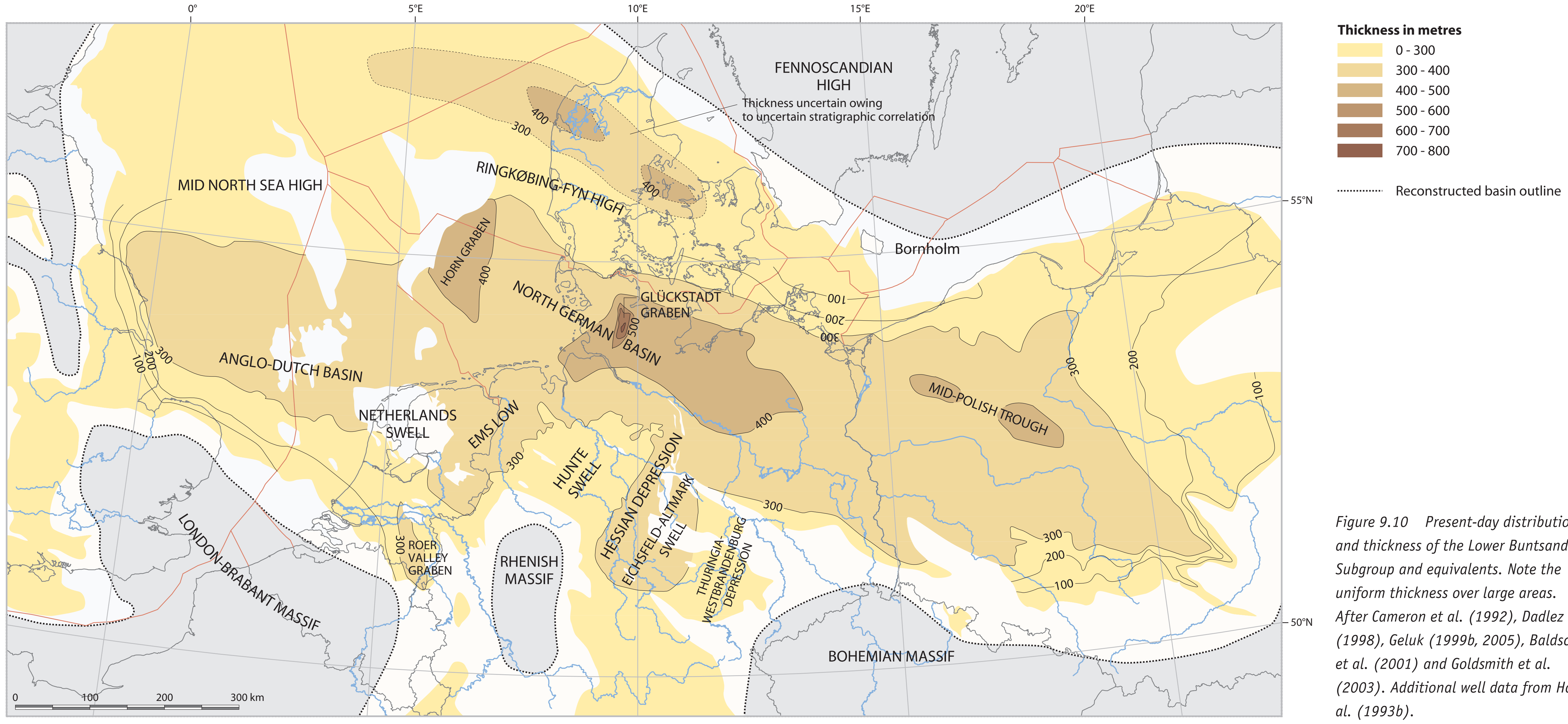


Figure 9.10 Present-day distribution and thickness of the Lower Buntsandstein Subgroup and equivalents. Note the uniform thickness over large areas. After Cameron et al. (1992), Dadlez et al. (1998), Geluk (1999b, 2005), Baldschuhn et al. (2001) and Goldsmith et al. (2003). Additional well data from Hoth et al. (1993b).

2.1.2 Middle Buntsandstein Subgroup and equivalents

An important structural reorganisation took place at the end of Lower Buntsandstein deposition, during the earliest Olenekian (Kozur, 1999; DSK, 2002, 2005). Tensional and transtensional stresses created north-north-east and west-north-westerly trending highs and lows that dissected the Lower Buntsandstein depositional areas and resulted in very variable amounts of subsidence (**Figures 9.8**, **9.12** & **9.13**). The sediment thickness reflects a combination of enhanced subsidence in the grabens, and uplift and erosion elsewhere (Geluk & Röhling, 1997, 1999; Frisch & Kockel, 2003). Five short-lived tectonic pulses (pre-Quickborn, pre-Volpriehausen, pre-Detfurth, pre-Solling and intra-Solling) have been identified within this tectonic phase; the strongest, the pre-Solling pulse (Röhling, 1991, 1999; Geluk & Röhling, 1997, 1999; Frisch & Kockel, 2003), gave rise to the Hardegsen Unconformity (Trusheim, 1961; Krämer & Kunz, 1969). These five pulses comprise the first tectonic phases that accompanied the breakup of Pangea (Ziegler, 1990a).

The Middle Buntsandstein Subgroup successions are especially thick in the Horn Graben (3500 m), Glückstadt Graben (2000 m), Mid-Polish Trough (more than 1000 m) and the Central Graben (500 m) (**Figure 9.12**). Numerous small faults and graben structures were active during deposition of the Middle Buntsandstein, in a pattern similar to that during Rotliegend deposition (cf. Figures 7.2 and 7.3). Subsidence of these grabens reflects west-north-west to east-south-east extension, with lateral movements accommodated by the Tornquist Fault Zone and other north-west trending faults.

In Germany, the Middle Buntsandstein Subgroup comprises the Volpriehausen, Detfurth, Hardegsen and Solling formations. These are tectonostratigraphic units bounded by unconformities, which can be recognised across much of the SPB area. The amount of erosion associated with the unconformities varies geographically. Pre-Volpriehausen erosion is noted mainly on the swells in Germany (Röhling, 1991), whereas pre-Detfurth erosion occurred in the southern Netherlands (Geluk et al., 1996). The most widely recognised unconformity is the pre-Solling, (Hardegsen, or H-) Unconformity (**Figure 9.13**).

Each of the Middle Buntsandstein Subgroup formations is a large-scale, fining-upward unit in which predominantly fluvial, aeolian and lacustrine shoreface sandstones grade upward into siltstone and claystone alternations (Geluk & Röhling, 1997, 1999). The basal sandstones of the Volpriehausen, Detfurth and Hardegsen formations form hydrocarbon reservoirs in the western SPB area (see field examples in Section 3.1).

Periodically higher rainfall in the hinterland led to an increase in fluvial activity and clastic input into the basin; sandy fluvial systems and shoreface facies prograded basinward. During the intervening drier periods, the sands were redistributed by aeolian processes, both in the basin (Fontaine et al., 1993) and in the surrounding mountains (Mader, 1983). The thickest and most stratigraphically complete sandstone successions were deposited in lows created by extensional tectonics; these successions onlapped the adjacent highs (Röhling, 1991; Geluk & Röhling, 1997, 1999; Geluk, 2005; **Figures 9.8** & **9.12**). A minor structural reorganisation between deposition of the Volpriehausen and Detfurth formations resulted in a shift in area of strongest subsidence from the Anglo-Dutch Basin and Roer Valley Graben to the North German Basin (Geluk & Röhling, 1997). The lows became increasingly isolated leading to more pronounced thickness and composition variations, mainly in the basal sandstones (Geluk & Röhling, 1997, 1999). A marked expansion of the playa lakes during wetter periods resulted in deposition similar to that of the Lower Buntsandstein.

Lacustrine conditions were more common during deposition of the middle and upper parts of the Middle Buntsandstein formations, when coarse-grained clastic deposits were confined mainly to the basin margins; the lake waters were brackish (Frisch & Kockel, 2003). In the UK southern North Sea, the Netherlands and southern Germany, the formations consist mainly of sandy facies (Geiger & Hopping, 1968; Cameron et al., 1992; Geluk et al., 1996).

The Volpriehausen and Detfurth formations and their equivalents are up to 200 m thick in the Central Graben and 100 m thick in the North German Basin and Mid-Polish Trough (Röhling, 1991; Roman, 2004; Geluk, 2005). The Hardegsen Formation comprises alternating thin-bedded sandstones, siltstones and claystones of mainly playa-flat and lacustrine origin. In contrast to north-western Germany (Röhling, 1991), there are only a few sandstones in the formation in the Netherlands. A significant number of sandstones are found in proximal areas such as the Hessian Depression, the southern Netherlands and the UK southern North Sea (Geluk & Röhling, 1999). As a result of pre-Solling uplift and erosion, only relics of the Hardegsen Formation remain, although they may be several hundreds of metres thick in the Horn and Central grabens, the Mid-Polish Trough and the Ems Low (**Figures 9.8** & **9.12**).

Marine ingressions during deposition of the Middle Buntsandstein Subgroup in Germany and Poland are confirmed by the presence of glauconite, acritarchs, sporadic foraminifers, ostracods and the bivalves *Bakevellia murchisoni* (Geinitz) and *Bakevellia*? *geinitzi* (Fritsch), referred to as *Avicula* or *Gervillea* in early works, as well as *Unionites* sp. (Wycisk, 1984; summarised in Becker, 2005). A connection to the Tethys Ocean through eastern Poland is generally favoured (**Figure 9.11**), and is compatible with the westward decrease of marine influence during early and mid-Buntsandstein times.

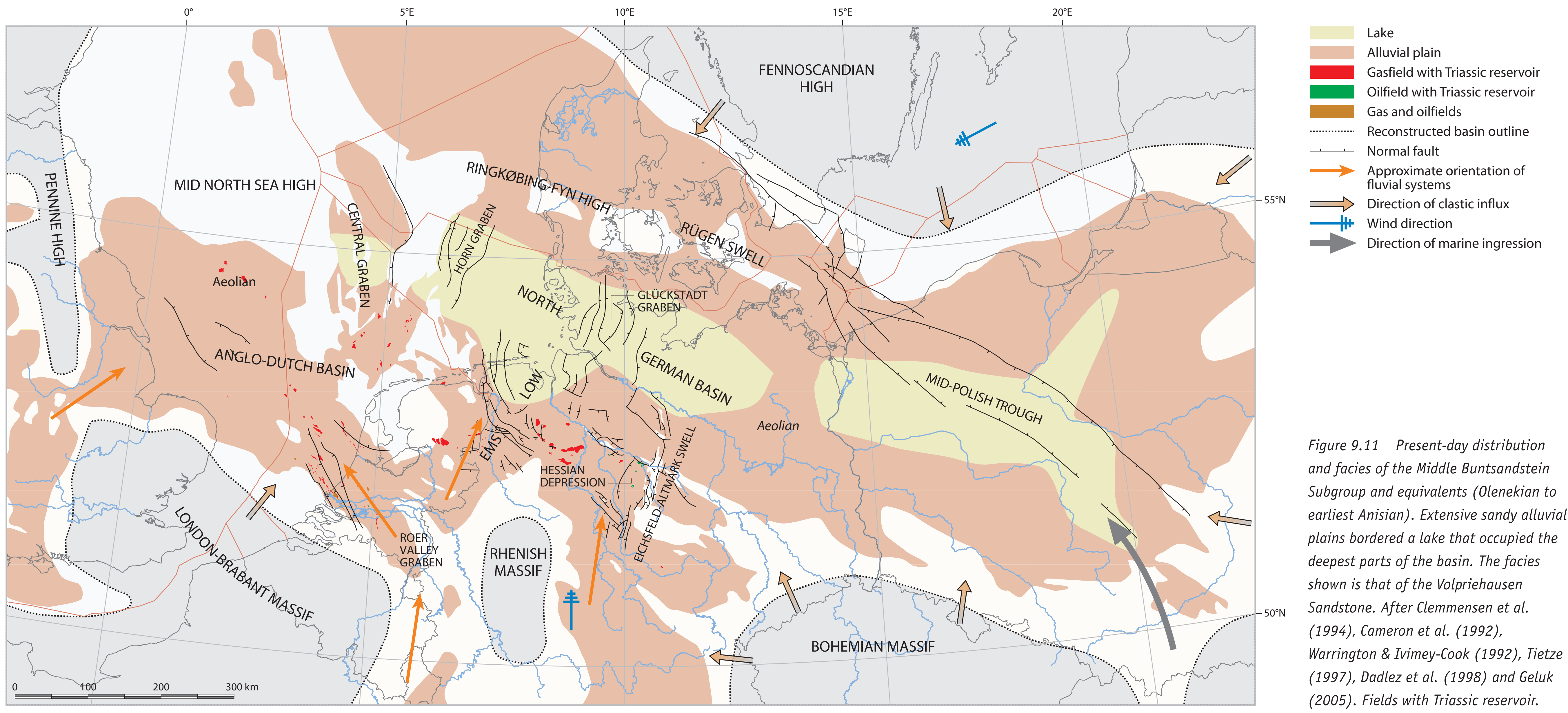


Figure 9.11 Present-day distribution and facies of the Middle Buntsandstein Subgroup and equivalents (Olenekian to earliest Anisian). Extensive sandy alluvial plains bordered a lake that occupied the deepest parts of the basin. The facies shown is that of the Volpriehausen Sandstone. After Clemmensen et al. (1994), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Tietze (1997), Dadlez et al. (1998) and Geluk (2005). Fields with Triassic reservoir.

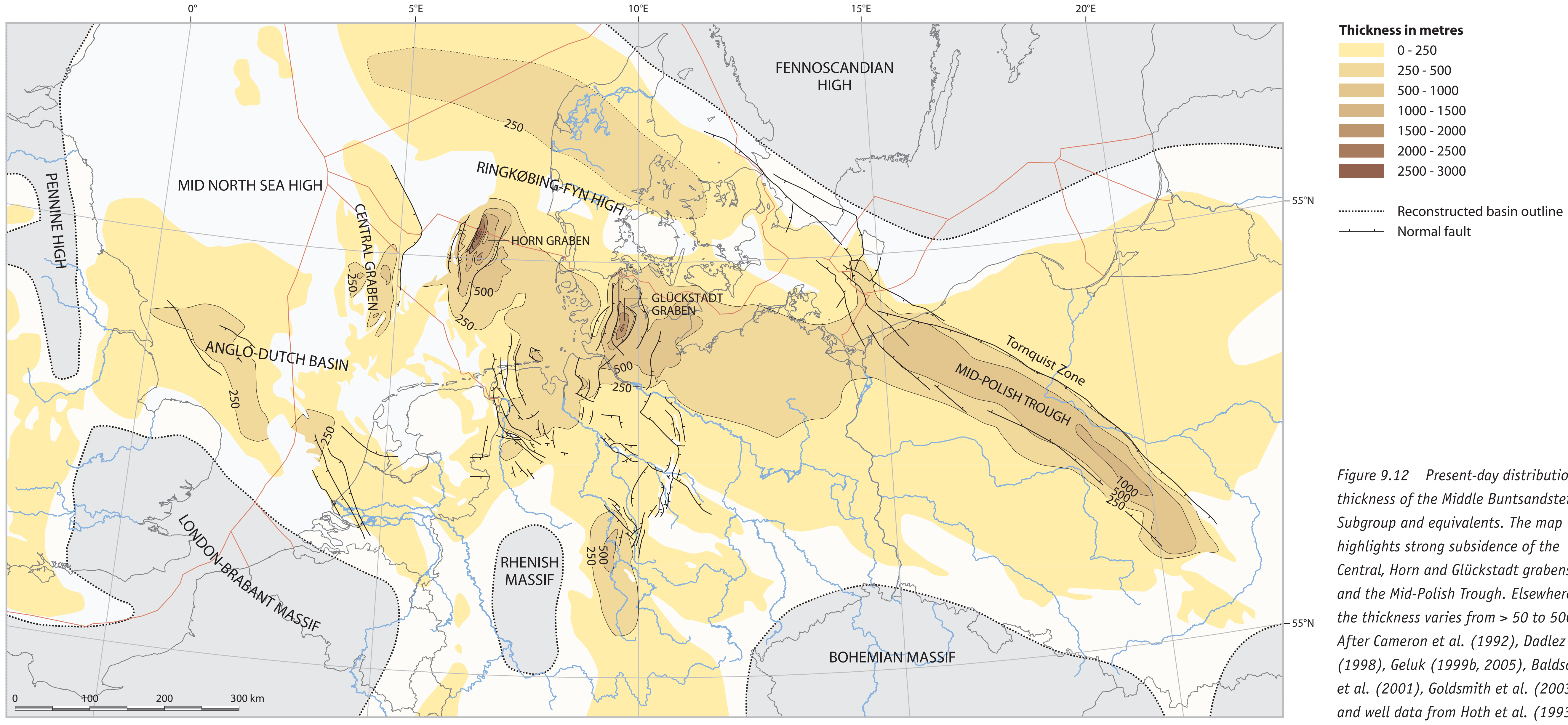


Figure 9.12 Present-day distribution and thickness of the Middle Buntsandstein Subgroup and equivalents. The map highlights strong subsidence of the Central, Horn and Glückstadt grabens and the Mid-Polish Trough. Elsewhere the thickness varies from > 50 to 500 m. After Cameron et al. (1992), Dadlez et al. (1998), Geluk (1999b, 2005), Baldschuhn et al. (2001), Goldsmith et al. (2003) and well data from Hoth et al. (1993b).

The Solling Formation rests unconformably on Lower and Middle Buntsandstein formations and pre-Triassic rocks separated by the pre-Solling (Hardegsen) Unconformity (**Figure 9.13**). The Solling Formation succeeded a tectonic re-arrangement of basin geometry and depositional conditions. The upper units of the formation are more closely related to the overlying Röt Formation than to older Middle Buntsandstein formations.

The thickest and most complete Solling Formation successions are found in the North German Basin and the northern part of the Hessian Depression, areas where greatest subsidence occurred. There was less subsidence in the Mid-Polish Trough and especially in the Anglo-Dutch Basin and probably the eastern UK, where only the upper part of the Solling Formation may be present (Geluk & Röhling, 1999; Geluk, 2005). The Anglo-Dutch Basin was an area of nondeposition during deposition of the lower parts of the Solling Formation and even of uplift prior to the intra-Solling unconformity (see below).

Rivers transported clastics into the SPB area from all sides, but mainly via the Hessian Depression (Bindig, 1992; Frisch & Kockel, 2003). An extensive playa lake occupied the central part of the basin (**Figure 9.11**) where occasional drying-out is recorded by desiccation cracks. In eastern Germany and the Mid-Polish Trough, the lower part of the Solling Formation is dominated by fluvial deposits and increasingly marine coastal clastic deposits occur towards its top (Roman, 2004; Becker, 2005).

In north-west Germany and the eastern Netherlands, aeolian sands (the Salzwedel and Dötlingen sandstones, respectively) occur in the lower part of the Solling Formation (NITG 1998, 2000; Schulz & Röhling, 2000). The dune areas were separated by an extensive playa-lake system that extended from the central SPB area into the present-day eastern Netherlands and southern Germany (Trusheim, 1963; Röhling, 1991). The playa deposits are dark grey mudstones with high gamma radiation (Trusheim, 1963; Baldschuhn et al., 2001).

Half-grabens in the Dutch North Sea sector are filled by middle Solling Formation aeolian sandstones (De Jager, 2007; De Jager & Geluk, 2007). The sandstones are related to an intra-Solling unconformity (referred to as the Solling unconformity; Krämer & Kunz, 1969; Rettig & Röhling, 1999) at the base of the Anisian (Bachmann & Kozur, 2004). Rifting was previously assumed to have started later, during deposition of the Röt Formation (Best, 1996; Thieme & Rockenbauch, 2001).

In the eastern UK, deposits interpreted as correlatives of the Middle Buntsandstein Subgroup form the unfossiliferous upper Sherwood Sandstone Group. Pebbly fluvial sandstones of the Nottingham Castle Sandstone Formation pass distally eastwards into non-pebbly sandstones of the Bunter Sandstone Formation, which extends offshore into the UK southern North Sea sector (Warrington, 1974a; Warrington et al., 1980; Cameron et al., 1992; Warrington & Ivimey-Cook, 1992; Johnson et al., 1994).

2.1.3 Upper Buntsandstein Subgroup (Röt Formation) and equivalents

Subsidence occurred mainly in the North German Basin during Upper Buntsandstein deposition (**Figure 9.14**). Tectonic activity only affected the lower evaporitic part of the Röt Formation. Sedimentary development was controlled by north-north-east-trending swells formed during the pre-Solling tectonic pulse, or Hardegsen phase (Frisch & Kockel, 2003; **Figures 9.13**, **9.14** & **9.15**). Isopachs of the Upper Buntsandstein Subgroup and the limit of the Röt Halite Member follow the contours of these highs, notably the Hunte and Eichsfeld-Altmark swells. In contrast, the earlier Cleaver Bank High and Netherlands Swell were covered by salt and the latter was also dissected by faults (Geluk, 1999b).

The Central, Horn and Glückstadt grabens were subjected to rapid subsidence. The Röt Formation is more than 300 m thick in parts of the Central Graben (Geluk, 1999). In the Horn and Glückstadt grabens, the local thickness of the combined Röt and Muschelkalk formations is up to 3000-4000 m (Baldschuhn et al., 2001). Differential movements ceased during deposition of the Röt Formation, as is reflected by less extreme thickness variations in the upper clastic part of the formation. Regional subsidence prevailed during deposition of the upper Röt Formation and the overlying Lower Muschelkalk Member. There were, however, some short-lived tectonic pulses, accompanied by regional uplift and erosion that resulted in a hiatus of up to 70 m (Röhling, 2005).

The transition from the Solling to the Röt Formation is marked by an increase in marine influence. A connection with the Tethys Ocean was established through the Silesian/Moravian and East Carpathian gates, resulting in deposition of the calcareous Rötdolomit and Rötkalk of southern Poland (**Figure 9.14**) (Trammer, 1972; Kozur, 1975). Open-marine conditions extended westwards to the central German area and eastwards to the foreland of the Holy Cross High (Szulc, 2000). In east Thüringia, the *tenuis* bed of the lower Röt Formation (Göschwitz Member) has yielded holothurians, molluscs (e.g. the bivalve *Costatoria costata* (Zenker) and the cephalopod *Beneckeia tenuis* (Seebach)) and reptiles that indicate marine conditions, although there are no crinoids, which were restricted to the Sub-Carpathian Depression.

The facies pattern of the lower Röt Formation is typical of a semi-closed evaporitic basin. Sea-water flowed over the East Brandenburg-Szczecin-Kalisz Swell, which only allowed a restricted connection between the Tethys Ocean and western SPB area (**Figure 9.13**). Arid conditions prevailed and a large salt basin

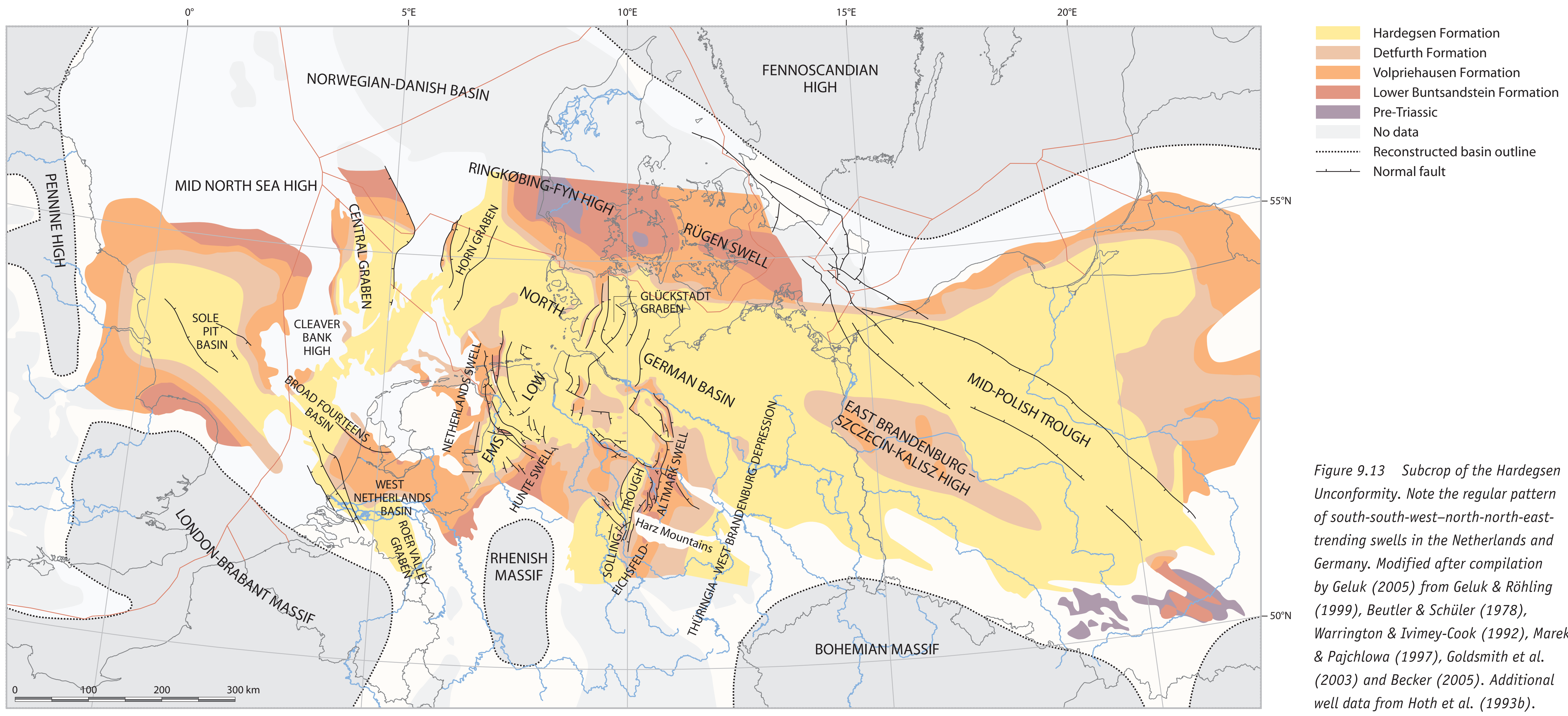


Figure 9.13 Subcrop of the Hardegsen Unconformity. Note the regular pattern of south-south-west–north-north-east-trending swells in the Netherlands and Germany. Modified after compilation by Geluk (2005) from Geluk & Röhling (1999), Beutler & Schüler (1978), Warrington & Ivimey-Cook (1992), Marek & Pajchlowa (1997), Goldsmith et al. (2003) and Becker (2005). Additional well data from Hoth et al. (1993b).

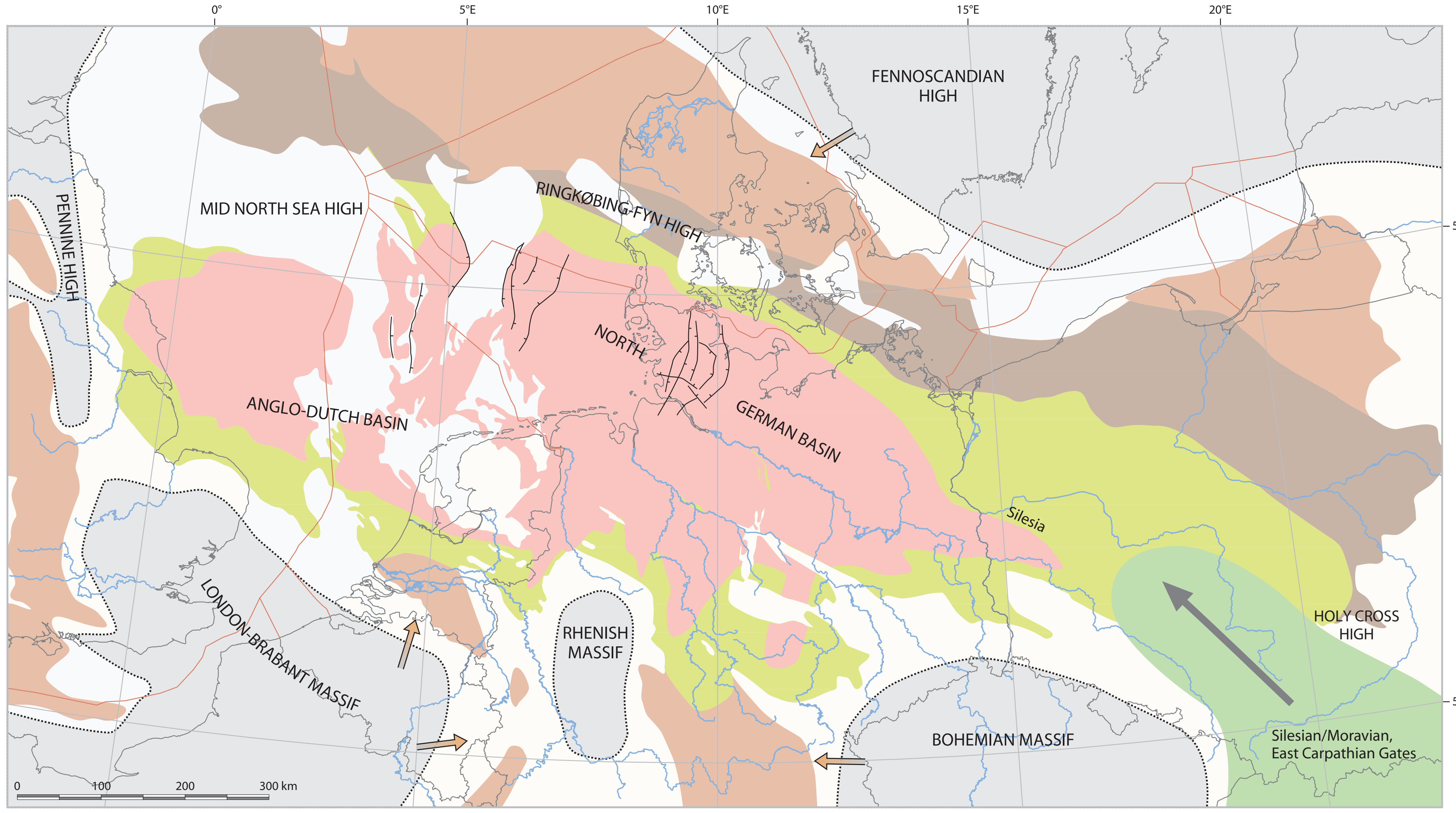


Figure 9.14 Present-day distribution and facies of the Upper Buntsandstein Subgroup (Röt Formation, early Anisian) and equivalents. After Wolburg (1969), Bertelsen (1980), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Dadlez et al. (1998), Geluk (1999b, 2005), Goldsmith et al. (2003) and Kędzierski (2007).

bordered by extensive sabkhas spread as far west as the area of north-east England (Warrington, 1974; Riddler, 1981; Schröder, 1982; Cameron et al., 1992; Geluk, 2005). The main depocentre was in northern Germany, but most of the Netherlands and the southern North Sea were also situated in this salt basin. Evaporites were not deposited in southern Germany (south of Stuttgart; Fels et al., 2003), north-east Poland and the southern Netherlands.

Following evaporite deposition, a large brackish-water lagoon developed, with deposits of fine-grained predominantly red clastics from which the name 'Röt' is derived. In the southern Netherlands and German part of the SPB area, the last fluvial coarse-grained clastic input came from the Variscan Mountains formed by the London-Brabant, Rhenish, Bohemian and Vindelician massifs, possibly reflecting an increase in humidity. South of the SPB area, in southern Germany and the Alsace region of France, conditions for plants and animals, including amphibians, were more favourable than during earlier Triassic times (Gall, 1971; Grauvogel-Stamm, 1978). However, the equivalent beds in the eastern UK, the Netherlands, north-west Germany and Poland may reflect occasional aridity.

A transgression began during this latest depositional phase of the Röt Formation and a shallow sea with carbonate sedimentation (*Myophoria* beds) gradually spread from Poland into eastern Germany (Kędzierski, 2002) heralding the Muschelkalk transgression that subsequently flooded the entire SPB area. However, in Poland, the corresponding Lower Gogolin Formation, with a stenohaline fauna, is included in the Lower Muschelkalk.

The correlatives of the Upper Buntsandstein Subgroup in the eastern UK form the lower part of the Mercia Mudstone Group. The inarticulate brachiopod *Lingula*, which indicates littoral conditions and a marine influence, is found in the lowest formation in that area (Rose & Kent, 1955), the Tarporley Siltstone Formation. This passes distally eastwards into the lower part of the finer-grained Sidmouth Mudstone Formation, including the Esk Evaporite Member, equivalent to the Röt Halite Member of the Dowsing Formation in the UK southern North Sea sector (Balchin & Ridd, 1970; Smith & Warrington, 1971; Warrington, 1974; Warrington et al., 1980; Riddler, 1981; Cameron et al., 1992; Warrington & Ivimey-Cook, 1992; Johnson et al., 1994; Hounslow & Ruffell, 2006; Howard et al., 2008).

2.2 Muschelkalk Group and equivalents

The carbonate-dominated Muschelkalk Group (Anisian and lower Ladinian) is divided into three subgroups and marks a fundamental change in palaeogeography (see **Figure 9.18**). A general sea-level rise and the opening of gateways in the south-east and south-west resulted in connections between the Tethys Ocean and that area. Up to 400 m of Muschelkalk Group sediments were deposited across much of the SPB (**Figures 9.16**, **9.21** & **9.22**). The combined thickness of the Röt Formation and Muschelkalk Group is up to 3000 m in the Horn Graben and 4000 m in the Glückstadt Graben (Baldschuhn et al., 2001).

The area of greatest subsidence during deposition of the Lower Muschelkalk Subgroup was in the North German Basin. Subsidence extended into the north-north-east-trending Hessian Depression and the Mid-Polish Trough during Upper Muschelkalk deposition (Beutler & Szulc, 1999; Dadlez et al., 1998). Deposition of the Muschelkalk Group took place at palaeolatitudes between approximately 25° to 35°N under relatively dry climatic conditions and, consequently, with low clastic influx from the surrounding highs.

More than 200 years of research has resulted in a very detailed lithostratigraphy for the Muschelkalk Group. The regional stratigraphy of the Germanic Basin has been established on the basis of conodonts and ammonoids (Kozur, 1968, 1974a, 1974b, 1975, 1999; Ulrichs, 1999; Narkiewicz & Szulc, 2004), and quasi-isochronous marker beds (Hagdorn & Simon, 1993, 2005; Kędzierski 2002; Lutz et al., 2005). Sedimentary cycles in the Muschelkalk are mostly interpreted as ~100 ka eccentricity cycles, which allow calculation of time spans and, in combination with isotopic dates and biostratigraphic data, correlation with Tethyan successions (Bachmann & Kozur, 2004; Menning et al., 2005).

This account is largely based on the work of Kozur (1974a, 1974b, 1975, 1999), Ziegler (1982b, 1990a), Baldschuhn et al. (2001), and Geluk (2005), with data on sequence stratigraphy from Aigner (1985), Aigner & Bachmann (1992) and Szulc (1999, 2000). For isotopic dates and chronostratigraphic correlation, see Bachmann & Kozur (2004), Menning et al., (2005) and Kozur & Bachmann (2008).

2.2.1 Lower Muschelkalk Subgroup and equivalents

Continuation of the earliest Anisian Röt transgression from Tethys via the East Carpathian and Upper Silesian gates led to deposition of the Lower Muschelkalk Subgroup (Kozur, 1968, 1974a, 1974b, 1975, 1980, 1999; Trammer, 1972; Brack et al., 1999; Szulc, 2000; Hagdorn & Simon, 2005). Marine conditions, which had been restricted to areas adjacent to these gates, expanded westwards during deposition of the uppermost Röt Formation (*Myophoria* beds), especially after another connection with Tethys, the Alemannic Gate, had opened. This gateway (formerly referred to as the 'Western Gate' by Szulc (2000)) was to the south of the SPBA area near the Alpenrhein Depression (Gisler et al., 2007; Götz & Gast, 2007) and was less important for the development of the area during Lower Muschelkalk deposition.

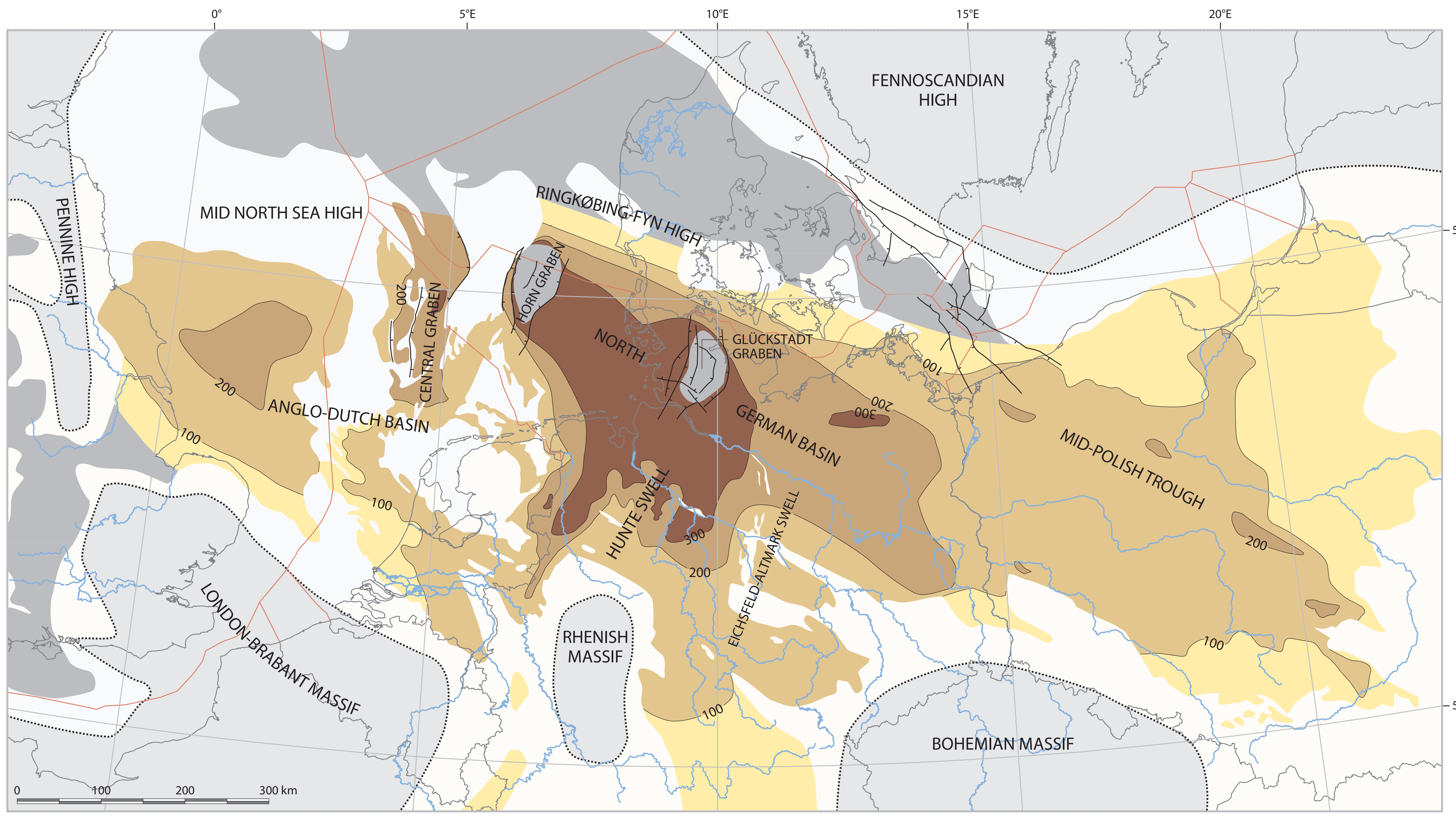
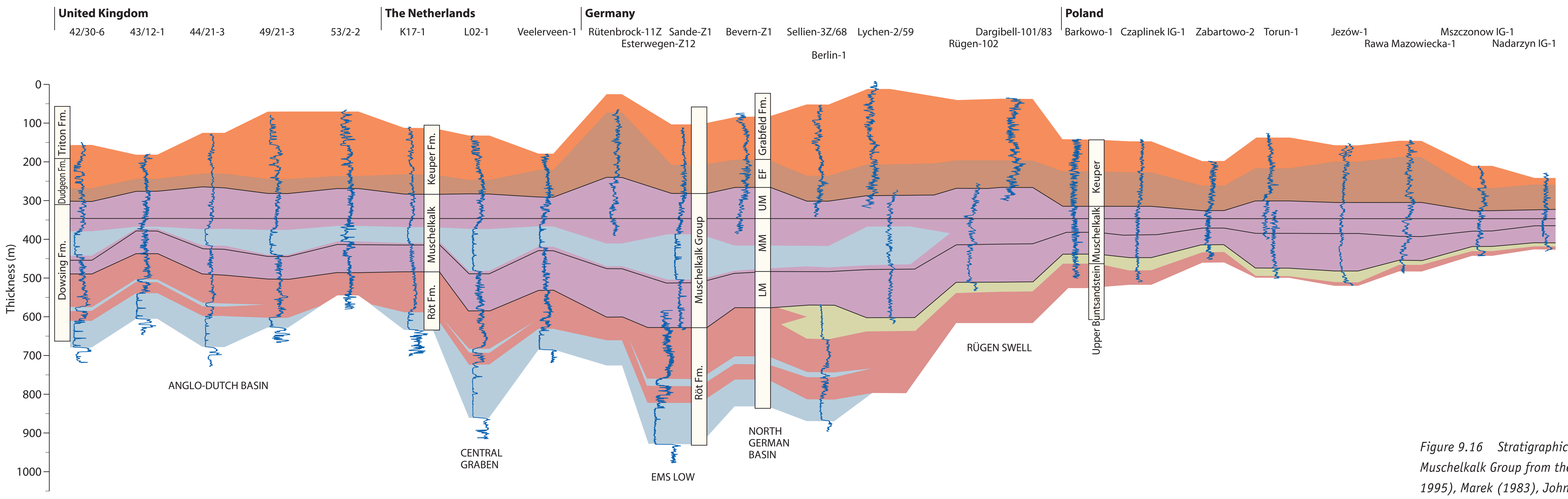


Figure 9.15 Present-day distribution and thickness of the Upper Buntsandstein Subgroup (Röt Formation) and equivalents. After Wolburg (1969), Bertelsen (1980), Cameron et al. (1992), Marek & Pajchlowa (1997), Tietze (1997), Geluk (1999b, 2005), Baldschuhn et al. (2001) and Goldsmith et al. (2003). Additional well data from Hoth et al. (1993b).



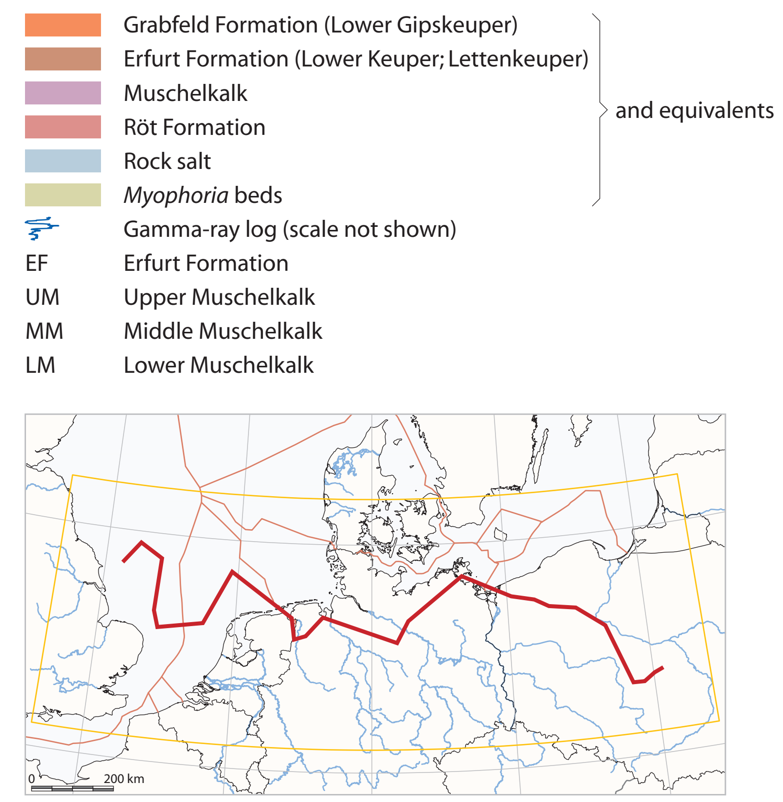
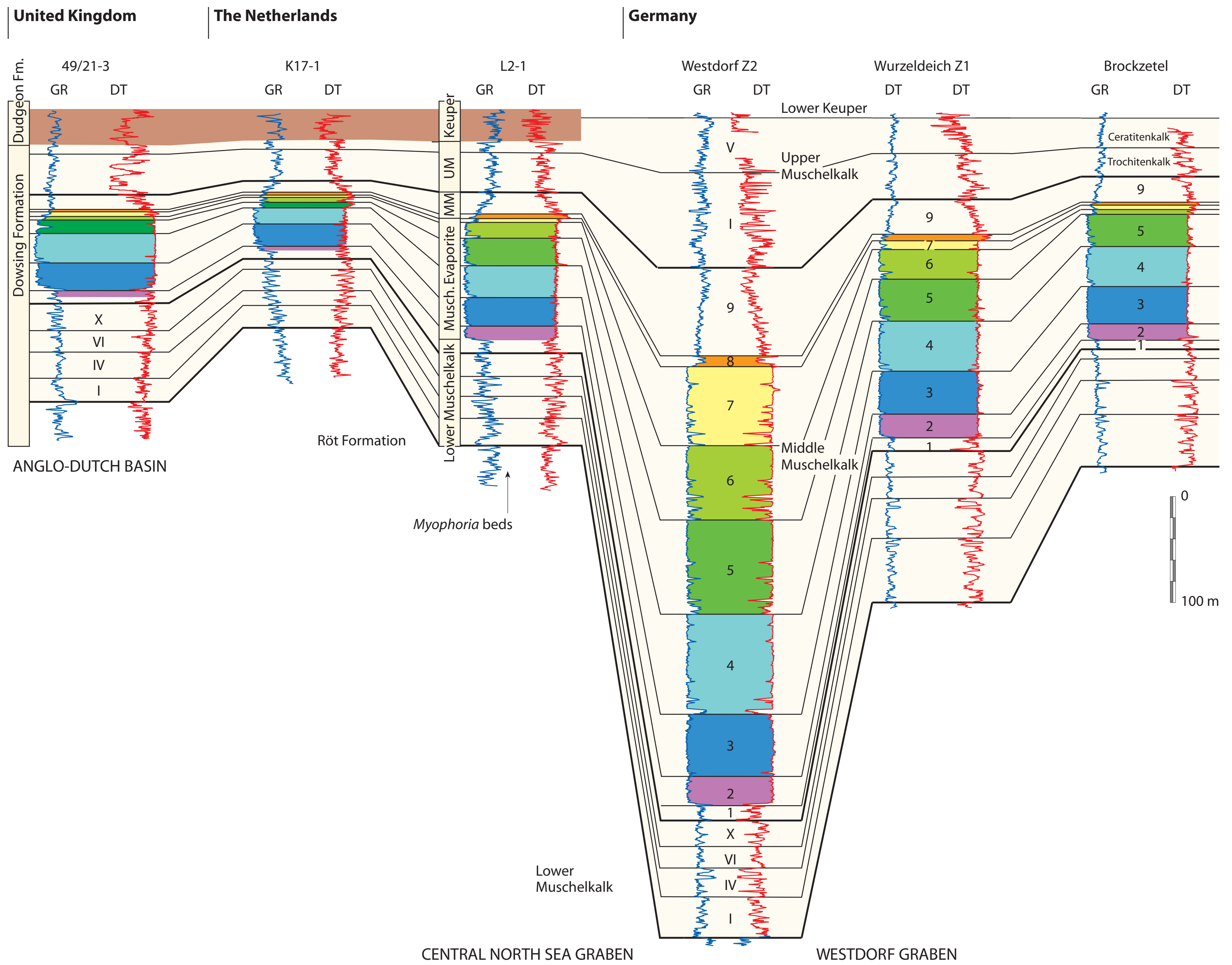


Figure 9.16 Stratigraphic correlation (gamma-ray logs) of the Upper Buntsandstein Subgroup (Röt Formation) and Muschelkalk Group from the UK into Poland. After compilation by Geluk (2005) from Dadlez (1976), Beutler (1980, 1993, 1995), Marek (1983), Johnson et al. (1994), Van Adrichem Boogaert & Kouwe (1993) and Marek & Pajchlowa (1997).

The Lower Muschelkalk transgression, though punctuated by minor short-lived regressions, gradually pushed the red, lagoonal, silty and sandy Röt facies westwards throughout a period of some 300 to 500 ka, until a shallow epeiric sea extended from eastern Poland to the southern North Sea area (**Figure 9.18**). The deposits in this sea were cyclic successions of alternating thinly bedded marls and marly limestones (the Wellenkalk facies of the Jena Formation in Germany), generally up to 130 m thick or 220 m in grabens (Bachmann & Kozur, 2004; Götz, 2004; Geluk, 2005; Menning et al., 2005). In the western SPB, the cycles contain biolaminates as well as bioclastic and oolitic marker beds, some of which are traceable for hundreds of kilometres. The stacked cyclic pattern was driven by transgressive-regressive sea-level oscillations. Desiccation cracks and reptile tracks at Winterswijk in the eastern Netherlands (Diedrich, 2001, 2008a, 2008b; Borkhataria, 2004; Borkhataria et al., 2006) indicate that the coastline was initially in the West Netherlands Basin and north of the Rhenish Massif. The marine influence extended as far north as the Norwegian-Danish Basin (Falster Formation; Bertelsen, 1980; Goldsmith et al., 2003).



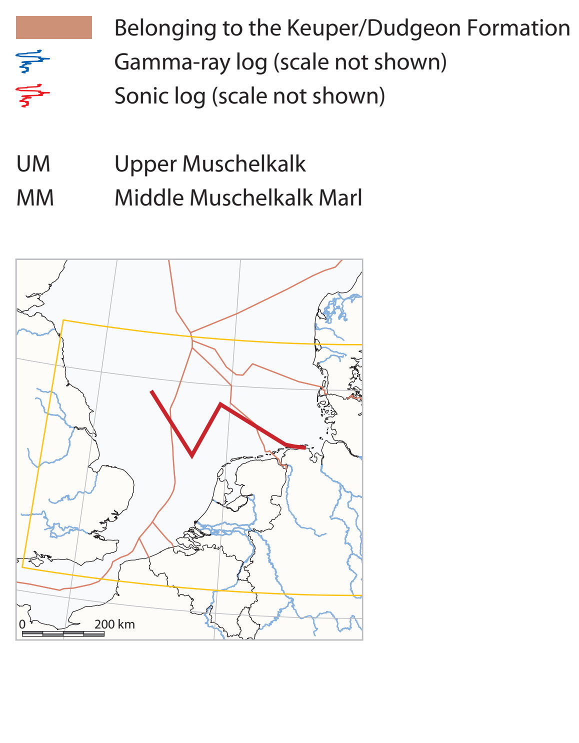


Figure 9.17 Detailed stratigraphic correlation (gamma-ray and sonic logs) of the Muschelkalk Group in the southern North Sea, the Netherlands and Germany. The main cycles of the Lower, Middle and Upper Muschelkalk subgroups are indicated and are traceable throughout a large area. Evaporitic cycles of the Middle Muschelkalk Subgroup have been highlighted. Towards the UK, the Lower and especially the Upper Muschelkalk subgroups grade into a clay-dominated succession, which is reflected in higher gamma-ray and sonic readings After Gaertner (1993), Brückner-Röhling (2000) and Geluk et al. (2000), with additional log data from Johnson et al. (1994).

The strongest marine influence was in the eastern SPB area where sediments in Upper Silesia (southern Poland) are characterised by coral and sponge buildups with a generally high diversity of Tethyan invertebrate faunas (Assmann, 1937, 1944; Bodzioch, 1994; Szulc, 2000; Morycowa & Szulc, 2006). Westward impoverishment of marine faunas reflects a salinity gradient. This faunal evidence is accompanied by a marked decrease in the limestone content of the Lower Muschelkalk Subgroup, which, in the UK southern North Sea sector, comprises mainly marls with thin marly limestone beds (Geiger & Hopping, 1968) that were deposited in a shallow-marine to lagoonal setting and form part of the Dowsing Formation (Cameron et al., 1992; Johnson et al., 1994; Hounslow & Ruffell, 2006). Correlative beds in eastern England form part of the Sidmouth Mudstone Formation (Howard et al., 2008) in which carbonates decrease and fine-grained clastics increase in a westward direction (Balchin & Ridd, 1970; Warrington, 1974) (**Figure 9.1**).

Subtle differences in water depth had a marked influence on the depositional environment. Shelly oolite bodies developed on palaeohighs near the coastline in various parts of the SPB area (e.g. Holy Cross High and Upper Silesia, south-west Poland; Brandenburg and Lausitz in eastern Germany; Szulc, 2000; Kędzierski, 2002), and in places were deposited throughout much of early Muschelkalk times.

2.2.2 Middle Muschelkalk Subgroup and equivalents

Falling sea level and tectonic movements in the area of the connecting gates restricted water exchange with Tethys and, under the prevailing arid to semi-arid climatic conditions, the SPB area became a large salina (**Figure 9.19**). Minor extensional tectonics enhanced subsidence in the Central, Horn and Glückstadt grabens, and other faults were reactivated in north-west Germany (Westdorf Graben), the UK southern North Sea sector (Dowsing Fault Zone) and the Mid-Netherlands Fault Zone (Geluk et al., 2000; Geluk, 2005), resulting in locally thicker and more complete salt successions (**Figure 9.17**). Fault-related subsidence also occurred in the north-north-east-trending Hessian Depression.

Marine dolomites were deposited in the south-west of the SPB area, close to the marine connections to Tethys (Assmann, 1937, 1944). However, there is a facies change to dolomitic marls with stromatolites (Karlstadt Formation) and a dramatic decrease in faunal diversity towards the west and the north. In the Brandenburg area, euryhaline molluscs, fish, and small pachypleurosaur and nothosaur reptiles indicate brief marine incursions. In the central and western SPB, the carbonates pass laterally into evaporites intercalated with dolomitic marls. The East Carpathian Gate was probably closed at that time as unfossiliferous dolomites were deposited at the southern margin of the Holy Cross High. Up to six gypsum-halite cycles were deposited in the western SPB area, whereas there are only two in eastern Germany and four in south-western Mecklenburg (Gaertner & Röhling, 1993; Brückner-Röhling, 2000). In the basinal facies of north-west Germany, the Middle Muschelkalk Subgroup is 125-150 m thick with more than 100 m of halite to the west of the lower River Elbe and in the Ems Low, thinning to less than 70 m towards the highs. The maximum thickness and greatest number of evaporite cycles are found in the grabens of the southern North Sea (Westdorf Graben, 170 m of halite in six cycles; Central Graben 300 m; Gaertner & Röhling, 1993).

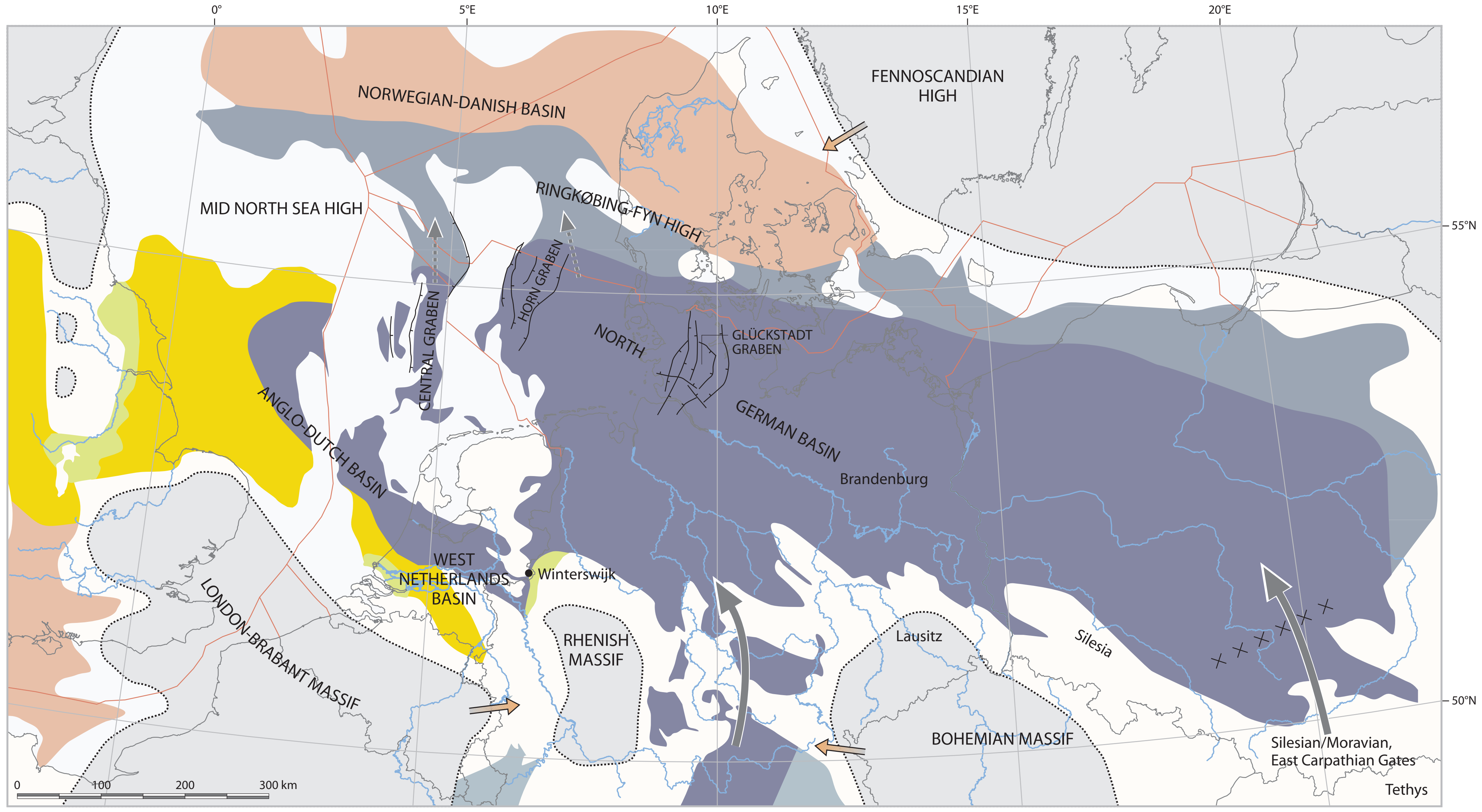


Figure 9.18 Present-day distribution and facies of the Lower Muschelkalk Subgroup and equivalents (Middle Anisian), showing the marine ingression from Tethys through the Silesian and Moravian gates in the east and the Alemannic gate in the SW. After Jubitz et al. (1988), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Marek & Pajchlowa (1997), Geluk (1999b, 2005) and Szulc (1999, 2000).

In the UK southern North Sea sector, correlative beds in the Dowsing Formation include the Muschelkalk Halite Member, which, unlike the Röt Halite Member, does not extend into eastern England (Warrington, 1974; Cameron et al., 1992; Warrington & Ivimey-Cook, 1992; Johnson et al., 1994). Correlative beds in eastern England occur in the Sidmouth Mudstone Formation (Howard et al., 2008), in which carbonates decrease and fine-grained clastics increase westwards (Balchin & Ridd, 1970; Warrington, 1974).

In north-east Germany and Poland, grey to reddish marls with charophytes and brackish-water ostracods indicate freshwater influx during late Middle Muschelkalk times (Kozur, 1974b; Bachmann & Kozur, 2004). At first, only euryhaline faunal elements, including dwarfed bivalves, siliceous sponges and ostracods, migrated into the SPB area following the opening of the Alemannic Gate. Stenohaline crinoids, conodonts, and cephalopods followed some 400 ka later. In north-east Germany and northern Poland, euryhaline elements persisted throughout late Muschelkalk times.

2.2.3 Upper Muschelkalk Subgroup and equivalents

A connection between the SPB area and the Tethys Ocean was re-established in late Anisian times and sea-water re-entered via the Burgundy and Alemannic gates to deposit marine carbonates in a shallow epeiric sea (**Figure 9.20**). The fossil record (Kozur 1974a, 1974b, 1975; Hagdorn & Simon, 1993; Szulc, 2000) indicates that the western gate(s) became the principal connection with the Tethys Ocean. In southern Germany and the Hessian Depression, the entire Upper Muschelkalk Subgroup is of carbonate facies with a marine fauna and may be more than 100 m thick. The Upper Muschelkalk Subgroup is up to 100 m thick in the central SPB area, where the upper part is mainly marls (Warburg Formation; Duchrow & Groetzner, 1984; Röhl, 1988; Gaertner, 1993), and up to 200 m thick in the Mid-Polish Trough (Dadlez et al., 1998). The equivalents of the carbonates of the Trochitenkalk and Meissner formations are traceable from the north-east Netherlands to Poland, where deposition of marls and shales began earlier than in Germany. The area with fully marine carbonate deposition was smaller than that of the Lower Muschelkalk Subgroup (cf. **Figures 9.18** & **9.20**).

In large parts of the SPB area, the Upper Muschelkalk Subgroup succession starts with thick-bedded crinoidal and shelly limestones (the Trochitenkalk Formation of north-west Germany). These are overlain by the Meissner and Warburg formations (**Figure 9.1**), deeper-water marly sediments characterised by abundant cephalopods and tempestite shell beds indicative of deposition between the normal and storm-wave base (Aigner, 1985). A younger belt of crinoidal limestones (upper Trochitenkalk, Willebadessen Member) that prograded north-eastwards (Kleinsorge, 1935; Röhl, 1988) surrounds the northern and western margin of the Rhenish Massif. A layer-cake, shoreline-detached, ooidal-grainstone complex with reservoir quality accumulated in the north-east Netherlands (Borkhataria et al., 2005; Pöppelreiter et al., 2005).

The Upper Muschelkalk Subgroup thins northwards towards the Rügen Swell and grades into reddish and greyish marls and dolomites deposited under brackish conditions (**Figure 9.21**) (Kozur, 1971, 1974a, 1974b, 1976; Althen et al., 1980; Beutler, 1993). In the north-east of the basin, marine sands of Fennoscandian provenance prograded as far south as northern Germany and north-eastern Poland (the 'Frombork Formation'). Continental conditions prevailed in the Norwegian-Danish Basin (Bertelsen, 1980; Goldsmith et al., 2003).

In the southern North Sea area, a predominantly marly succession, comprising the upper part of the Dowsing Formation and the lowest beds in the Dudgeon Formation, was deposited in a shallow-marine to lagoonal setting (Cameron et al., 1992; Warrington & Ivimey-Cook, 1992; Johnson et al., 1994). In eastern England, correlative beds form part of the Sidmouth Mudstone Formation (Howard et al., 2008) in which carbonates decrease and fine-grained clastics increase westwards (Balchin & Ridd, 1970; Warrington, 1974).

2.3 Keuper Group and equivalents

During the late Ladinian, the marine conditions of the Muschelkalk Group were rapidly replaced by deltaic, hypersaline and nonmarine environments of the Keuper Group, representing the upper Ladinian to Rhaetian successions of the Germanic Triassic (**Figures 9.22** & **9.23**). The Keuper Group is typically 400 to 600 m thick in most parts of the southern North Sea, northern Germany and Poland. Regional thickness variations were caused by halokinesis and early Cimmerian rifting and transpressional tectonics. Reduced thicknesses are common on swells, as indicated by erosional unconformities. However, thicknesses may increase to more than 2000 m in syndepositional grabens with up to 5000 m in the Glückstadt Graben (Frisch & Kockel, 1997, 1999; Barnasch et al., 2005; DSK, 2005; Barnasch, 2009).

The Keuper Group is divided into three subgroups (**Figures 9.1** & **9.22**). The Lower and Upper Keuper deposits are predominantly grey and accumulated in a range of environments from restricted marine to deltaic, estuarine, lagoonal, fluvial and lacustrine. In contrast, the varicoloured clastics, evaporites and carbonates of the Middle Keuper Subgroup were deposited mainly in ephemeral-lake and fluvial systems; pedogenic features are the most common indicator of their early diagenesis. Thin carbonate beds with impoverished marine faunas were deposited during brief marine ingressions into parts of the SPB area during sea-level highstands.

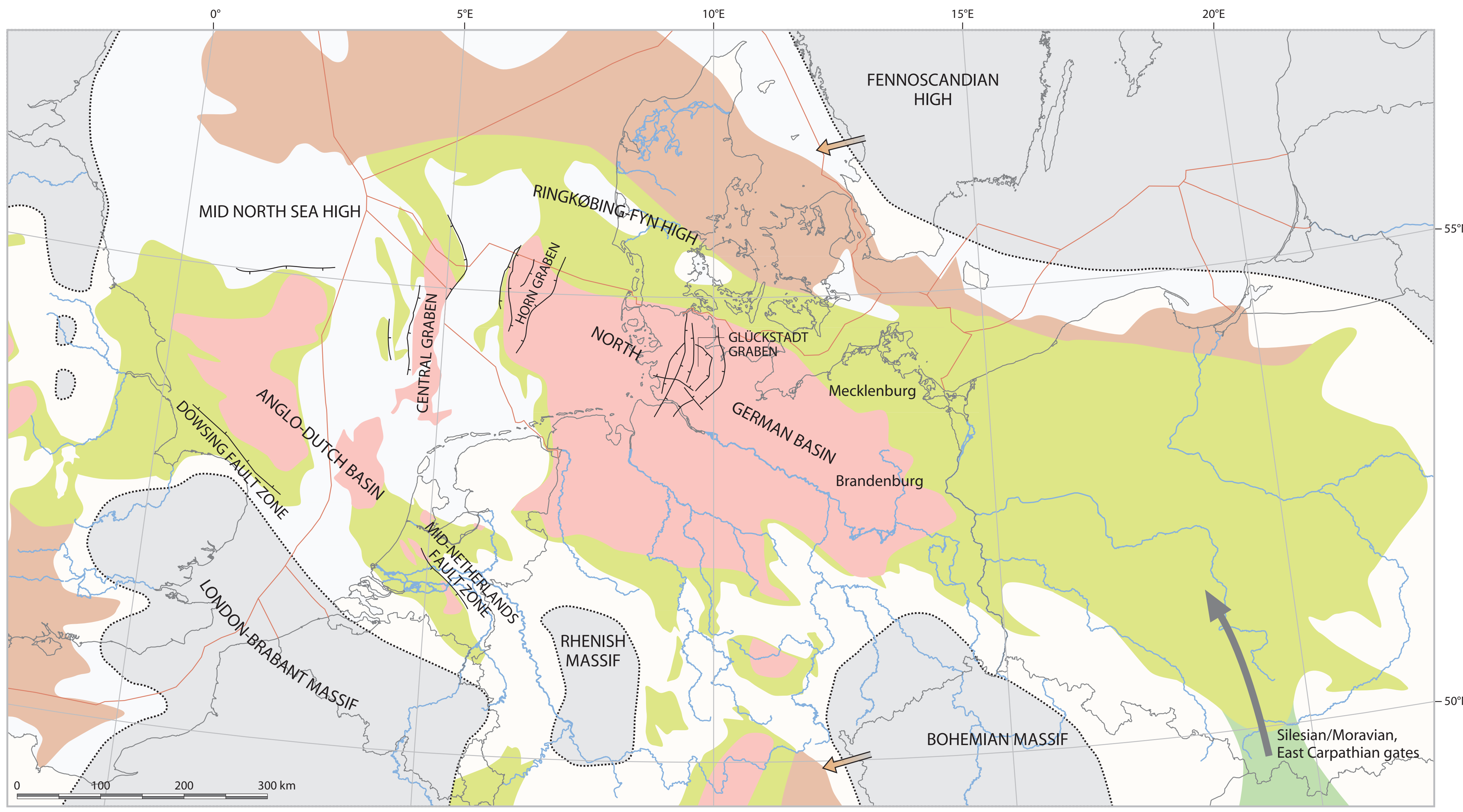


Figure 9.19 Present-day distribution and facies of the Middle Muschelkalk Subgroup and equivalents (late Anisian). After Bertelsen (1980), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Beutler (1993), Marek & Pajchlowa (1997), Geluk (1999b, 2005), Dadlez et al. (1998), Szulc (1999, 2000) and Goldsmith et al. (2003).

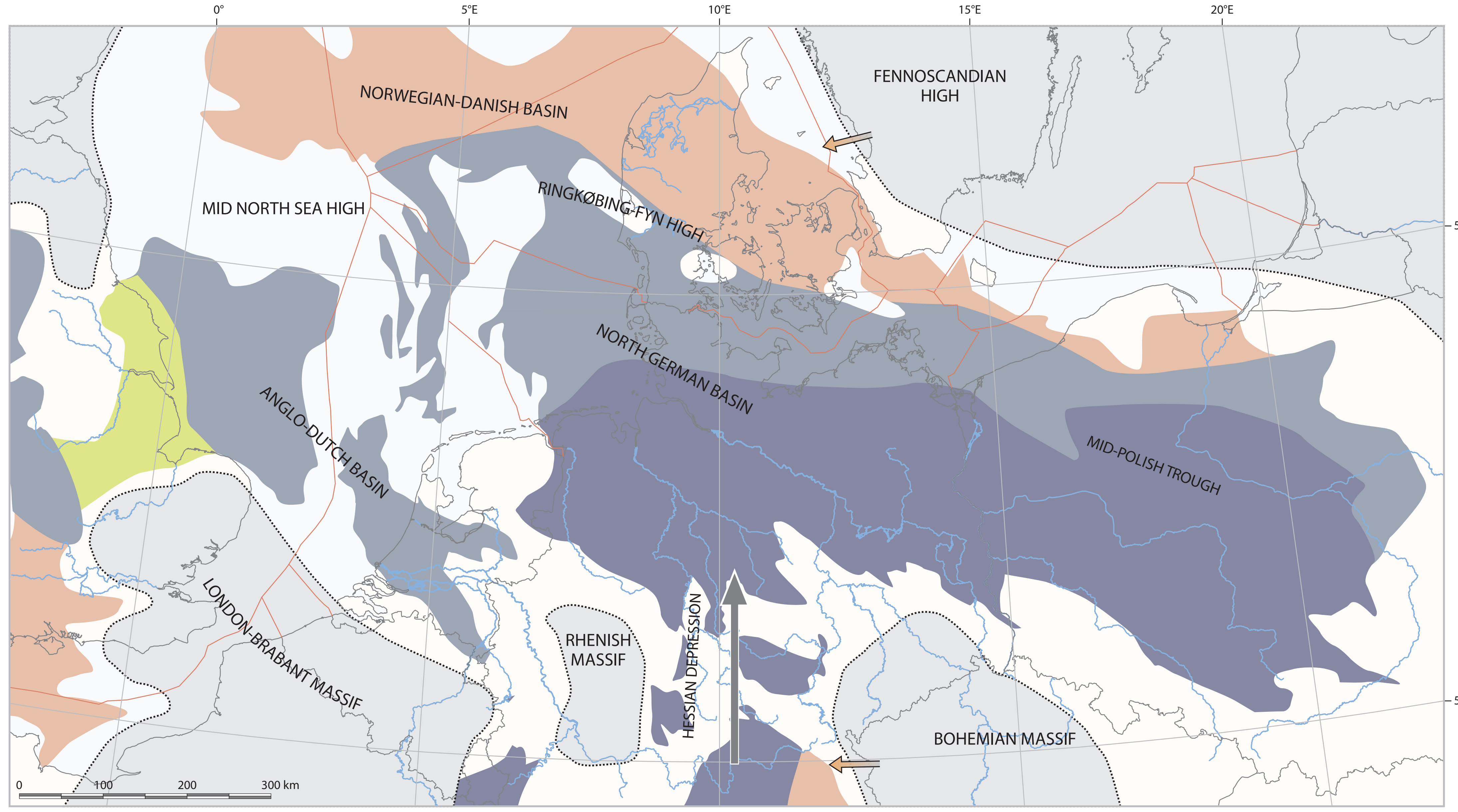


Figure 9.20 Present-day distribution and facies of the Upper Muschelkalk Subgroup and equivalents (late Anisian to early Ladinian). After Bertelsen (1980), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Beutler (1993), Marek & Pajchlowa (1997), Geluk (1999b, 2005), Dadlez et al. (1998), Szulc (1999, 2000) and Goldsmith et al. (2003).

The climate was influenced predominantly by the northern reaches of the Pangean megamonsoon at about 30 to 35° northern palaeolatitude (Golonka et al., 1994). It gradually changed from arid in the late Ladinian and Carnian, with a distinct mid-Carnian humid interval during deposition of the Stuttgart Formation and equivalents (Kozur, 1972, 1975; Simms & Ruffell, 1989; Kozur & Bachmann, 2009), to arid to semi-arid during late Carnian, Norian and Rhaetian times. The pronounced cyclicity seen throughout the succession is most prominent in the lacustrine mudstones and evaporites. Individual cycles, each about 10 to 30 m thick, can be correlated over hundreds of kilometres and are thought to represent Milankovich-type climatic fluctuations. Poor biostratigraphic control and the presence of unconformities preclude determination of the duration of these cycles by time-frequency analysis. However, their duration can be estimated from sedimentological considerations as between 100 and 400 ka, which allows the time represented by sediments and by nondepositional and erosional hiatuses to be estimated (Reinhardt & Ricken, 2000; Bachmann & Kozur, 2004; Menning et al., 2005; Nitsch et al., 2005; Franz 2008; Barnasch, 2009).

2.3.1 Lower Keuper Subgroup (Erfurt Formation) and equivalents

The Lower Keuper Subgroup has a rather uniform thickness, typically between 80 and 125 m except in the Glückstadt Graben and the Krośniewice Depression of Poland where it is up to about 600 to 700 m thick (Frisch & Kockel, 1997, 1999; Dadlez et al., 1998), and up to 200 m thick in the southern Central Graben and Ems Low (Geluk, 1999b, 2005; Barnasch, 2009) (**Figures 9.22**, **9.23**).

The Lower Keuper Subgroup reflects a fundamental change in the drainage pattern of the SPB area. Following closure of the East Carpathian and Silesian/Moravian gates (Szulc, 2000), an extensive clastic, fluvial to deltaic/estuarine system gradually prograded southwards from Fennoscandia and interfingered with brackish-marine to paralic deposits in a 600 km-wide zone extending from the area of northern Germany to northern Switzerland. Depositional environments varied from fluvial (channels) and freshwater lacustrine (with charophytes), to brackish estuarine (channels, deltaic bars), restricted-marine (with carbonate muds and storm-generated shell lags) and evaporitic ponds (**Figure 9.23**). Rooted palaeosols are common in the fluvial and deltaic deposits, and muddy coal seams developed in interchannel swamps and deltaic lowlands during periods of high fluvial run-off. Nevertheless, the climate remained arid at times, as indicated by widespread gypsiferous aridisols throughout the Lower Keuper Subgroup and marine gypsum deposits in marginal locations in south-west Germany.

The area was very flat, and depositional conditions may have been controlled by fluctuations in relative sea level and run-off from the neighbouring highlands. Marine ingressions reached northern Germany via the Burgundy-Alemannic Gate, through the Hessian and Thüringian depressions, and the East Carpathian Gate (Köppen, 1997; Pöppelreiter, 1999; Szulc, 1999, 2000; DSK, 2005). Fission-track and K-Ar ages of detrital grains indicate source areas to the north of the SPB area, in the Norwegian Caledonides and the Oslo Graben (Köppen, 1997; Köppen & Carter, 2000; Paul et al., 2008, 2009). The clastic influx can be explained by the uplift of a large rift shoulder within the Caledonides of present-day western Scandinavia leading to enhanced orographic precipitation from north-westerly trade winds, similar to the situation seen later in the Stuttgart Formation (Ziegler, 1990a; Szulc, 1999, 2000; DSK 2005; Kozur & Bachmann, 2009). This fluvial system was deflected south-eastwards, and clastic input entered the north-east German and Polish sectors of the SPB area east of the Ringkøbing-Fyn High (Beutler & Schubert, 1987; DSK, 2005). The depositional conditions and uniform thickness of the Lower Keuper succession strongly suggest that there was little tectonic activity in the SPB area, where the tectonic regime evidently differed from that north of the Teisseyre-Tornquist-Zone.

The Anglo-Dutch Basin was remote from both the source areas and the marine gates. Lacustrine to lagoonal conditions prevailed, although anhydrite reflects episodic evaporitic conditions. Thin dolomite beds record occasional marine incursions or large lake systems and the sediments were often subaerially exposed (Southworth, 1987 in Cameron et al., 1992). In contrast to Germany, there is no record of coaly intervals in the Anglo-Dutch Basin or in eastern UK successions.

Correlative beds in the UK southern North Sea sector comprise the lower part of the Dudgeon Formation (Cameron et al., 1992; Johnson et al., 1994), and part of the Sidmouth Mudstone Formation in eastern England (Howard et al., 2008). These sediments consist mainly of red gypsiferous mudstones, some laminated and deposited in water; westwards, siltstones and thin sandstones increase proximally into eastern England.

2.3.2 Middle Keuper Subgroup and equivalents

2.3.2.1 Grabfeld Formation (Lower Gipskeuper) and equivalents

The Grabfeld Formation reflects a dramatic environmental change in the SPB area. The climate became fully arid and fluvial discharge almost completely ceased, resulting in widespread evaporite deposition. Furthermore, strong extensional tectonics led to highly differentiated subsidence patterns. A large number of isolated fault-bounded depressions formed (**Figures 9.22** & **9.24**) in which salinas developed. Halite deposits occur at up to five distinct levels and, despite their local distribution, are correlatable over large distances (Beutler, 1995; Frisch & Kockel, 2003; DSK, 2005; Geluk, 2005; Barnasch et al., 2007; Barnasch,

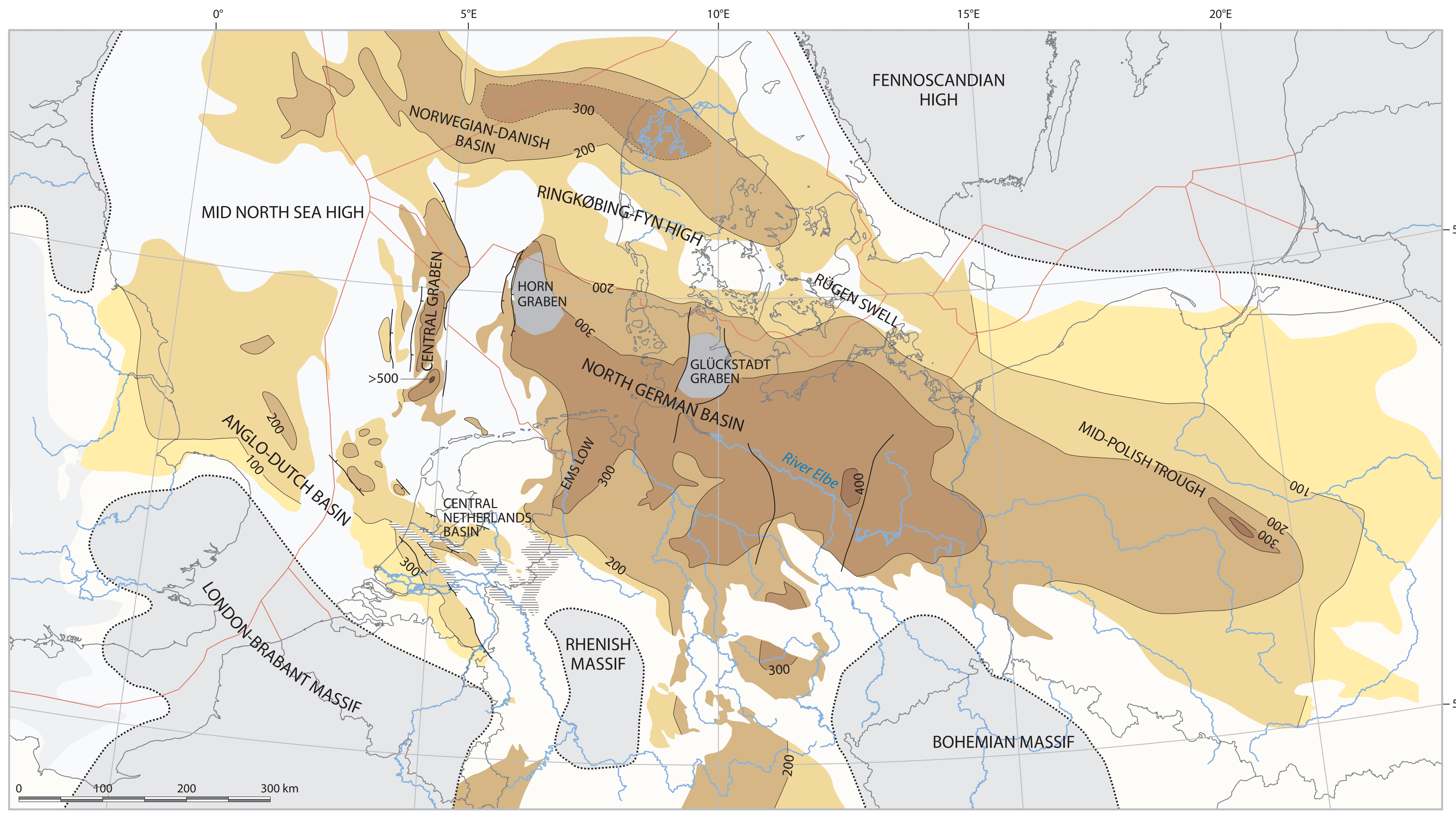


Figure 9.21 Present-day distribution and thickness of the Upper Muschelkalk Subgroup and equivalents (Middle Anisian to early Ladinian). After Wolburg (1969), Bertelsen (1980), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Beutler (1993), Geluk (1999b, 2005), Marek & Pajchlowa (1997), Dadlez et al. (1998), Szulc (1999, 2000) and Goldsmith et al. (2003).

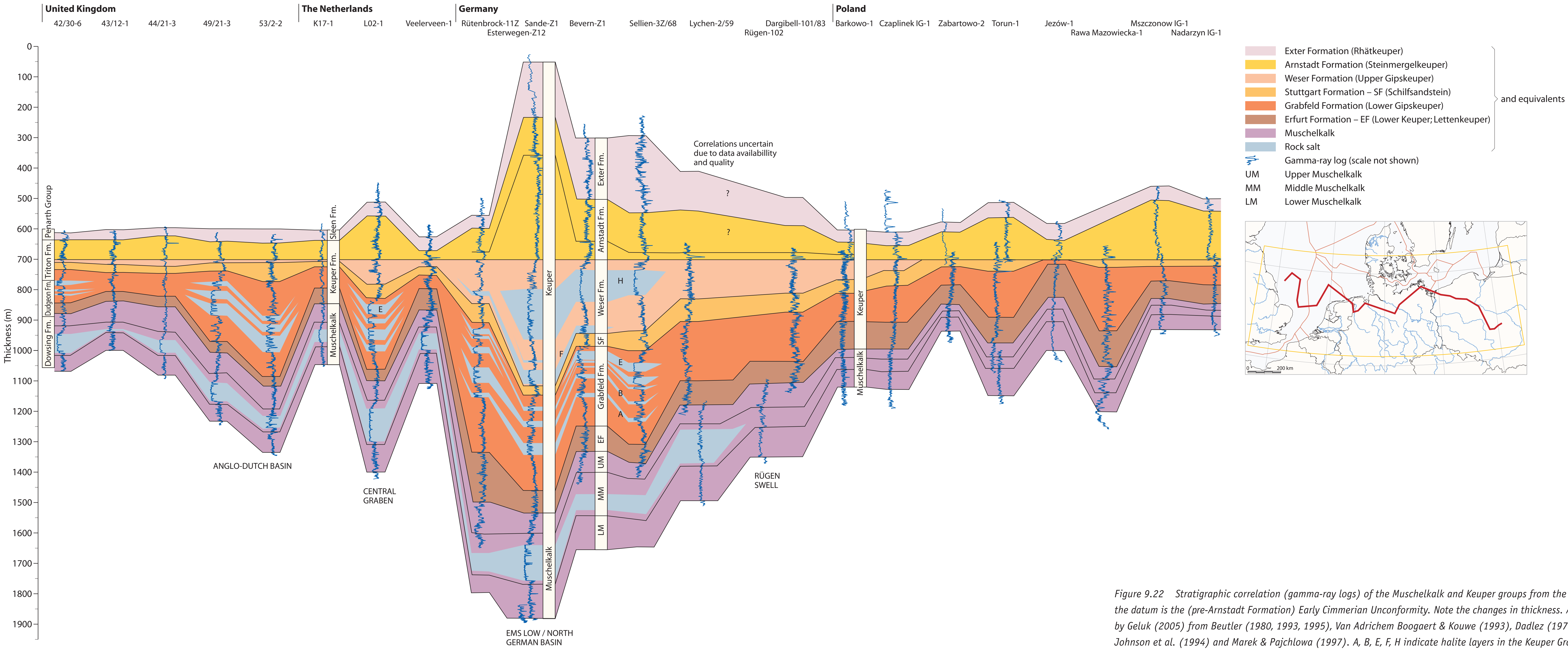


Figure 9.22 Stratigraphic correlation (gamma-ray logs) of the Muschelkalk and Keuper groups from the UK into Poland; the datum is the (pre-Arnstadt Formation) Early Cimmerian Unconformity. Note the changes in thickness. After compilation by Geluk (2005) from Beutler (1980, 1993, 1995), Van Adrichem Boogaert & Kouwe (1993), Dadlez (1976), Marek (1983), Johnson et al. (1994) and Marek & Pajchlowa (1997). A, B, E, F, H indicate halite layers in the Keuper Group.

2009). In the more stable areas surrounding these depressions, the Grabfeld Formation consists mainly of claystones and siltstones with intercalated anhydrite beds and nodules deposited under sabkha or playa conditions (Cameron et al., 1992; Beutler, 1995; DSK, 2005).

Large amounts of halite accumulated as far north as the Anglo-Dutch and Norwegian-Danish basins and the Horn and Glückstadt grabens (Bertelsen, 1980; Goldsmith et al., 2003). In the UK southern North Sea sector, the Keuper Halite Member of the Dudgeon Formation is less extensive than the halite members in the underlying Dowsing Formation (Warrington, 1974; Cameron et al., 1992; Johnson et al., 1994). Correlative beds in eastern England are predominantly red-brown mudstones in the upper part of the Sidmouth Mudstone Formation. The siltstone and sandstone content of this succession increases westwards and there is palynological evidence of a late Ladinian to earliest Carnian age at the level of the Cotgrave Sandstone Member (Howard et al., 2009) (**Figure 9.1**).

Several short-lived marine ingressions entered the southern German area through the Burgundy-Alemannic Gate, and some spread as far north as central Germany and western Poland. No marine fossils have been found farther to the north-west and no direct marine connection has been established for the salinas in the North Sea or adjacent areas. The marine contribution to these salt accumulations (e.g. Warrington, 1974) may therefore be less than those in the Röt Formation and the Middle Muschelkalk Subgroup; processes such as the reprecipitation of Zechstein salt (e.g. Brunstrom & Kent, 1967; Trusheim, 1971; Fisher & Mudge, 1998) or wind-borne marine aerosols (Nitsch, 2003) may have made a more significant contribution than previously recognised.

In the area of north-west Germany, the strongest subsidence occurred in parts of the Glückstadt Graben, where the Grabfeld Formation is some 2700 m thick; it is locally 1000 to 1500 m thick in other grabens. The thickness of the formation in areas unaffected by differential subsidence varies from 50 to 300 m (Dadlez et al., 1998; Baldschuhn et al., 2001; Geluk, 2005). The southern Central Graben, with more than 400 m of Grabfeld Formation sediments, and the Ems Low and Krośniewice Depression, with 700 m, show differential subsidence, though not of the magnitude recorded in north-west Germany. The formation also thickens distinctly along rift-raft zones (western Central Graben, Dowsing Fault Zone, and North Dogger Fault Zone) (Cameron et al., 1992; Griffiths et al., 1995; Chapter 4).

2.3.2.2 Stuttgart Formation (Schilfsandstein) and equivalents

In contrast to the underlying and overlying units, the Stuttgart Formation was deposited during a period of relative tectonic quiescence. The unit overlies the Grabfeld Formation unconformably and varies in thickness from 20 to 60 m to more than 100 m locally (Beutler, 1995; Dadlez et al., 1998). To the north of the SPB area, uplift of Caledonian rocks along rift basins between north-west Europe and Greenland (Ziegler, 1988), in combination with a temporarily wetter climatic phase due to a shift in the megamonsoonal system (Kozur, 1972, 1975; Simms & Ruffell, 1989; Köppen & Carter, 2000; Kozur & Weems, 2007; Paul et al., 2008, 2009; Kozur & Bachmann, 2009), resulted in large quantities of clastics being transported southwards. The Stuttgart Formation comprises mudstones and sandstones deposited in a large fluvial-plain to fluviodeltaic system, which flowed south towards Tethys (**Figure 9.25**).

Following its recognition in southern Germany (Wurster, 1964), this depositional system was seen elsewhere in Germany and in Poland (Beutler & Häusser, 1982; Duchrow, 1984; Marek & Pajchlowa, 1997; Dadlez et al., 1998; DSK, 2005). The palaeogeography closely resembled that of the Lower Keuper Subgroup, but was dominated by fluvial activity. The Stuttgart Formation only passes into a facies like that of the 'Lettenkohle' in the German Lower Keuper to the south of the SPB area, near Lyon in France. In northern Germany, there was much less marine influence than during Lower Keuper deposition. A restricted-marine influence is evident in the lowermost claystones of the Stuttgart Formation in central and eastern Germany, although limnic conditions were generally predominant (Kannegieser & Kozur, 1972). Some marine and tidal influence is recorded from the formation in southern Germany and Luxembourg (Barth et al., 1984; Gehrmann & Aigner, 2002; Shukla & Bachmann 2006).

Equivalent beds in the Anglo-Dutch Basin consist largely of red or black lacustrine mudstones. Sandstones up to 5 m thick are only found in the Ems Low and the southern Central Graben. However, in eastern England, mudstones pass westwards into a sandstone-dominated unit, the 'Hollygate skerries' (Elliott, 1961; Balchin & Ridd, 1970) or 'Hollygate Sandstone Member' (Barnasch et al., 2007; Howard et al., 2008, 2009; Barnasch, 2009) which is up to 9.5 m thick in south Nottinghamshire. This unit represents the Arden Sandstone Formation (Howard et al., 2008), which has yielded plant remains, conchostracans, remains of selachian fish and trace fossils in neighbouring Leicestershire. Elsewhere in the UK, this formation has also yielded bivalves, remains of amphibians, and a late Carnian (Tuvalian) microflora (Old et al., 1991; Warrington & Ivimey-Cook, 1992; Hounslow & Ruffell, 2006). Beds around the level at which this formation occurs in the Mercia Mudstone Group have a distinctive clay mineralogy characterised by a high smectite content, similar to that of the Stuttgart Formation in Germany (Carney et al., 2004; Howard et al., 2008, 2009). At the western margin of the SPB area, palaeocurrent directions are broadly eastwards as seen in the Arden Sandstone Formation in Leicestershire, (Warrington & Ivimey-Cook, 1992).

It is not clear if the Carnian succession in the western SPB area is complete or has major erosional gaps, although the presence of microfloras no younger than earliest Carnian around the level of the Cotgrave Sandstone Member, and of late Carnian microfloras in the Arden Sandstone Formation, suggest that the succession of eastern England may be relatively complete.

2.3.2.3 Weser Formation (Upper Gipskeuper) and equivalents

Following deposition of the Stuttgart Formation, evaporitic conditions returned during deposition of the typically 50 to 200 m-thick Weser Formation (**Figure 9.22**). Salina formation was localised; however,

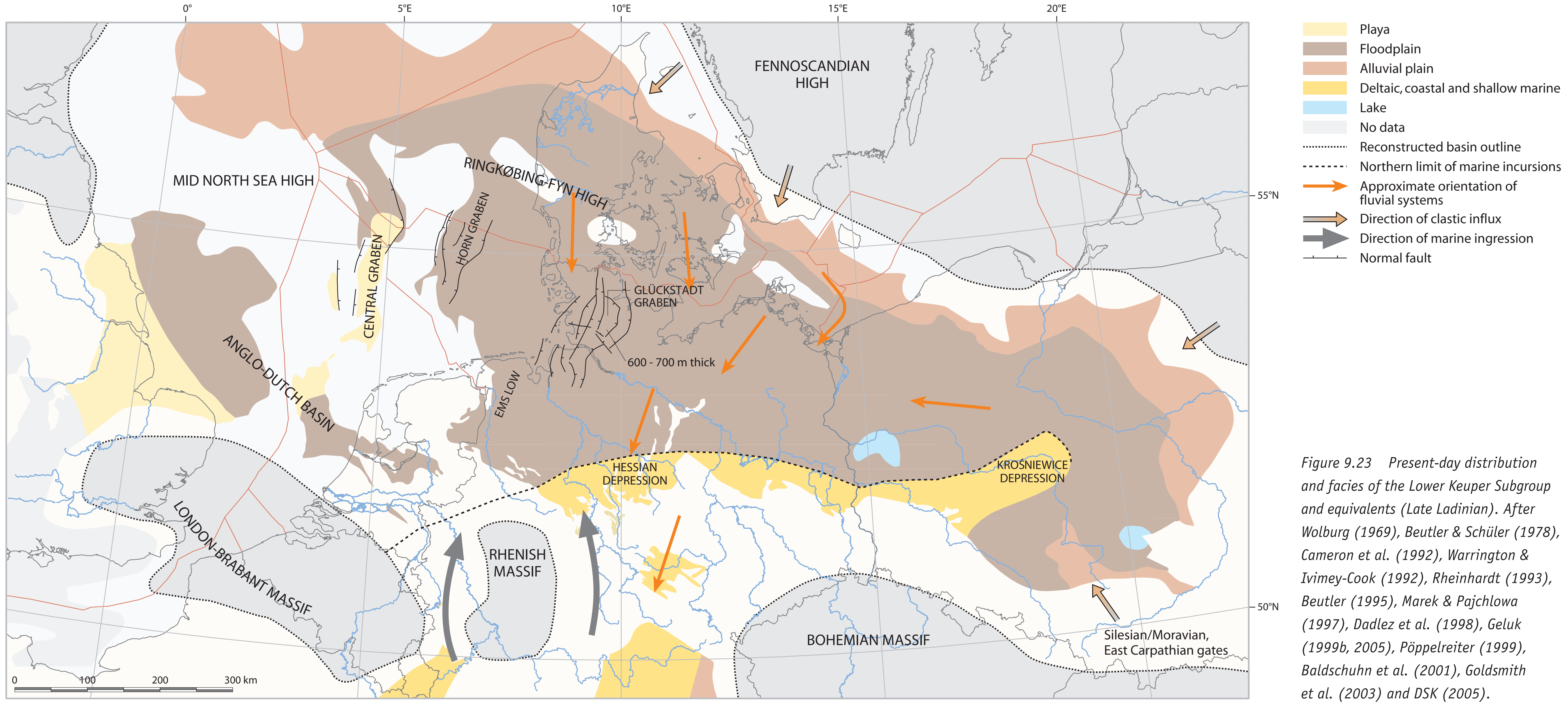


Figure 9.23 Present-day distribution and facies of the Lower Keuper Subgroup and equivalents (Late Ladinian). After Wolburg (1969), Beutler & Schüler (1978), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Rheinhardt (1993), Beutler (1995), Marek & Pajchlowa (1997), Dadlez et al. (1998), Geluk (1999b, 2005), Pöppelreiter (1999), Baldschuhn et al. (2001), Goldsmith et al. (2003) and DSK (2005).

sabkhas and playa mudflats were widespread in the SPB area. There were a few marine ingressions that gave rise, for example, to the Dolomie de Beaumont and equivalents in Switzerland, north-east France and parts of south-west Germany. Halite accumulated at three distinct stratigraphic levels in isolated salinas that covered a smaller area than those that developed during deposition of the Grabfeld Formation. There were significant fluctuations in freshwater input resulting in a few thin dolomite beds with freshwater to marine-brackish faunas. The most widespread of these dolomites, the Lehrberg Beds, occur between the first and second halite levels and can be traced for more than 350 km across the SPB area (Seegis, 1997). In northern Germany, the Heldburg Gypsum is a stack of nodular gypcretes up to 50 m thick at the top of the Weser Formation, which extends into Poland (Franz et al., 2007a), the Netherlands and offshore UK, and corresponds to the Tutbury Gypsum (up to 4 m thick) onshore in the UK (Barnasch et al., 2007; Barnasch, 2009). This interval marks the so-called 'Early Cimmerian Unconformity', one of the most pronounced unconformities in the Triassic (**Figure 9.26**).

Extensional tectonics caused major subsidence in a number of grabens, broadly comparable to those where the Grabfeld Formation was deposited. However, there are differences in detail between the patterns of faults active during deposition of the Grabfeld and Weser formations (Frisch & Kockel, 1997, 1999). The greatest subsidence in the Glückstadt Graben took place in the north and south, where halite-bearing sediments up to 4500 m thick were deposited; elsewhere in north-west Germany the sediments are up to 1000 m thick. The thickest deposits are related to salt withdrawal associated with nearby salt diapirism. Sabkhas covered most of the area, and fault-bounded salinas only formed in the Danish Basin, the Central, Horn and Glückstadt grabens, and a number of smaller lows in north-west Germany.

In the central SPB area, the Keuper Anhydrite Member is apparently of late Carnian age. This unit is correlated using borehole geophysical logs into the UK southern North Sea sector, where it is considered to be younger (see below: Arnstadt Formation). This suggests that geophysically correlatable units in the Triton and Branscombe Mudstone formations in the western SPB area may be diachronous.

2.3.2.4 Arnstadt Formation (Steinmergelkeuper) and equivalents

The Arnstadt Formation was deposited after major structural changes in the SPB area, with marked uplift of the basin margins and intrabasinal highs (**Figures 9.22** & **9.28**). The formation is a post-rift unit that covered the palaeorelief of the Early Cimmerian Unconformity in a sheet-like manner (Wolburg, 1969; Beutler & Schüler, 1978; Baldschuhn et al., 2001; Barnasch et al., 2005, 2007; Geluk, 2005; Bachmann et al., 2008; Franz, 2008, Barnasch, 2009). The formation and its equivalents overlie a range of older sediments, notably in grabens and on uplifted areas in Germany (**Figure 9.26**), and onlap onto the basin margins in the southern Netherlands, southern Germany and Poland (Schröder, 1982; DSK, 2005).

In marked contrast to the mostly variable thicknesses of the underlying Keuper formations, the Arnstadt Formation is more uniform, but varies from around 50 m in the southern Netherlands to 200 m in the Central Graben and more than 400 m in the Glückstadt Graben and Piotrków Trybunalski Depression in the southern Mid-Polish Trough. Reactivation of the south-east to north-west-striking Kraków-Hamburg Fault Zone in Upper Silesia resulted in the unusual 30 m-thick, spring-fed, palustrine Wozniki Limestone, which occurs to the north of Katowice and extends over a distance of 80 km (Szulc et al., 2000, 2006).

The Arnstadt Formation was deposited in a playa system (**Figure 9.27**) with a sparse limnic to brackish-water fauna (Will, 1969). Some species indicate marine affinity, and two carbonate beds may be of brackish-marine origin, particularly in southern Germany and northern France (Beutler, 1995, 1998; Reinhardt & Ricken, 2000). Cyclic freshwater input is indicated by fluvial sandstones on a braidplain more than 200 km wide (Löwenstein Formation; DSK, 2005) that prograded from the Bohemian Massif and its south-western extension, the Vindelician Massif, over much of southern Germany and interfingered with playa mudstones in central and southern Germany. The Anglo-Dutch Basin was remote from sources of both marine and freshwater, and playa conditions prevailed, with periodic evaporitic intervals.

Correlative beds in the UK southern North Sea sector comprise the Triton Formation, which includes the Keuper Anhydrite Member (Cameron et al., 1992; Johnson et al., 1994). The age of this formation is Late Triassic, probably Norian, based on palynological dating of the beds above and below (Johnson et al., 1994; see above: Weser Formation). Correlative beds in eastern England include the Branscombe Mudstone and succeeding Blue Anchor formations (Hounslow & Ruffell, 2006; Howard et al., 2008). The former includes substantial concentrations of sulphate evaporites which, in Leicestershire and Nottinghamshire, occur in the highest beds in the formation. Based on stable isotope evidence, these evaporites originated from brines of partly marine and partly continental origin (Taylor, 1983). The dolomitic Blue Anchor Formation is Norian to Rhaetian in age, based on palynological and magnetostratigraphic evidence (Hounslow et al., 2004; Gallet et al., 2007) from the UK outside the SPB area, where a marine influence on the depositional environment of the upper part of the formation is indicated by biomarkers (Thomas et al., 1993), dinoflagellate cysts and other fossils (Warrington & Ivimey-Cook, 1992; Hounslow et al., 2004). Dinoflagellate cysts also occur in the formation at the western margin of the SPB (Howard et al., 2009). The Blue Anchor Formation is unconformably overlain by the marine Westbury Formation of the Penarth Group (**Figure 9.1**).

2.3.2.5 Upper Keuper Subgroup (Exter Formation) and equivalents

The Upper Keuper Subgroup is the youngest (Rhaetian) part of the Triassic. In large parts of the SPB area, it comprises the transition from Late Triassic nonmarine environments, through paralic systems to marine

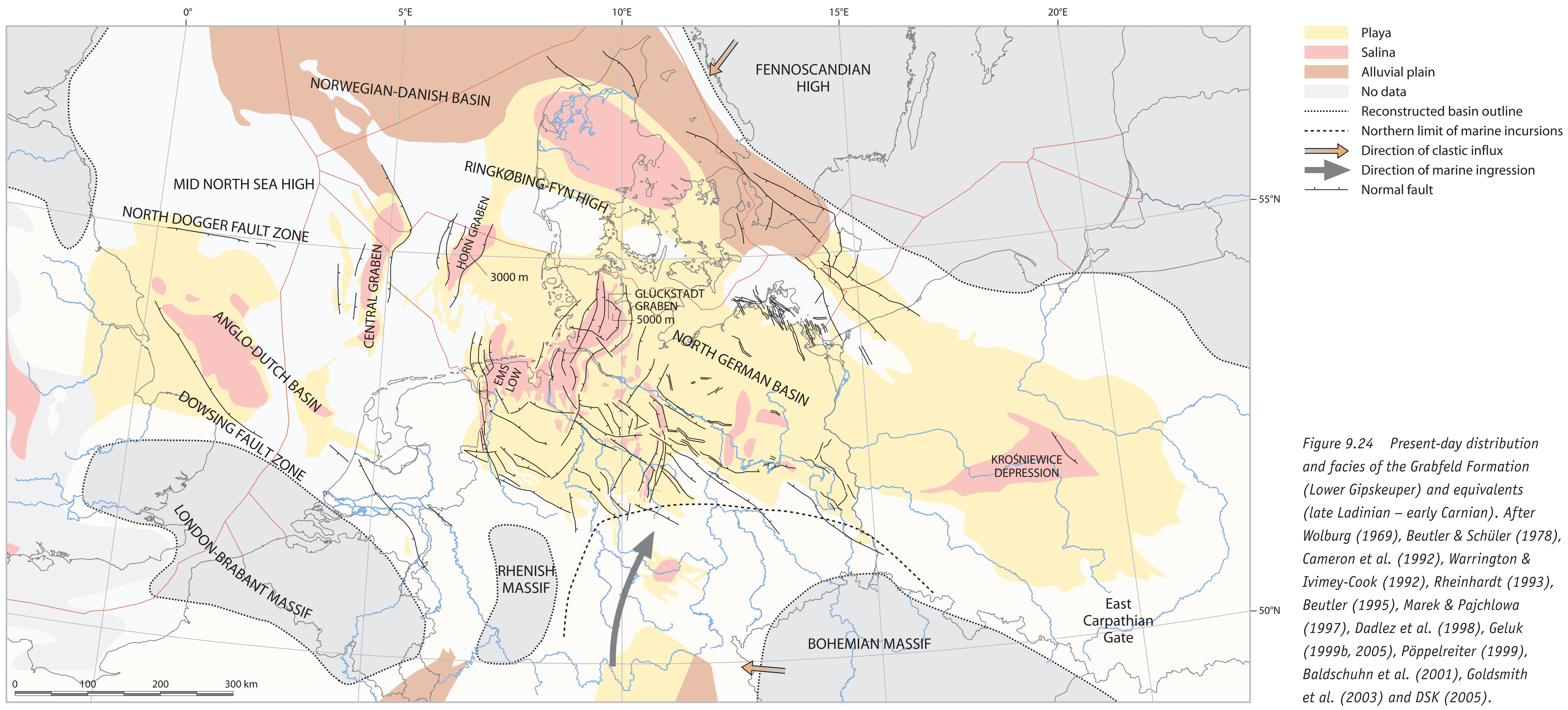


Figure 9.24 Present-day distribution and facies of the Grabfeld Formation (Lower Gipskeuper) and equivalents (late Ladinian – early Carnian). After Wolburg (1969), Beutler & Schüler (1978), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Rheinhardt (1993), Beutler (1995), Marek & Pajchlowa (1997), Dadlez et al. (1998), Geluk (1999b, 2005), Pöppelreiter (1999), Baldschuhn et al. (2001), Goldsmith et al. (2003) and DSK (2005).

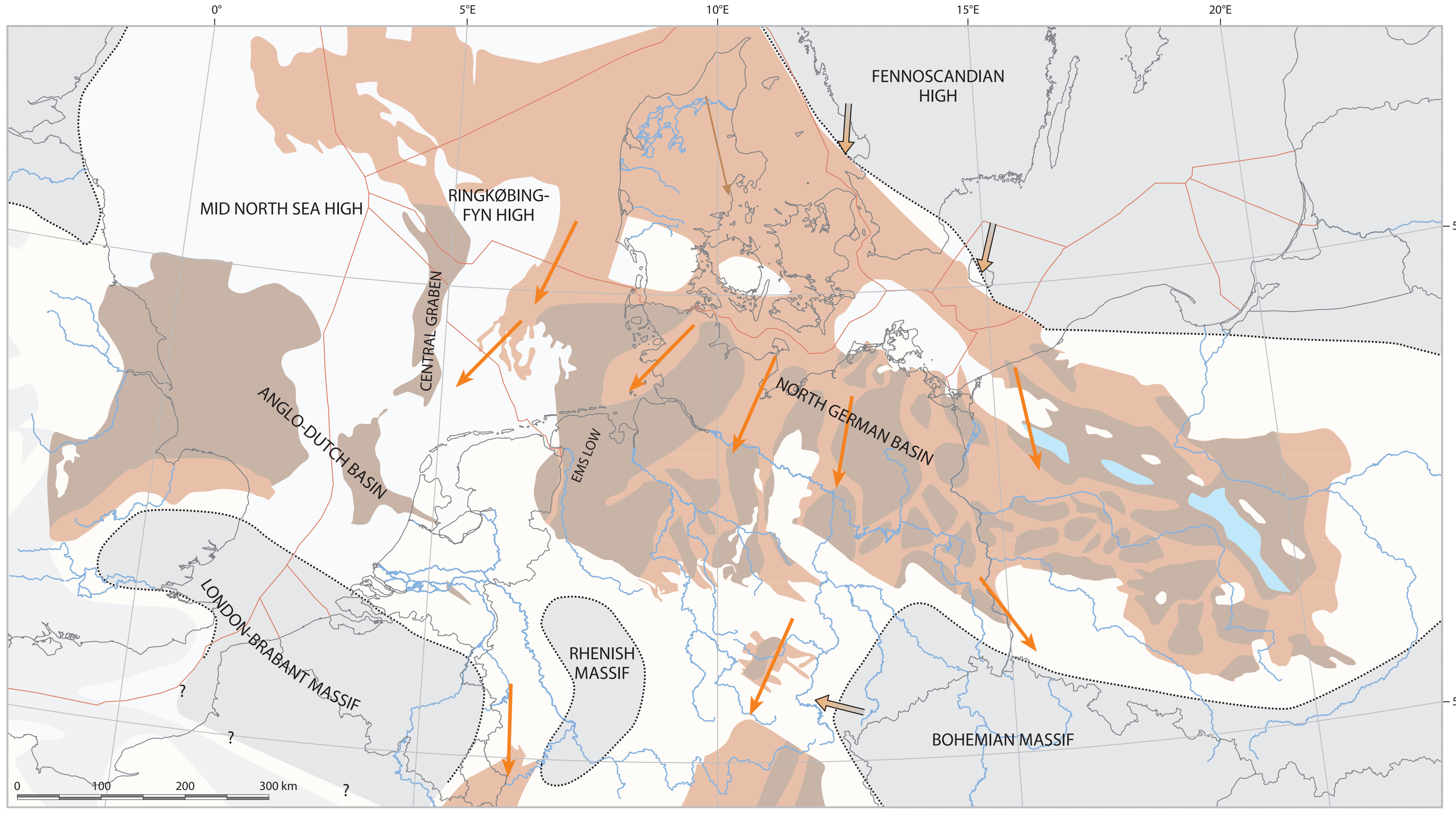


Figure 9.25 Present-day distribution and facies of the Stuttgart Formation (Schilfsandstein) and equivalents (Carnian). The main sediment supply originated from an uplifted rift shoulder in the Caledonides of present-day western Scandinavia. After Wurster (1964), Beutler & Häusser (1982), Beutler & Schüler (1987), Jubitz et al. (1988), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Beutler (1998), Dadlez et al. (1998), Geluk (1999b, 2005), Baldschuhn et al. (2001), Goldsmith et al. (2003) and DSK (2005).

conditions in the Early Jurassic. The Upper Keuper Subgroup is 20 to 100 m thick in the Anglo-Dutch and Polish basins, 100 to 300 m thick in the North German Basin, and up to 600 m thick in the southern part of the Glückstadt Graben (Baldschuhn et al., 2001); it thickens locally in other grabens in north-west Germany. The lowermost part of the Upper Keuper Subgroup may be missing in the Netherlands and the southern North Sea area (**Figure 9.1**).

The western half of the SPB area was dominated by open-water deposits, mainly dark grey to green bioturbated mudstones, sometimes rich in organic matter (**Figure 9.28**). From bottom to top they bear brackish (e.g. *Unionites posterus* (Deffner & Fraas)), marine (e.g. *Rhaetavicula contorta* (Portland)) and limnic biota (mainly ostracods) that record major changes in marine influence. Plant remains are common and indicate freshwater input (Will, 1969; Cameron et al., 1992; Beutler, 1995; DSK, 2005; Geluk, 2005). These environmental phases are bounded by low-angle unconformities in many places and are commonly truncated at the base of the Jurassic, with one or more absent regionally (Beutler, in DSK, 2005).

The correlatives of the Upper Keuper Subgroup in eastern England are the Westbury and Lilstock formations of the Penarth Group (Warrington et al., 1980). Microfloras from the marine Westbury Formation include dinoflagellate cysts (Orbell, 1973, in Carney et al., 2004; Morbey, 1975; Howard et al., 2009), and *Rhaetavicula contorta* is present in the macrofaunas (Howard et al., 2009). The Cotham Member, which forms most of the Lilstock Formation in this area, has been regarded on macrofaunal evidence as deposited in fresh or brackish water, although it also contains acritarch and dinoflagellate-cyst associations similar to those in the Westbury Formation (Orbell, 1973, in Carney et al., 2004; Morbey, 1975; Howard et al., 2009), which indicate a marine influence. Tethyan conodonts, including *Misikella coniformis* Swift and *Chirodella verecunda* Swift, are found in the Langport Member at the top of the Lilstock Formation and *Misikella posthernsteini* Kozur & Mock has been recovered from the lowest beds of the succeeding Lias, which are regarded as Triassic in age (Swift, 1989, 1995). This succession extends into the UK southern North Sea sector (Lott & Warrington, 1988).

In Poland and north-east Germany, the entire Upper Keuper Subgroup consists of nonmarine fluvial and lacustrine deposits with minor coals (Marek & Pajchlowa, 1997; **Figure 9.28**). Units in this succession are correlatable over large distances, even to the western part of the basin (Grodzicka-Szymanko, 1976; DSK, 2005; Franz et al., 2007a, 2007b).

An approximately 100 km-wide belt of shallow-marine, coastal and deltaic sandstones with minor mudstone intercalations separates the open-water and floodplain regions in the basin. Marine influence diminishes eastwards across this belt, and the number of coal seams and palaeosols increases. The most easterly indications of marine influence are two thin dinocyst-bearing beds in southern Sweden regarding episodes of high sea level (Nielsen, 2003; Lindström & Erlström, 2006), and sporadic marine bivalves and limulids in rocks in central north Germany (Hauschke & Wilde, 1991; DSK, 2005).

The paralic facies belt was remarkably stable in position and remained so during the brackish, marine and freshwater phases of the Upper Keuper Subgroup (Will, 1969; DSK, 2005). It extends in a north–south direction from Denmark across Germany, where it crops out in Thüringia and, beyond the SPBA area, from Württemberg in south-western Germany to western Switzerland. Similar shallow- to marginal-marine facies are developed near the northern rim of the Paris Basin, at the southern edge of the SPB area.

Connections with the open sea were farther west than during earlier Triassic times (cf. **Figures 9.21** & **9.23**). A connection with the Boreal Ocean through the central and northern North Sea areas can be ruled out (Goldsmith et al., 2003). The Tethys Ocean was probably connected with the SPB area through a new gate between the Pennine High and the London-Brabant Massif, with connections farther west (Ziegler, 1990a; Warrington & Ivimey-Cook, 1992). A connection may also have persisted through the Burgundy-Alemannic Gate (DSK, 2005).

3 Hydrocarbon geology

Economic hydrocarbon accumulations in Triassic rocks have been found mainly in the western part of the SPB area (e.g. the southern North Sea, the Netherlands and north-west Germany; see Chapter 13). Gas is the most common constituent, although there are small oil accumulations in the West Netherlands Basin and north-west Germany. There is a clear differentiation according to the stratigraphy of the reservoir horizon; most gas reserves occur in the Lower Triassic Buntsandstein Group, whereas the oil reserves are divided between the Lower Triassic Buntsandstein Group and the Upper Triassic Keuper Group. Total Triassic reserves are up to some 500 bcm of gas and 150 mmbbl (~24 mln m^3)of oil in around 150 fields; the Triassic reserves are therefore several orders of magnitude smaller than those of the Rotliegend. Most of the gas reserves are found in the Netherlands (280 bcm), followed by Germany (140 bcm) and the UK (70 bcm). The lack of exploration success in other parts of the SPB area, notably in the east, is attributed to the absence of charge windows through the thick sealing claystones and evaporites of the Rotliegend and Zechstein, in combination with the absence of a regional Triassic salt top seal.

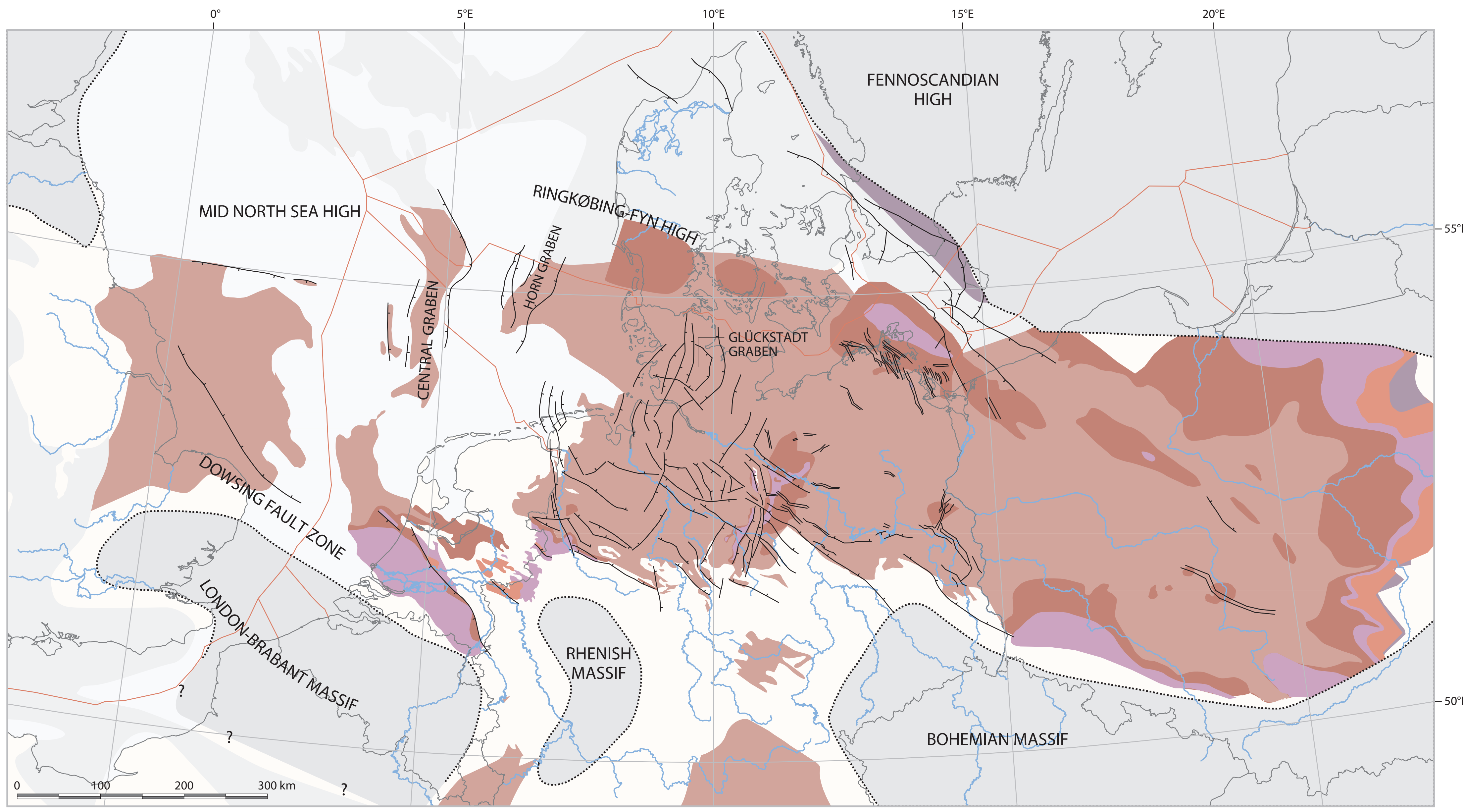


Figure 9.26 Subcrop of the Early Cimmerian Unconformity. After Wolburg (1969), Beutler & Schüler (1978), Cameron et al. (1992), Rheinhardt (1993), Beutler (1995), Marek & Pajchlowa (1997), Geluk (1999b, 2005), Baldschuhn et al. (2001) and DSK (2005).

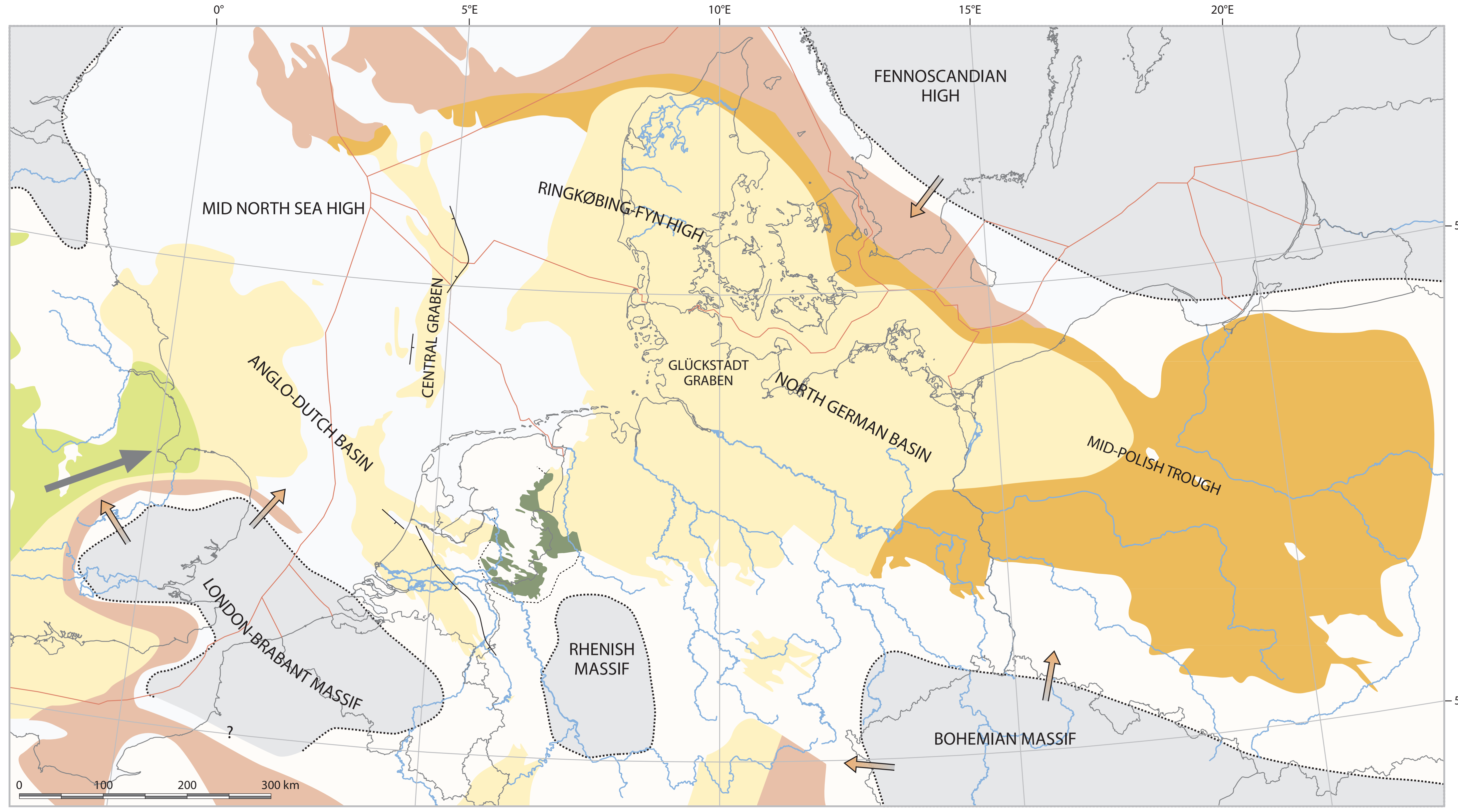


Figure 9.27 Present-day distribution and facies of the Arnstadt Formation (Steinmergelkeuper) and equivalents (Norian). After Wolburg (1969), Beutler & Schüler (1978), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Rheinhardt (1993), Beutler (1995), Marek & Pajchlowa (1997), Dadlez et al. (1998), Geluk (1999b, 2005), Pöppelreiter (1999), Baldschuhn et al. (2001), Goldsmith et al. (2003) and DSK (2005).

In the Netherlands and north-west Germany, the first discoveries of gas in Triassic rocks were made in the late 1940s and 1950s (Plein, 1994; NITG, 2000). These include the De Wijk field in the Netherlands (20 bcm) (see Section 3.1.2), and Hengstlage in north-west Germany (60 bcm). In the southern North Sea, Triassic gasfields were among the first to be discovered and include Hewett in the UK sector (Cooke-Yarborough, 1991) and P6 in the Dutch sector (Chapter 8). The largest fields were discovered during the early exploration stages, except for the L09-FD, FH and FI fields in the Netherlands, in which gas (26 bcm) was found between 1993 and 1995 in a previously unknown thick aeolian reservoir in the Solling Formation (De Jager & Geluk, 2007). This indicates the relatively mature exploration stage of the play.

Reservoirs in the Triassic are formed mainly by clastic rocks; fluvial and aeolian sandstones in the Lower Triassic and fluviodeltaic sandstones in the Upper Triassic Rhaetian (Cameron et al., 1992; Plein, 1994; De Jager & Geluk, 2007). The Lower Triassic sandstones were derived from the south, whereas there are progressively more shales to the north. In the south, the Main Buntsandstein Subgroup forms a thick massive reservoir package, which breaks up northwards into several thinner sandstone units. These units include the Volpriehausen and Detfurth formations, which are separated by claystones and siltstones that form regional seals (Ames & Farfan, 1996; Geluk, 1999b). The best reservoirs occur along the south-western basin margin, where excellent gas-production rates of several million cubic metres per day have been achieved (De Jager & Geluk, 2007). Salt plugging of the reservoirs is a serious risk to the Triassic play in the area of thick Zechstein salt (Cameron et al., 1992; Fontaine et al., 1993; Purvis & Okkerman, 1996). Salt-plugged reservoirs have been found, particularly near salt walls and along fault planes, and are often characterised by a phase reversal of the seismic response of the top of the reservoir. Careful study of seismic amplitudes may indicate whether or not good reservoirs are present.

It is exceptional for Triassic carbonates to form reservoir rocks, but this is the case in some fields in the Netherlands (De Wijk, Coevorden) where both the Lower and Upper Muschelkalk subgroups form one of the reservoir layers (Borkhataria et al., 2005; Pöppelreiter et al., 2005). Even more exceptional is the reservoir comprising oolites of the Lower Buntsandstein Subgroup of the De Wijk field in the eastern Netherlands (Gdula, 1983; Bruijn, 1996; Palermo et al., 2008) (see Section 3.1.2).

In terms of source rocks, the Triassic gas play shares the Upper Carboniferous coals and Namurian shales with the Rotliegend, Zechstein and Carboniferous plays (see **Figures 9.48** & **9.49**). The Triassic gas play therefore only works where the Zechstein salt, the regional top seal of these other plays, was either not deposited (e.g. in the West Netherlands Basin) or is locally breached by salt withdrawal or faulting. In the West Netherlands Basin and the Gifhorn Trough (Lower Saxony Basin, Germany), the Lower Jurassic Posidonia Shale also acts as an oil source rock where it is mature and juxtaposed with Triassic rocks (De Jager et al., 1996). Availability of Tertiary to Recent charge is an important success factor (De Jager & Geluk, 2007). Marine organic-rich shales of the Upper Permian Zechstein provide the source rock in Thüringia.

The regional top seal for the Main Buntsandstein Subgroup gasfields is formed by the Solling Claystone and Röt Evaporite (Ames & Farfan, 1996; Geluk et al., 1996). Tight evaporites and carbonates of the Muschelkalk and Keuper groups form top seals for the Röt Formation sandstones, and claystones for the Rhaetian sandstones. In the western part of the Dutch offshore sector, the 8 to 12 m-thick Solling Claystone and overlying tight sandstones are capable of holding a gas column of up to 300 m (Spain & Conrad, 1997). Locally, Lower Cretaceous claystones have also been found sealing truncation traps (Bruijn, 1996; De Jager & Geluk, 2007).

Triassic gasfields occur in a variety of trap styles (see **Figure 9.49**). A twofold subdivision is applied between areas with and without salt. In areas with Permian Zechstein salts, the predominant traps are broad anticlinal structures that developed either as inverted synclines (turtle-back anticlines) or salt-cored anticlines. Examples are the Esmond, Gordon, Forbes (Bifani, 1986), Caister-A (see Section 3.1.1) (Ritchie & Pratsides, 1993) and Hunter fields in the UK southern North Sea; P6, L05-FA, F15-A (see Section 3.1.3) and Roswinkel in the Netherlands, and Hengstlage and other fields in north-west Germany. Fields adjacent to diapirs have been found in the Dutch offshore sector in blocks G14 and G17; Lower Cretaceous shales form the top seal. In areas where salts are thin or absent, such as the West Netherlands and Broad Fourteens basins, the typical trap in this play consists of Late Jurassic horst blocks in which the reservoir is vertically sealed by Upper Triassic evaporitic shales and laterally by Upper Triassic to Lower Jurassic shales (De Jager et al., 1996). Lateral seal risks occur where fault-throws are so large that cross-fault juxtaposition is against the sandy Upper Jurassic sequence. Locally, downthrown fault traps have also been found working in the West Netherlands Basin (e.g. well Gaag-5).

There are differences in the timing of charge and structural development in the SPB area. Published examples of anticlinal fields in the UK sector appear to be underfilled, with a gas-water contact (GWC) situated much higher than the structural closing contour (Ritchie & Pratsides, 1993; Fisher & Mudge, 1998). In contrast, the GWC in some of the Dutch fields coincides with the deepest closing contour (Fontaine et al., 1993; Bruijn, 1996). One explanation for this may be that gas charge in the Netherlands postdates the formation of the structures, whereas in the UK sector the charge was earlier and the structures developed during and after the charge of gas.

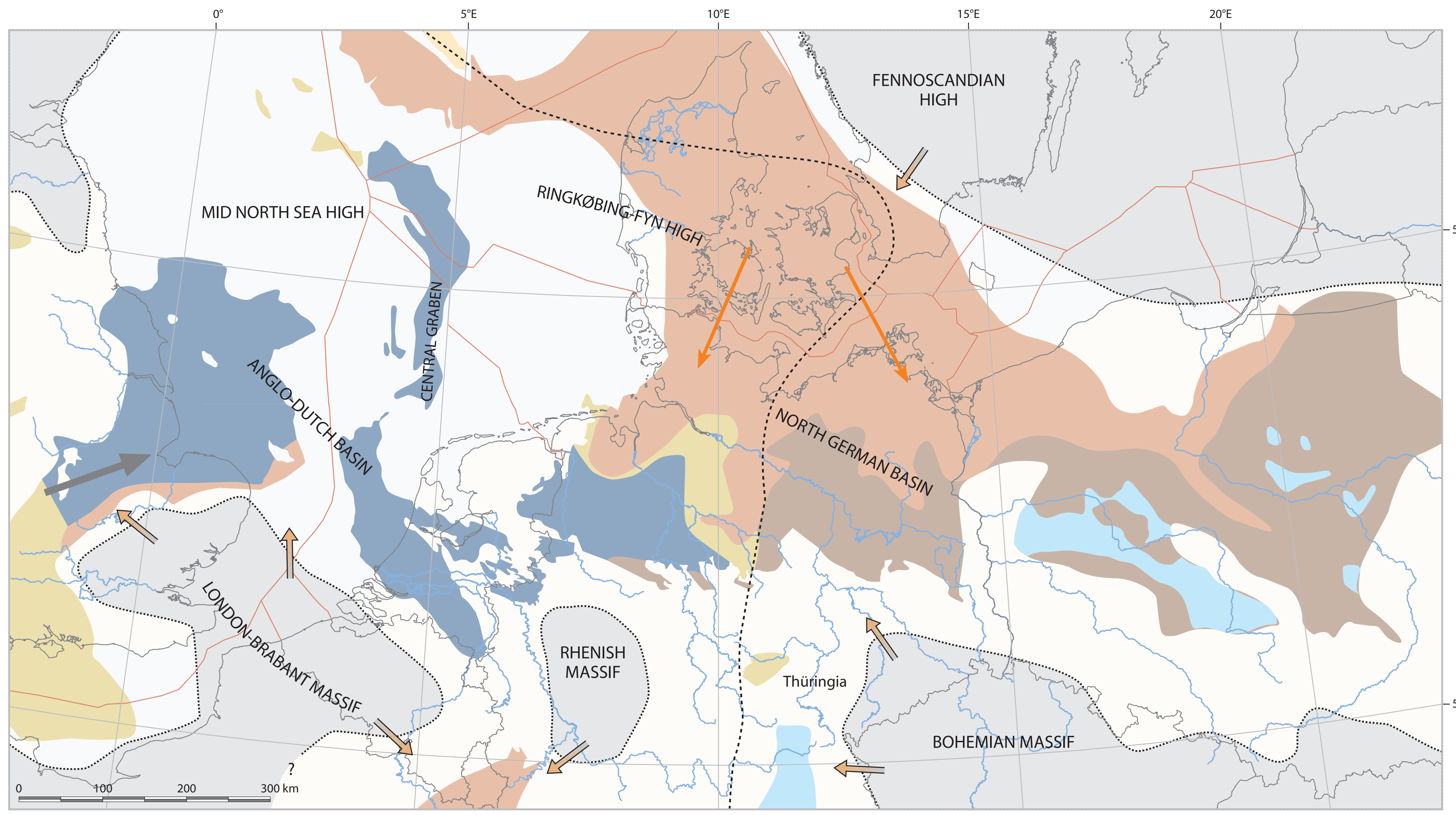


Figure 9.28 Present-day distribution and facies of the Upper Keuper Subgroup and equivalents (Rhaetian). After Ziegler (1990a), Cameron et al. (1992), Warrington & Ivimey-Cook (1992), Beutler (1998), Dadlez et al. (1998), Geluk (1999b, 2005), Baldschuhn et al. (2001) and DSK (2005).

The Triassic gas play in the UK has resulted in fewer discoveries than in the Netherlands. Most of the anticlinal structures have been drilled, but only water-bearing sandstones were discovered. It has been suggested that the dominance of gently deformed salt pillows in the UK sector, as opposed to the salt walls in the Dutch sector, has resulted in fewer breaches of the thick Zechstein salt seal on the UK side (Fisher & Mudge, 1998). The salt walls in the Netherlands not only resulted in migration pathways from the Carboniferous into the Triassic, but salt walls in the area of the Terschelling Basin and southern Dutch Central Graben seal off separate pressure cells in which the Triassic reservoirs occur (Crepieux et al., 1998). In some of these cells, reservoir pressures equal the minimum horizontal stress and cause the seal to be breached. Deeper culminations in these pressure cells may be protected against seal failure.

The gas quality in the Triassic sandstones varies between methane values of more than 90% in the area of the West Netherlands Basin, and 60 to 80% in north-west Germany and the north-east Netherlands. These values mirror the variations in Carboniferous, Zechstein and Rotliegend gas composition (cf. Lokhorst et al., 1998), therefore the suggestion by Fisher & Mudge (1998) that the lower methane content in Triassic gas is caused by tortuous longer migration routes from the Carboniferous appears invalid. It is assumed that the timing of charge (especially recent charge) and the source-rock type (coals versus hot shale, maturity level) are the main factors responsible for the variations in gas quality.

Triassic reservoirs are used for gas storage in Germany, both in depleted gasfields (Allmenhausen, Döttlingen, Kalle, and Uelsen) and aquifers (Berlin, Buchholz). In north-east Germany, geothermal energy is produced from Triassic rocks (Neubrandenburg) (see Chapter 16).

In the eastern Netherlands, gas production from the Triassic Roswinkel field on the border with Germany has induced a number of earthquakes since 1986. Despite the field having been in production for many decades, a large number of earthquakes with magnitudes of up to 3.4 on the Richter Scale were registered during a period of more than 10 years (Dost & Haak, 2007).

3.1 Hydrocarbon field examples

3.1.1 Caister (Bunter) gasfield, offshore UK

The Caister (Bunter) gasfield is situated approximately 165 km off the Yorkshire coast in UK block 44/23 on the Cleaver Bank High (**Figure 9.29**). The field was discovered by well 44/23-1 in 1984. The Triassic field overlies a deeper Carboniferous gasfield (known as Caister C). A detailed overview of the field, on which this description is largely based, has been given by Ritchie & Pratsides (1993).

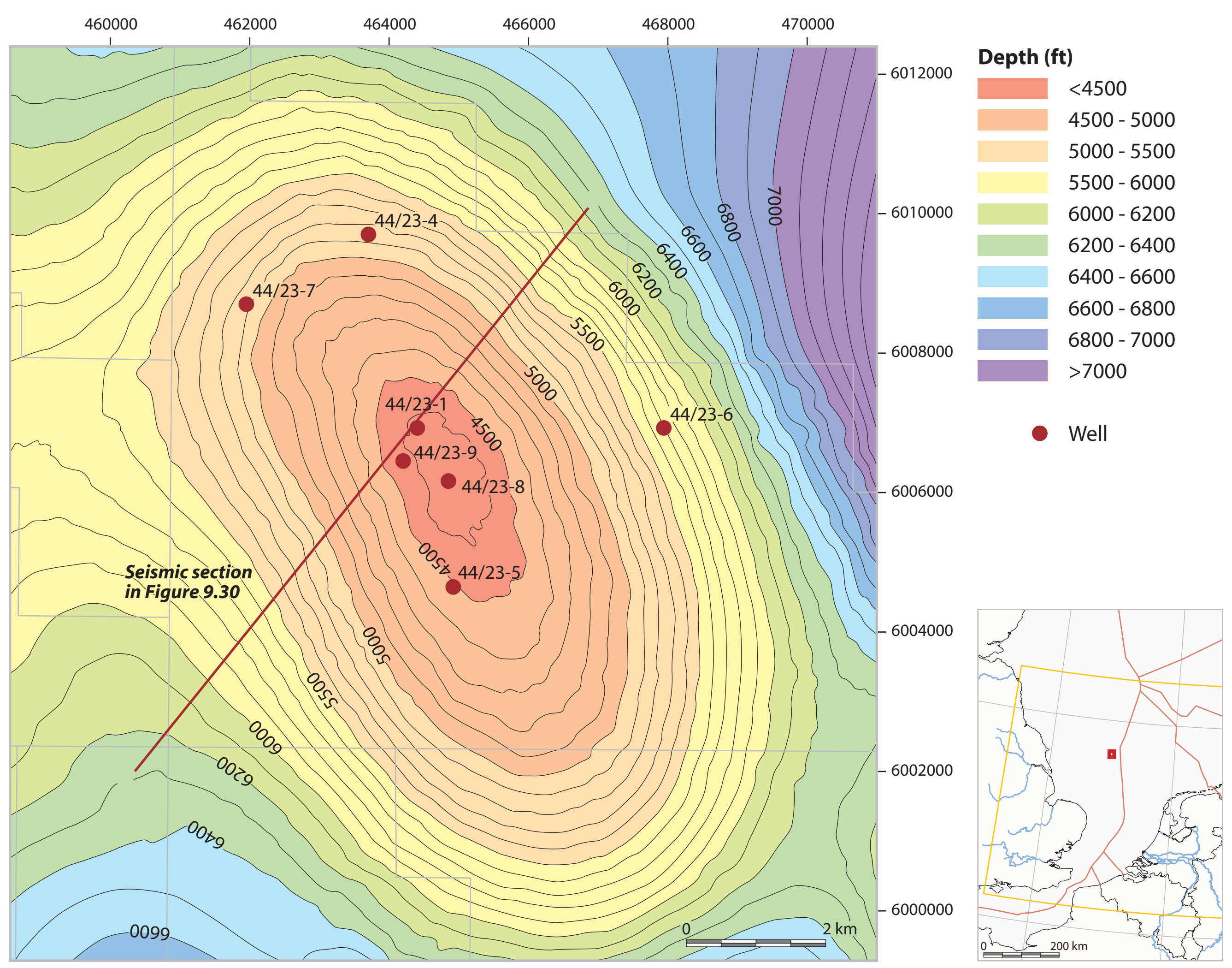


Figure 9.29 Depth-structure to the top of the Bunter Sandstone Formation in the Caister B gasfield, UK southern North Sea. Note that the structural closing contour (~5600 ft) lies much deeper than the gas-water contact (~4600 ft), indicative of underfilling of this structure (courtesy of ConocoPhillips).

The Caister (Bunter) gasfield is a 4-way dip closure situated above a Zechstein salt pillow. The field is similar to other 4-way dip closures, such as Esmond, Gordon, and Forbes (Bifani, 1975). The area of the Bunter closure is 7.5 km^2; compared to the closing contour of the 4-way dip closure, which lies at least 1800 m, the structure is considerably underfilled with respect to hydrocarbons. The underfilling is probably due to lack of charge, possibly related to Cenozoic movement of the salt pillow (**Figure 9.30**). The gas accumulation is sealed by the Solling Claystone / Röt Evaporite. The source rocks for the gas are Westphalian Coal Measures (**Table 9.1**).

The Triassic reservoir is formed by fluvial and aeolian sandstones of the Bunter Sandstone Formation. This formation was deposited under semi-arid conditions by distal sheetfloods in a lake-margin to braidplain setting. The lower part of the formation is dominated by fluvial deposits (**Figure 9.31**). Halite is an important pore-filling mineral especially in the water zone, causing a bulk shift of the sonic log towards the right below the GWC (Ritchie & Pratsides, 1993). Halite is a common pore-filling mineral in other Triassic gasfields both in the UK (Bifani, 1986) and the Netherlands (Purvis & Okkerman, 1996). Some correlatable claystone barriers that delineate different reservoir zones have been identified across the field.

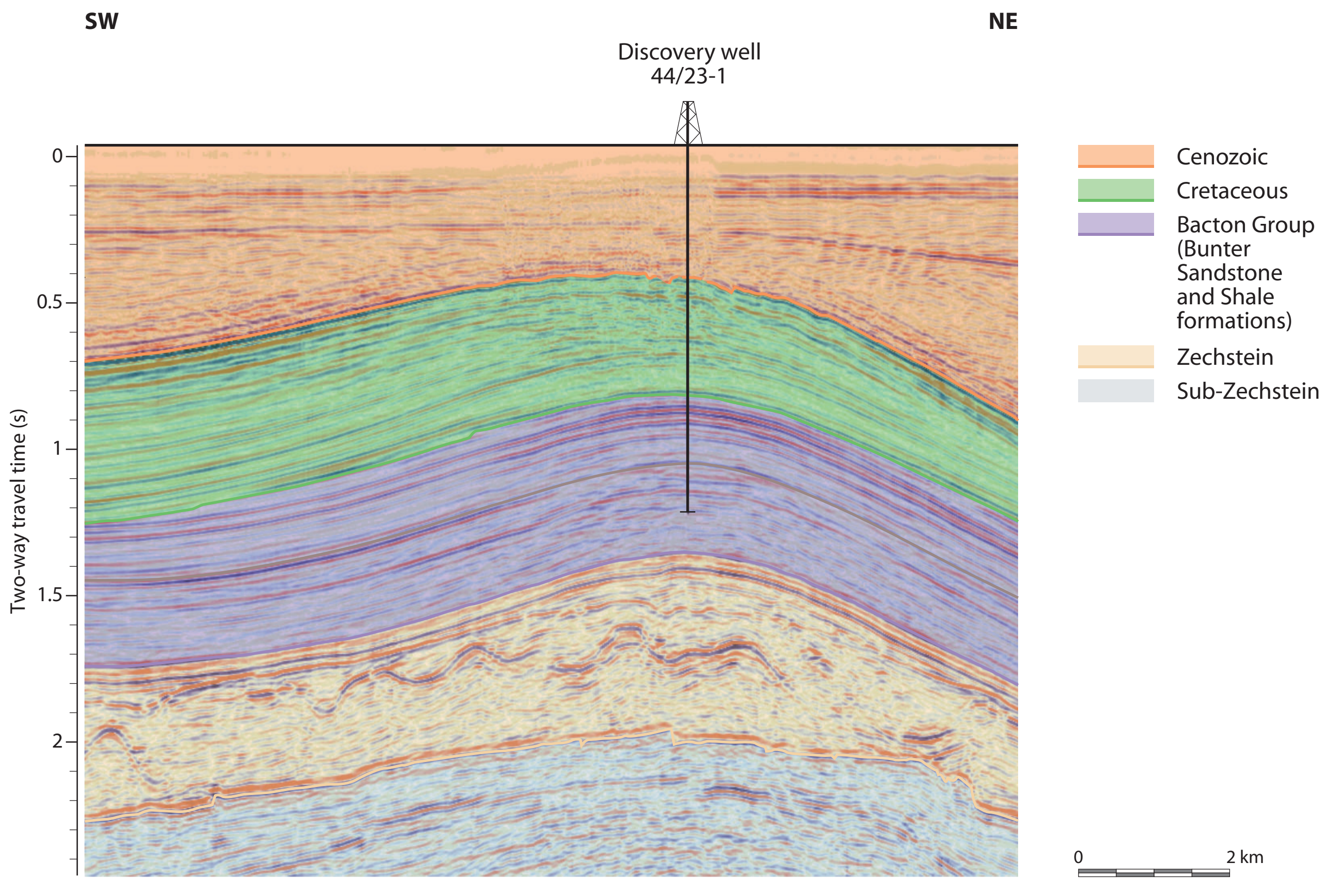


Figure 9.30 Seismic section across the Caister B gasfield, UK southern North Sea (courtesy of ConocoPhillips). See Figure 9.29 for location.

Table 9.1 Properties of the Caister B gasfield.

Reservoir	Bunter Sandstone Formation
Lithology	Sandstone
Depth to top (m)	1325
GWC/GOC.OWC (m)	1400
Maximum column height (m)	75
Net reservoir thickness (m)	150
Net to gross ratio	0.98
Porosity (%)	21 (11-30)
Gas saturation (%)	66
Permeability (mD)	100
Fluid type	Gas
Gas composition	C1 84%, N_2 15%, CO_2 0.05%
Initial pressure (bar)	143.1
Source rock	Westphalian Coal Measures
Seal	Solling Claystone / Röt Salt

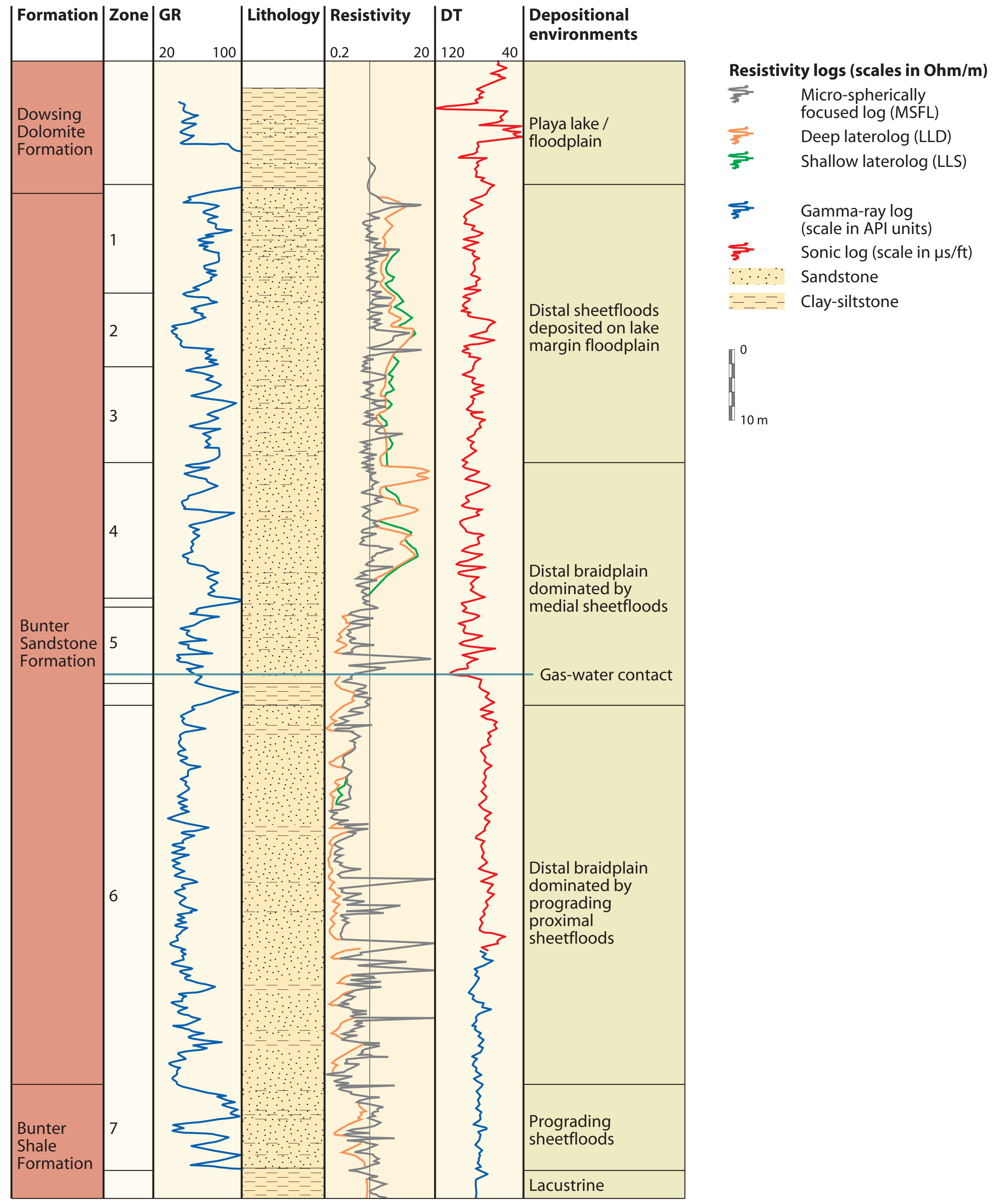


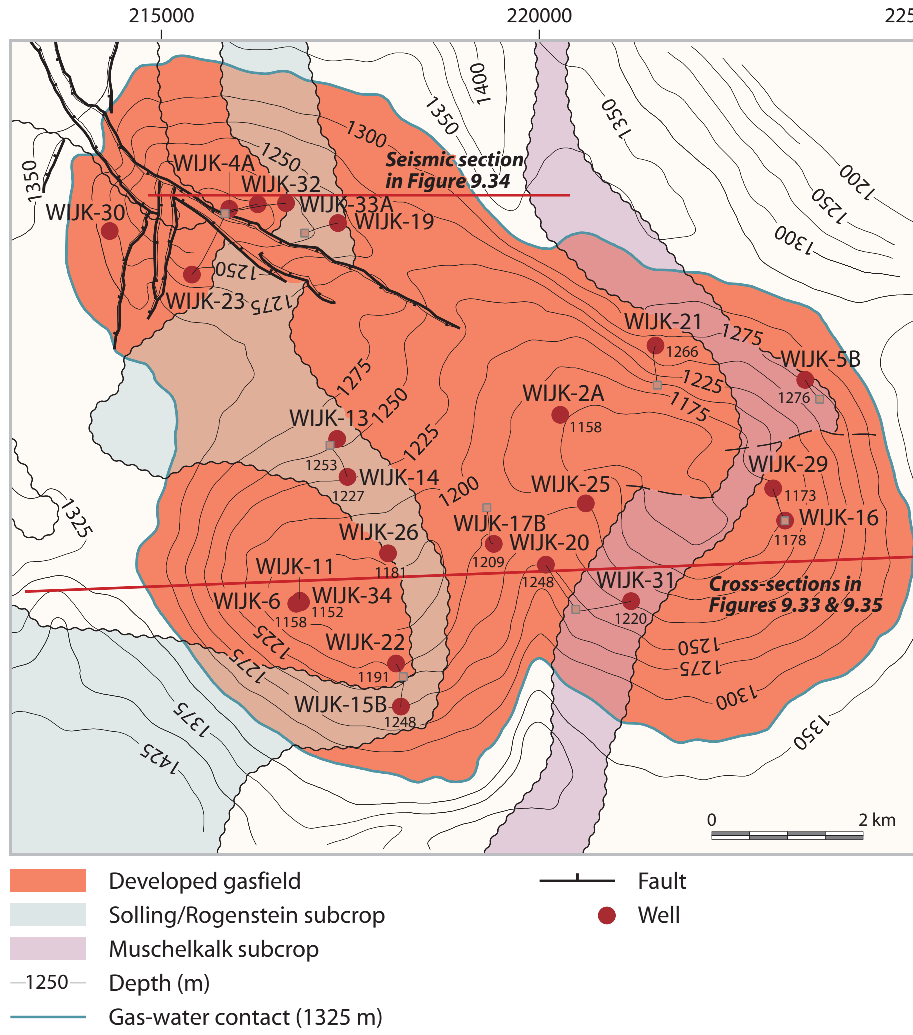
Figure 9.31 Type log of the Bunter Sandstone Formation of the Caister gasfield, well 44/23-4 (after Ritchie & Pratsides, 1993). See Figure 9.29 for location.

3.1.2 De Wijk gasfield, onshore Netherlands

The De Wijk field is an unusual gasfield located in the north-east Netherlands at the western margin of the Lower Saxony Basin (**Figure 9.32**). It has a large number of stacked reservoirs; besides the main Triassic reservoirs, gas has also been produced from Cenozoic, Cretaceous, Permian and Carboniferous accumulations. The Triassic reservoir of the Lower Volpriehausen Sandstone consists of a low N:G oolite complex in the Lower Buntsandstein Formation. The field was discovered in 1949 and has been in production since 1955. Detailed descriptions of the field have been provided by Gdula (1983) and Bruijn (1996); Borkhataria et al. (2005) and Pöppelreiter et al. (2004) supplied details on the reservoir architecture of the Lower Muschelkalk Subgroup.

The field can be described as a broad, salt-induced structure with three culminations in combination with a truncation trap below the Base Cretaceous Unconformity. These 4-way dip closures have a common GWC of 1325 m. Seismic sections across the field are characterised by a clear GWC and gas effects (**Figures 9.33** & **9.34**). The field is large, with an area of some 80 km^2. The Upper Triassic Muschelkalk Group subcrops at the Base Cretaceous Unconformity in the eastern part of the field, whereas in the western part this is the Main Claystone (**Figure 9.36**). The structural setting of the field is in this aspect similar to that of the offshore M7 and G17 gasfields. The top seal for the Triassic gas accumulation is formed by Lower Cretaceous claystones. The source rocks for the gas are Westphalian Coal Measures (**Table 9.2**).

The stacking of Triassic reservoirs in this field is unprecedented in the SPB area (**Figures 9.35** & **9.36**). In the eastern part of the field, dolomitic grainstone beds of the Muschelkalk Formation form the producing horizons (Borkhataria et al., 2005). Detailed reservoir studies show that some zones were not optimally connected to the wells. Additional perforations in the Rogenstein Member and Muschelkalk Formation proved that in some zones the pressure was lagging behind, indicating some degree of compartmentalisation. Although the porosities of this unit are fair (up to 25%), permeabilities are generally below 10 mD. The western part of the field is even more unusual; here, prominent 5 m-thick oolite layers of the low N:G Rogenstein Member of the Lower Buntsandstein Formation form the main producing intervals, with additional production from the conventional Lower Volpriehausen Sandstone reservoir. The thickness of the Rogenstein Member is some 160 m, 40 m of which are oolite grainstone beds. The reservoir characteristics of the oolite beds in the Rogenstein Member were initally attributed to leaching below the Late Cimmerian Unconformity (Gdula, 1983); however, recent studies have revealed that it is related to favourable depositional conditions for oolite grainstones on top of a slightly elevated high (Palermo et al., 2008).



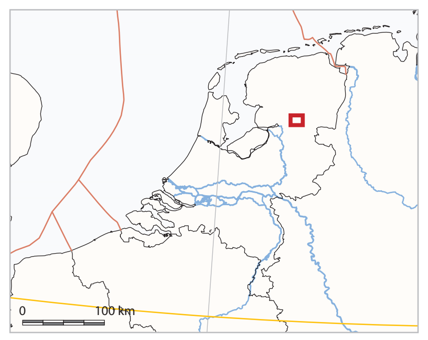


Figure 9.32 Depth-structure to the base of the Cretaceous unconformity combined with a subcrop map of the De Wijk field, eastern Netherlands (courtesy of NAM).

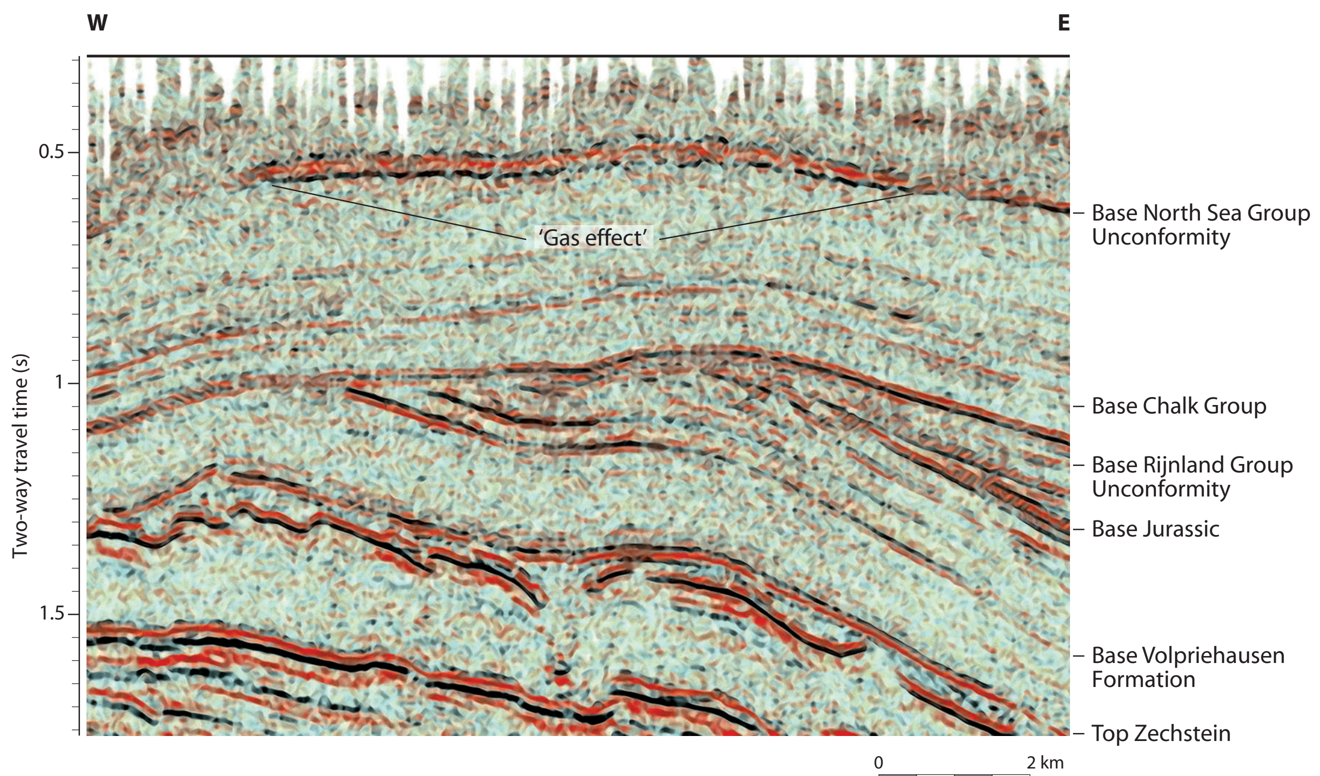


Figure 9.33 Seismic section across the De Wijk field. The section coincides with the geological cross-section of Figure 9.35. A black loop represents a positive amplitude ('soft kick') and a red loop a negative amplitude ('hard kick'). Note the amplitude brightening of the shallowest reservoir (indicated with gas effect). After Bruijn (1996). See Figure 9.32 for location.

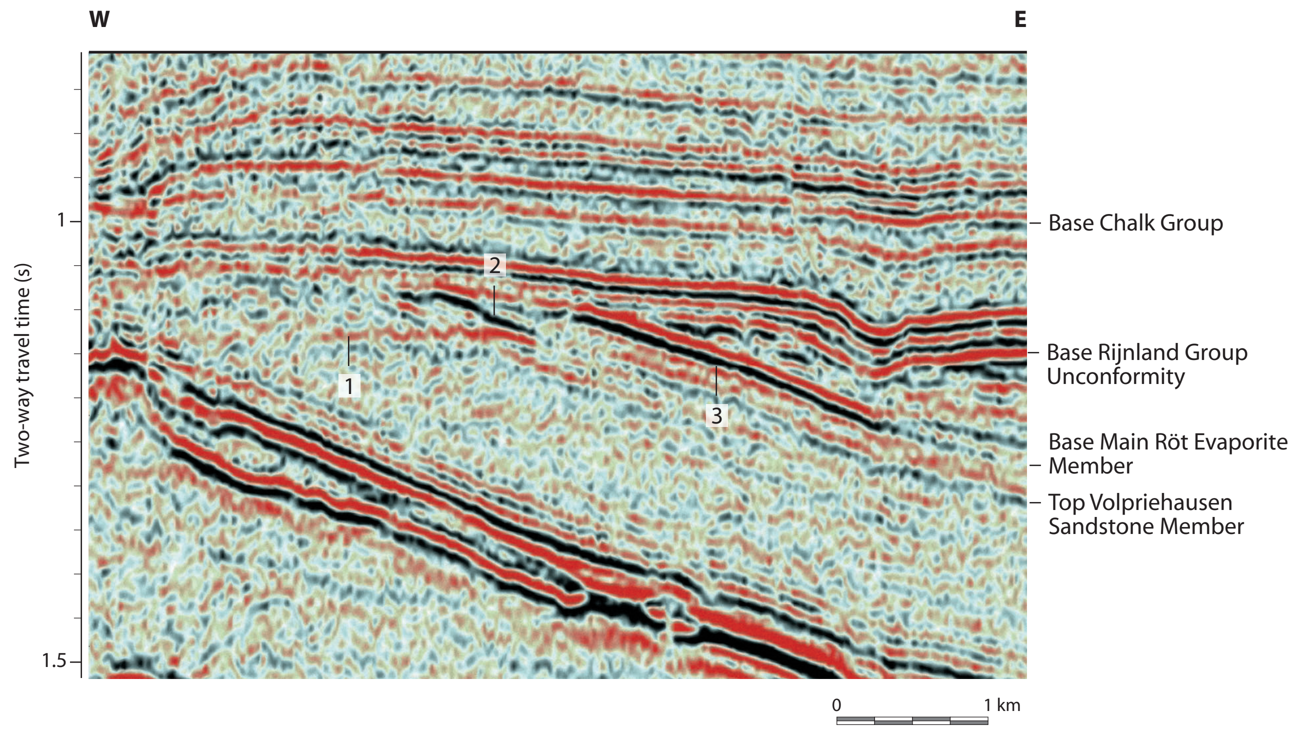


Figure 9.34 Seismic section showing effects of gas fill, sand distribution and leaching of evaporites. 1. flat event in the Rogenstein Member, interpreted as the GWC; 2. amplitude brightening of the Lower Volpriehausen Sandstone above the GWC; 3. brightening of the Röt Evaporite as a result of leaching of rock-salt. After Bruijn (1996). See Figure 9.32 for location.

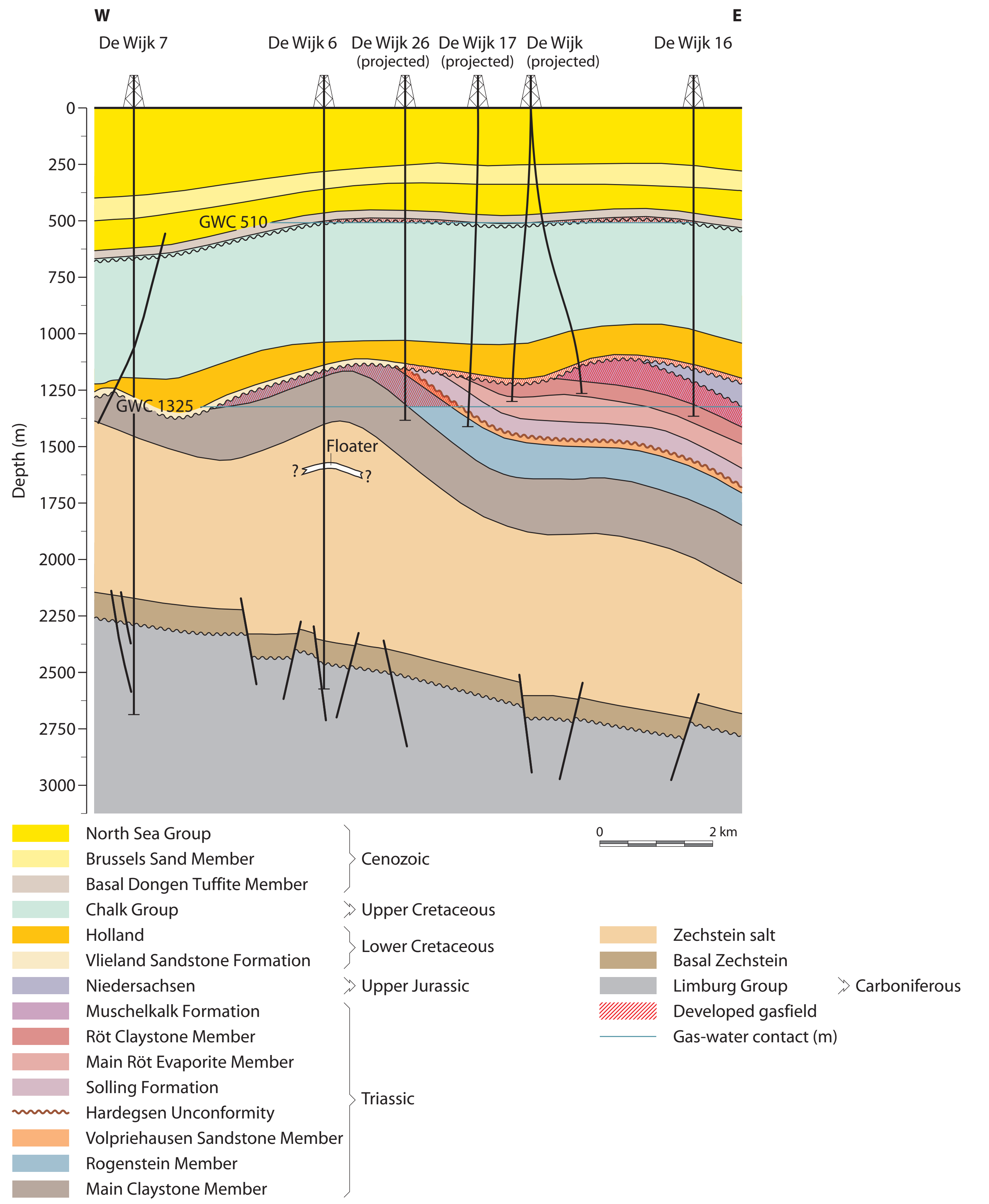


Figure 9.35 Geological cross-section across the De Wijk field. Note the stacking of different reservoirs in the vertical sense as well as the variation in the Triassic reservoirs horizontally. Modified after Bruijn (1996). See Figure 9.32 for location.

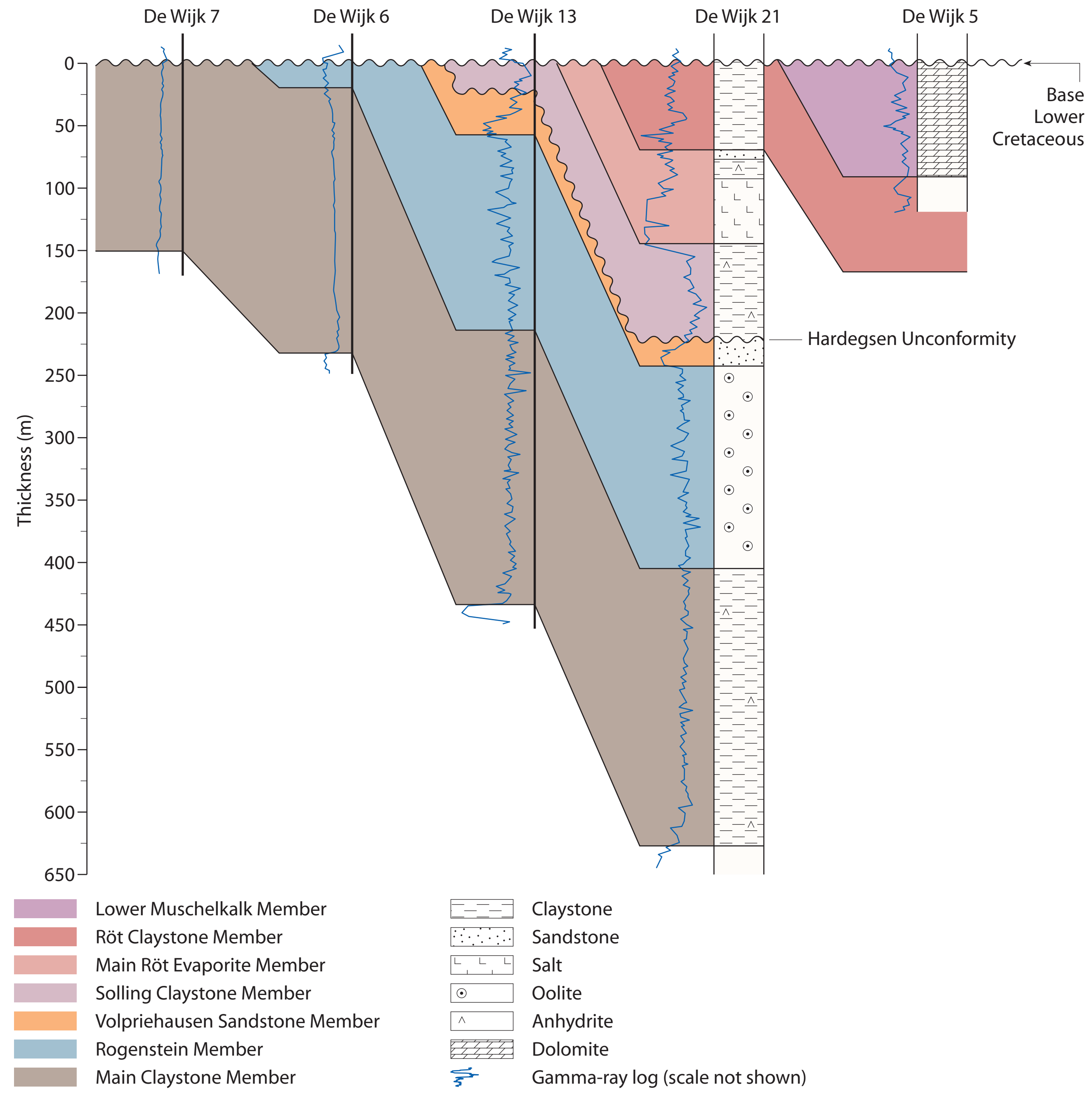


Figure 9.36 Stratigraphic correlation of the Triassic reservoirs of the De Wijk field (modified after Gdula, 1983). See Figure 9.32 for locations of wells.

Table 9.2 Properties of the De Wijk field.

Reservoir	Rogenstein Member	Lower Volpriehausen Sandstone	Lower Muschelkalk
Lithology	Oolites	Sandstone	Dolomite
Depth to top (m)	1150		
GWC/GOC.OWC (m)	1325		
Maximum column height (m)	175		
Net reservoir thickness (m)	5-65		
Porosity (%)	<10	25	15-25
Gas saturation (%)	40-85		
Permeability (mD)	25		
Fluid type	Gas		
Gas composition	C1 90%, N_2 5%, CO_2 0.03%		
Initial pressure (bar)	60-170		
Source rock	Westphalian Coal Measures	Westphalian Coal Measures	Westphalian Coal Measures
Seal	Vlieland Claystone Formation (Lower Cretaceous)	Vlieland Claystone Formation (Lower Cretaceous)	Vlieland Claystone Formation (Lower Cretaceous)

3.1.3 F15-A gasfield, the Netherlands

The F15-A field is located in the Netherlands F15 offshore block, approximately 100 km north-north-west of the island of Terschelling. The field was discovered by well F15-4 in 1986, and was brought on stream in 1993 (Fontaine et al., 1993). Apart from the Triassic, Upper Jurassic rocks have also been found to be gas bearing. Other Triassic gas occurrences in the area were found in blocks L2, L5, L9 and M1 (De Jager & Geluk, 2007).

F15-A is a complex north-north-east-trending turtle-back anticline situated in an intermediate position between the Dutch Central Graben and the Schill Grund High. The anticline is bordered on both the eastern and western sides by elongated salt diapirs (**Figures 9.37** & **9.38**). To the north-north-east, it is delineated by a west-north-west-trending collapse graben of Triassic age filled with a thick succession of Upper Jurassic sediments (**Figure 9.40**) (Fontaine et al., 1993). The reservoir is sealed by the Volpriehausen Clay-Siltstone / Solling Claystone / Röt Evaporite (**Figures 9.39**, **9.40** & **9.42**). The source rocks for the gas are the Westphalian Coal Measures (**Table 9.3**); charge occurred through large faults where Rotliegend rocks are offset against Triassic.

The reservoir is formed by fluvial and aeolian sandstones of the Lower Volpriehausen Sandstone (Main Buntsandstein Formation; **Figure 9.41**), which is about 40 m thick and comprises dune, inter-dune and fluvial deposits. Porosities vary from 8 to 18%, but permeabilities are reduced throughout the unit by anhydrite and salt cementation (Fontaine et al., 1993). Other reservoirs, such as the thicker sandstones within the Volpriehausen Formation and the basal Detfurth Sandstone, have poor reservoir characteristics due to salt and anhydrite plugging. This type of evaporite plugging is common in Triassic fields; in the area of the Dutch Central Graben it has been traced back to the Zechstein deposits (Purvis & Okkerman, 1996).

Table 9.3 Properties of the F15 field.

Reservoir	Lower Volpriehausen Sandstone Member
Lithology	Sandstone
Depth to top (m)	3500
GWC/GOC.OWC (m)	3665
Maximum column height (m)	165
Net reservoir thickness (m)	40
Net to gross ratio	0.52
Porosity (%)	13
Fluid type	Gas
Gas composition	C1 85.6%, C2 3.5%, N_2 9.6%, CO_2 0.9%
Initial pressure (bar)	674
Temperature (°C)	140
Source rock	Westphalian Coal Measures
Seal	Volpriehausen Clay-Siltstone / Solling Claystone / Röt Evaporite

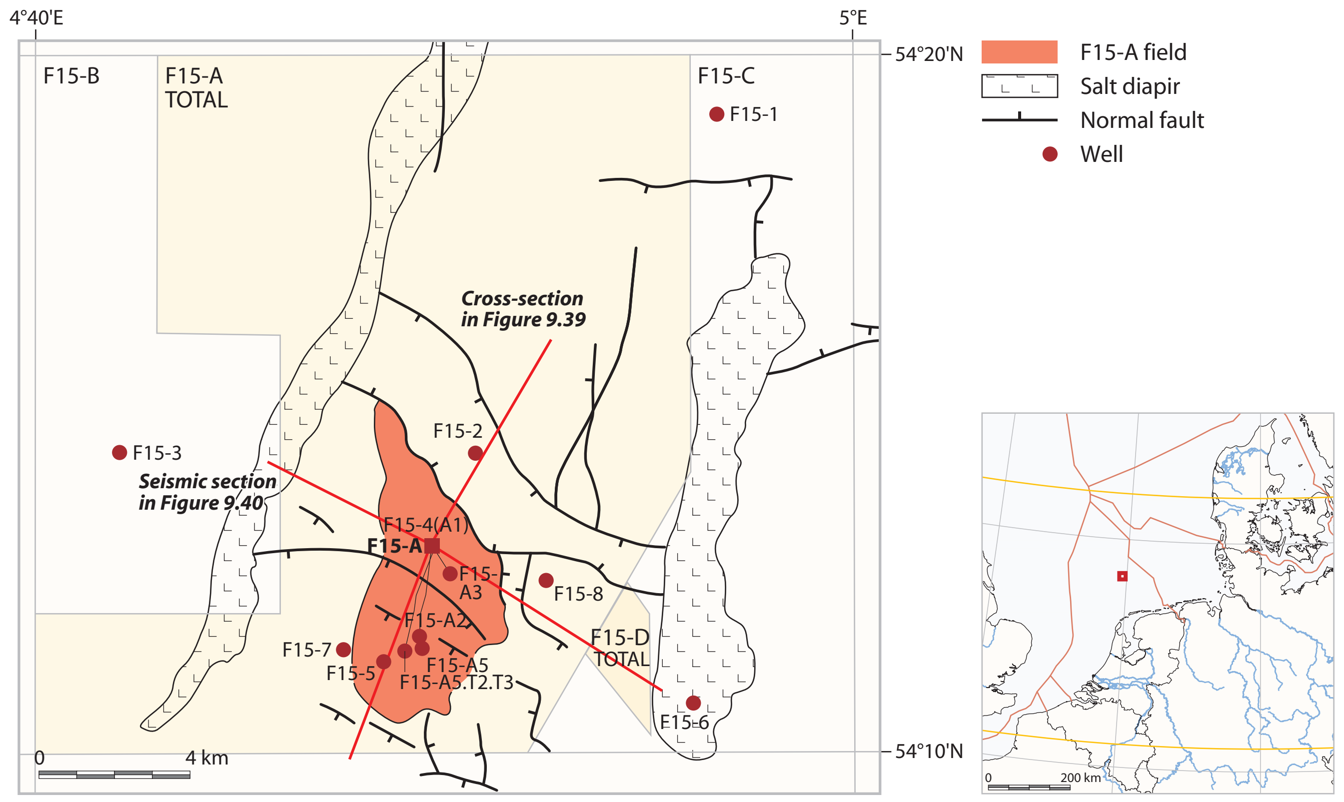


Figure 9.37 Location of the F15-A field.

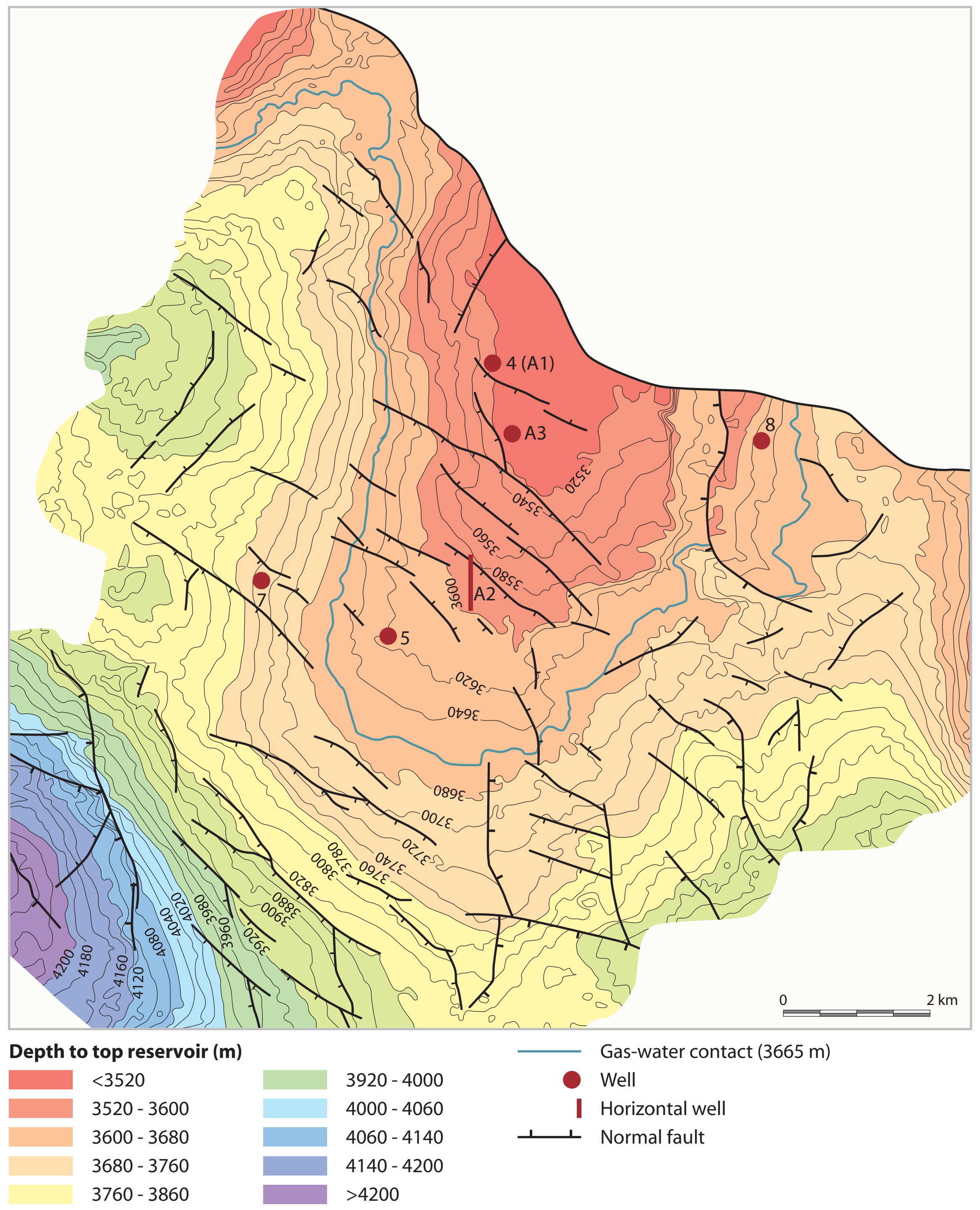


Figure 9.38 Depth-structure to the top of the reservoir in the F15-A gasfield (courtesy of Total).

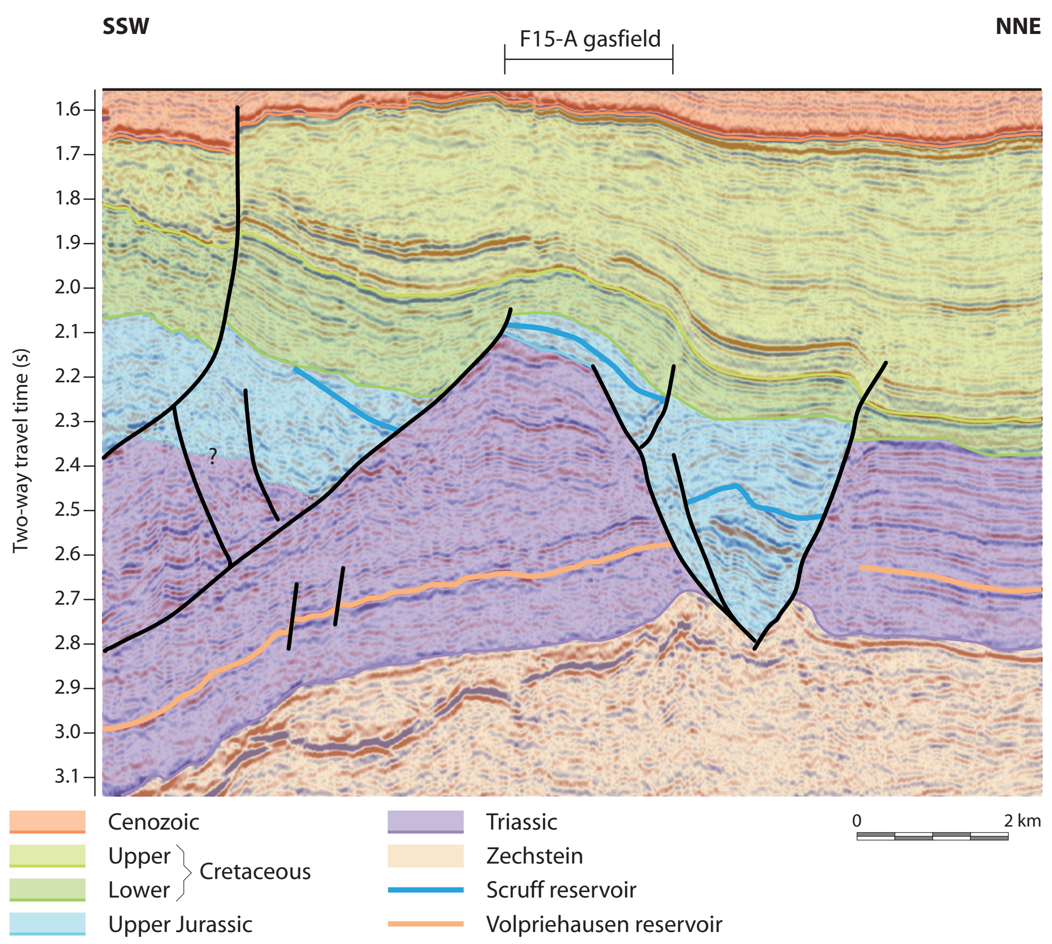


Figure 9.39 Interpreted seismic section across the F15-A field. The north-east boundary of the field is formed by a pronounced graben (courtesy of Total). See Figure 9.37 for location.

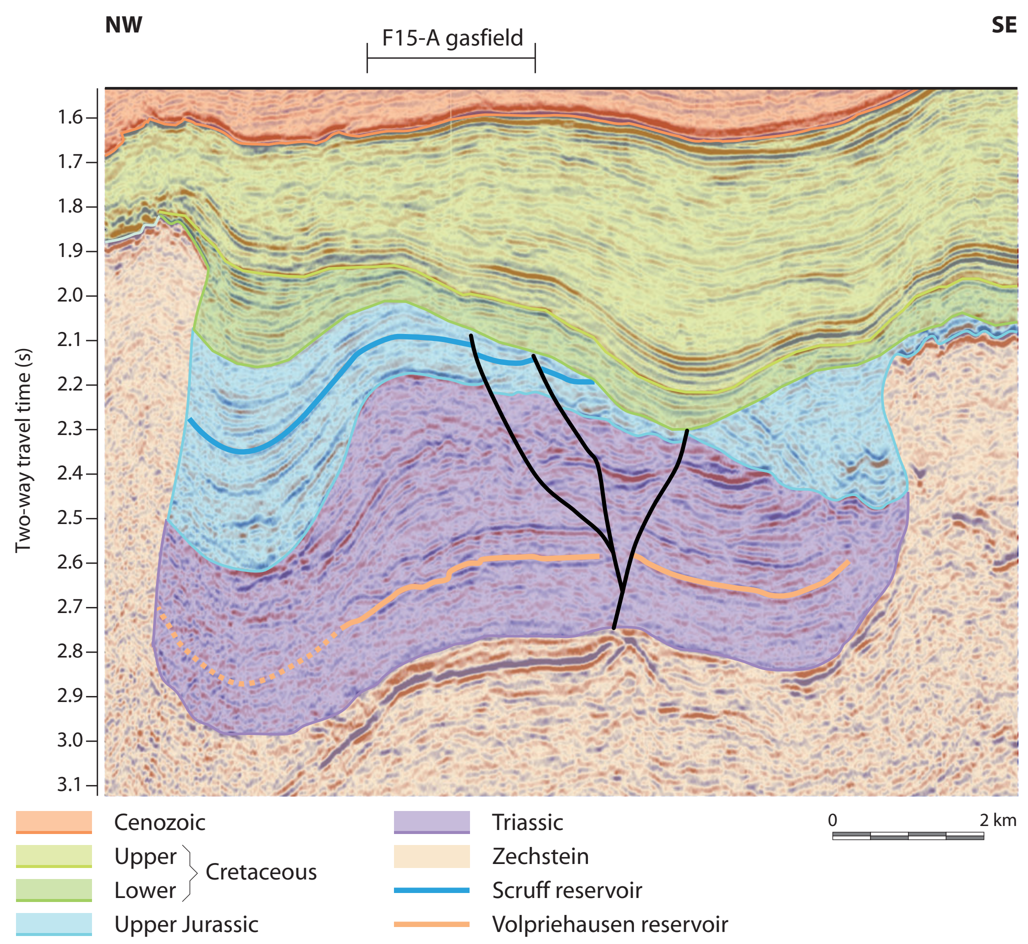


Figure 9.40 Seismic section showing the structure of the F15-A field. In this section the structure is a turtle-back anticline bordered by two salt structures and their rim-synclines (courtesy of Total). See Figure 9.37 for location.

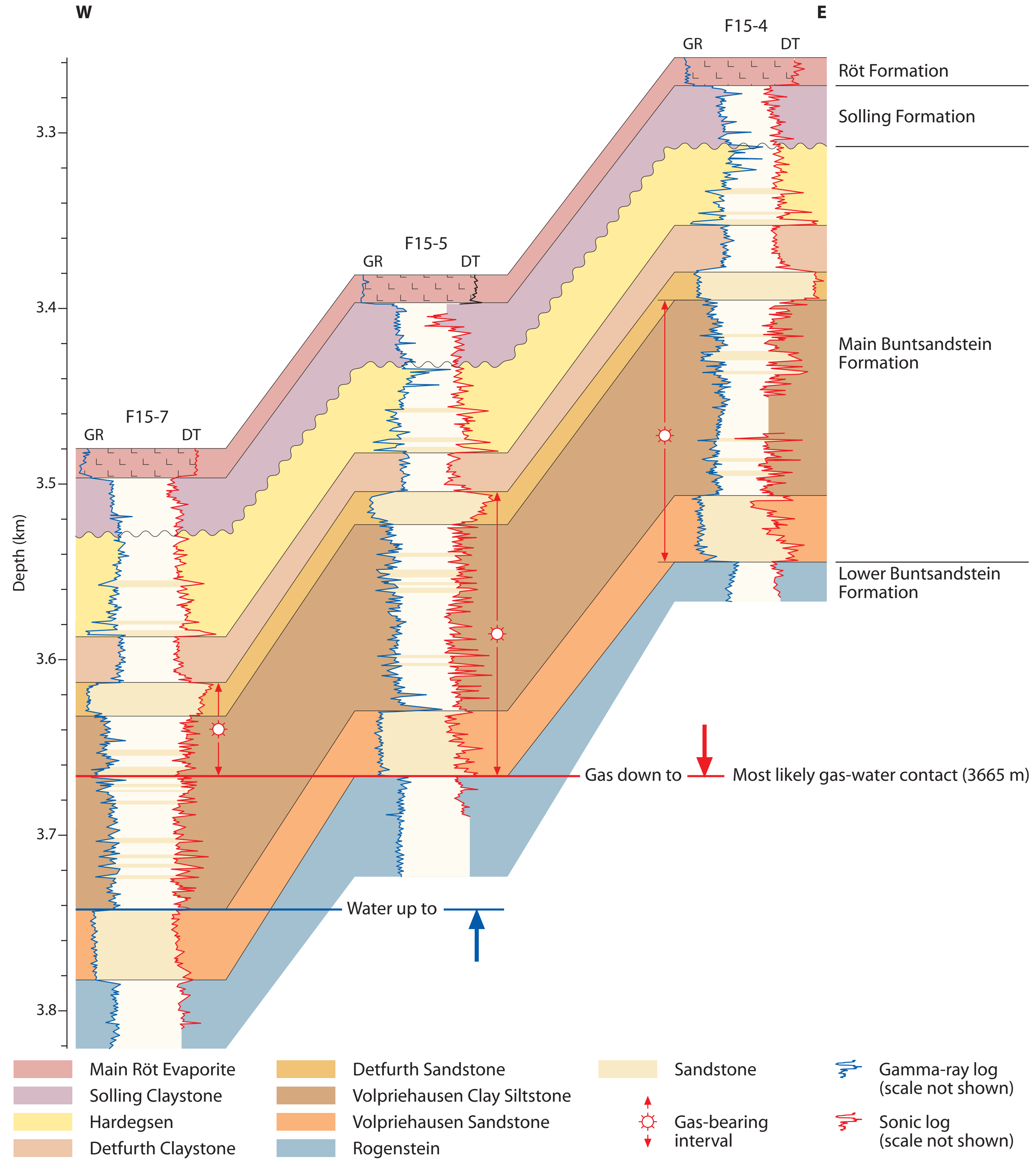


Figure 9.41 Well-log correlation of the Main Bundsandstein Formation. The Lower Volpriehausen Sandstone forms the main reservoir of the F15-A field. Note the uncertainty in the GWC, most likely situated at 3665 m. See Figure 9.37 for locations of wells.

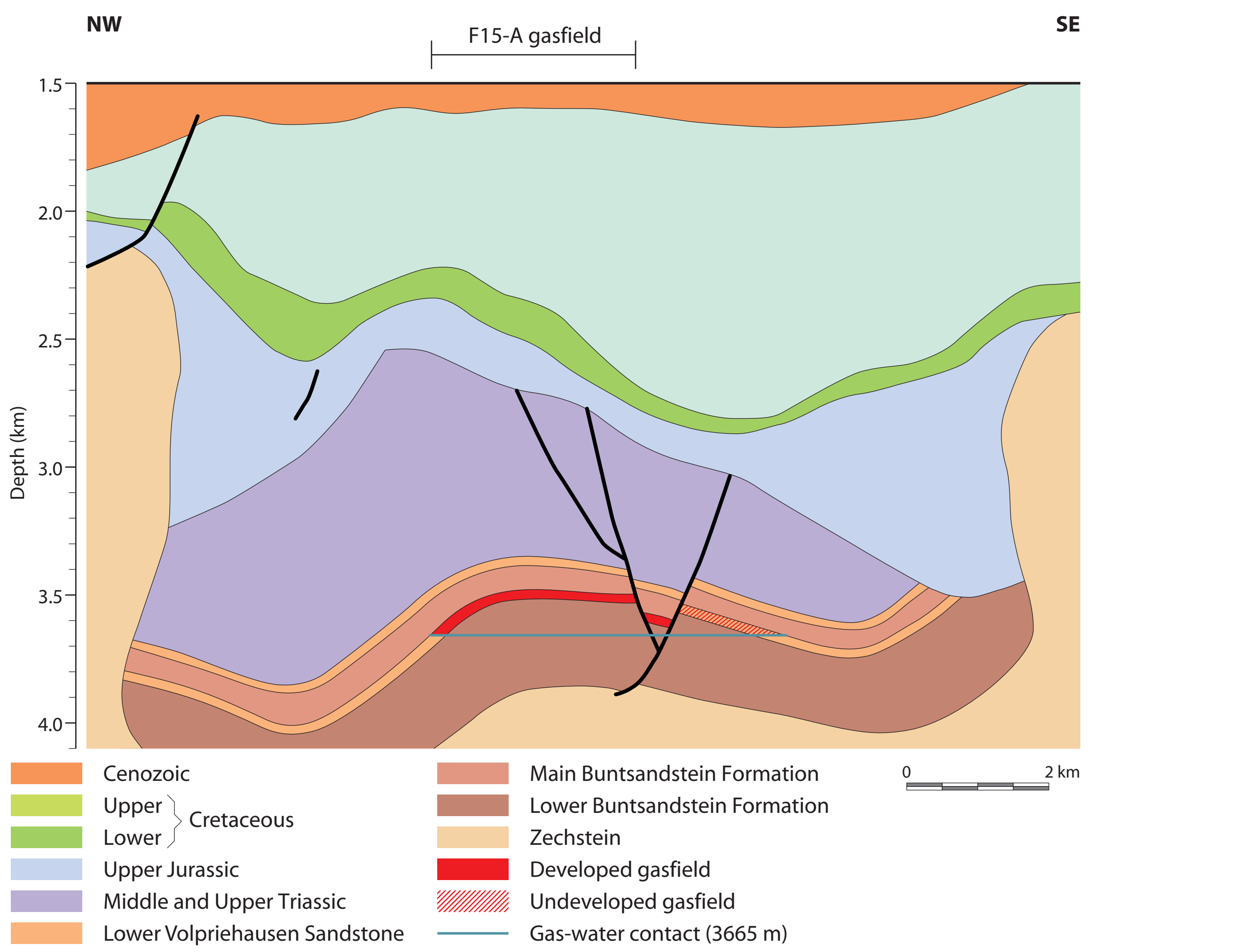


Figure 9.42 Structural cross-section through the F15-A field (courtesy of Total).See Figure 9.37 for approximate location (equivalent to seismic section in Figure 9.40).

3.1.4 Pernis-West oilfield/gasfield, onshore Netherlands

The Pernis-West fields are situated just south-west of Rotterdam. They lie at the southern margin of the West Netherlands Basin in an area with Cenozoic gas charge (De Jager et al., 1996). The field is unique in having an oil rim below the gas in Triassic reservoirs.

The structure is a north-north-west-trending horst block, densely faulted in its southern part (**Figures 9.43** & **9.44**). Reservoirs are formed by the Röt Fringe Sandstone and the Main Buntsandstein Formation (mainly Hardegsen and Detfurth formations; **Figure 9.45**). The seal is formed by claystones, carbonates and anhydrites of the Muschelkalk and Keuper formations (**Table 9.4**). The combination of oil and gas has been ascribed to gas charge from Carboniferous coals and oil charge from the juxtaposed Lower Jurassic Posidonia and Aalburg shales.

The reservoir rocks comprise an alternation of fine- to medium-grained sandstones, predominantly from braided-river channels, with minor intercalations of aeolian dune, damp sandflat and sheetflood deposits (**Figure 9.45**).

Table 9.4 Properties of the Pernis-West field.

Reservoir	Main Buntsandstein (Hardegsen and Detfurth Formations)	Röt Fringe Sandstone
Lithology	Sandstone	Sandstone
Depth to top (m)	2570	
GWC/GOC.OWC (m)	2769 (GOC) and 2804 (OWC)	
Maximum column height (m)	130	
Net reservoir thickness (m)	200	
Porosity (%)	13	11
Gas saturation (%)	56-90	
Oil saturation (%)	35-85	
Fluid type	Oil and gas	Oil and gas
Gas composition	C1 86.7%, C2 6.5%, C3 2%, N_2 0.5%, CO_2 2.9%	
Initial pressure (bar)	287	
Temperature (°C)	103	
Source rock	Gas charge from Carboniferous coals and oil charge from the juxtaposed Lower Jurassic Posidonia and Aalburg shales	Gas charge from Carboniferous coals and oil charge from the juxtaposed Lower Jurassic Posidonia and Aalburg shales
Seal	Claystones, carbonates and anhydrites of the Muschelkalk and Keuper formations	Claystones, carbonates and anhydrites of the Muschelkalk and Keuper formations

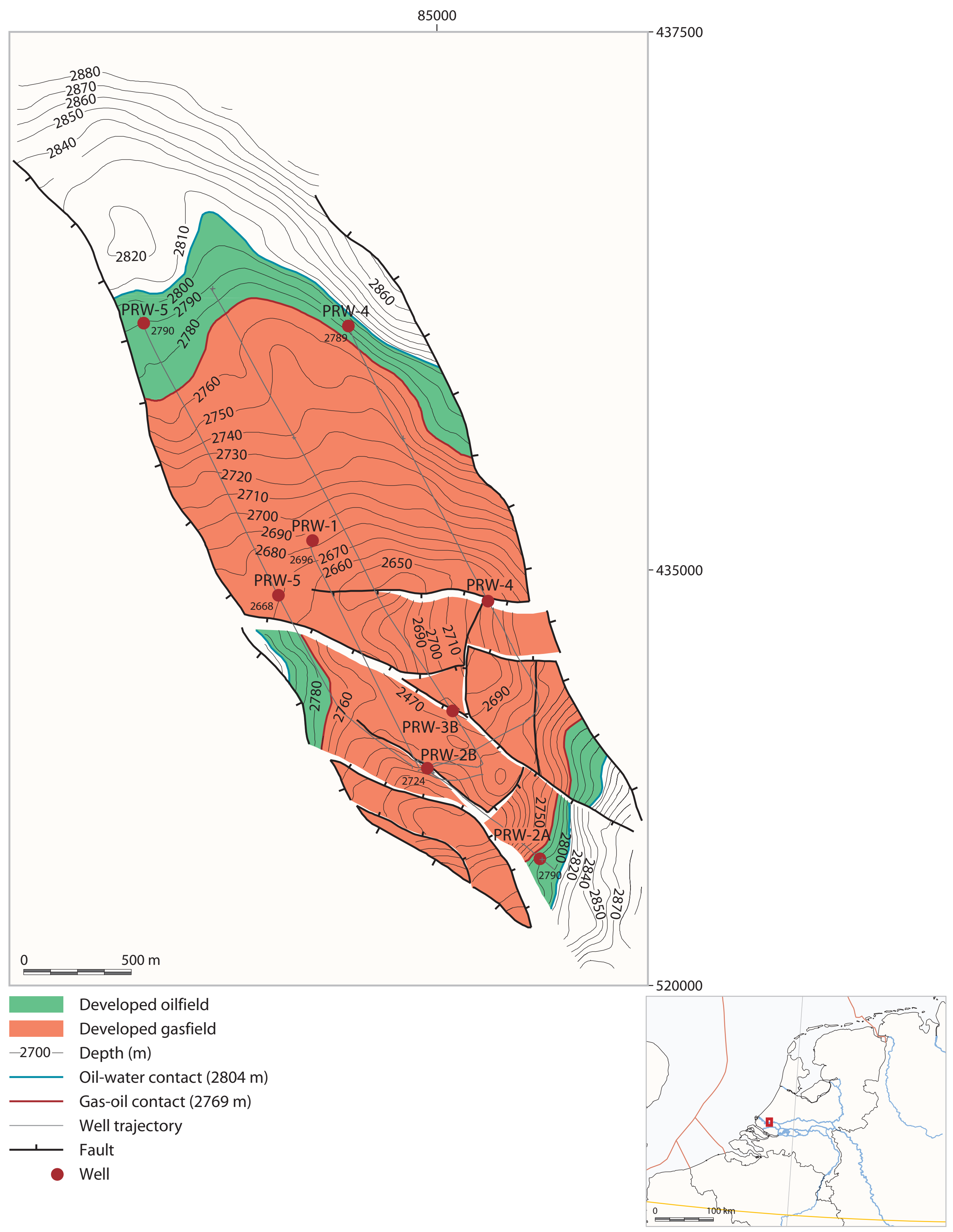


Figure 9.43 Depth-structure to the top of the Bunter Sandstone Formation in the Pernis-West field (courtesy of NAM).

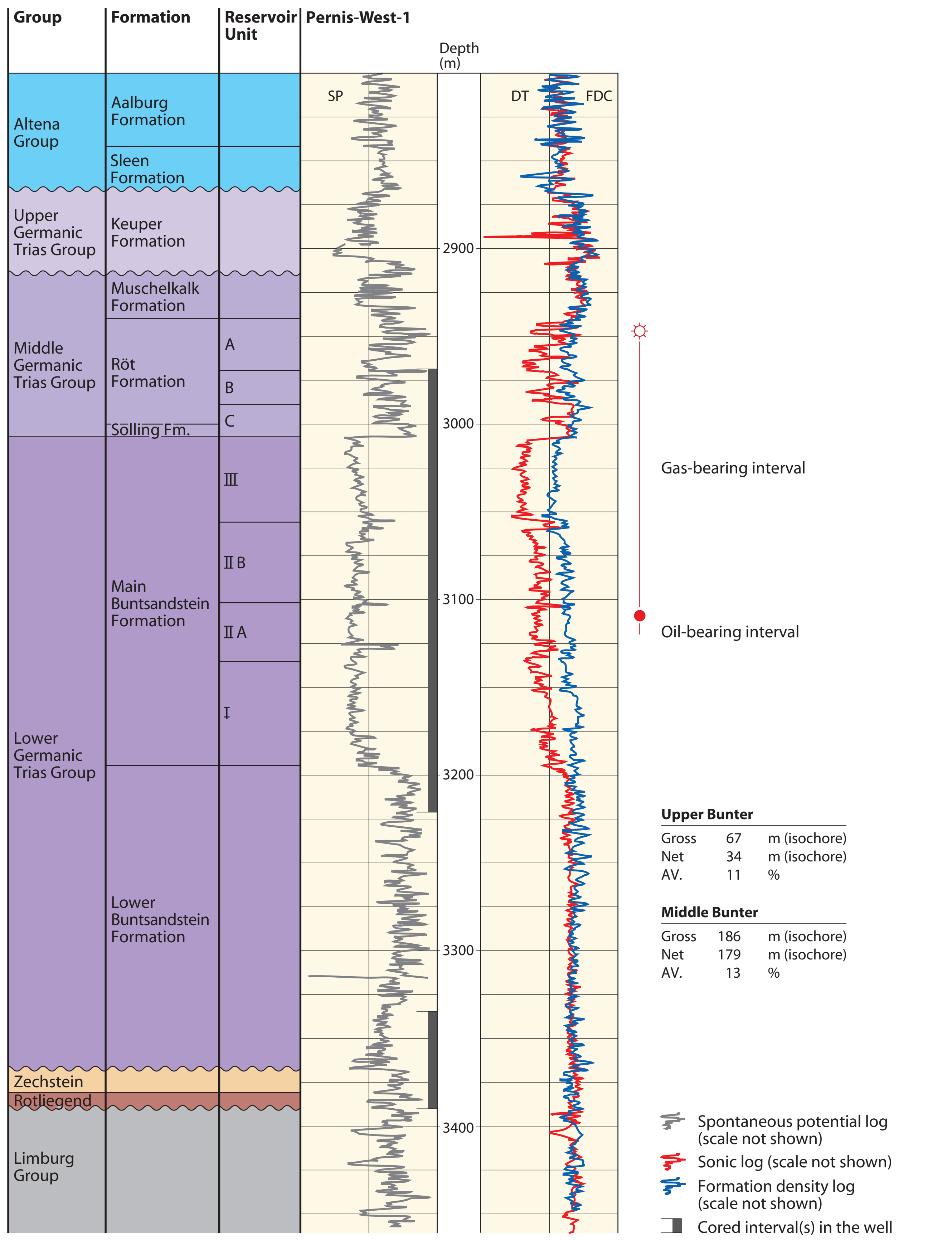


Figure 9.45 Type log of the Pernis-West field (Pernis-West-1). The reservoir comprises the massive sandstones of the Main Buntsandstein Formation and thinner sandstones in the Röt Formation. See Figure 9.43 for location (PRW-1).

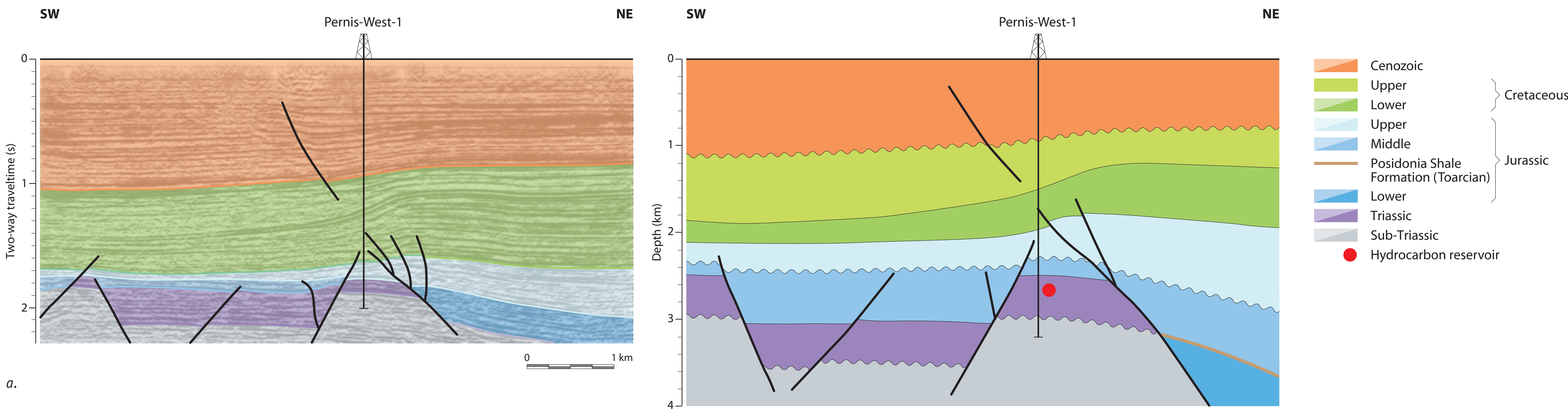


Figure 9.44 a. Seismic section; and b. Interpreted section through the Pernis-West field. After De Jager et al. (1996). See Figure 9.43 for location of Pernis-West-1 (PRW-1).

3.1.5 Rehden gasfield, onshore Germany

The Rehden gasfield is located in north-west Germany, near Diepholz between Bremen and Osnabrück (Lower Saxony Basin; **Figure 9.46**). The field has three stacked reservoirs, of which the Lower Triassic Middle Buntsandstein Subgroup is the uppermost (**Figure 9.47**); the other two are the Upper Permian Zechstein 2 (Main Dolomite) and Upper Carboniferous sandstones (**Figures 9.48**). The first gas was discovered in the Zechstein Main Dolomite in 1952 and production started in 1954. In 1961, two wells were deepened to the Upper Carboniferous where another reservoir was found. As the older Zechstein wells had encountered gas shows in the Lower Triassic, a detailed exploration of the Buntsandstein Group was started in 1962. Reservoirs were found in the uppermost Lower Buntsandstein and in the Middle Buntsandstein, with a very high initial pressure of 247 bars (Anonymous, 1963) (**Table 9.5**). Furthermore, gas shows have been found in the Middle Triassic Muschelkalk Group. The Triassic reservoirs are not in hydraulic communication with the lower two reservoirs. All three reservoirs are currently in production.

The Rehden structure was essentially formed during the Late Cretaceous compressional inversion phase. It is a broad, 7 to 8 km-long inversion anticline that was upthrown to the south-west along a north-east dipping fault. Towards the north-north-east, it is upthrown against the Donstorf Trough along two shallow-dipping reverse faults. The Lower and Middle Buntsandstein subgroups in the central fault block are undisturbed (Baldschuhn & Best, 1998). The faults in the overburden form an inverted Late Jurassic to Early Cretaceous step graben, but die out in the Röt evaporites. Significant offset and uplift of Upper Carboniferous and Lower Zechstein strata occurred along a major fault in the area of the present gasfield, compared to the same formations in the Late Cretaceous Donstorf Trough just north of the structure, leading to an intensely faulted flower structure tilted towards the north-north-east. Evaporite successions within Zechstein, Rotliegend and Upper Jurassic strata are also responsible for the complex structural setting of the Rehden field.

The Buntsandstein Group of the Rehden gasfield consists of 228 m-thick Lower Buntsandstein sediments (Calvörde and Bernburg formations) and 163 m of Middle Buntsandstein deposits. The latter comprise the basal Volpriehausen Formation (74 m thick), unconformably overlain by the Solling Formation. The stratigraphically incomplete succession reflects its palaeogeographic position on the Hunte Swell (**Figure 9.46**).

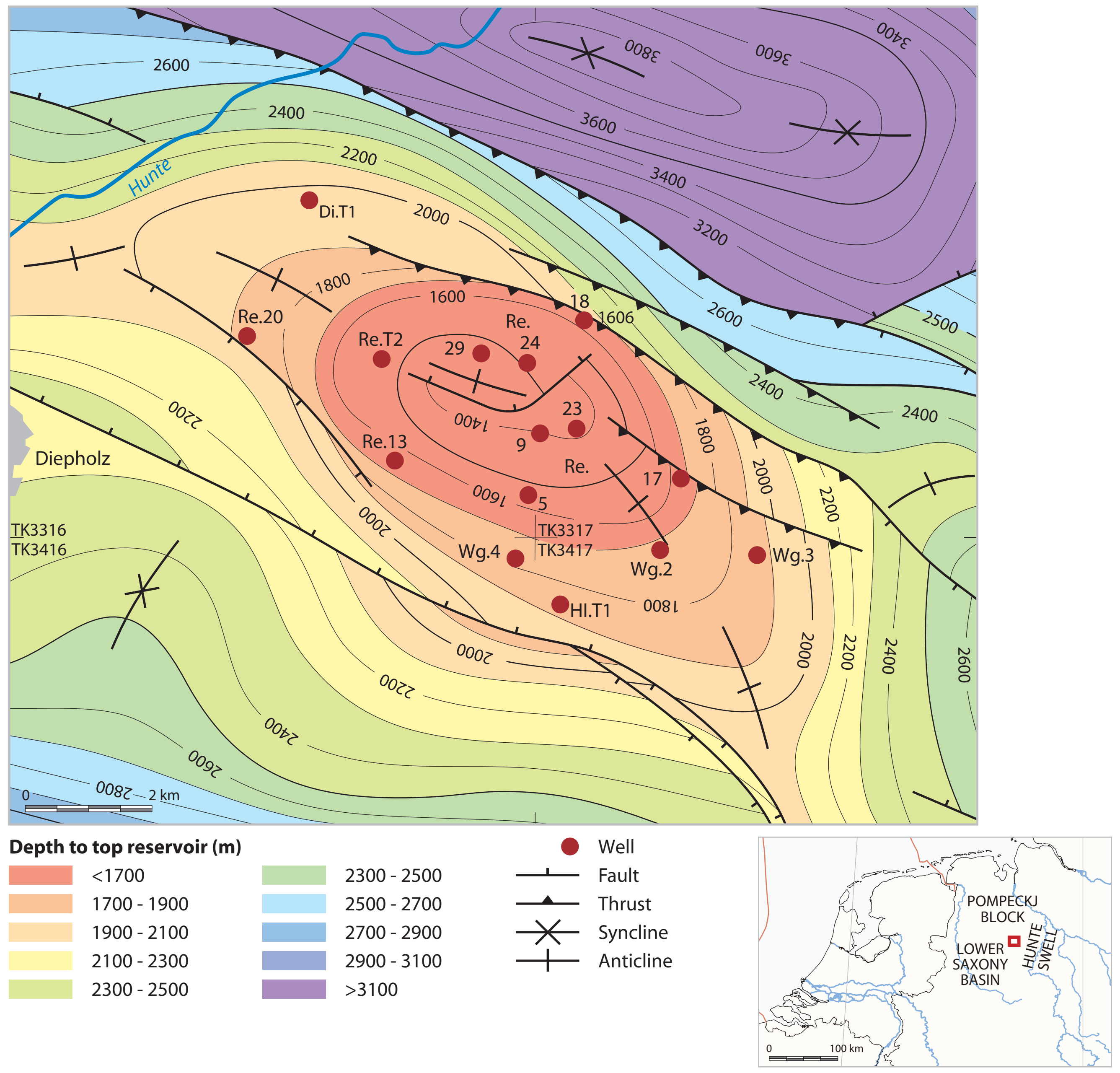


Figure 9.46 Depth-structure to the top of the Middle Buntsandstein Subgroup in the Rheden gasfield near Diepholz, Lower Saxony. After Baldschuhn & Best (1998).

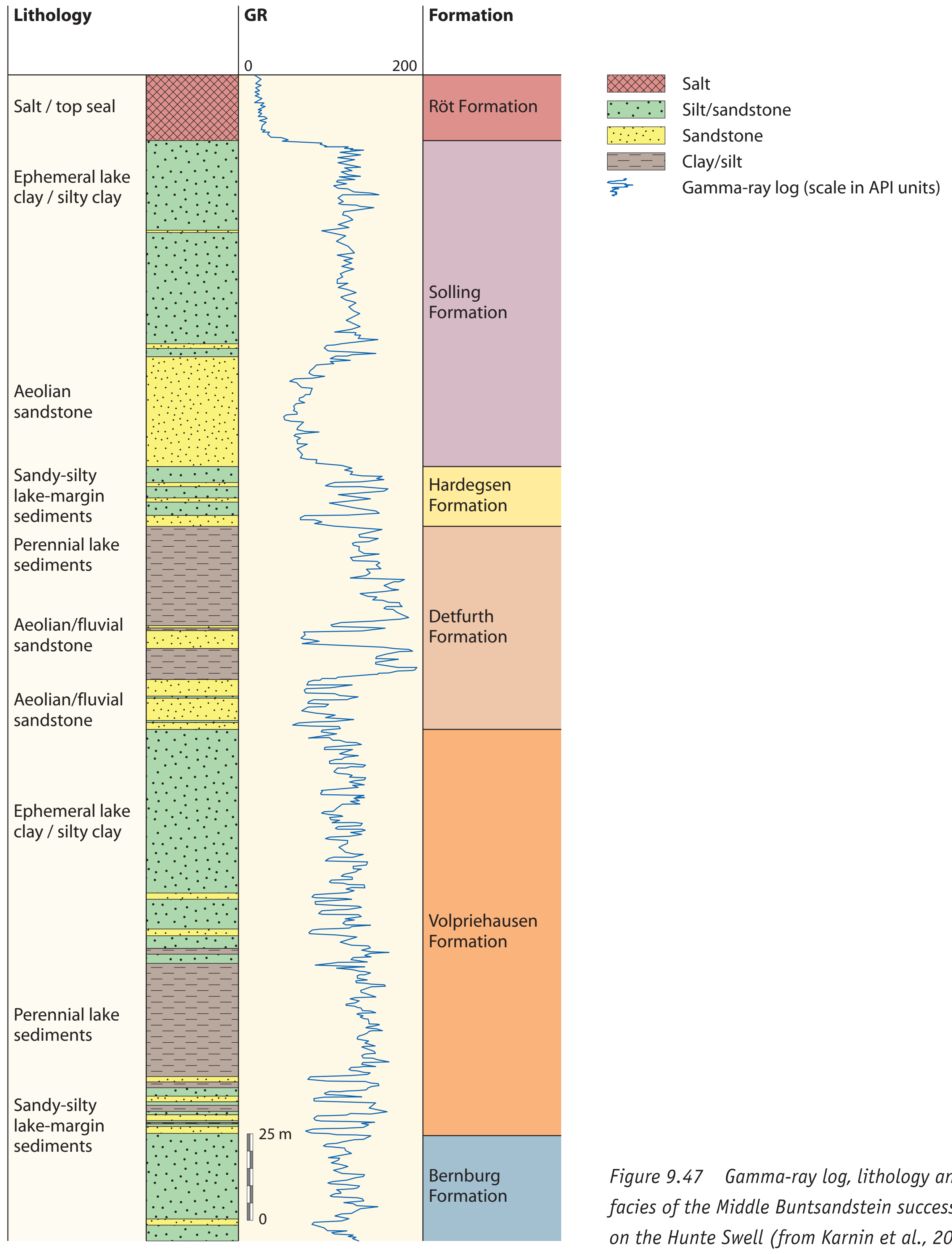


Figure 9.47 Gamma-ray log, lithology and facies of the Middle Buntsandstein succession on the Hunte Swell (from Karnin et al., 2006).

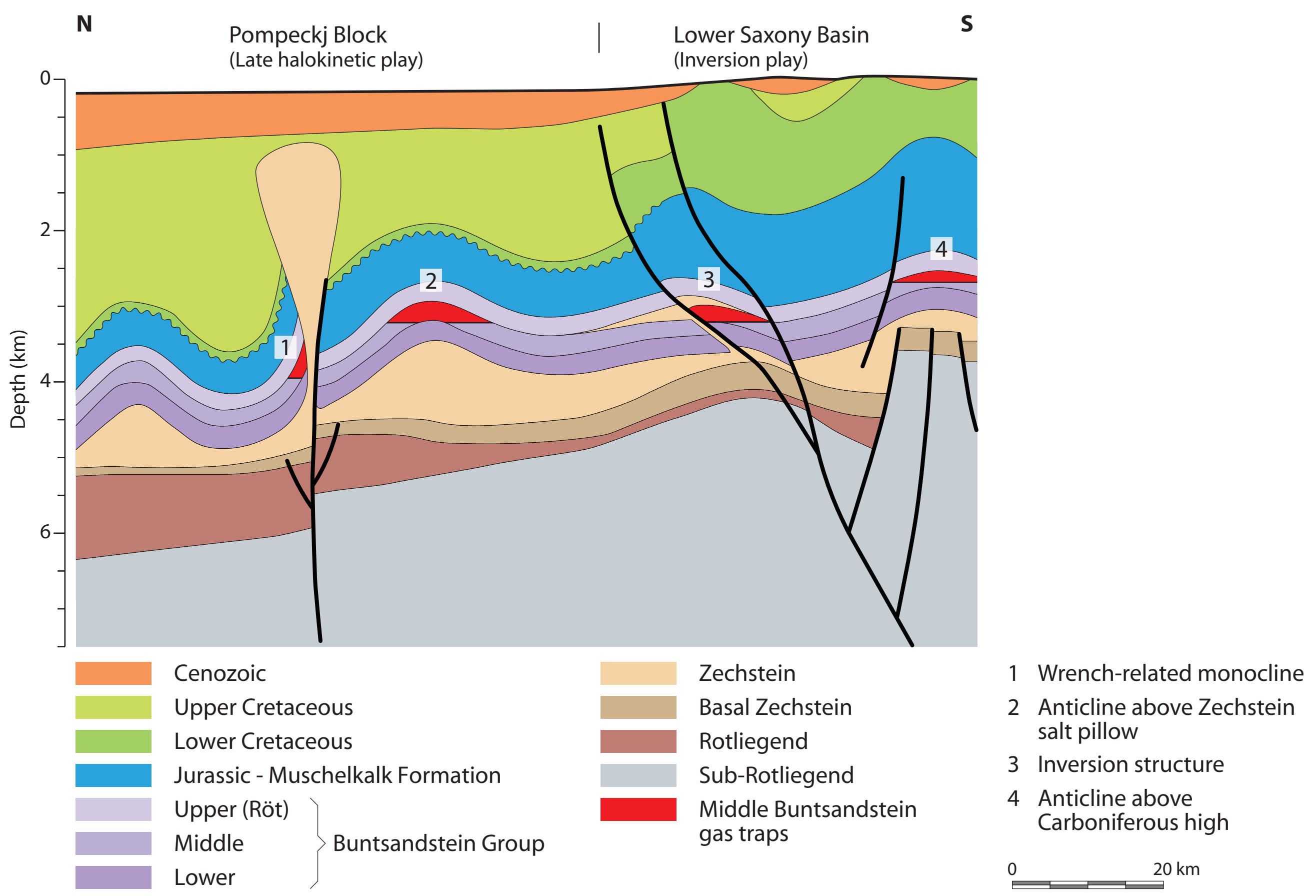


Figure 9.48 Schematic cross-section showing Middle Buntsandstein structural types in north-west Germany (from Karnin et al., 2006).

Table 9.5 Properties of the Rehden field.

Reservoir	Lower Triassic Middle Buntsandstein
Lithology	Sandstone
Depth to top (m)	1540-1800
Maximum column height (m)	25
Porosity (%)	10
Permeability (mD)	0.5
Fluid type	Gas
Gas composition	C1 91.4%, C2 <0.9%, CO_2 1.3%, N_2 6.4%
Initial pressure (bar)	247
Source rock	Westphalian Coal Measures
Seal	Lower to Middle Triassic evaporites

3.1.6 Thönse gasfield, onshore Germany

The Thönse gasfield, located approximately 20 km north-east of Hannover, is the only Mesozoic gas/condensate field in the Hannover oil province. It lies in the eastern part of the Lower Saxony Basin (**Figure 9.50**) and was found to be gas-bearing in 1951 by well Grossburgwedel T1.

The structural history of the Lower Saxony Basin is characterised by remarkably strong Early Cretaceous subsidence and tilting followed by Late Cretaceous inversion, partly due to salt migration towards the neighbouring salt domes (Betz & Fahrion, 1991). Inversion resulted in the formation of a dome-shaped anticline with a diameter of 6 to 7 km. The top seal of the accumulation is formed by Rhaetian and Liassic shales. The gas/condensate can be tied back to the Lower Jurassic Posidonia Shale source rock (**Figure 9.51**).

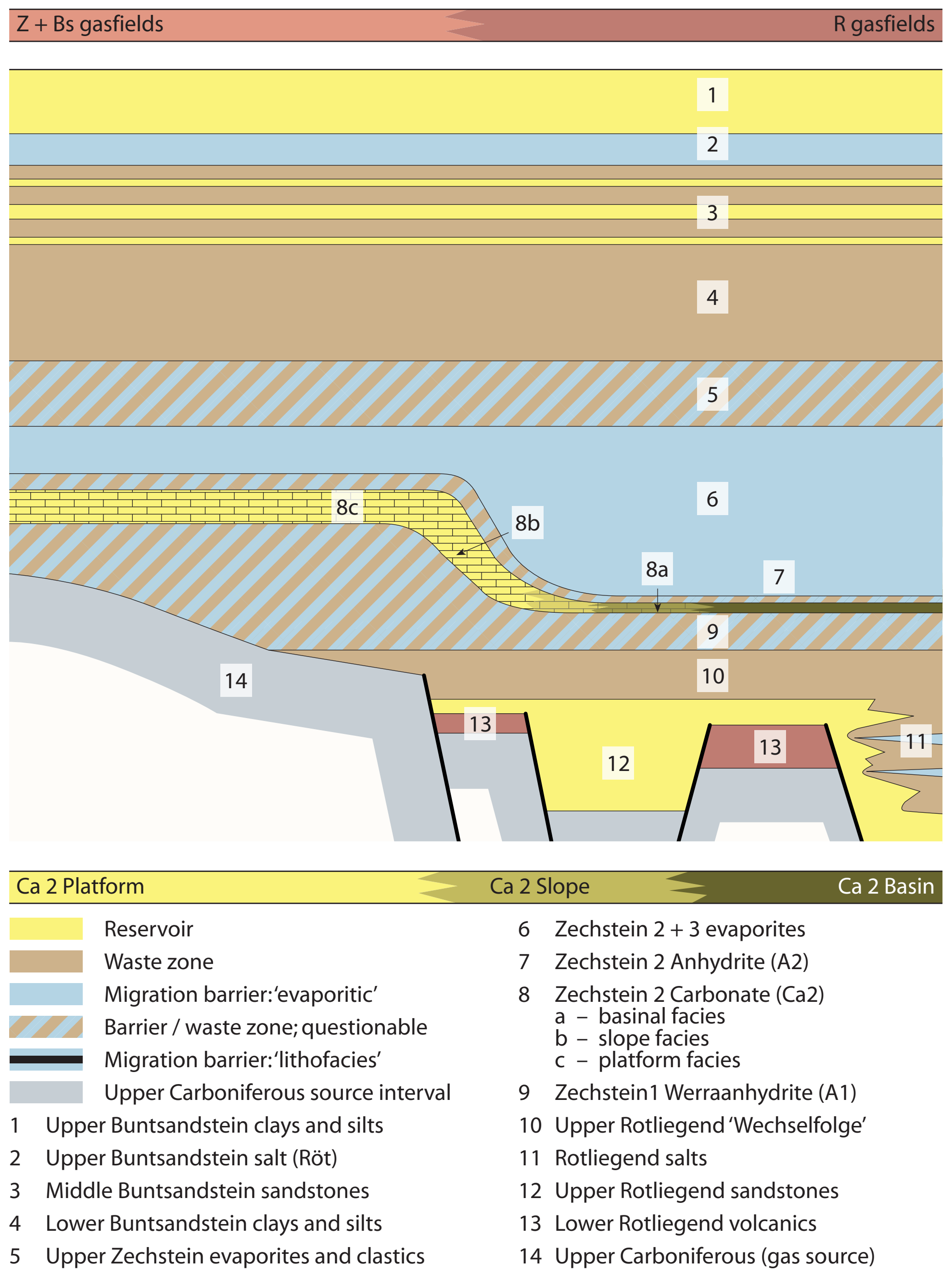
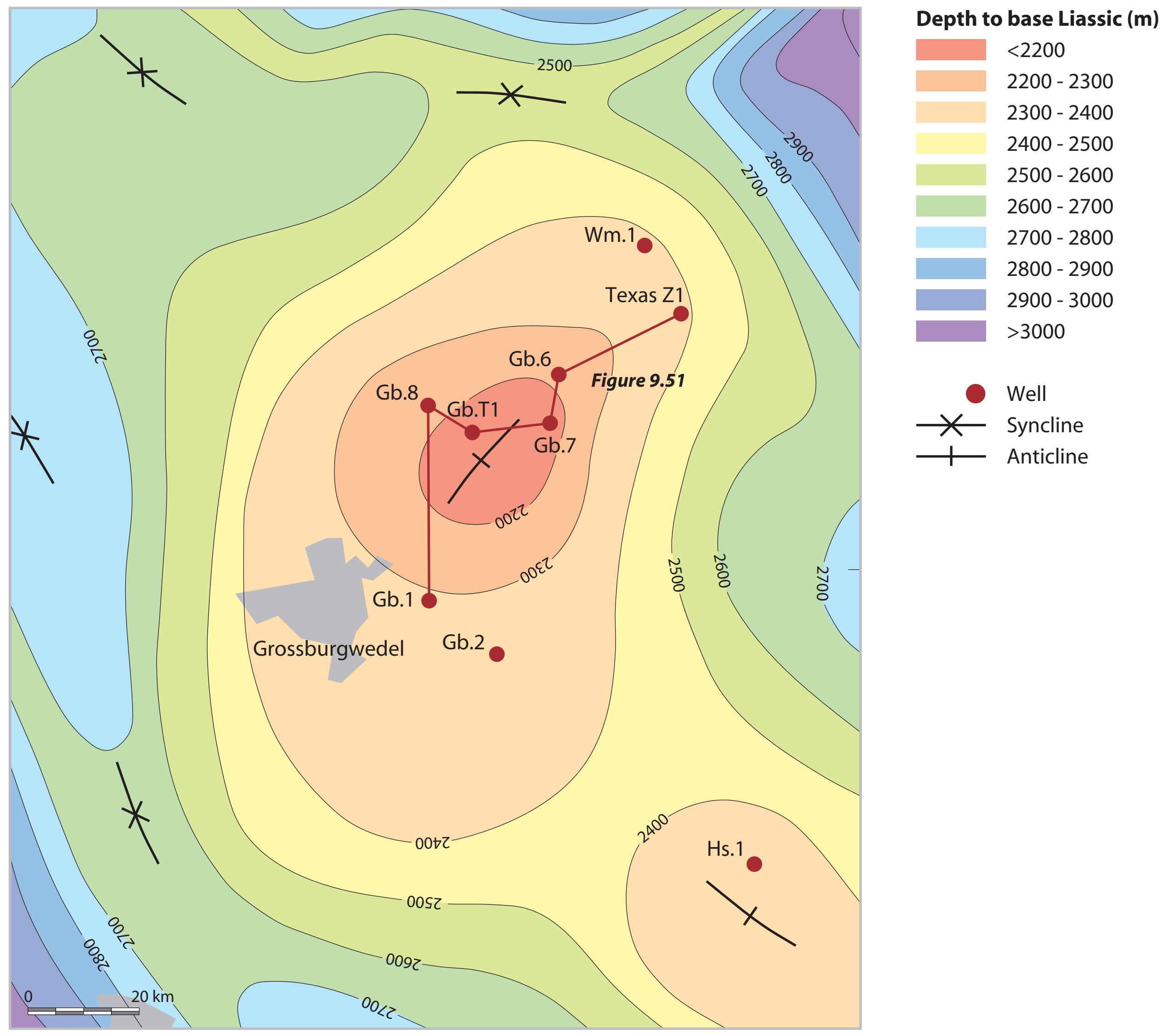


Figure 9.49 Schematic cross-section of the Upper Carboniferous to Buntsandstein source / migration barrier / reservoir system of the north-west German gas province. Halokinetic salt movements and withdrawals are not shown; compare Figure 9.48 (from Karnin et al., 2006).

Reservoir rocks are sandstones of the Dogger epsilon (Bathonian) and the middle Rhaetian, and carbonates of the upper Malm. The sandstones have excellent reservoir properties. The Dogger reservoir covers a productive area of 36 km^2 with an average thickness of 6.5 m, porosities up to 10 % and permeabilities up to 50 mD (**Table 9.6**). The productive area in the Rhaetian sandstones is much smaller (12 km^2) as the sandstones coalesce in part of the structure. The middle Rhaetian sandstones have an average thickness of 6 m and were deposited in a westward-prograding fluvial-dominated delta in an area transitional between a sand-dominated lower delta plain with fluvial-channel sedimentation to the east and delta-front/prodelta sedimentation to the west (Gaupp 1991). Porosities of more than 9% are limited to medium-grained sandstones of the distributary channels and structureless sandstones of the mouth bars with bed thicknesses of more than 1 m (Gaupp, 1991; Kuttner & Riepe, 1991). Porosities show a positive correlation with bed thicknesses. The abnormal reservoir temperatures and the high maturity of the organic material in the sediments reflect the field's unusual thermal history.

Table 9.6 Properties of the Thönse field.

Reservoir	Bathonian sandstones	Rhaetian sandstones
Lithology	Sandstones and carbonates	Sandstones and carbonates
Maximum column height (m)	6	
Net reservoir thickness (m)	6.5	
Porosity (%)	10	
Permeability (mD)	50	
Fluid type	Gas	
Gas composition	C1 88.5%, C2 6%, CO_2 4%, N_2 1.2%	C1 88.5%, C2 6%, CO_2 4%, N_2 1.2%
Source rock	Lower Jurassic Posidonia Shale	Lower Jurassic Posidonia Shale
Seal	Rhaetian and Liassic shales	Rhaetian and Liassic shales



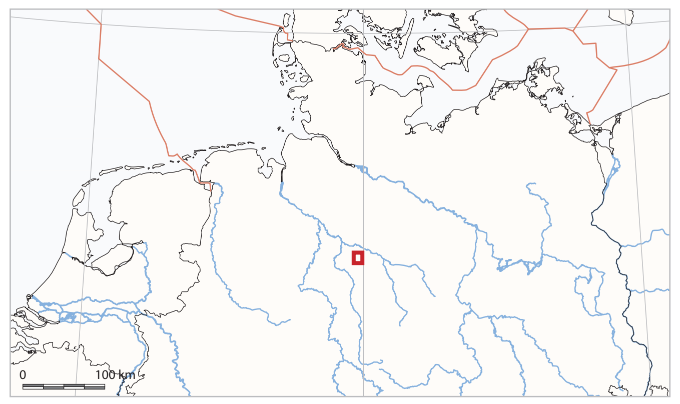


Figure 9.50 Depth-structure to the top of the Upper Triassic Keuper (Rhaetian) in the Thönse gasfield (modified after Baldschuhn & Best, 1985).

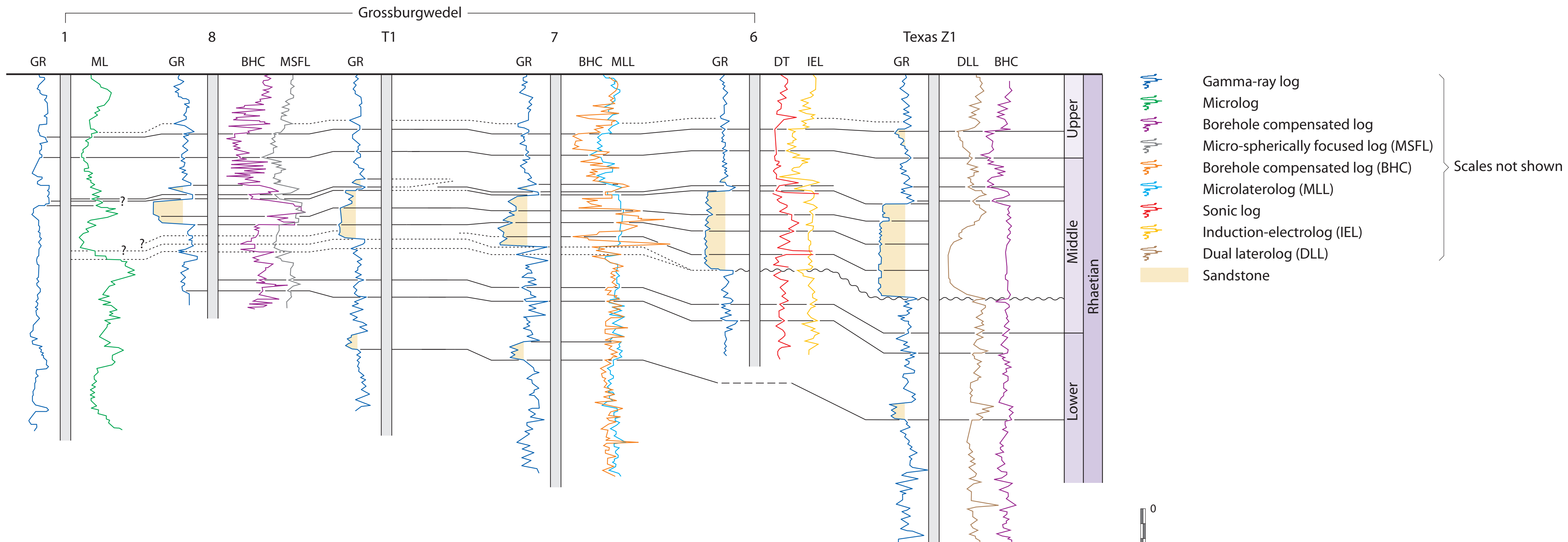


Figure 9.51 Well-log correlation of the Rhaetian in the Thönse gasfield with the Middle Rhaetian sandstone reservoir 'Mittelrhät-Hauptsandstein' (modified after Gaupp, 1991). See Figure 9.50 for locations.

Acknowledgements

The authors are indebted to Dr Heinz W. Kozur (Budapest) for valuable information on stratigraphy and Dr Ivo Rappsilber (Halle) for geophysical information. Dr T. Hornung (Salzburg), Dr Paul Pratsides (Aberdeen) and Prof. Dr Klaus W. Tietze (Marburg) are thanked for their careful reviews and useful suggestions. Prof. Dr Hillert Ibbeken (Berlin) kindly provided the title photo of Helgoland.