*Corallian Group (mid-upper Oxfordian) succession in the cliffs north of Filey Brigg on the North Yorkshire coast. The Corallian Group comprises one of the most distinctive lithostratigraphic divisions of the Jurassic of the Southern Permian Basin area. They form a highly variable shallow-marine succession of bioclastic and ooidal limestones, with interbedded sandstones containing abundant siliceous spicules of the sponge* Rhaxella perforata. *Offshore they can be identified as a significant topographic feature at sea bed and also form a clearly defined seismic event in the subsurface.*

# Chapter 10 Jurassic

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**Bibliographic reference**
Lott, G.K., Wong, T.E., Dusar, M., Andsbjerg, J., Mönnig, E., Feldman-Olszewska, A. & Verreussel, R.M.C.H., 2010. Jurassic. *In:* Doornenbal, J.C. and Stevenson, A.G. (editors): Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v. (Houten): 175-193.

## 1 Introduction

The Jurassic rocks of western and central Europe, which form the core of the SPB area, were deposited in a shallow epicontinental basin that extended from the present-day UK area through the Netherlands, eastwards into Poland, and from southern Germany to Denmark in the north (**Figures 10.1** to **10.7**). Throughout much of the Jurassic, there were connections through the North Sea to a northern Boreal Ocean and, via the 'Hessian Seaway' and 'East Carpathian Gate', to the Tethys Ocean to the south. The waxing and waning of these two oceanic areas had a profound influence not only upon sedimentation and facies in the Jurassic of the SPB area, but also for biostratigraphic correlation across the basin (Callomon, 2003; Page, 2003; Zeiss, 2003). The eastern limit of the basin was marked throughout the Jurassic by the Fennoscandian-Belorussian High where deposition was dominated by nonmarine clastic sedimentation along its margins. The subsidence patterns in this extensive basin were periodically disrupted, most notably during the Mid-Jurassic (Underhill & Partington, 1993) and by tectonic events beyond the area, directly linked to a continuation of extensional rifting in the Central Atlantic and Tethyan areas (De Jager, 2007; Chapter 3). The palaeogeographic position of the European area in sub-tropical latitudes throughout the Jurassic also meant that sedimentation in the basin was characterised, particularly during deposition of the Lower Jurassic Lias Group, by both warm-water Tethyan influences from the south, where carbonate sedimentation dominated, and Boreal (cold-water) influxes from the north, where deposition was characterised by detrital clastic, marginal-marine and nonmarine sedimentation.

A major phase of tectonic inversion and erosion took place during the Late Cretaceous to Early Cenozoic. As a result, Jurassic sediments have not only been uplifted and exposed at outcrop across much of the SPB area, but are also now preserved on the north-west European continental shelf as a series of disconnected basin remnants subcropping variable thicknesses of Cretaceous and Cenozoic sediments (**Figures 10.1** to **10.6**).

The regional context of Jurassic sedimentation in the area has been described by Ziegler (1990a), Ziegler et.al (2006), Lokhorst et al. (1998) and Pieńkowski & Schudack (2008). There are also many detailed investigations of individual basins in the area (Cameron et al., 1992; Partington et al., 1993; Feldman-Olszewska, 1997; Fraser et al., 2002; Husmo et al., 2002; Herngreen et al., 2003; Michelsen et al., 2003; Pieńkowski, 2004; Wong et al., 2007a; Pieńkowski & Schudack, 2008 (and references therein)).

The Jurassic succession in the SPB area includes lithological units that have proved to be of significance not only in terms of their proven source-rock potential (Lower and Upper Jurassic organic-rich mudstones), but also as potential and proven hydrocarbon reservoir units (Lower, Middle and Upper Jurassic sandstone and carbonate facies). However, over much of the area, migration pathways from the deeper Carboniferous source rocks of the basin are inhibited by the presence of the thick Permian evaporite and Triassic mudstone-evaporite sequences that consistently underlie the Jurassic succession (Chapters 8 & 9).

### *1.1 Principal outcrops and depocentres*

Jurassic rocks have limited outcrop areas, particularly in the European mainland, although they have long been known to occur much more extensively at depth (Arkell, 1956). In contrast, Lower, Middle and Upper Jurassic rocks crop out extensively in the UK in the Cleveland, East Midlands, Wessex and Weald basins and continue eastwards below the surface into the southern North Sea Basin. In Belgium, Jurassic outcrops on the southern slopes of the Ardennes correlate with the Paris Basin succession and are not discussed in this chapter; Lower Jurassic rocks subcrop the Belgian part of the Roer Valley Graben and extend into the Netherlands where there is a more complete succession. Although there are no Jurassic rocks at outcrop in the Netherlands, there is an almost stratigraphically complete sequence buried within the onshore and offshore West, Central and Dutch Central grabens. In Denmark, Lower and Middle Jurassic rocks are only seen at outcrop on Bornholm, although they are widespread at depth both onshore and offshore in the Danish Central Graben and Danish Basin. There are only small outcrops of Jurassic rocks in the North German Basin in Lower Saxony, northern Westphalia and Hesse, whereas in southern Germany there are extensive outcrops in the Swabian and Franconian Alb at the southern margin of the SPB. These two large basinal areas were mostly separated by the Rhenish-Bohemian massifs, although they were periodically connected across the present-day Upper Rhine region. Jurassic rocks crop out in Poland around the fringes of the Holy Cross Mountains and in the Polish Jura Chain, although their main depocentre lay along the now largely concealed axial Mid-Polish Trough, broadly coincident with the Teisseyre-Tornquist Zone and Trans-European Suture Zone (Dadlez et al., 1995).

Despite the apparently disconnected nature of these Jurassic outcrops, many decades of research, supported by extensive hydrocarbon deep-drilling and seismic-exploration programmes, have shown that Jurassic rocks are continuous at depth, linking the outcrop areas across the region. Much of the current understanding of the Jurassic of the SPB area relies on information provided by these on-going hydrocarbon-exploration programmes. The work has also enabled the compilation of a new regional stratigraphic correlation diagram (**Figure 10.1**) showing the regional extent and inter-relationships of these remnant basin sequences. Correlation of the deeper successions from basin to basin relies heavily on recent improvements in the quality of deep-seismic data, the processing and interpretation of which is now much better co-ordinated between exploration companies, consultancies and national geological surveys.

Within the constraints of data quality, structure contours of major surfaces, thickness and structural maps, log-correlation diagrams and paleogeographic maps have been prepared for selected intervals. The resulting maps, compiled from industry sources and extensive literature searches (Cameron et al., 1992; Feldman-Olszewska, 1998a; Dadlez, 2001a; Ineson & Surlyk, 2003; Duin et al., 2006), show the present-day distribution of the principal stratigraphic units and the interpreted (palaeogeographical) position of the basin margin during the deposition of each unit (**Figures 10.1** to **10.8**).

## 2 Stratigraphy

The Jurassic System takes its name from the Jura Mountains of eastern France and Switzerland, and was first used by Brongniart in 1829 (Page, 2003; Pieńkowski & Schudack, 2008). The Jurassic is broadly divisible into three major subdivisions, the Lower, Middle and Upper Jurassic (von Buch, 1839). The Early Jurassic was characterised by a period of gradual, tectonically quiescent subsidence; the Middle Jurassic by both local and regional tectonic events and the Late Jurassic by a gradual lull in tectonic activity. These three intervals are separated by significant regional, tectonically driven, events and their associated eustatic sea-level changes. A marine transgression at the onset of rifting in the central Atlantic Ocean (Chapters 3 & 9) at the end of the Triassic marked the start of a period of rising global sea level that largely continued throughout the Jurassic, although this was punctuated by significant sea-level falls within individual basins. These regional changes in basin structure, and therefore sedimentation patterns, are commonly masked by more local intrabasinal tectonism including thermal doming, fault reactivation and continued movement of Zechstein salt diapirs in the deeper basinal areas.

The development of the Jurassic succession in the SPB area is therefore a consequence of inter-related intrabasinal and extrabasinal tectonic activity, both largely driven by active extensional rifting in the contiguous Mid-Atlantic and Tethyan provinces. Although the European area was peripheral to much of this activity, its palaeogeographical position in sub-tropical latitudes throughout Jurassic times resulted in sedimentation that is characterised by the switching between warm-water Tethyan influences from the south and Boreal (cold-water) influxes from the Arctic north. The Fennoscandian- Belorussian High provided a permanent limit to the more restricted sedimentary environments that developed in the north and east of the area (**Figure 10.8**).

### *2.1 Lower Jurassic (Hettangian to Toarcian)*

The SPB area was characterised during most of the Triassic by low global sea level with mainly arid, terrestrially dominated sedimentation (Chapter 9). By the end of the Triassic, rising sea levels had flooded this terrestrial hinterland and there is clear evidence of a transition to more marine conditions during the earliest Jurassic. Transgression from the Tethys Ocean encroaching from the south and west during the Rhaetian to Hettangian, coupled with local tectonic subsidence established over the west of the area, formed an open, shallow epicontinental sea extending from the present-day UK into the Netherlands, Germany and west and central Poland. Sedimentation was more terrestrial farther to the north and east in the Danish, German and Polish regions. In these areas, the sediments are commonly coarser-grained, particularly along the eastern boundary with the Fennoscandian–East European Platform area and adjacent to the London-Brabant, Rhenish and Bohemian massifs to the south.

The Early Jurassic is subdivided into four stages, Hettangian, Sinemurian, Pliensbachian and Toarcian. The marine sections of each stage have a rich fauna, most notably characterised by the first appearance and flourishing of ammonite faunas (Page, 2003). Marine intervals are less evident farther east in the SPB (with exceptions such as an ammonite-bearing Pliensbachian interval in north-western Poland), therefore there are fewer ammonites available for stratigraphic correlation. Correlations with the interbedded shallow-marine, brackish, deltaic and continental facies of Poland become more equivocal and rely on sequence stratigraphy and rich microfloral assemblages (Pieńkowski, 2004).

The global transgressive event and sea-level rise that started in latest Triassic to earliest Jurassic times is characterised by the development of shallow, open-marine, fine-grained mudstone sedimentation as seen in the UK (Lias Group), Belgium (Aalburg Formation), the Netherlands (Aalburg and Posidonia Shale formations), Denmark (Fjerritslev Formation) and Germany (Lias Group), and shallow-marine/brackish-water sandstones in western and central Poland (Skloby Formation). This variably calcareous mudstone and sandstone facies is gradually replaced to the north and east by coarse-grained, clastic-dominated, fluviodeltaic and nonmarine sedimentation in north-eastern Germany (mainly Lias Group), Denmark (Gassum Formation) and much of Poland (Zagaje Formation). Very coarse-grained clastic sedimentation was also predominant on local fringing highs such as the Bohemian and Rhenish massifs, where sandstones up to 80 m thick (Psilonoten and Liassicus sandstones) were deposited. The eastern part of the basin (east of Berlin and in Poland) remained an area of predominantly siliciclastic marginal-marine (brackish) or continental sedimentation until fully marine conditions reached the area during the late Sinemurian. The gradual nature of the transgression is characterised in the southern UK by the progressive onlap of Lower Jurassic strata onto the Anglo-Brabant High. East of this high, Lower Jurassic deposits must once have been connected, although they are now restricted to the Roer Valley Graben and eastern Paris Basin; all traces of this connection have been removed by Cimmerian uplift.

The most significant palaeogeographical change during the Sinemurian to Pliensbachian stages was the gradual establishment of a northern seaway linking the SPB area with the Boreal Sea to the north via the present-day northern North Sea. This link is reflected in the subsequent development of a transitional area between northern cold-water clastic-dominated facies and southern warm-water carbonate belts. This event coincides with a significant sea-level rise in the early Pliensbachian and eastward transgression that brought fully marine conditions as far as the central Polish area (**Figure 10.8**).

Evidence of continuous open-marine sedimentation in the UK is seen in the outcrops of the Lias Group in the Wessex-Weald, Bristol-Somerset, East Midlands and Cleveland basins. This style of sedimentation continued eastwards at depth into the Southern North Sea Basin where the succession is more than 800 m thick in the Sole Pit Trough and in local rim-synclinal structures. The group has a generally consistent thickness of 250 to 300 m in the East Midlands Shelf and thickens (400 m) in the fault-bounded Cleveland and Sole Pit basins. Up to 300 m of similar fine-grained sediments were deposited in the more rapidly subsiding Weald Basin to the south of the Anglo-Brabant High. These thickness variations reflect the different subsidence patterns that had already been established in the area during Early to Mid-Triassic times. The lithologies are predominantly a monotonous sequence of grey calcareous mudstones and argillaceous micritic limestones, with thin beds of ooidal, chamositic and sideritic ironstone deposited during Sinemurian and Pliensbachian times. In the lower Toarcian succession, fissile bituminous shales (Jet Rock Member) are locally developed in the Cleveland Basin. Upper Toarcian sediments are absent over much of eastern England due to a pre-Aalenian erosional phase. However, they are preserved in the Cleveland Basin where they comprise coarsening-upward, micaceous, muddy, fine-grained sandstones (Blea Wyke Sandstone Formation) that represent the progressive shallowing of the Lias sea.

Lower Jurassic rocks of the Aalburg and Posidonia Shale formations are found in the Lower Saxony Basin and other Mesozoic basins, including the offshore parts of the Dutch and Danish Central Graben and onshore West Netherlands Basin. The relationship with the underlying Triassic in these basins is conformable over much of the area, but in the Lower Saxony Basin the sediments unconformably overstep the sediments of the Muschelkalk Formation. The Hettangian to lowermost Toarcian succession is mainly dark grey to black,

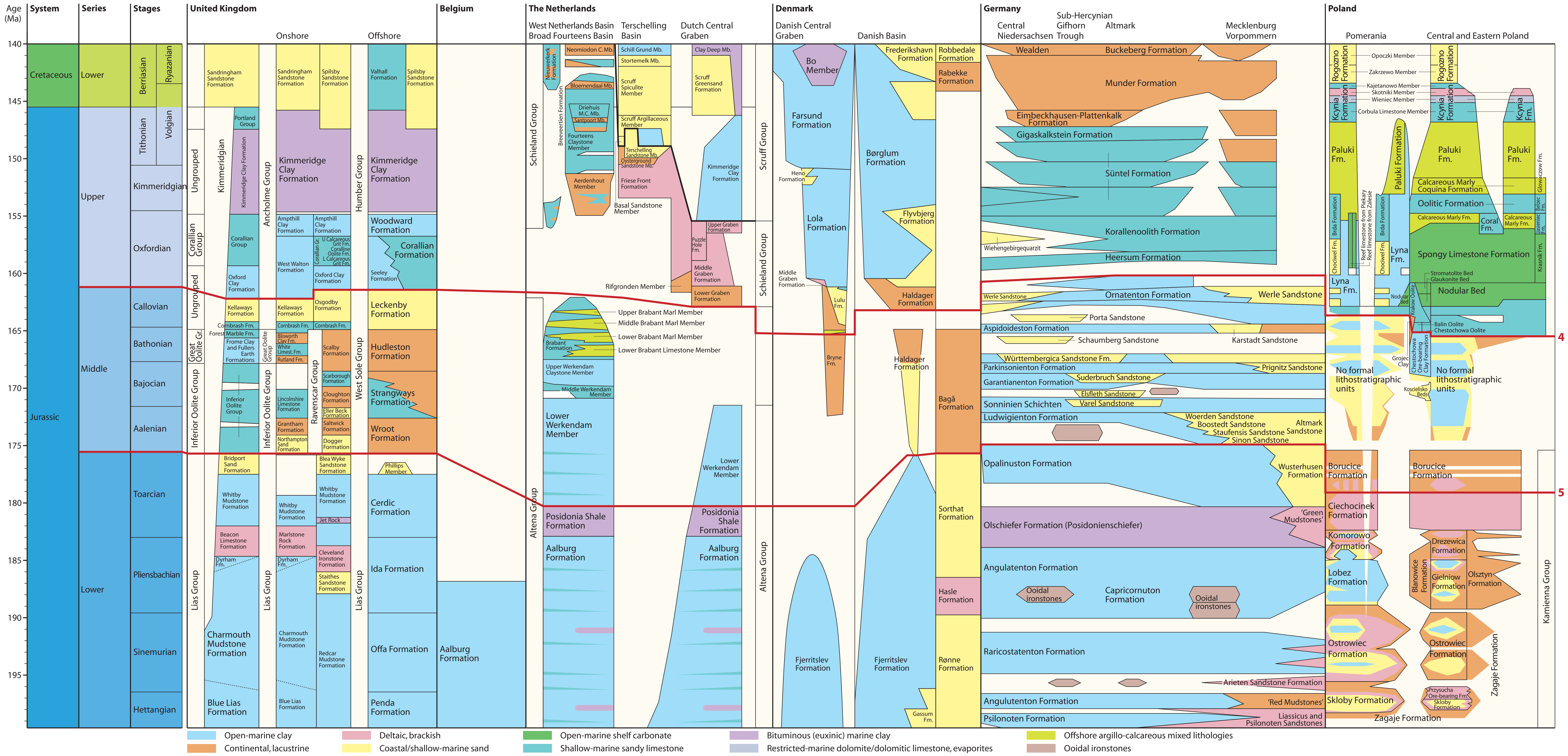



*Figure 10.1 Tectonostratigraphic correlation chart. The red lines at the base of the Oxfordian (4) and the top of the Lias Group (5) are the lithostratigraphic horizons used to map the depth to near base Upper Jurassic and near base Middle Jurassic. See Figures 1.5, 10.4 and 10.6.*

variably calcareous, marine mudstones/claystones that are up to 700 m thick. Basinwide circulation became more restricted during the Toarcian (Toarcian Anoxic Event) and a thin 30 m-thick unit of bituminous shales (Posidonia Shale Formation) was deposited across much of this central European area. The upper part of the Lower Jurassic succession in the Netherlands is variably truncated due to uplift and erosion during Mid-Jurassic times.

In northern Belgium, the Lower Jurassic succession in the Roer Valley Graben forms a southward extension of the Aalburg Formation of the Netherlands. The sediments comprise more than 450 m-thick Hettangian to Pliensbachian grey to dark grey, fossiliferous, locally sandy and silty marine mudstones/claystones. The upper surface of the formation is erosively truncated and overlain by Upper Cretaceous rocks; younger Jurassic sediments are absent.

The Lower Jurassic succession in Denmark is comprised mainly of the Gassum and Fjerritslev formations. The Rhaetian to lower Sinemurian Gassum Formation, which is only found in the Danish Basin, is a heterolithic succession of mainly pale-coloured fluvial and shoreface marine sandstones that are up to 300 m thick, with thin claystones and coalbeds. The formation is conformably overlain by a thick (up to 1000 m), monotonous succession of more distal, dark grey to black, sporadically calcareous claystones, deposited in a marine-shelf setting and assigned to the upper Rhaetian to lower Aalenian Fjerritslev Formation. The Gassum Formation is absent to the west in the Danish Central Graben offshore, and consequently the Fjerritslev Formation, although poorly known, is thought to lie disconformably on uppermost Triassic (Rhaetian) sedimentary rocks. Lower Toarcian dark-coloured organic-rich mudstone developments correlate with similar anoxic successions elsewhere in the SPB area (e.g. Posidonia Shale Formation).

The main sediment source for the Gassum Formation was the Fennoscandian High over which the unit backstepped as the shoreline retreated and sea-level rise progressed. Farther to the east in the Lower Jurassic outcrops of Bornholm and the contiguous Rönne Graben, the proximity and influence of this Fennoscandian margin is even more distinct. Here, the Gassum and Fjerritslev formations are replaced by the sandstone, mudstone and coal-bearing nonmarine and paralic successions of the 500 m-thick Rönne Formation. The overlying shallow-marine sandstones and ammonite-bearing mudstones of the 140 m-thick Hasle Formation indicate a significant regional sea-level rise in the early Pliensbachian. This was followed during the late Pliensbachian to Toarcian by a return to alluvial sedimentation characterised by the coal-bearing succession of the 200 m-thick Sorthat Formation (Michelsen et al., 2003).

Lower Jurassic (mostly Lias Group) rocks in Germany crop out in the north in Lower Saxony and parts of Westphalia and Sachsen-Anhalt, but are separated from the southern outcrops of the Swabian-Franconian Alb area by the Rhenish-Bohemian Massif. Elsewhere in Germany, Lower Jurassic rocks are buried beneath thick Cretaceous and Cenozoic strata that extend across the North German Basin into the North Sea Basin and southwards into France. A succession of more than 1000 m-thick Lias Group rocks are preserved at depth beneath the area north-west of Lower Saxony. The Lower Jurassic sequence is conformable with the underlying Triassic (Rhaetian) strata in each of these areas. However, the upper boundary of the Lias Group is locally disconformable with the overlying Middle Jurassic Aalenian sedimentary rocks. The stratigraphy and distribution of these buried Jurassic successions is based on the description and interpretation of many thousands of boreholes drilled as part of the continuing exploration and exploitation of the area for hydrocarbons, salt and iron ores.

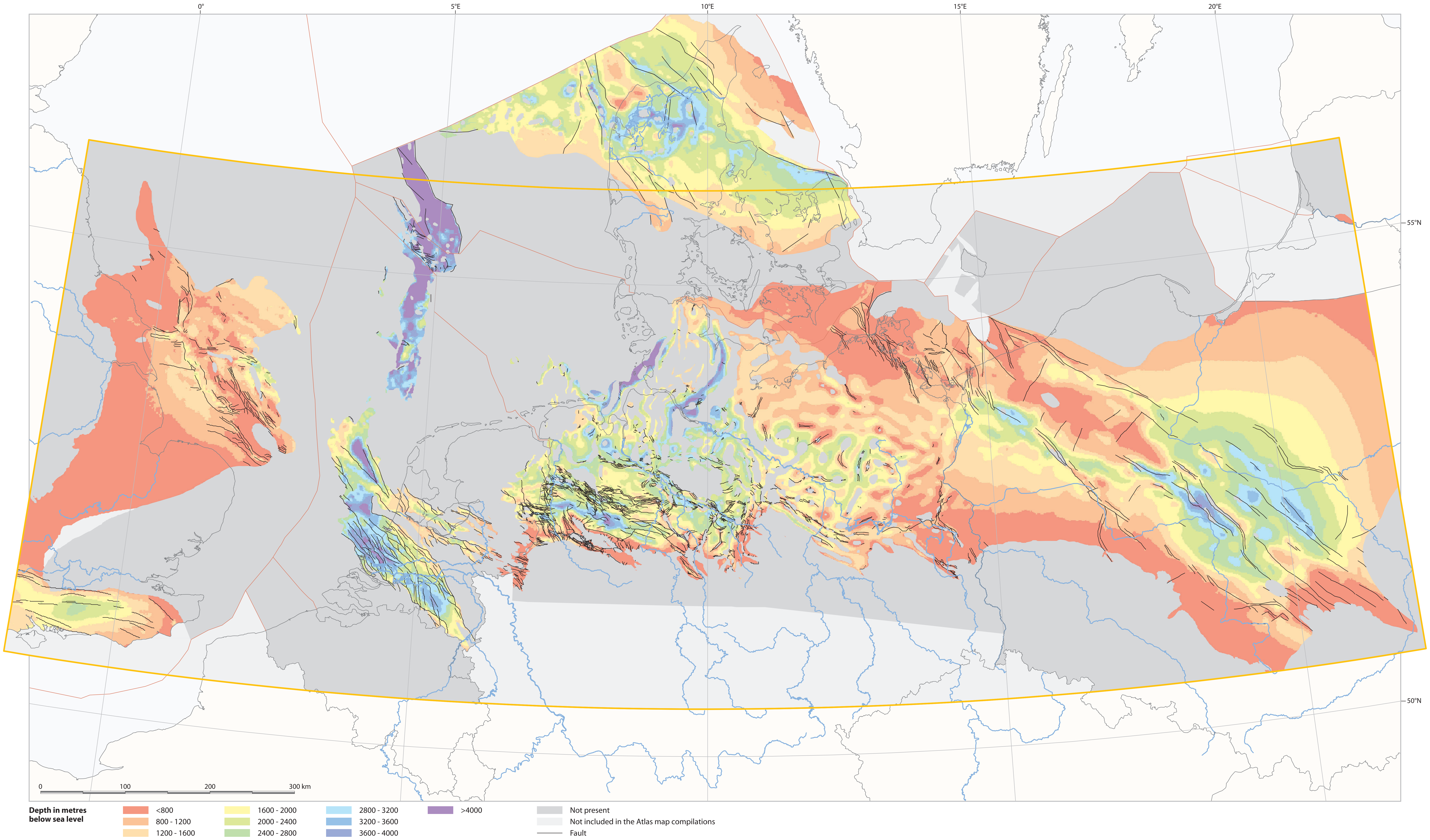



*Figure 10.2 Depth to near base of the Lower Jurassic (base of the Lias Group). This lithostratigraphic horizon is shown as Horizon 6 on Figures 1.5 and 9.1.*

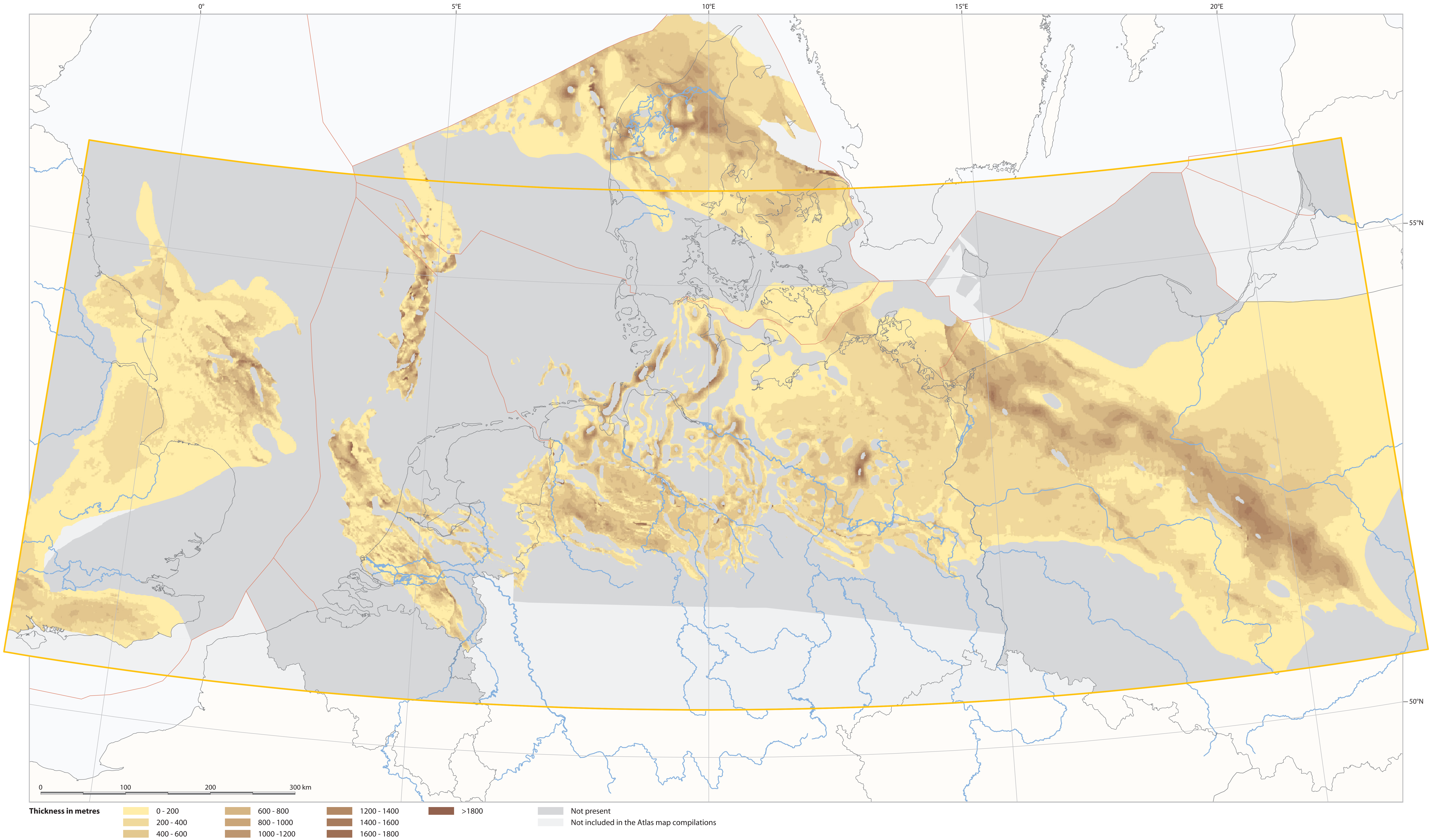
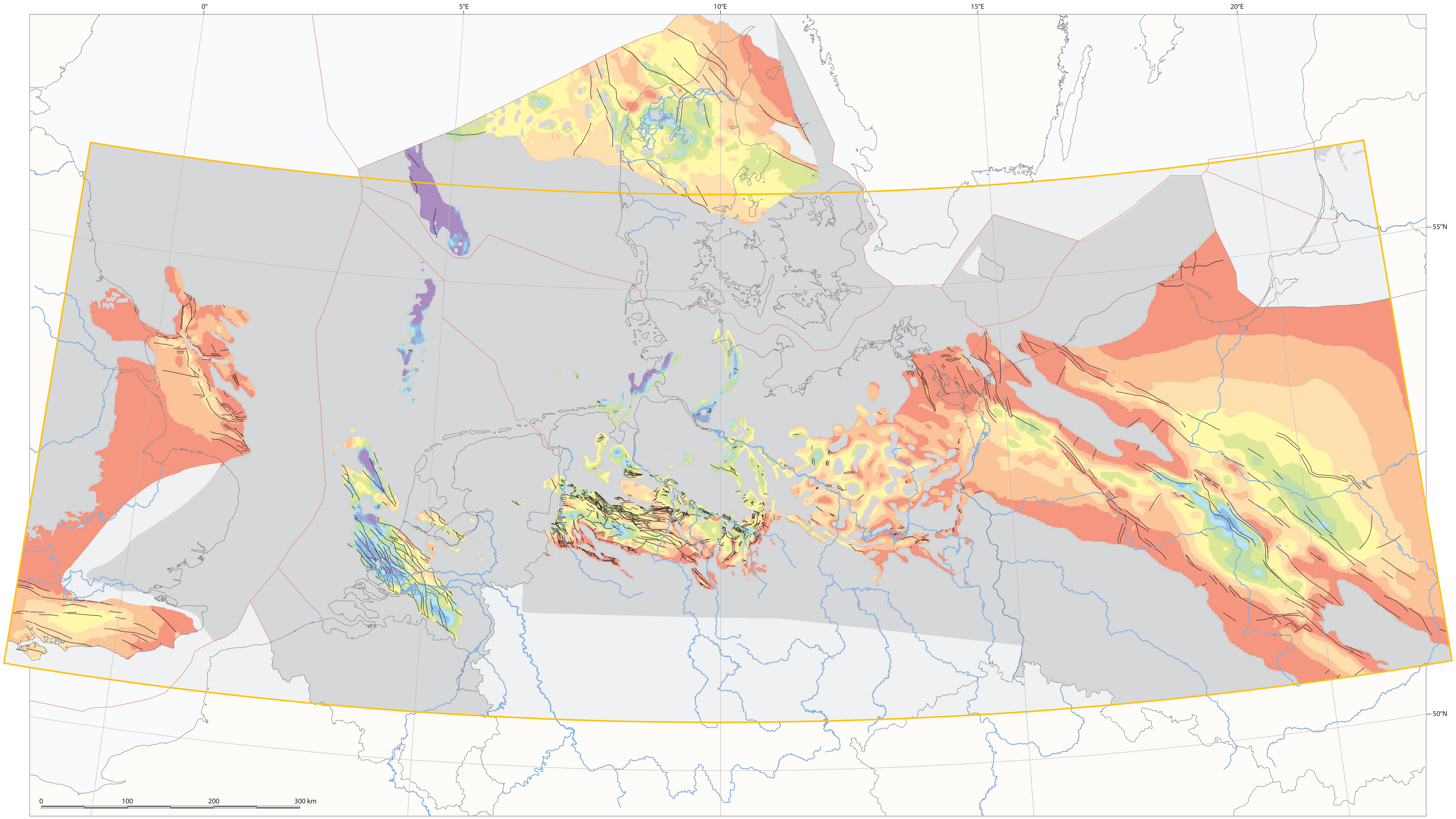


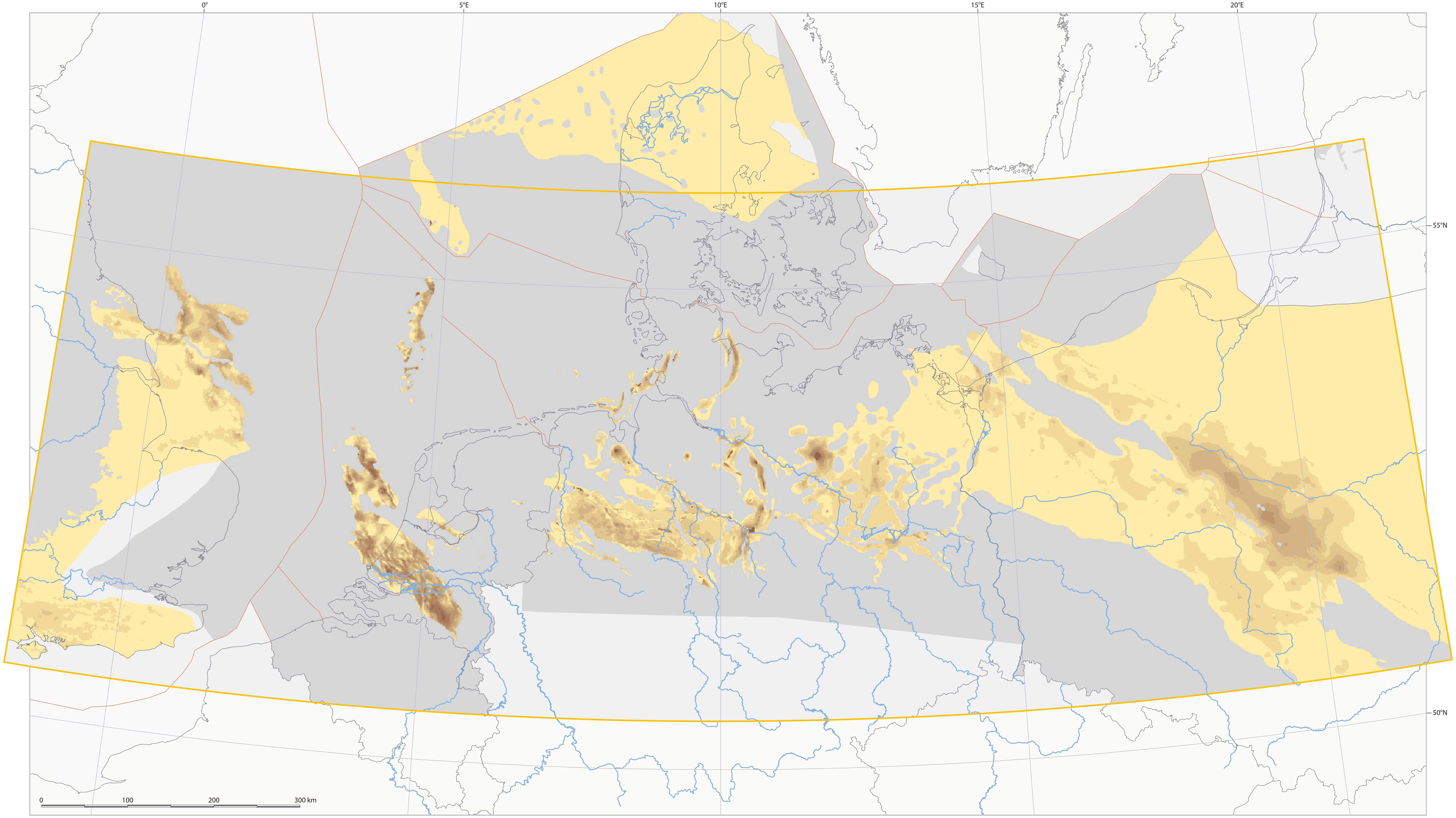

*Figure 10.3 Thickness of the Lower Jurassic.*




**Depth in metres below sea level**

- <800
- 800 - 1200
- 1200 - 1600
- 1600 - 2000
- 2000 - 2400
- 2400 - 2800
- 2800 - 3200
- 3200 - 3600
- 3600 - 4000
- >4000
- Not present
- Not included in the Atlas map compilations
- Fault

*Figure 10.4 Depth to near base of the Middle Jurassic (top of the Lias Group). This lithostratigraphic horizon is shown as Horizon 5 on Figures 1.5 and 10.1.*




**Thickness in metres**

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

*Figure 10.5 Thickness of the Middle Jurassic.*

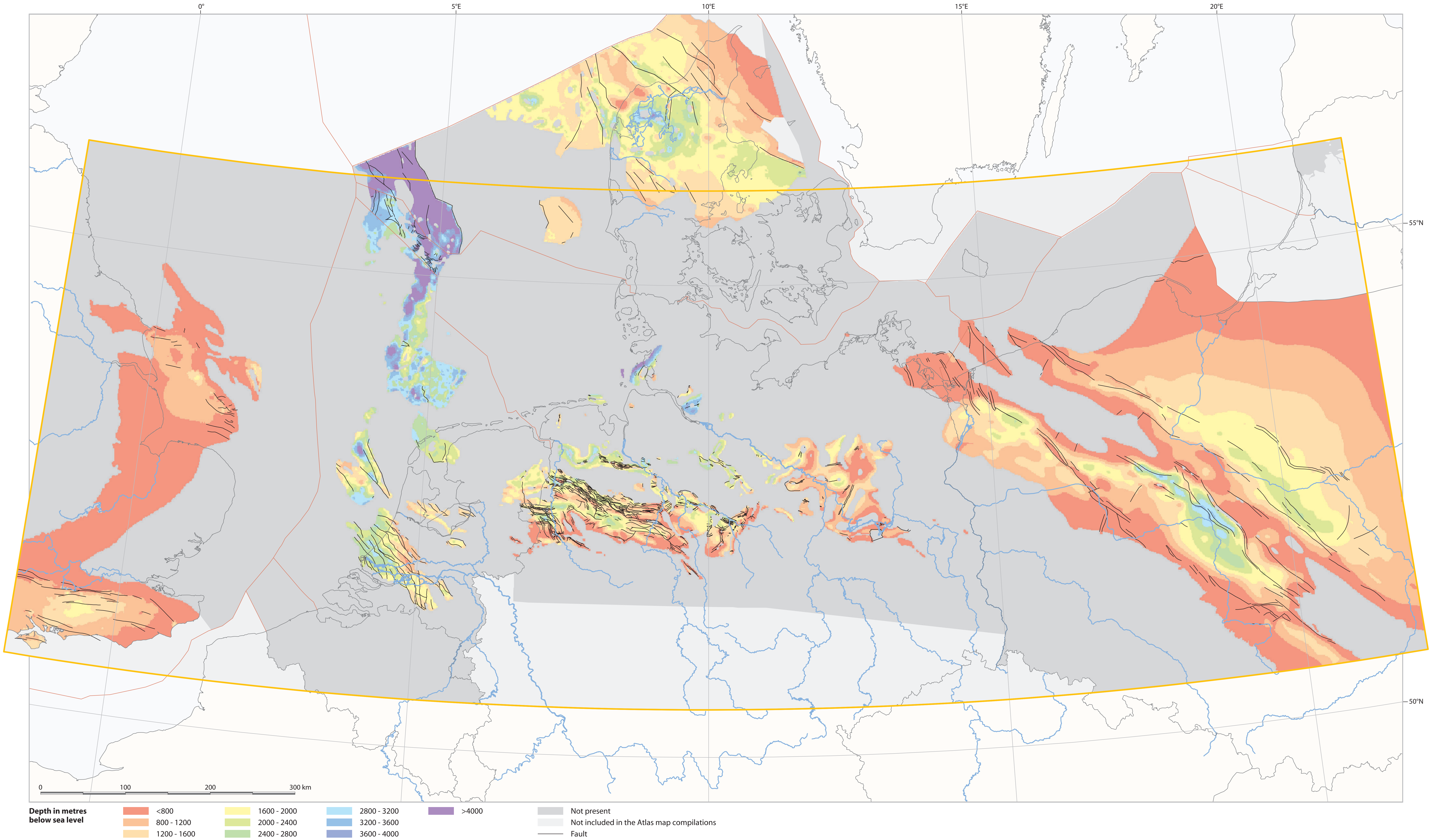



*Figure 10.6 Depth to near base of the Upper Jurassic (corresponding to a level varying from the Callovian to the base of the Oxfordian). This lithostratigraphic horizon is shown as Horizon 4 on Figures 1.5 and 10.1.*

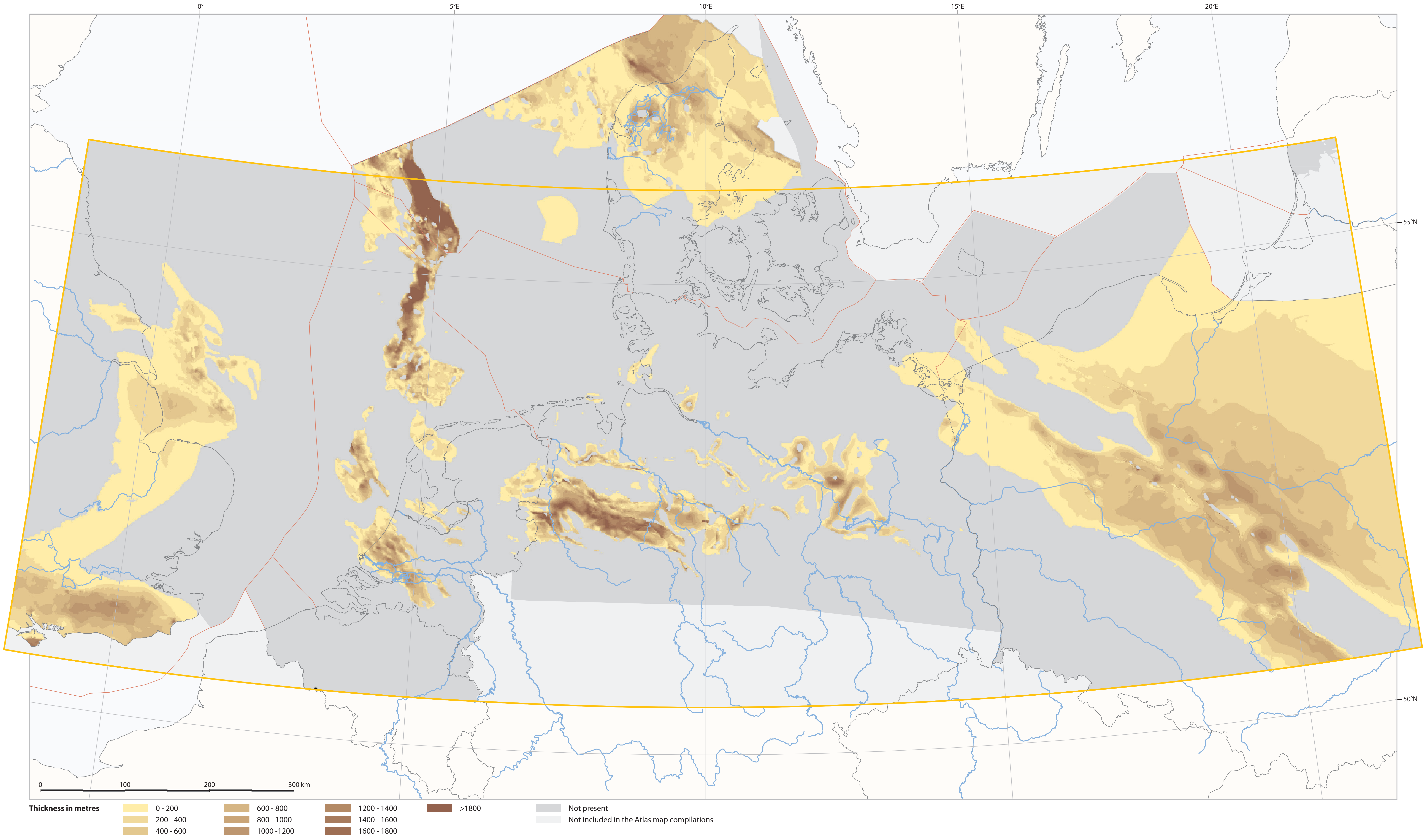



*Figure 10.7 Thickness of the Upper Jurassic.*

The Lias Group succession of northern Germany comprises dark grey, fossiliferous, shallow-marine mudstones, which may be up to 1300 m thick in the main basin areas such as the Nordoldenburg-West Holstein Trough (Mönnig, 2005). The succession passes north-eastwards into sandstone-dominated, shallow-marine shoreface and fluviodeltaic deposits in the areas marginal to the Fennoscandian High. To the south and west, more fine-grained carbonate-rich lithologies equate with similar rocks in the lower part of the Aalburg Formation of the Netherlands. Within the Lias Group, the distinctive ooidal chamositic, sideritic or limonitic ironstone beds that sporadically occur within the Sinemurian and Pliensbachian succession provide useful local marker beds. These beds are formed by local concentrations of iron within the more typical open-marine shelf, argillaceous and micritic limestone lithologies. Similar ironstone developments are also found in the Lias Group successions of eastern England. The ironstones have been of significant commercial importance in both the UK and Germany. A bituminous black mudstone facies developed in the lower Toarcian succession of much of the SPB area. The bituminous Ölschiefer Formation of northern Germany is the main source rock for oilfields in the Lower Saxony Basin, Gifhorn and Holstein troughs.

The Lower Jurassic rocks of southern Germany (Lias or Schwarzer Jura) were deposited on parts of an epicontinental shelf lying along the north-western edge of the Tethyan basin (Pieńkowski & Schudak, 2008). Bounded to the east by the Bohemian Massif and to the west by the Rhenish Massif, this area occupied a connecting link (the Hessian Seaway) between the Tethyan and North German / North Sea basins. The initial Tethyan transgression at the end of the Triassic caused reworking of earlier carbonate sediments and local sandstone deposition. Subsequent deposits of late Hettangian to early Toarcian age are characterised mainly by grey and black, variably calcareous mudstones (Psilonotenton (15 m thick), Angulatenton (10 m), Arietenkalk (25 m), Obtususton (up to 65 m), Numismalismergel (15 m) and Amaltheenton formations (40 m)) interbedded with thin fossiliferous or bioturbated limestones (Oolithenbank and Costatenkalk). Nearshore-marine and fluviodeltaic sands were deposited farther east around the massif areas and now crop out in the Swabian Alb (Angulaten, Bayreuth and Gryphea sandstones). The lower Toarcian is represented in this area by the Posidonienschiefer Formation, which is again characterised by bituminous, fissile black mudstones up to 35 m thick in which their diverse fauna (reptiles, fish, crinoids and cephalopods) were uniquely preserved by the anoxic conditions that developed. However, in this southern end of the basin, increasing Tethyan influences are again evident in the succession at the end of the Early Jurassic, as open-marine sedimentation was re-established in the area with the deposition of the fossiliferous lime-mudstones of the Jurensismergel Formation.

The Lower Jurassic rocks of Poland crop out over a limited area along the southern margin of the Mid-Polish Trough in the region of the Holy Cross Mountains (Pieńkowski, 2006) and Polish Jura Chain. Elsewhere, they are mostly buried beneath Cretaceous and Cenozoic strata of variable thickness (**Figure 10.3**). The main centre of Jurassic sedimentation was along the north-west–south-east-trending Mid-Polish Trough (the Mid-Polish Swell is a more recent feature and did not emerge until the latest Cretaceous to earliest Paleogene), which extends from western Pomerania to the Holy Cross Mountains and is aligned with the Teisseyre-Tornquist Zone to the north (Chapter 3).

The Lower Jurassic rocks conformably overlie Triassic strata over much of Poland. In the north-west–south-east-trending Mid-Polish Trough, sedimentation was almost continuous into the Aalenian; however, outside the trough, the top of the succession is variably truncated by pre-Bathonian erosion. The thickest Lower Jurassic successions are associated with the gradually subsiding Mid-Polish Trough where sediments more than 1300 m thick accumulated in the Kutno Depression. The trough is bordered to the north-east by the wide, stable East European Platform area with a sediment cover up to 300 m thick. To the south-west, the trough is bounded by the more stable Paleozoic Platform (Szczecin-Piotrkow-Silesia-Krakow region) with Lower Jurassic deposits up to 400 m thick. Within this platform area, sedimentation rates were much higher in a series of long narrow grabens (Kaleje-Kamiensk and Laska-Posnan grabens) in which the deposits are about 400 to 800 m thick (Deczkowski & Franczyk, 1988).

The Lower Jurassic rocks of Poland are represented by the Kamienna Group, which is subdivided into 12 formations (Pieńkowski, 2004) (**Figures 10.1** & **10.3**). In contrast to the sediments of much of the western SPB area, the Lower Jurassic (Hettangian to Toarcian) succession of Poland is characterised mainly by shallow-marine/brackish to fluviodeltaic sediments, commonly containing coalified plant debris and paralic (lagoonal and deltaic) or continental (lacustrine, swamp) mud-dominated units with thin coal and sideritic horizons. Fully marine conditions (Lobez Formation) only developed in the present-day Pomerania region during early and late Pliensbachian times, and are characterised by mudstones with good ammonite fauna. Unlike the western part of the SPB area, the lower Toarcian succession here is not characterised by fissile bituminous shales, but by greenish or grey mudstones with interbedded sandstones of brackish-water origin (Ciechocinek Formation). Fluviodeltaic deposits continued to dominate the basin (Borucice Formation) during the late Toarcian at the end of the Early Jurassic.

Detailed sedimentary examination and interpretation of numerous boreholes and well logs, together with correlations with the successions known at outcrops, has led to the recognition of a series of ten depositional sequences that reflect frequent changes in sea level within the shallow epeiric Early Jurassic basin of the Polish area (Pieńkowski, 2004). During this interval, the sea transgressed the Polish Basin several times from the west and occupied much of the western and central parts of the Mid-Polish Trough.

Sedimentation within the trough seems to have been largely continuous into Mid-Jurassic times. The lowermost Jurassic coarse-grained clastic sediments appear to lie conformably on Upper Triassic (Rhaetian) strata. However, sedimentation was interrupted periodically in the adjacent platform areas and the successions are less complete or more condensed (Pieńkowski & Schudack, 2008). Zechstein salt diapiric activity has also resulted in local thickness variations within the trough.

## 2.2 *Middle Jurassic (Aalenian to Callovian)*

At the end of the Early Jurassic, the SPB area formed part of a shallow-water epicontinental basin in which fine-grained marine-clastic sedimentation dominated in the west and south, and coarse-grained siliciclastic, paralic and nonmarine sedimentation dominated in the north and east. Eustatic sea-level rise continued into early Mid-Jurassic times across much of the SPB area, but still left exposed a series of local highs (Anglo-Brabant, Rhenish, Bohemian highs and the East European Platform) that persisted largely into the Late Jurassic. The Anglo-Brabant structural high was further affected by tectonic uplift assigned to the mid-Cimmerian phase, which removed 3000 m of its post-Caledonian cover including the Lower Jurassic (Vercoutere & Van den Haute, 1993). By Bajocian to Bathonian times, this simple depositional pattern was significantly disrupted by the growth, development and subsequent deflation of a major thermal volcanic complex centred on the Mid North Sea High triple-rift junction. From late Toarcian times, this complex was associated with concurrent re-activation and uplift of the adjacent Ringkøbing-Fyn and Mid North Sea highs to the west and south-east (Ziegler, 1990a; Underhill & Partington,1993; Calloman, 2003; Page, 2003; Zeiss, 2003). Erosion of these and surrounding highs continued into the Bathonian, with the removal of a significant thickness of Lower Jurassic and older rocks. An extensive series of progradational fluviodeltaic complexes gradually infilled the subsiding, peripheral, Cleveland, Sole Pit, West Netherlands, northern German and Danish basins in the south, and the Central and Northern North Sea basins and Danish Central Graben to the north. Sedimentation in the Dutch Central Graben did not

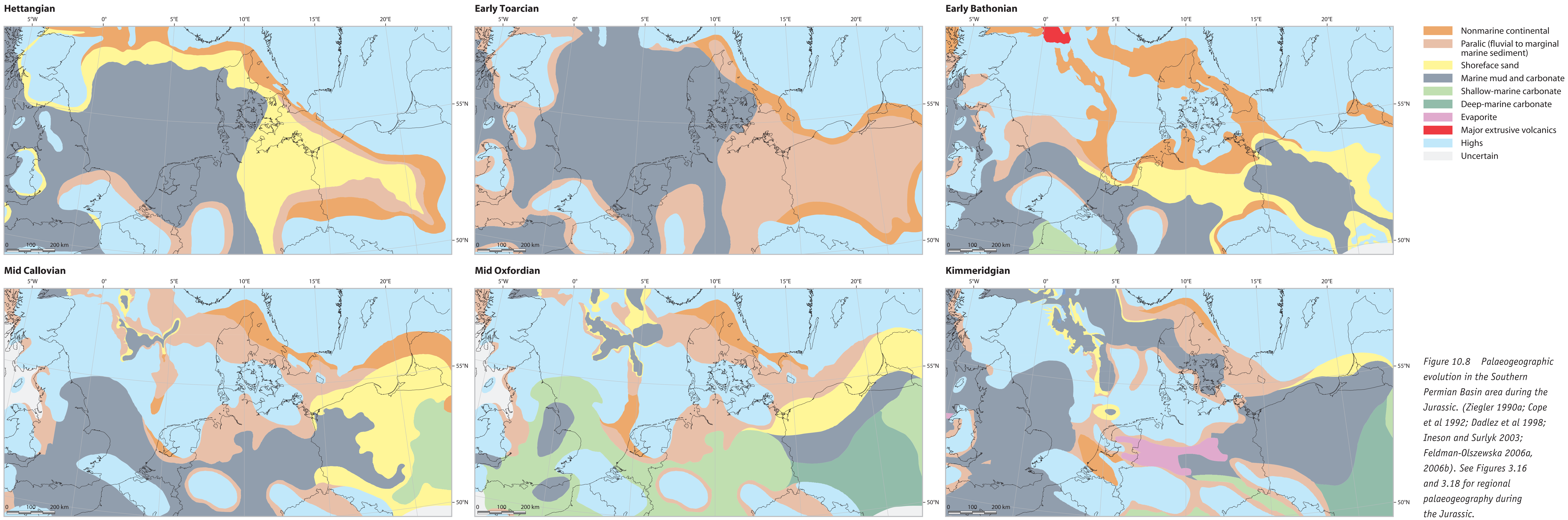



*Figure 10.8 Palaeogeographic evolution in the Southern Permian Basin area during the Jurassic. (Ziegler 1990a; Cope et al 1992; Dadlez et al 1998; Ineson and Surlyk 2003; Feldman-Olszewska 2006a, 2006b). See Figures 3.16 and 3.18 for regional palaeogeography during the Jurassic.*

begin until the mid-Callovian. Another important effect of the growth of this extensive area of uplift was to temporarily break the existing connection via the North Sea between the northern Boreal Ocean and southern Tethys Ocean (Calloman, 2003).

The Polish Basin became partly isolated from the basins of western Europe during Aalenian and Bajocian times (Dadlez, 1998a; Feldman-Olszewska, 1998a). At the same time, a connection with the Tethyan basin opened in the south-east via the East Carpathian Gate (Dayczak-Calikowska & Moryc, 1988). The Mid-Polish Trough continued to be the most important palaeotectonic element of the Mid-Jurassic basin, characterised by marine clastic sedimentation sourced primarily from the north-east (Fennoscandian-Belorussian Highs) and south-west (Szczecin-Silesian-Kraków uplifted area). Connections between the Polish Basin and western Europe were re-established by the late Bathonian and Callovian (**Figure 10.8**).

The Middle Jurassic interval has four stages, the Aalenian, Bajocian, Bathonian and Callovian. The subdivision and correlation of these stages relies mainly on marine ammonite assemblages. In contrast to the Lower Jurassic, biostratigraphic resolution and correlation across the European area is still contentious in places because of the wide range of contrasting depositional environments and facies developments that formed across the basin. Environmentally, the area spans the temperate to sub-tropical climate zones, which is reflected in the faunal and floral assemblages across the area. Warm-water carbonate Tethyan assemblages are best developed in the fully marine beds in the south of the basin and Boreal cold-water assemblages dominate the clastic marine sediments prevalent in the north. Consequently, biostratigraphic correlation between these areas has been equivocal until relatively recently (see Callomon, 2003). Regional biostratigraphic correlations are further complicated by the predominantly paralic and nonmarine clastic sedimentation areas in northern Denmark, where marine beds, and therefore ammonites in particular, are rarely found. In the Polish Basin, Aalenian to early Bajocian age-diagnostic ammonites are found only in the central and southern Mid-Polish Trough, whereas Bathonian and Callovian biochronozones are most stratigraphically complete in north-western (Dayczak-Calikowska, 1977) and southern Poland (Kopik, 1998; Matyja et al., 2006). Various stratigraphic non-sequences have been observed outside the Mid-Polish Trough, with ammonite faunas evident mainly during transgressive intervals (Feldman-Olszewska, 1997).

In general, the Middle Jurassic succession throughout the SPB area has a variably erosive and unconformable relationship with the underlying Lower Jurassic, which it may also overstep in places. In contrast, the gradual deflation of the central North Sea thermal uplift by the end of Mid-Jurassic times led to renewed marine incursions across this shallow basinal area, which resulted in broadly continuous sedimentation into the overlying marine-dominated Upper Jurassic successions. However, onlapping relationships against persistent high areas, such as the Anglo-Brabant, Rhenish and Bohemian highs, remained a feature of the Middle Jurassic.

### *2.2.1 Stratigraphy*

In the UK onshore, the Lower Jurassic (Lias Group) succession is overlain disconformably by the carbonate-dominated successions of the Inferior Oolite and Great Oolite groups (Aalenian to earliest Callovian age) as far north as the Market Weighton High, including the East Midlands and Wessex-Weald basins. In contrast, sedimentation was continuous into Mid-Jurassic times in the Cleveland Basin to the north of this high, where the clastic-dominated succession is assigned to the Ravenscar Group. Elements of both these Middle Jurassic successions are evident in the adjacent area of the southern North Sea where they equate with the West Sole Group (Rhys, 1974), which despite having a much more limited subsurface dataset, has been shown to be largely of Mid-Jurassic age (Lott, 1992; Lott & Knox, 1994).

The different lithostratigraphic nomenclatures applied in these basinal areas reflect the contrasting depositional settings that characterised each area. Sedimentation across the platform area from the East Midlands Basin south-westwards into the Wessex and Weald basins was dominated by high-energy, ooidal and bioclastic limestones and thick, lower energy, fossiliferous marine mudstones. In contrast, in the Cleveland Basin (and Central North Sea Graben) to the north, the succession is dominated by nonmarine, fluviodeltaic and associated fine-grained paralic sediments with only sporadic, thinly developed, but regionally significant, marine limestone incursions from the southern platform area. The relationship between the isolated Ravenscar Group of the Cleveland Basin and the more southern and northern basins was equivocal for many years, because much of the Jurassic succession had been removed by Early Cretaceous erosion across the intervening Market Weighton High. However, exploration drilling in the adjacent offshore area has subsequently revealed the transitional nature of the southern boundary between the two areas, which is preserved and revealed within the West Sole Group of the Sole Pit Basin.

The Middle Jurassic succession is about 70 m thick onshore in the East Midlands Basin and 150 m in the Cleveland Basin, but is more than 300 m thick in the offshore Sole Pit Basin and its associated halokinetic rim-synclinal structures, and more than 400 m thick in the Wessex and Weald basins.

The Middle Jurassic succession in the Cleveland-Sole Pit basins is a mostly Bajocian fluviodeltaic, mudstone- and sandstone-dominated succession sourced from the developing Mid North Sea thermal uplift and Pennine High to the north and west. These thick clastic sequences show a gradual westward transition beyond the Sole Pit-South Hewett fault zones into the marine limestone-dominated successions of the more stable East Midlands Basin. Despite a lack of detailed subsurface sample information from the largely non-prospective offshore succession, correlation of the log responses between the two areas generally emphasises the vertical and lateral continuity of the facies developments recognised in the East Midlands and Cleveland basins into the offshore area. The four subdivisions recognised offshore, the Wroot, Strangways, Hudleston and Leckenby formations, can therefore be correlated directly with their well-documented equivalents that crop out on land (**Figure 10.1**; Lott & Knox, 1994; Cope, 2006).

Middle Jurassic rocks are preserved only in southern Belgium along its margin with the Paris Basin, to the west of the SPBA area. The Middle Jurassic rocks of the Netherlands (the Werkendam and Brabant formations) crop out only in the Lower Saxony Basin. Elsewhere, in both the onshore and offshore areas, these formations are buried beneath a thick Cretaceous and Cenozoic succession that is known only from deep drilling and seismic surveys. These sediments, which are up to 1000 m-thick, are partially preserved in a series of basin remnants that were separated by tectonism in the Late Cretaceous to Early Tertiary. The main depocentres were the three major rift systems that cross-cut the Netherlands, all of which were well established by the end of the Triassic. These are the north–south oriented offshore Dutch Central Graben; the east–west Lower Saxony Basin, which also extends into northern Germany; and the north-west–south-east-trending graben/basin complexes of the Roer Valley, Central and West Netherlands and Broad Fourteens basins. Sedimentation in the Dutch Central Graben and Broad Fourteens Basin was significantly disrupted by the thermal uplift of the central North Sea and associated Ringkøbing-Fyn High such that there is a generally disconformable contact with the widespread underlying Lower Jurassic rocks (Altena Group). For example, in the Dutch Central Graben, Callovian sediments of the Schieland Group diconformably overlie Aalenian and older sediments of the Altena Group. Much of the graben was therefore an area of nondeposition during Mid-Jurassic times. Sedimentation in the Lower Saxony Basin was also affected by the thermal uplift, although the Jurassic succession here has been severely truncated by erosion and so the evidence is missing.

To the south, where the most complete Middle Jurassic succession is seen in the West Netherlands Basin and contiguous Roer Valley Graben, the impact of uplift was clearly negligible and deposition was continuous into the Oxfordian. Sedimentation was characterised initially by thick (up to 650 m) shallow-marine, silty, calcareous mudstones with sporadic fine-grained marine sandstones in each of the many basins and grabens (Aalenian to Bajocian Werkendam Formation) followed by sandy carbonates and lime-mudstones that are up to 350 m thick (Bathonian Brabant Formation) (Wong, 2007). In the Achterhoek area of the Netherlands to the south, fine-grained mudstones indicate that marine sedimentation also continued farther away from the centre of uplift from Mid-Jurassic into late Callovian times. As a further consequence of the local uplift linked to the thermal 'doming' to the north, Middle Jurassic sediments are largely absent from the Dutch Central Graben, western Lower Saxony and Central Netherlands basins despite these areas being proximal to the uplift centre. The subsequent initiation of alluvial sedimentation in the Dutch Central Graben during the late Callovian was due mainly to the cessation of uplift and a renewed rifting phase, and led to the accumulation of up to 560 m-thick sandstones and mudstones that form the Lower Graben Formation. Another significant factor in the local development of the sediment fill in these depocentres was the influence of synsedimentary halokinetic movements throughout the Middle Jurassic, which disrupted subsidence patterns and influenced facies developments in some basinal successions.

The Middle Jurassic succession of Denmark mainly reflects the extensive erosion and deposition that took place during late Aalenian to early Bajocian thermal uplift in the central North Sea area. Middle Jurassic rocks crop out only on Bornholm where they are represented by the erosively truncated Aalenian to Bathonian Bagå Formation, which rests unconformably on paralic Lower Jurassic rocks. The formation is more than 190 m thick and is a succession of fluvial and lacustrine, fine- to medium-grained, weakly laminated sandstones and mudstones with common carbonaceous debris, rootletted horizons and coaly beds (up to 2.5 m thick). Coarse-grained boulder beds are also found locally. The formation is eroded at its top, and no Upper Jurassic rocks are found on Bornholm (Pieńkowski & Schudak, 2008).

Elsewhere in Denmark, Middle Jurassic rocks are buried beneath a thick succession of Cretaceous and Cenozoic strata and are known only from hydrocarbon-exploration drilling. The main Mid-Jurassic depocentres were in the central and north-eastern parts of the Danish Basin and the offshore Danish Central Graben. The Middle Jurassic sequence rests unconformably on the Lower Jurassic Fjerritslev Formation in both locations and appears to range from Aalenian to Callovian in age, with sedimentation continuing in the basins into Early Cretaceous times.

The Haldager Sand Formation of the Danish Basin is characterised by a varied succession of fluvial to shallow-marine, fine- to coarse-grained sandstones. In the adjacent downfaulted Sorgenfrei-Tornquist Zone, the formation is up to 150 m thick and comprises fine- to coarse-grained fluvial and marine sandstones and siltstones interbedded with claystones and thin coalbeds. The sediment sources were probably the Ringkøbing-Fyn High to the west and the more stable Skagerrak-Kattegat Platform on the margin of the Fennoscandian High to the north-east.

Mid-Jurassic sedimentation in the Danish Central Graben was characterised by the fluviodeltaic deposits of the Bryne Formation (>200 m thick), which comprise laterally extensive fluvial and paralic sandstones interbedded with commonly fining-upward cycles of sandstones and mudstones with up to 7 m-thick sporadic coal layers (**Figure 10.9**). The overlying upper Callovian Lulu Formation is between 30 and 60 m thick and is a coarsening-upward sequence of shallow-marine and paralic sandstones interbedded with paralic carbonaceous mudstones, coal seams and marine mudstones (Michelsen et al., 2003). This phase of paralic sedimentation ended in these Danish basins with a major marine transgression from the north during the latest Callovian to early Oxfordian following the onset of rifting in the Danish Central Graben, which re-established marine sedimentation throughout much of the Danish area.

The Middle Jurassic (mainly Dogger Group) rocks of Germany crop out in the Lower Saxony Basin in the north and in the mountains of the Swabian and Franconian Alb of southern Germany (Mönnig, 2005; Pieńkowski & Schudak, 2008). They are buried beneath a thick succession of post-Jurassic sediments throughout much of Germany. On-going work is aimed at understanding the stratigraphy of these concealed successions and their correlation with the better known successions at outcrop. Mid-Jurassic depositional patterns in the Lower Saxony Basin were overprinted by the continued movement of Permian salt diapirs, which, as elsewhere, formed areas of positive relief and associated subsidence (rim-synclines) often creating local facies developments and sediment traps within parts of the basin (Pieńkowski & Schudack, 2008).

Mid-Jurassic (early Aalenian) sedimentation in the North German Basin was characterised initially by continued shallow-marine mud deposition. More regressive shallow-marine deltaic sedimentation had been established by the late Aalenian, with coarsening-upward, dark-coloured, pyritic mudstones, siltstones and sandstones with sporadic ooidal ironstone beds. The succession is about 400 m thick on average, but may be up to 1000 m thick in local depocentres such as the Gifhorn Trough. Much of the clastic sediment supply to this basinal area came from the developing Mid North Sea and Ringkøbing-Fyn uplift areas to the north-west, from which prograding deltaic depositional systems extended periodically southwards (Pieńkowski & Schudack, 2008). However, during the Callovian, the collapse of Mid North Sea thermal uplift is evident from the cessation of coarser-grained clastic sedimentation in the basin and, as sea level was rising, its replacement by restricted shallow-marine mud environments with faunal assemblages of boreal aspect.

Eleven formations have been identified in the North German Basin (**Figure 10.1**), within which fourteen discrete sandstone developments are recognised in the eastern part of the basin; Sinon, Altmark, Wasendorf, Hankensbuttel, Boostedt, Woerden (Aalenian); Varel, Elsfleth, Suderbruch, Prignitz, Württembergia (Bajocian); Schaumberg, Karstaedt (Bathonian); and Porta, Werle (Callovian). These porous sandstones were deposited in a variety of shallow-marine, high-energy environments and are between 15 and 50 m thick; all have been exploited locally as hydrocarbon reservoirs (Ziegler, 1990a; Mönnig pers comm., 2007).

The Middle Jurassic sequence (Brauner Jura) of southern Germany is characterised by the continuation of shallow-marine, fossiliferous, mudstone-dominated successions. However during the late Aalenian to Bathonian interval, and locally into the later Callovian, there was a change to ferruginous sandstone and more characteristically ooidal ironstone deposition with a wide array of local formation names such as the Murchisonaeoolith, Humpriesioolith, Segenthal, Macrocephalenoolith and Wutach formations (see Mönnig, 2005; Pieńkowski & Schudack, 2008). The lowermost Callovian sediments in much of the area are commonly characterised by the ammonite-bearing pyritic mudstones of the Ornatenton Formation, which gradually pass upwards into less-restricted glauconitic lime-mudstones of early Oxfordian age.

The predominantly marine Middle Jurassic succession of Poland crops out around the fringes of the Holy Cross Mountains and in the Polish Jura Chain. Elsewhere, Middle Jurassic rocks are buried beneath thick Cretaceous and Cenozoic sediments and are therefore known mainly from core descriptions. No formal lithostratigraphic scheme has yet been proposed for the Middle Jurassic sequence. The main Middle Jurassic depocentre in the Polish area continued to be the north-west–south-east-trending axial Mid-Polish Trough, where more than 1100 m of sediments were deposited. Sedimentation in the trough continued throughout the Mid-Jurassic interval and, in the central and southern parts, Aalenian rocks conformably overlie upper Toarcian sediments. Elsewhere, the base of the Middle Jurassic succession is generally marked by an erosional unconformity (Feldman-Olszewska, 1997).

The succession is thinner (<300 m thick, average 150 m) and more condensed on the adjacent platform areas where sedimentation was disrupted by several nondepositional and/or erosional events related to sea-level falls. Rising global sea level led to periodic transgressions that resulted in the deposition of thin sediments. Zechstein salt diapiric activity also resulted in local thickness variations within the trough.

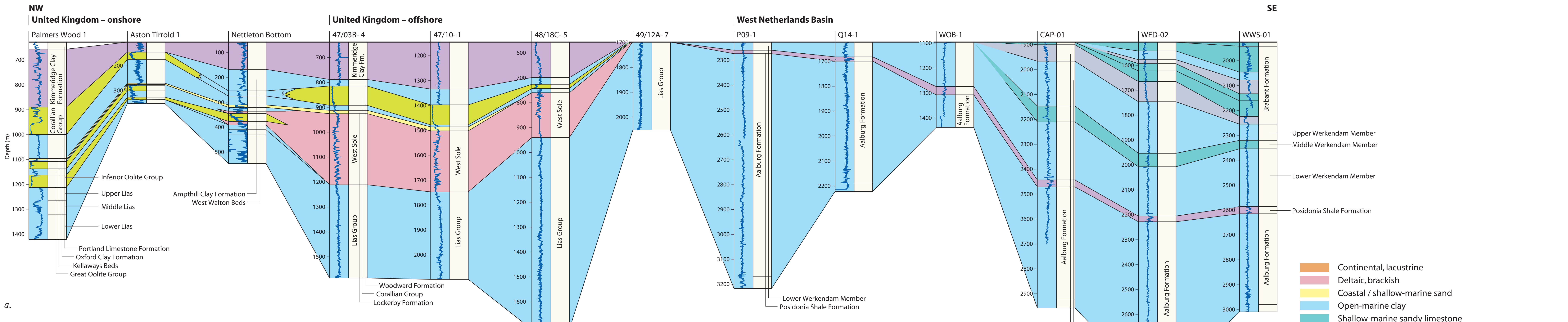
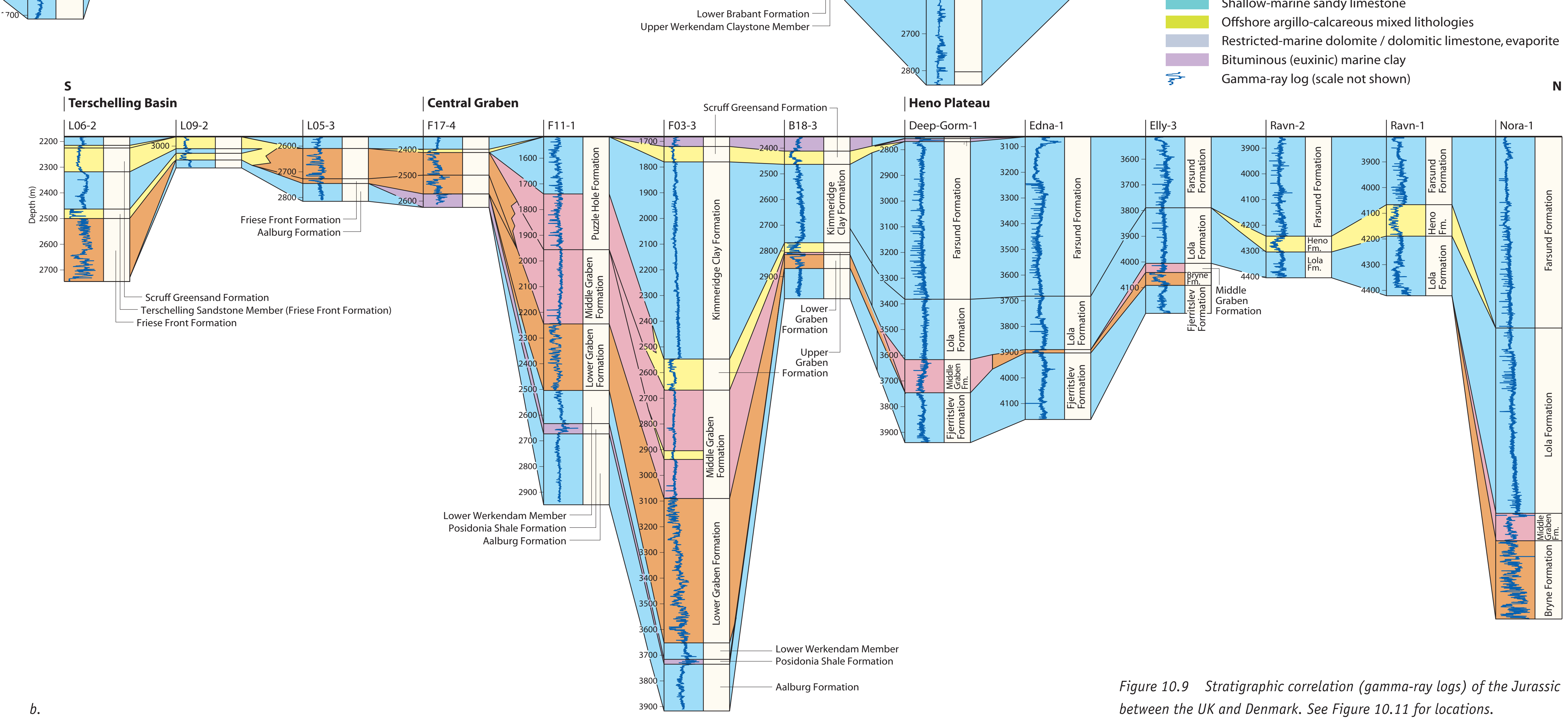




*Figure 10.9 Stratigraphic correlation (gamma-ray logs) of the Jurassic between the UK and Denmark. See Figure 10.11 for locations.*

Deposition in the Polish Basin was characterised by eight transgressive-regressive sedimentary cycles (**Figure 10.10**). From Aalenian to early Bathonian times, the deposits were mainly anoxic/dysoxic marine mudstones followed by upward-coarsening shoreface sandstone units. There were clear differences between the western/south-western parts and the central/eastern parts of the basin during mid- to late Bathonian and Callovian times. The former was characterised by repetitive mudstone-sandstone cycles; the latter by heterolithic shallow-marine lithologies that include calcareous sandstones, dolomites and organic-rich limestones with ferruginous ooids (Feldman-Olszewska, 1997, 2006a; Pieńkowski & Schudack, 2008). Reliable correlation of the succession between the trough and adjacent south-western platform has been possible due to the presence of good ammonite assemblages. However, correlation is more difficult on the East European Platform where ammonites are rare in the more condensed deposits. Sedimentation on this platform was characterised by marginal-marine and shallow-marine shelf clastics and carbonates (Feldman-Olszewska, 1998b; **Figure 10.10**). Middle to upper Callovian and lower Oxfordian deposits in the central, eastern and southern parts of the Polish Basin were strongly condensed to form a number of 'nodular beds' with thicknesses from a few to several tens of centimetres, which can span several ammonite zones (Dayczak-Calikowska & Moryc, 1988).

Unlike the basins to the west, deposition in the Polish area during Mid-Jurassic times was largely unaffected by the thermal-uplift and rifting events in the North Sea Basin. The clastic sediments supplied to the Polish Basin were derived mainly from the Fennoscandian High to the north-east and the Bohemian High to the south-west. Connections with the North German Basin to the north-west were restricted during Aalenian to Bathonian times. However, links with the Tethys Ocean to the south remained open, but were restricted to the axial part of the basin (the Mid-Polish Trough). In southern Poland, there is clear evidence of the continuing influence of the Tethys Ocean on sedimentation from the development of marine, mud-dominated deposits with ammonite faunas in Aalenian to Bajocian times, as global sea levels continued to rise and by more open-marine, sandy, glauconitic and bioclastic limestone developments in the late Bathonian and Callovian interval.

## 2.3 *Upper Jurassic (Oxfordian, Kimmeridgian and Volgian)*

The onset of Early Jurassic sedimentation was marked by a eustatic marine transgression, which gradually flooded almost the entire epicontinental basin that formed the SPB area throughout Early and Mid-Jurassic times. The gradual collapse of the Mid North Sea thermal uplift led to the re-opening of direct connections between the Tethyan and Boreal seas, whereas the breakup of Pangea and subsequent rifting associated with the on-going opening of the central Atlantic Ocean continued to have a significant effect on local tectonic and sedimentation patterns in the UK, Netherlands and northern Germany. In the Polish area, Late Jurassic sedimentation patterns were controlled by tectonic events to the south, which caused regional subsidence of the central and southern Polish platform and the re-opening of the northern links to the Boreal Sea (Ziegler, 1990a; **Figure 10.8**).

The Late Jurassic interval is subdivided into three stages, the Oxfordian, Kimmeridgian and Volgian (Tithonian); subdivision and correlation of the stages principally relies on marine ammonite assemblages (see Zeiss, 2003). The biostratigraphic resolution is similar to that of the Middle Jurassic in that correlation across Europe is still contentious in places due to the contrasting biostratigraphic assemblages that developed in the warm-water Tethyan carbonate sediments that dominate in the south, and the cool-water Boreal assemblages found in the clastic-dominated sediments to the north. However, the extension of marine sedimentation northwards and eastwards across the Polish area during the Late Jurassic generally improved correlations into, and within, this eastern part of the epicontinental basin.

### 2.3.1 *Stratigraphy*

The Upper Jurassic (Oxfordian to Volgian) succession of the UK is fully marine and is assigned principally to the Ancholme and Humber groups in the north, and Oxford Clay Formation, Corallian Group, Kimmeridge Clay Formation and Portland-Purbeck (part) groups to the south. Throughout the area, the succession rests conformably on the thin transgressive marine Callovian sandstones (Kellaways and Leckenby formations) that terminated deposition of the underlying Middle Jurassic succession. The boundary is unconformable with the overlying Lower Cretaceous Spilsby Sandstone Formation in the north. However, to the south, it is conformable in the Wessex-Weald basin where sedimentation continued throughout the Volgian into the Ryazanian.

The Upper Jurassic succession has a maximum proven thickness of about 300 m in the UK, although it is generally less than 200 m. Thickening is evident in halokinetic rim-synclinal structures, but these are restricted to the offshore sector. The succession thins northwards across the Mid North Sea High where marine sandstone remnants have been proved in a few isolated exploration wells, before significantly thickening to the north in the Central Graben (Fulmar, Heather and Kimmeridge Clay formations; Richards et al., 1993). To the south, the Upper Jurassic succession thins and onlaps the Anglo-Brabant High then thickens southwards to more than 700 m in the Wessex-Weald basin.

Sedimentation during the Late Jurassic was dominated in the northern Cleveland Basin by the silty, variably calcareous and/or organic-rich, fossiliferous marine mudstones of the Oxford and Kimmeridge Clay formations. These formations are separated over much of the area by a succession of coarse-grained higher-energy, shallow-marine, sandy, spicular, bioclastic and ooidal limestones, which comprise the Oxfordian Corallian 'Group' (>60 m thick). This same tripartite north–south facies transition is seen in

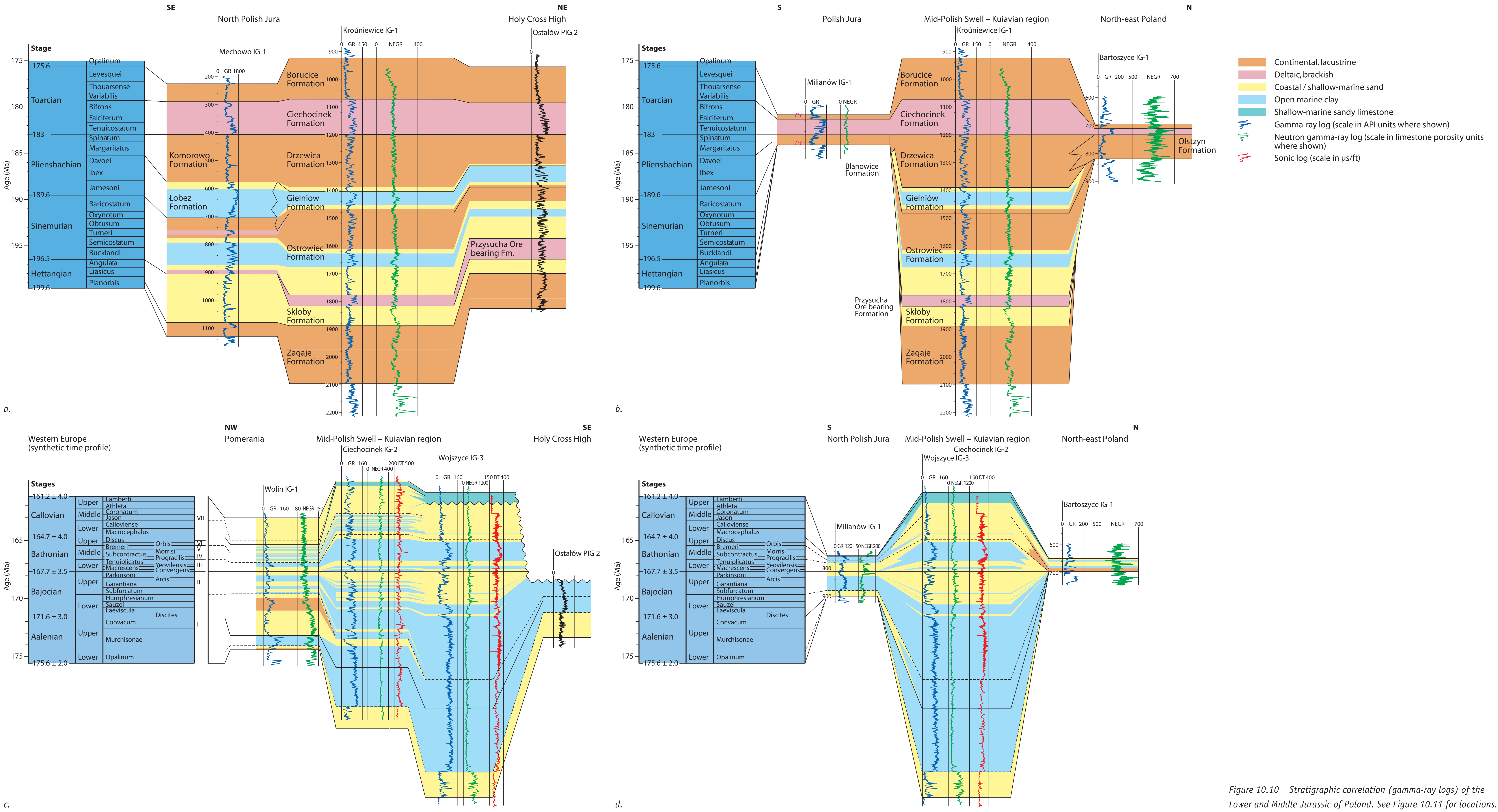



*Figure 10.10 Stratigraphic correlation (gamma-ray logs) of the Lower and Middle Jurassic of Poland. See Figure 10.11 for locations.*

the southern North Sea, where the ooidal limestones of the Corallian 'Formation' developed along the axis of the now inactive Sole Pit Trough and pass westwards across the East Midlands Shelf into the marine silty and calcareous mudstones of the Seeley Formation (Lott, 1992; Lott & Knox 1994). Although this depositional basin originally extended eastwards into the West Netherlands Basin, subsequent uplift and erosion during the latest Jurassic to earliest Cretaceous has removed much of the Jurassic succession, obscuring detailed relationships between the two basins.

Southwards, over the Market Weighton Axis, the 'Corallian' limestone is replaced in the East Midlands Basin by marine silty and calcareous mudstones of the West Walton Formation; the limestones re-appear as an ooidal-bioclastic facies along the northern and southern margins of the Anglo-Brabant High and thicken southwards (~50 m thick) into the Wessex-Weald basin. Thin sandstone developments are found locally within the Kimmeridge Clay Formation in the northern onshore area.

There are no Upper Jurassic rocks preserved in Belgium. The Upper Jurassic succession of the Netherlands is buried beneath variably thick and extensive Cretaceous and Cenozoic sediments. Sedimentation was continuous across the Middle to Late Jurassic transition only in the Dutch Central Graben, where the very variable upper Callovian to Volgian (Tithonian) successions are assigned to the Schieland and Scruff groups. The Schieland Group is characterised by mainly continental and paralic deposits, but becomes interbedded with marine sediments of the overlying Scruff Group, which is restricted mainly to the Dutch Central Graben (Wong, 2007). Elsewhere, the base of the Schieland Group is strongly diachronous. Continental sedimentation appears to have been initiated at different times in areas such as the West Netherlands and Broad Fourteens basins, where deposition resumed in the Kimmeridgian or Volgian (Tithonian) with lacustrine and lagoonal fine-grained clastics.

In the north, sedimentation in the Dutch Central Graben and adjacent Terschelling Basin led to the accumulation of up to 2000 m-thick sediments of the Central Graben Subgroup (uppermost Callovian to Volgian (Tithonian)). The basin-fill of this subgroup can be divided into three depositional sequences (Abbink et al., 2006). The oldest sediments (Sequence 1 – Lower, Middle and Upper Graben formations) are restricted to the Dutch Central Graben proper, where sedimentation during the Callovian to Volgian took place in nonmarine fluvial, lacustrine and deltaic environments, becoming fully marine during the late Oxfordian to Volgian. The sediments were mainly marine mudstones (Sequence 2 – Kimmeridge Clay Formation) followed by a change to shallow-marine, glauconitic and spicular sandstones deposited during the latest Volgian (Sequence 3 – Scruff Greensand Formation). This type of sediment fill represents distinct phases of Late Jurassic rift initiation, transgression, deepening and finally the cessation of rifting (Andsbjerg & Dybkjaer, 2003; Abbink et al., 2006). Sedimentation started later in the east–west oriented Terschelling Basin at the southern edge of the Dutch Central Graben and was characterised by a thick transgressive sequence initially dominated by shallow-marine spicular sandstone and subsequently by mudstone deposition (Sequence 2 - lower Kimmeridgian to Volgian). Regional transgression then extended this marine-sandstone depositional environment across the entire area, with sedimentation continuing into the Cretaceous (Sequence 3 – Volgian to Ryazanian).

In the Broad Fourteens, West Netherlands and Central Netherlands basins, and the Roer Valley Graben to the south, the Upper Jurassic succession is assigned to the Delfland Subgroup of the Schieland Group (Oxfordian to Ryazanian (Barremian)). The succession is up to 1500 m thick in the Broad Fourteens Basin. Upper Jurassic sediments in these basins were initially dominated by syn-rift, fluviodeltaic and lacustrine sandstones and mudstones with sporadic coalbeds. Occasional marine incursions led to the development of shallow-marine sandstones. However, fully marine sedimentation during the Kimmeridgian was restricted mainly to the northern end of the Dutch Central Graben where there are up to 760 m-thick dark olive-grey, silty, fissile, bituminous mudstones with thin argillaceous limestones typical of the Kimmeridge Clay Formation (Wong, 2007). These bituminous marine mudstones were gradually replaced by limestones and glauconitic and spicular sandstones in the uppermost Volgian (Tithonian) succession. In contrast, up to 500 m of lacustrine mudstones with evaporites were deposited in the then-isolated Lower Saxony Basin to form the lower part (Kimmeridgian to Volgian (Tithonian)) of the Niedersachsen Group.

Mafic volcanic activity (Zuidwal Volcano) in the Late Jurassic (Oxfordian to Volgian) is particularly evident in the Vlieland Basin where there is a thick succession of volcanic breccias and agglomerates (Van Bergen & Sissingh, 2007). These, and other volcanic events in adjacent basins, appear to coincide with a major phase of rifting and crustal extension that developed in the North Atlantic area during the Late Jurassic to Early Cretaceous (Chapter 3).

The Upper Jurassic rocks of Denmark are restricted to the Central Graben and Danish Basin. Sedimentation in both depocentres was continuous from the Callovian to the Volgian (Tithonian). Deposition was initially characterised by fine-grained, paralic and fluviodeltaic clastic sediments with sporadic thick coal seams that reflect the start of rifting (Andsbjerg & Dybkjaer, 2003). Gradual sea-level rise and continued gradual subsidence led to the accumulation of more than 4000 m of shallow-marine, organic-rich mudstones (Lola and Farsund formations) in the Tail End Graben. These two sequences are separated by a fine-grained sandstone unit (Heno Formation; >100 m thick), which was deposited locally in the northern part of the graben during the late Kimmeridgian. Organic-rich marine-mudstone deposition of the Farsund Formation (including the Bo Member 'hot shale' unit) then continued into the Early Cretaceous. Deep-water clastic sediments were shed from parts of the adjacent Ringkøbing-Fyn High (Poul Formation) along the eastern margin of the graben.

In the Danish Basin to the east of the Ringkøbing-Fyn High, Late Jurassic deposition was also initially characterised by fluviodeltaic sediments with sandstones, mudstones, thin coals and rootletted horizons. However, rising sea levels caused a gradual upward transition to shallow-marine sedimentation characterised by fossiliferous mudstones and glauconitic fine-grained sandstones (Flybjerg Formation). Fine-grained, shallow- to deeper-water marine clastic sedimentation continued in the basin into Early Cretaceous times (the Borglum (up to 300 m thick) and Fredrikshaven (up to 230 m thick) formations).

The Upper Jurassic rocks of Germany (mainly the Malm Group) crop out in the Lower Saxony Basin in the north and in the mountains of the Swabian and Franconian Alb in the south (Mönnig, 2005). Elsewhere in the Lower Saxony Basin, Upper Jurassic sediments up to 3000 m thick are buried and preserved beneath a thick succession of Cretaceous to Cenozoic sediments. Depositional patterns in the basin are overprinted by continued re-activation of the numerous Permian salt diapirs that deform and locally pierce this Mesozoic and Cenozoic cover.

During early Oxfordian times, sedimentation in much of the North German Basin was initiated by a transgression from the southern Tethys Ocean. The deposits are initially characterised by fine-grained carbonates, although higher-energy, spicular, coralliferous and ooidal limestones were also deposited as a series of bioherms and patch reefs (Heersum, Korallenoolith and Humeralisoolith formations) during early, mid- and late Oxfordian times respectively. Subsequent regression led to a distinct change in sedimentation patterns during the Kimmeridgian (Süntel Formation) with deposition of a varied succession of continental (local evaporites), fluvial and paralic sediments, which gradually became more marine and carbonate-rich during the Volgian.

Continental and paralic deposits dominate the Kimmeridgian and Volgian succession in the isolated Lower Saxony Basin to the west, where the sequence includes up to 1500 m-thick red-bed and evaporitic sediments (Münder Formation), which are characterised locally by dinosaur footprints on exposed surfaces. A series of transgressions started during the early Volgian (Tithonian) and periodically re-established coarser-grained limestone (ooidal, serpulitic and stromatolitic) sedimentation in the area (Gigaskalk, Aldorfer Serpelkalk and Otolithenpflaster limestones), which continued uninterrupted into the Early Cretaceous.

The carbonate-dominated Upper Jurassic sediments of southern Germany are assigned to the Weisser Jura. Sedimentation was continuous but condensed across the Callovian-Oxfordian boundary and is characterised by sandy, glauconitic lime-mud deposition (Glauconsandmergel Member). By the mid- to late Oxfordian interval, these marine-shelf environments at the margin of the main Tethys Ocean were characterised by lime-mudstones and siliceous sponge-rich limestone reefs. Massive carbonate-reef (e.g. Massenkalk Formation) and bedded-limestone (e.g. Solnhofen Formation) sedimentation continued throughout Kimmeridgian to Volgian (Tithonian) times (Mönnig, 2005; Pieńkowski & Schudak, 2008). Post-Jurassic erosion in this area has removed any evidence of sedimentation across the Jurassic-Cretaceous boundary.

The Upper Jurassic rocks of Poland crop out in the Holy Cross Mountains (Kutek, 1994; Gutowski et al., 2006 and references therein) and in the Polish Jura Chain (Matyja & Wierzbowski, 2006 and references therein). During the early Late Jurassic, deposition was initially restricted to the axial parts of the Mid-Polish Trough and was dominated in the north by clastic sedimentation (>800 m thick in the Pomeranian Basin). A general southward transition to carbonate-dominated shelf sedimentation (>1450 m thick in the Kuiavian Basin) (Niemczycka & Brochwicz-Lewinski, 1988) can be linked to the northward expansion of the Tethys Ocean, which eventually covered much of the Polish area. Links to the north with the contiguous Danish and North German basins were also maintained throughout Late Jurassic times, allowing free migration of faunas (notably ammonites) and floras (notably dinoflagellates) between the Boreal and Tethys oceans.

From early Oxfordian times, deposition in the central, western and northern part of present-day Poland was characterised by the deposition of lime-mudstones, carbonate-cemented glauconitic sandstones and sponge-rich lime-mudstones (Lyna Formation), which interfinger northwards with the sandstones of the Chociwel Formation and ooidal and bioclastic limestones of the Brda Formation. Chronostratigraphically, the Lyna Formation ranges from Oxfordian in Pomerania and Oxfordian to mid-Volgian in north-east Poland (Dembowska, 1979; Kutek & Zeiss, 1994).

The equivalents of these formations become increasingly carbonate-dominated to the south and include the 'Spongy' Limestone Formation (central Poland) and Krasnik Formation (eastern Poland) (Gazdzicka, 1998). These formations are characterised by massive, partially silicified, sponge-rich or dolomitised, biohermal and bedded sponge-microbial limestones. Coral bioherms (Coral Formation) are locally developed in the upper Oxfordian strata of central and eastern Poland. Where present, the finer-grained micritic limestone facies surrounding these sponge bioherms is assigned to the Calcareous Marly Formation, which interfingers eastwards and southwards with the Jasieniec Formation (Niemczycka, 1976, 1997). A return to high-energy, carbonate-shelf sedimentation characterised late Oxfordian / early Kimmeridgian times (Oolitic Formation) when westward-prograding carbonate-ramp systems developed comprising coarse-grained, ooidal and bioclastic carbonates (Gutowski et al., 2005). The Belzec Formation is the equivalent of this formation to the east (Lublin Region).

This period of carbonate sedimentation was abruptly ended throughout the area by the deposition of early Kimmeridgian deeper-water, fine-grained siliciclastic, marine, pelitic limestones and calcareous mudstones with oyster-beds and rich ammonite faunas (Paluki, Calcareous-Marly and Glowaczow formations). This style of sedimentation continued into early Volgian times. In the most south-easterly part of the Lublin Basin, sedimentation was characterised by the deposition of evaporites and carbonates in playa-lake and lagoonal environments (Ruda Lubycka Formation).

By late Volgian times, falling sea levels had led to shallowing that formed a restricted brackish-water basin in which carbonate and evaporite sediments were deposited (Kcynia Formation). Middle Volgian limestones with shell beds (Corbula Limestone Member) pass progressively upwards into upper Volgian (Riasanian) anhydrites, dolomites and gypsum, with ostracod-rich limestones (Wieniec Member), marls (Skotniki Member) and sandstones (Kajetanowo Member). Pre-Cenomanian erosion subsequently removed much of the Volgian sequence such that remnants are found only in the central part of the Polish Basin.

It is considered likely that much of the Upper Jurassic succession in north-west and south-east Poland was subsequently removed following Late Cretaceous to Paleocene inversion of the Mid-Polish Trough (Mid-Polish Anticlinorium) (Dadlez, 2003).

## 3 Hydrocarbon systems

Oil and gas systems are developed in a number of the Jurassic basins of the SPB area (**Figure 10.11**). These basins contain both source rocks and reservoir facies and their development as hydrocarbon systems are closely associated with their subsequent inversion in the Late Jurassic to Late Cretaceous.

### *3.1 Hydrocarbon discoveries in the Jurassic*

Most of the Jurassic hydrocarbon discoveries and subsequent field developments in the SPB area are of oil rather than gas, although gas shows have been recorded in a number of localities across the area. The first Jurassic subsurface hydrocarbon discoveries in southern England took place in the early 19$^{th}$ century in Sussex, where gas was detected in water wells drilled at Heathfield. Subsequent drilling in 1896 led to the UK's first producing gas well from the Kimmeridge Clay Formation. Despite further extensive exploration in the basin before and after World War II (1930s to 1960s), with minor gas shows recorded in the Bathonian Great Oolite Group and Upper Jurassic Portland Group and oil in the Callovian Kellaways Formation, no commercial discoveries were made in the Weald Basin until 1980 when oil was discovered at Humbly Grove (Sellwood et al., 1985); the field was developed from 1985. There are no oil or gas discoveries in the Jurassic successions of the East Midlands or contiguous southern North Sea.

Oil was first discovered in the Netherlands at Corle in 1923 when drilling of the Zechstein evaporites and Carboniferous sandstones yielded 1.5 barrels of oil. Although oil finds have been recorded at a number of stratigraphic levels, no commercially viable oil discoveries have been made subsequently in the Jurassic succession either in the offshore or onshore area (Wong, 2007).

Oil occurrences in the Jurassic sandstones of Germany have been known since medieval times (e.g. oil seeps around Celle), but modern commercial oil drilling and production began in 1859 with the discovery of oil in Upper Triassic, Jurassic and Lower Cretaceous sandstones at Wietze (Figure 1.2). This structurally complex field lay on the flanks of a salt-piercement structure; its heavy oil-bearing sands were subsequently mined from a series of shafts and galleries before its closure in 1963. Subsequent oil discoveries were associated with a number of other salt structures in Middle Jurassic sandstones at, for example, the Oberg (1916) and Oelheim fields. Later, in the offshore sector in the Gifhorn and East Holstein Trough rim-synclines, Middle Jurassic oil discoveries were developed in the Swedeneck-See (1956) and Kiel fields. The Mittelplate discovery in the Heide Trough (see Section 3.6.4) was the first Jurassic offshore field development in the German sector of the southern North Sea.

### *3.2 Source-rock distribution and maturity in the Jurassic of the SPB area*

In the UK Weald Basin (**Figure 10.12**), mudstones of the Lias Group, Oxford Clay and Kimmeridge Clay formations have the greatest source-rock potential. All contain kerogens of types II, III and II/III (Ebukanson & Kinghorn, 1985). However, the maturity of these units is highly variable because of the complex structural evolution of the basin. Despite the low-maturity estimates using vitrinite reflectance, it is clear from the widespread occurrence of hydrocarbons in the basin that maturation and oil generation must have taken place at some time in the basin's history. The Kimmeridge Clay is considered to be an extremely rich oil-prone source, with total organic carbon (TOC) contents in excess of 10% (Butler & Pullan, 1990), perhaps reaching up to 20 wt.% TOC in some black shales (Penn et al., 1987), although it is thought to be immature in much of southern England including the Weald Basin (Ebukanson & Kinghorn, 1985, 1986b; Penn et al., 1987). Calculated time and temperature integral (TTI) values and maturity studies predict that the base of the Kimmeridge Clay has entered the oil window in the axial part of the Weald Basin (Penn et al., 1987; Butler & Pullan, 1990; DTI/BGS Report, 2007).

The Oxford Clay Formation consists mainly of variably bituminous fissile and blocky mudstones. Fissile mudstones in the lower and middle Oxford Clay Formation have up to 12% TOC; values for the basal parts of the Oxford Clay are up to 5% (Butler & Pullan, 1990). TTI profiles suggest that the formation falls in the oil-generation window in the Weald Basin, where it is likely to have reached the peak of maturity for oil generation (Penn et al., 1987). Organic maturity (VR%) values of 0.74 for the Oxford Clay Formation at Penshurst in the centre of the Weald Basin (Ebukanson & Kinghorn, 1986a) support this interpretation. Elsewhere, the formation may at best be marginally mature or insufficiently mature enough to have generated oil. Burial history diagrams suggest that oil generation from the Oxford Clay Formation may have begun in the Early Cretaceous and continued throughout the Cenozoic (Penn et al., 1987).

The Lias mudstones are moderately rich in organic material, particularly in the lower Lias Group of southern England (Hallam, 1960), with TOC contents in the range of 0.5% to 2.1% (Butler & Pullan, 1990); some mudstones contain up to 7 wt% TOC (Ebukanson & Kinghorn, 1985). However, the succession does show considerable vertical and lateral richness variations, deteriorating in quality in the eastern part of the basin. Regional studies suggest that the oilfields in the Weald Basin are most probably sourced from the Lias Group (Hancock & Mithern, 1987). The TTI profiles predict that the Lias Group mudstones fall within the

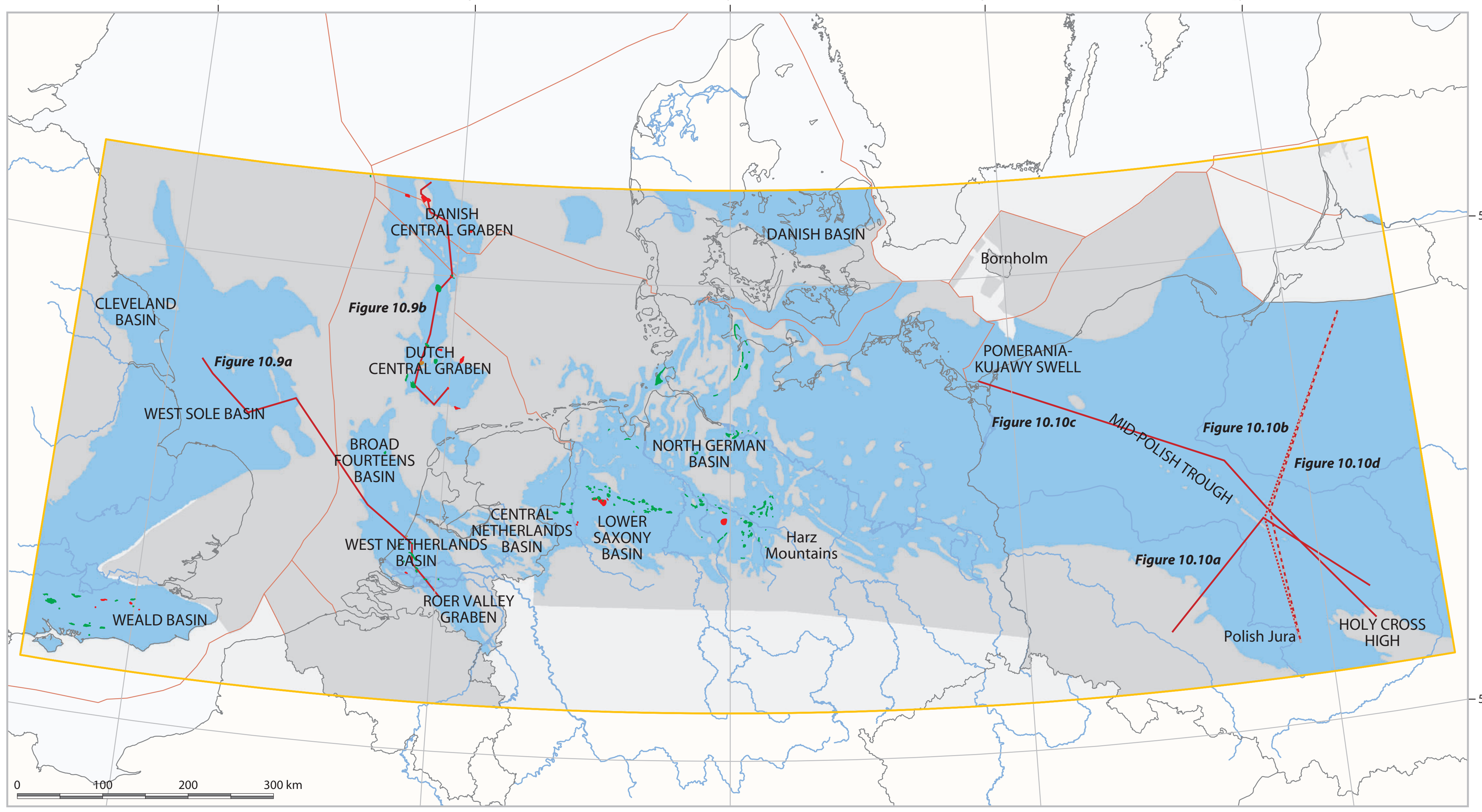



*Figure 10.11 Distribution of Jurassic hydrocarbon reservoirs. Fields with Jurassic reservoir.*

zone of oil generation over much of the Weald Basin, and are possibly overmature in the deepest parts of the basin (Penn et al., 1987). The Lower Lias Group is probably immature over the Hampshire-Dieppe High (Penn et al., 1987). VR% values for the Lias at Penshurst in the centre of the Weald Basin vary from 0.8 to 0.9 (Ebukanson & Kinghorn, 1986b), occurring in the main oil-generation phase and supporting the maturity predictions. The Lower Lias is marginally mature at Henfield, Warlingham and Winchester, around the periphery of the Weald Basin. Oil generation from Lias source rocks probably began during deposition of Lower Cretaceous sediments and peaked at about mid-Cretaceous times (Penn et al., 1987).

Carboniferous sediments, possibly containing humic kerogen from the Westphalian Coal Measures, may also form a secondary source of gas in parts of the Weald Basin (Taylor, 1986; Butler & Pullan, 1990). However, they can only be present beneath allochthonous basement, as the youngest basement rocks that have been drilled are Dinantian in age (Smith, 1985).

All the Jurassic oils studied from the Weald Basin are light crudes, with API gravities in the range of 35° to 42°, and are similar isotopically (Butler & Pullan, 1990). The closest match between oils and source rocks is with the Lower Liassic shales, but the results suggest a degree of mixing is evident, with contributions from more than one source interval. The gas is dry and its source is enigmatic, with most of the gas found in Upper Jurassic and Cretaceous reservoirs and only in structures of Tertiary age (Butler & Pullan, 1990). The gas may have its origins in release from pore waters at shallow depths, or it originated in deeper reservoirs, migrating preferentially to higher levels than oil during Tertiary uplift.

Although thin organic-rich mudstones are common at various levels within the Lower Jurassic succession, they are best developed in the Netherlands, Germany and Poland where they are the significant source-rock facies of the Posidonia Shale Formation (**Figure 10.12**). The formation typically consists of fissile, organic-rich, calcareous mudstones between 20 and 40 m thick. They contain kerogens of types I and II with TOC contents ranging from 5% in the Netherlands up to 12% in north-west Germany. These organic-rich mudstones are the principal source rocks for most of the oilfields in the eastern and central Lower Saxony Basin and Schleswig-Holstein (Lokhorst et al., 1998).

The Lower Jurassic Posidonia Shale Formation is the main oil source rock in the Netherlands (Bodenhausen & Ott, 1981; Wong, 2007). Both marine algal sapropel and land-derived organic matter are present (type II kerogen). The relatively small oil occurrences in most of the Netherlands may be attributed to the patchy distribution of the formation due to severe erosion during later tectonic phases. There are additional oil source rocks in the Coevorden Formation in the Lower Saxony Basin, which generated the oil of the relatively large Schoonebeek oilfield (see Section 4.1 in Chapter 11) (De Jager & Geluk, 2007). This horizon is also a known oil source rock in the German part of the basin, where it is part of the Bückeberg Formation. Moreover, the Lower Jurassic Aalburg Formation, with its type II source-rock characteristics, probably contributed to some degree to oil accumulations in the Dutch Central Graben (Wong et al., 1989) and West Netherlands Basin (De Jager et al., 1996). The bituminous Clay Deep Member of the Kimmeridge Clay Formation in the northern part of the Dutch Central Graben also has oil-generating potential (**Figure 10.13**). However, the areal and stratigraphic extents of this member are much more limited than those of the equivalent and very productive 'hot shales' in the Kimmeridge Clay Formation in the UK and Danish sectors of the North Sea. The coal-bearing strata of the Puzzle Hole, Middle Graben and Friese Front formations may have generated gas in places. However, the burial of these coals is considered insufficient to have yielded economic quantities (Wong et al., 1989).

The 27 to 70 m-thick bituminous black marls of the Ölschiefer Formation are the main source rocks for oilfields in the Lower Saxony Basin, and the Gifhorn and Holstein troughs (Pieńkowski & Schudack, 2008).

### *3.2.1 Jurassic coals*

Jurassic coals are rare in the UK area of the SPB; however, thin coal seams crop out in many places, for example, in the Eskdale and Howardian hills within the paralic successions of the Ravenscar Group in the Cleveland Basin (Saltwick and Cloughton formations). These deposits have been mined in the past for local fuel supplies. The coals are generally 0.15 to 0.3 m thick, but may be up to 0.6 m, and contain a rich, well-documented plant floral assemblage comprising ferns, cycads and conifers. *Ginkgoales* and *Equisetums* are also common and often form large allochthonous rafts or washouts of organic debris, but may also occur in upright *in situ* growth positions. Vitrinite reflectance and other studies show that these Middle Jurassic coal-bearing sediments, which are now exposed along the axis of the basin, reached the maturity zone for oil generation. This suggests that inversion of the basin during the Tertiary led to the removal of considerable thicknesses (>1500 m) of Upper Jurassic and Cretaceous sediments (Hemingway and Riddler, 1982).

Within the bituminous, fissile, marine mudstones of the Jet Rock Member of the Upper Lias succession of the Cleveland Basin, there are concentrations of thin lenses, laminae and nodules of 'jet', a hard, lustrous black lignite (compressed araucarian wood). Jet formed the basis of a once important local 'jewellery' industry.

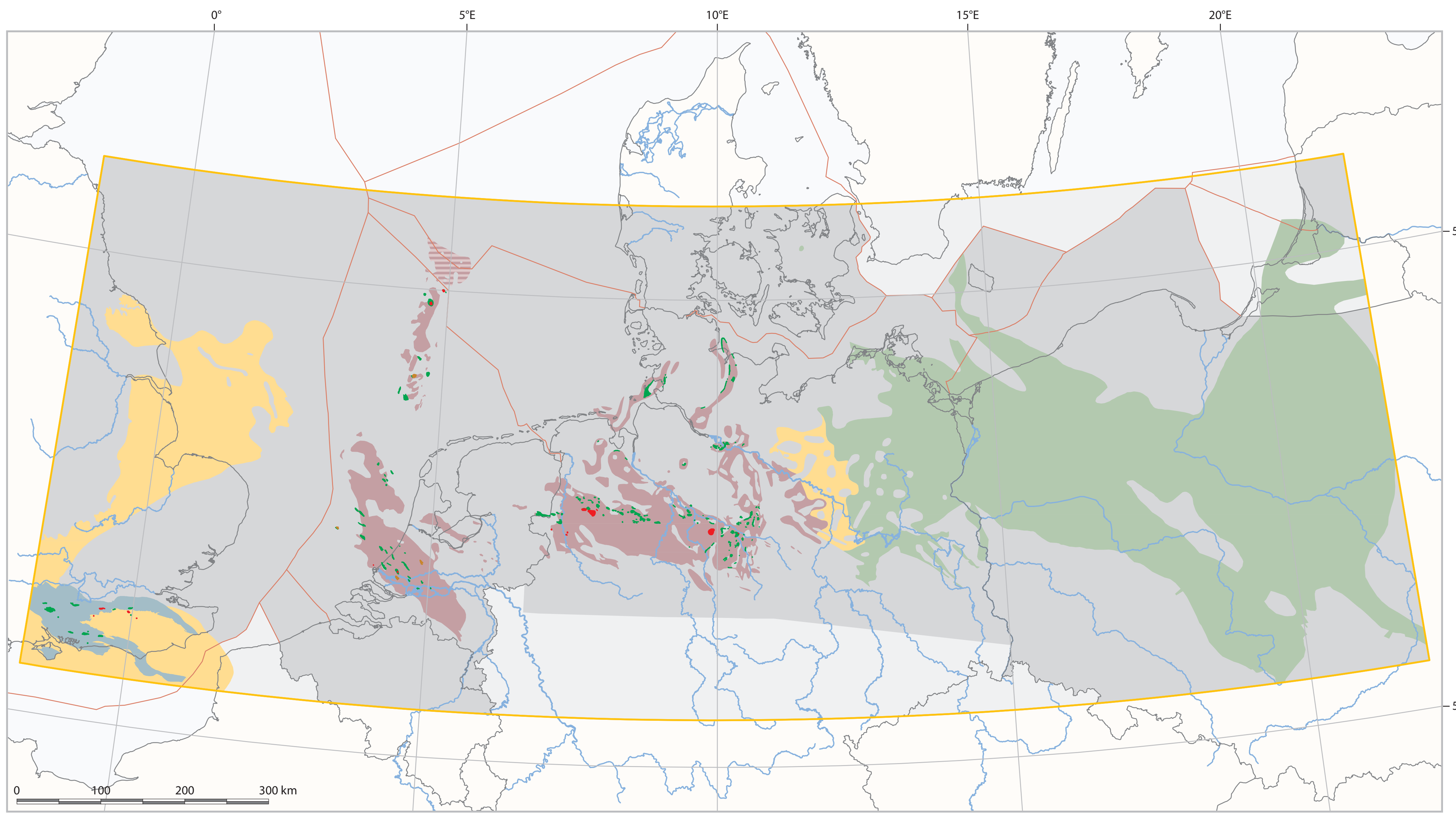



*Figure 10.12 Lower Jurassic source rocks.*

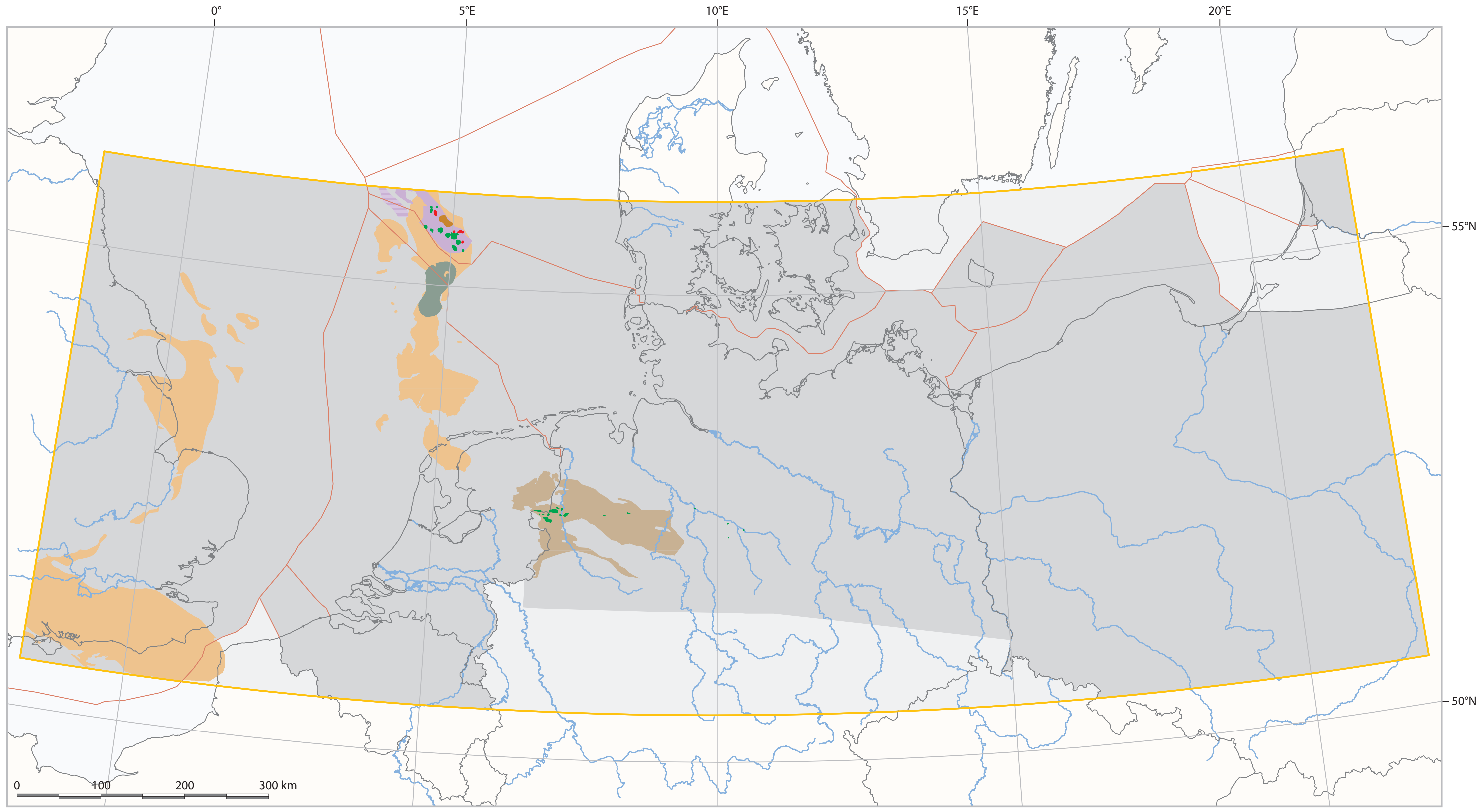



*Figure 10.13 Upper Jurassic / Lower Cretaceous source rocks.*

There are no coals in the Jurassic succession of Belgium; however, Late Jurassic coals occur within the Central Graben and Terschelling Basin in the deltaic successions of the Puzzle Hole, Friese Front and Zurich formations (Wong et al., 2007b) of the Netherlands.

Jurassic coals are found in both the onshore (Fennoscandian Border to Bornholm areas) and offshore (Danish North Sea-Søgne basins) successions of Denmark (Petersen et al., 2003b; Petersen, 2004). The coals are most widespread in Lower and Middle Jurassic rocks, although there are sporadic coals in the Upper Jurassic successions offshore. The coals are of low rank in the Bornholm area, whereas in the Søgne Basin offshore they are thermally mature and hydrocarbon generating. They have a maximum thickness of almost 2 m in the Bornholm area (Middle Jurassic) where they formed in inland freshwater mires. Nine seams have been recorded in the Søgne Basin and, in contrast to the onshore seams, they formed in a coastal-plain setting. The offshore coals, with their high thermal maturity, are thought to be the source of the hydrocarbon accumulations in the Harald and Lulita fields. Variations in the types of hydrocarbons found in these fields can be related to the different source-rock facies of the coal (Carr and Petersen, 2004).

Thinly developed Lower Jurassic coals are found only locally in the lower Hettangian (Liassicus sandstone) paralic succession of north-east Germany. Sporadic thin coals also developed in the deltaic deposits of the Lower and Middle Jurassic successions of Poland.

### *3.2.2 Jurassic oil 'shales'*

Oil 'shales' are found at a number of stratigraphic levels in the Lower (Lias Group of Yorkshire and Somerset) and Upper Jurassic (Oxfordian and Kimmeridgian of Dorset and Yorkshire) successions of the UK. Middle Jurassic oil shales occur only in Scotland to the north-west of the SPB area. There is no universally agreed definition of the term 'oil shale' in the UK. Organic matter in the form of kerogen, bitumen and hydrocarbons occurs in variable concentrations in most fine-grained sedimentary rocks. The name 'bituminous mudstone' has commonly been used when the organic concentration is sufficiently high to have a noticeable affect on the lithology of the rock, or where it imparts an organic smell to the freshly broken rock. The term 'oil shale' is used where destructive distillation of a mudstone by the breakdown of kerogen yields appreciable quantities of oil (Gallois, 1979). Most of the oil shales have potential oil yields in the range 312 litres/tonne.

The most important oil-shale horizons are within the Kimmeridge Clay Formation in the Jurassic rocks of the UK. There have been several attempts to exploit these oil-shale horizons in Dorset commercially, where from earliest times they were burnt as a coal substitute, and in Norfolk since the 17$^{th}$ century, but none have had lasting success. The high sulphur content of the shales has proved a particular problem. The Kimmeridge Clay Formation crops out extensively in England from the Kimmeridge Bay type sections on the south coast of Dorset to the coastal sections in Yorkshire, and continues at subcrop into the southern North Sea (Cox et al., 1987; Gallois, 1979). The succession consists of almost entirely argillaceous shallow-marine mudstones, with local coarser-grained clastic developments. The succession is up to 560 m thick in the Weald Basin and is subdivided into lower, middle and upper units in which a complex sequence of small-scale rhythmic cycles has developed. These are basal, thin, silty mudstones in the lower part of the succession, overlain by dark grey mudstones and pale grey calcareous mudstones; in the middle unit, they are bituminous oil shales overlain by dark grey mudstones and pale grey calcareous mudstones. The uppermost part of the Kimmeridge Clay Formation consists of sandy and calcareous mudstones, but with no oil shales (**Figure 10.14**). Many of these individual cycles can be correlated over tens of kilometres (Cox & Gallois, 1981). There are organic-rich mudstones throughout the formation, but oil shales are confined to five specific intervals known as the Lower *eudoxus*, Upper *eudoxus*, *elegans*, *wheatlyensis* and *pectinatus* bands. Most of these oil-shale intervals can be traced at outcrop from Dorset into North Yorkshire and offshore into the Sole Pit Basin.

The potential oil yields, as determined by IFP/Rock-Eval methods, range from 10 to 85 US gal / US ton but are mostly in the range 20 to 55 US gal / US ton. The yields for a particular seam are relatively constant over large areas. 'The 'shale-oils', as derived by pyrolysis at 500°C, are markedly different from naturally occurring crude oils in their physical and chemical properties. They are poor in hydrocarbons and rich in resenes, asphaltenes and sulphur, and are similar to heavy oils and natural asphalts of tar sands and mineral veins. The kerogens and bitumens extracted from the Kimmeridge Clay Formation oil shales show them to be thermally immature. Their present depth of burial suggests they are probably not generating petroleum onshore in the UK (Gallois, 1979). However, in the past they may have been small-scale oil source rocks in some basinal areas when their depth of burial was greater, for example, in the Weald Basin, south Dorset and North Yorkshire.

Fissile, silty, bituminous mudstones with sporadic thin oil-shale horizons are also found within the lower Toarcian Whitby Mudstone Formation in the Cleveland Basin. The mudstones are part of the Jet Rock Member, which is in part coeval with the more extensive organic-rich mudstone developments of the Posidonia Shale Formation of mainland Europe.

There are no oil-shale developments in the Jurassic successions of Belgium, the Netherlands or Denmark. In local areas of northern Germany, the Lower Jurassic mudstone succession may have high enough organic content to be considered an oil shale.

## *3.3 Oil and gas generation and migration during the Jurassic*

Hydrocarbon generation from the Lias Group in the UK probably began in the deepest parts of the Weald Basin in Early Cretaceous times (Penn et al., 1987), with peak generation in the mid- to Late Cretaceous. The Oxford Clay Formation was deposited in the deepest parts of the basin in latest Cretaceous times and the Kimmeridge Clay Formation probably reached maturity in the very centre of the basin at about the same time (Penn et al., 1987; Butler & Pullan, 1990). The Lower Lias may have entered the gas-generation window in the deepest part of the Weald Basin in Late Cretaceous times. Tertiary uplift progressively lifted the source rocks out of the temperatures and pressures required for hydrocarbon generation such that it had effectively ceased by Miocene times, although it may have continued in the less disturbed western areas. Uplift led to an important second phase of oil migration and re-migration of both oil and gas as the result of tilting of pathways and destruction of many earlier traps. Two phases of migration are supported by the fact that ferroan cements appear to have been inhibited by the presence of hydrocarbons in some early-formed structures.

Migration pathways in the Weald Basin were influenced by both sedimentary and tectonic factors. The presence of three major widespread fissile mudstone/clay sections created three vertically separated fluid regimes with reservoir intervals of the Triassic, the Middle Jurassic and the Upper Jurassic. The Great Oolite is the best studied and documented of these pathways, and it permitted movement well away from the mature source area, although its effectiveness would have been reduced with time as progressive cementation presumably took effect. For example, the Stockbridge and Goodworth fields are situated some 30 km away from the postulated edge of maturity in the Weald Basin (which also demonstrates the effectiveness of the Oxford Clay Formation seal; Butler & Pullan, 1990). Tectonic controls on migration were provided by faults. There is a clear relationship between major faults and the occurrence of multiple reservoir horizons with hydrocarbons at both shallow and deeper levels, with hydrocarbons distributed throughout the stratigraphic column in areas strongly affected by Tertiary inversion. Movement along faults seems likely, because reservoir-reservoir juxtapositions are not seen and hydrocarbons are often found when drilling through fault planes (Butler & Pullan, 1990).

The main oil source in the Netherlands is the Posidonia Shale Formation, which is preserved only in the rift basins. Although the Kimmeridge Clay Formation is a prolific source in the Central and Northern North Sea basins, it has not been a significant source of oil in these southern rift basins. Oil generation from the Lower Jurassic probably began in Late Jurassic to Early Cretaceous times and emplacement has been restricted largely to the rift-basin areas. It is thought that there has been limited gas generation from the coal-bearing Jurassic successions of the Dutch Central Graben (De Jager & Geluk, 2007).

The oil generated in the Jurassic successions of Denmark was probably derived primarily from the organic-rich shales of the Upper Jurassic Farsund Formation; the upper part of the formation is generally considered to be the most oil-prone. However, the oil accumulations of the Lulita and Harald fields in the Danish Central Graben are sourced from Middle Jurassic fluvial and paralic humic coals (type III kerogen) (Carr & Petersen, 2004).

Oil generation from the principal source rocks in Germany, the Posidonienschiefer and Olschiefer formations, probably took place following basin inversion during Late Cretaceous to Early Cenozoic times (see Chapter 13). No oil occurrences are known in the Jurassic successions of Belgium or Poland.

## *3.4 Reservoir rock units within the Jurassic*

There are no proven hydrocarbon reservoirs within the SPB area in the Jurassic of Belgium or Poland.

There are a number of both clastic and carbonate potential reservoir units in the Jurassic succession of the UK within the SPB area, although hydrocarbon fields are proven only in the Jurassic of the Weald Basin. The main reservoirs in the basin are the Middle Jurassic (Bathonian) Great Oolite Group limestones in which oil was first discovered at Storrington in 1986. These limestones form reservoirs in the Humbly Grove, Horndean, Goodworth, Singleton and Stockbridge oilfields, and in the undeveloped Baxter's Copse and Lidsey discoveries (Trueman, 2003). Oil production is from wells in the western half of the basin, as the quality of the reservoir decreases to the east due to facies variation and variable diagenetic history (McLimans & Videtich, 1987; Scott & Colter, 1987). Few data are available on reservoir quality, which may be significantly affected by diagenesis. The best primary intergranular porosity in the Great Oolite Group limestones is developed in well-sorted, ooidal and bioclastic grainstones and relatively clean packstones (McLimans & Videtich, 1987). Throughout the basin, similar lithologies in the Great Oolite Group have porosities ranging from less than 5% to in excess of 20% in Storrington 1 (McLimans & Videtich, 1987). The variation in porosity occlusion by cementation is particularly dependent on the residence times in the freshwater diagenetic environment. Short residence times provided some early cementation, but also provided framework support and protection during subsequent burial and compaction, whereas long residence times have significantly reduced the porosities. These variations are illustrated by the porosities

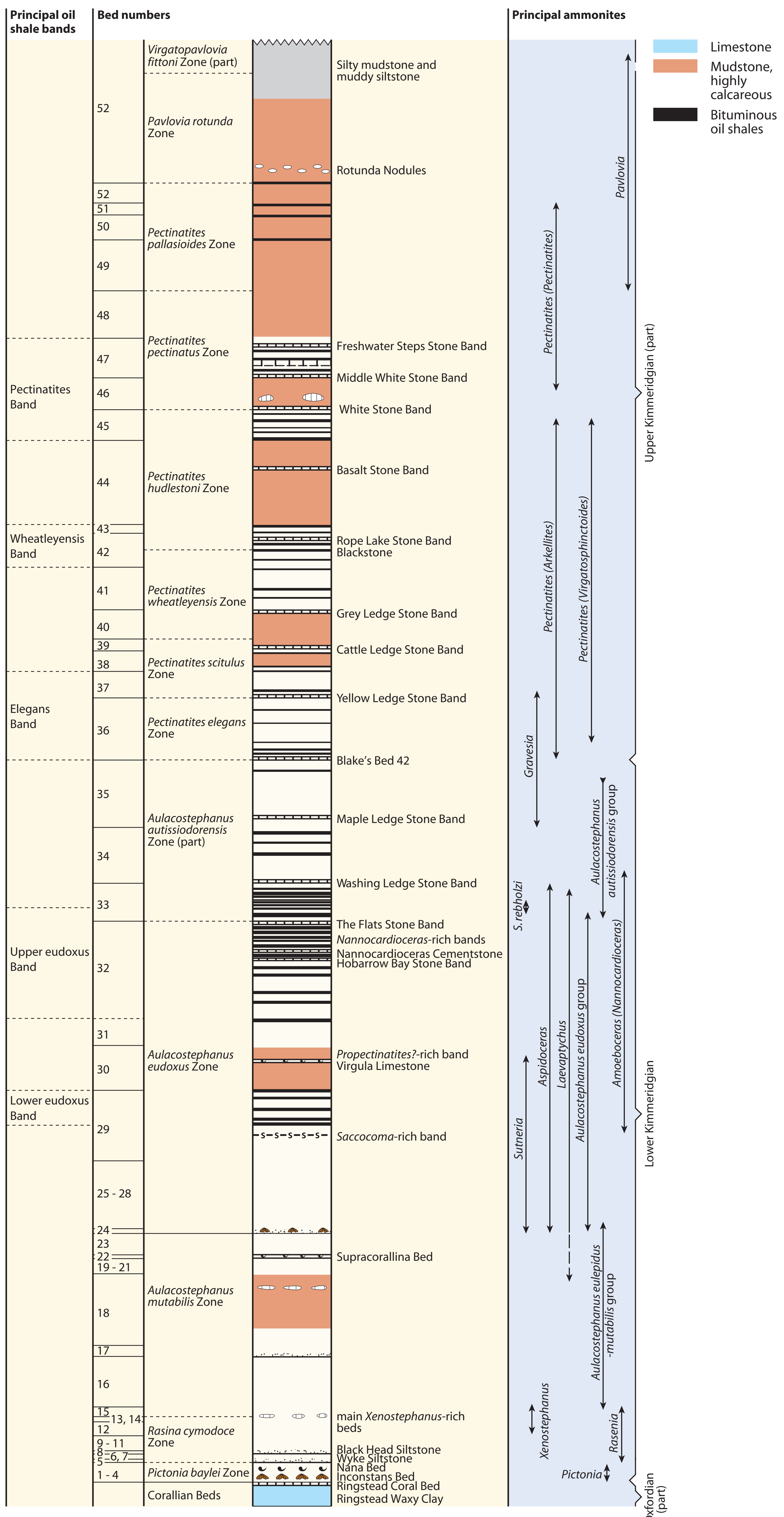



*Figure 10.14 Stratigraphic distribution of oil shales in the Kimmeridge Clay Formation of the UK.*

of 11 to 13% in Baxter's Copse and Palmers Wood, whereas the Great Oolite Limestone in Normandy 1 and Bordon 1 shows that nearly all porosity is occluded by early fringe cements (McLimans & Videtich, 1987).

Three principal phases of cementation have been recognised (Sellwood et al., 1989). Early calcite-rim cements are followed by later 'saddle' dolomite with associated sphalerite, and finally by weakly ferroan calcite. The latter forms a pervasive cement throughout the Great Oolite Group limestones and appears to have been the main cause of porosity reduction in the Weald Basin. Globules of oil trapped between the early calcite cement and the saddle dolomite and numerous inclusions containing oil, gas, or both, are present in the ferroan calcite cement (Butler & Pullan, 1990). However, ferroan cementation appears to have been inhibited in some older structures due to the presence of migrated hydrocarbons (Hancock & Mithern, 1987; Sellwood et al., 1989). The first phase of migration was probably associated with expulsion of fluids from Lias Group mudstones during latest Jurassic to Early Cretaceous times. The timing of the second phase of migration and re-migration with associated precipitation of ferroan calcite is more difficult to determine. Although it was inhibited from forming in the crests of pre-Tertiary structures, it does seem to occur in the crests of Tertiary structures.

Due to the depositional environments prevalent at the time, most of the Jurassic reservoirs are of better quality around the margins of the Weald Basin, with significant deterioration in quality towards the basin centre (Penn et al., 1987; Butler & Pullan, 1990). Most of the Jurassic sediments in the Weald Basin were deposited in low-energy, wave-dominated environments with no significant clastic source. It is thought that the Bridport Sand Formation and the Corallian Group limestones and sandstones may have only marginal prospectivity in much of the Weald Basin. The Bridport Sand Formation is poorly developed in the basin, and there does not appear to be an effective seal between this level and the Inferior Oolite and the Great Oolite groups. The Inferior Oolite Group limestones have had interesting shows. The lower beds of the Corallian Group may provide an effective reservoir in the northern and eastern parts of the basin where carbonates form the reservoir in the Bletchingley gas discovery. The upper beds of the Corallian Group similarly have their greatest potential in the east–west-trending belt just south of the London-Brabant Platform where the thickest sandstones are developed. The Palmers Wood oilfield has established the Corallian sandstones as a major reservoir (see Section 3.6.1). The Warlingham borehole to the south of London has also proved oil and gas in the uppermost Corallian Group limestones. Production tests established a daily production rate calculated at 5 to 10 gallons of oil and gas at 35 000 scf (Worssam & Ivimey-Cook, 1971). The limestones and sandstones of the Portland Group may be developed in reservoir facies, although the formation passes laterally into mudstones towards the south-east Weald Basin (Penn et al., 1987). The Portland Group has proved productive of gas at Godley Bridge, whereas the sands in the Corallian and Portland groups clearly indicate that there was a good clastic source on the London Platform towards the end of the Jurassic.

The Lower Cretaceous Purbeck anhydrite at Godley Bridge forms an effective seal to the beds of the Portland Group (Butler & Pullan, 1990). Corallian reservoirs are sealed by the overlying thick Kimmeridge Clay Formation mudstones and the Great Oolite Group limestone reservoirs are sealed by the Oxford Clay Formation mudstones. Significantly, no real overpressures exist in the Weald Basin and it seems likely that faults in the basin may provide a pressure-release mechanism and so, in general, are not sealing faults.

Structural closures containing Jurassic reservoirs in the UK fall into two main categories: upfaulted tilt-blocks and horsts, and major mid-Tertiary inversion structures developed by reversal of motion on earlier normal faults (Underhill & Stonely, 1993; Underhill, 2003). Prospective tilt-blocks and horsts can occur anywhere, but are probably best developed around the northern, western and southern margins of the Weald Basin and the southern margin of the Hampshire-Dieppe High. The most important inversion structures occur along the Pewsey-London Platform and Wardour-Portsdown structures. Their prospectivity is again dependent on the levels of structural disturbance during Tertiary inversion.

The first phase of oil migration (Late Jurassic to Early Cretaceous) led to the accumulation of oil in structures of pre-Late Cretaceous age (Butler & Pullan, 1990), for example at the Palmers Wood and Humbly Grove oilfields. Other traps were formed by tilted fault blocks on which syndepositional movements occurred on the faults throughout the Jurassic and Early Cretaceous. Traps around the margin probably remained relatively undisturbed throughout Tertiary uplift/inversion, although they must have been affected by some regional tilting. However, Tertiary inversion did affect the Weald Basin, particularly in the basin centre where accumulations were probably destroyed or breached during Tertiary movements (Butler & Pullan, 1990). The second, probably Early Tertiary, phase of hydrocarbon generation and migration led as indicated to the modification or breaching of existing traps and accumulation in new traps. An example of a modified existing trap is the Storrington oilfield, where gas break-out may have occurred during Tertiary uplift and tilting leading to the formation of gas caps. The Godley Bridge field, although containing a minor oil phase, represents a gas accumulation; the trap origins for which lie in the Tertiary movements (Butler & Pullan, 1990).

There may be other minor structural traps either within rollover anticlines that developed against basin-controlling faults, which may have been modified ('tightened') during Tertiary movements, or tight folds associated with reversed north-west–south-east-trending faults, such as at Detention in Kent. No commercial accumulations have been found in structures associated with these intense local inversion movements, which may be due to, for example, there being no closure at depth to sealing problems along faults. Stratigraphic pinch-out has not been demonstrated as a mechanism of hydrocarbon entrapment in the Weald Basin. Closures are likely to be small, and they must represent high-risk targets.

In the Netherlands, oil and local gas accumulations have been discovered in Upper Jurassic sandstones of the Lower Graben, Upper Graben and Friese Front formations of the Dutch Central Graben. Oil and gas have been found in sandstone beds of the Breeveertien Formation in the Broad Fourteens Basin. In the West Netherlands Basin, various members of the Brabant and Nieuwerkerk formations are locally oil and gas-bearing. The traps in the Dutch Central Graben area are associated with salt tectonics, and are present mainly as 4-way dip closures in turtle-back anticlines. Some of the reservoir rocks in this area are strongly fractured. Elsewhere, there are combinations of fault- and dip-closed structures. The top seals are formed by various Upper Jurassic mudstone beds (Wong, 2007).

The Middle Jurassic Ludwigienton Formation of Germany includes oil-bearing sandstones; the Suderbruch Sandstone is productive in some fields between Bremen and Hamburg. The sandstones are typically non-fossiliferous, moderately well-sorted and fine to medium grained. Up to eight such sandstone horizons between depths of 1500 and 33 000 m may be stacked one above the other in the proximal areas of the basins. Diagenetic changes are significant, as the depth of burial increases in these sandstones with high porosities and permeabilities near ground surface reduced by silica, carbonate and various clay-mineral cements (Zimmerle, 1995).

### 3.5 Hydrocarbon plays

There are no established plays in the Jurassic successions of Belgium and Poland.

In the UK, Middle and Upper Jurassic shallow-marine, ooidal and bioclastic limestones and associated sandstones are the most important play concepts in the Wessex Basin. The Great Oolite Group limestone is the main proven hydrocarbon reservoir and is typically 45 to 60 m thick. Most proven Jurassic reservoirs fall in this category with Lias, Oxford Clay and Kimmeridge Clay formation organic-rich mudstones and 'oil-shales' forming the principal source rocks. The main seals are Oxfordian and Kimmeridgian mudstones and Lower Cretaceous evaporites.

The Upper Jurassic and Lower Cretaceous oil and gas plays of the Netherlands are restricted to Cimmerian rift basins such as the Dutch Central Graben and the Broad Fourteens, West and Central Netherlands, and Lower Saxony basins (De Jager & Geluk, 2007). The reservoirs occur in clastic syn-rift and early post-rift deposits, which show rapid facies variations ranging from continental to marine. There is also a great variation in trap styles. The plays are much richer in oil than other plays in the Netherlands, mainly because they are charged from the Lower Jurassic Posidonia Shale Formation, which has been preserved only within these extensional Late Jurassic to Early Cretaceous rift basins. Most of the gas is derived from the Westphalian and from Jurassic coal-bearing sequences and/or deeper Jurassic mudstones of the Aalburg Formation in the Dutch Central Graben. In the West Netherlands Basin, both gas and oil have been discovered in the sandstones of the Upper Jurassic syn-rift deposits of the Rijswijk, Pijnacker, De Lier, IJsselmonde, Wassenaar, Zoetermeer and Moerkapelle oilfields, but production is mainly from the Lower Cretaceous sandstones. Exploration in the late 1970s to early 1990s led to further discoveries, both offshore and onshore at Berkel, Barendrecht, Rotterdam, Pernis and Pernis West (Bodenhausen & Ott, 1981). Many of the older fields have been abandoned or closed-in over the last few years, and only Berkel, Rotterdam and Pernis West are currently producing oil. The best reservoirs are the post-rift Rijswijk, Berkel and IJsselmonde sandstones, which were deposited in coastal-barrier complexes overlying the Late Cimmerian Unconformity (De Jager et al., 1996). Other reservoirs are found in the sandstones of the younger De Lier and Holland Greensand Member (Albian) and the older syn-rift Delfland Subgroup. Many of the reservoirs have oil columns with a gas cap, with the younger reservoirs generally containing more gas (De Jager et al., 1996). The presence of gas is often a disadvantage as, not only does it reduce the potential oil volumes in traps, it is also found in insufficient quantities to justify gasfield development.

The Upper Jurassic oil and gas plays of the Broad Fourteens Basin are essentially the same as those of the West Netherlands Basin with the same source rocks and reservoir sandstones. All of the known trapped hydrocarbons are located along the north-eastern margin of the inverted basin in the Q1 quadrant (Helm, Hoorn, Helder, Haven and Halfweg fields; Roelofsen & De Boer, 1991). In the inverted areas of the Broad Fourteens Basin, as in the West Netherlands Basin, there is a timing problem with regard to hydrocarbon generation and trap formation. The Carboniferous source rocks in these areas became mature in the Late Jurassic or the Cretaceous prior to the main phase of trap formation, which is Late Cretaceous or even younger. Several oil discoveries have been made in Upper Jurassic and Lower Cretaceous sandstones in the Dutch Central Graben (Wong et al., 1989; Wong, 2007). The largest field is F03-FB (see Section 3.6.2), where several sandstones in the Upper Jurassic Central Graben Group contain light oil (about 55° API) and gas. The volume of oil initially in place in this field is about 100 million barrels (16 mln $m^3$). Other Jurassic oil accumulations have been found at F03-FA, F14-FA, F17-FA, F17-FB, F18-FA, L01-FB, L02-FA and L05-FA. Gas caps are present in F03B and F18-FA, whereas mainly gas is trapped in F03-FA. Most of these hydrocarbons have been generated from the Posidonia Shale Formation, with minor contributions from the Aalburg and Sleen formations and from coals in the Central Graben Subgroup.

The principal Jurassic hydrocarbon plays in Denmark are found in the Middle Jurassic successions of the Danish Central Graben. The reservoirs occur in the coal-bearing fluviodeltaic sandstones of the Bryne and Lulu formations (**Figure 10.9**). Two Jurassic fields are known at Harald West (West Lulu) and Lulita. Harald West is a tilted fault-block structure with a 100 m-thick sandstone reservoir; the Lulita field is a structural fault-bounded trap with a sandstone reservoir (Carr & Petersen, 2004).

## *3.6 Hydrocarbon field examples*

### *3.6.1 Palmers Wood oilfield, onshore UK*

The Palmers Wood oilfield in Surrey is located at the northern margin of the Weald Basin about 15 km south-west of London. It was discovered in 1983 by Conoco and tested for oil in a sandstone unit within the Upper Jurassic Corallian Group. Two appraisal wells were drilled in 1984 and a third in 1986. Operatorship of the field was transferred to Cairn Energy plc in 1989, who took it through to development, and subsequently to Cairn Energy Onshore Ltd in 1994. The field is currently owned and operated by Star Energy UK Onshore Ltd. Cumulative oil production from the field (to 2006) was 373 000 tonnes.

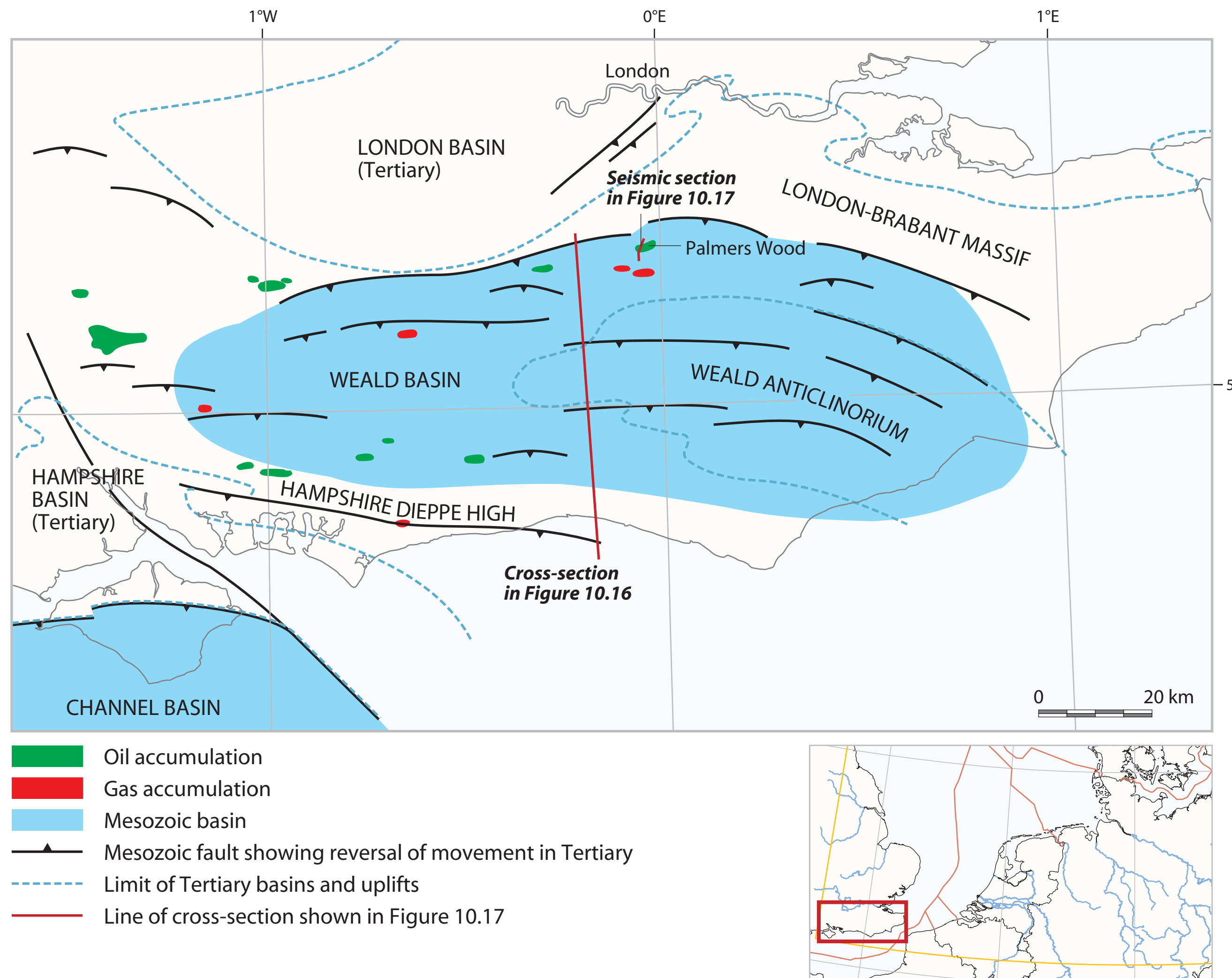



*Figure 10.15 Location of the Palmers Wood field.*

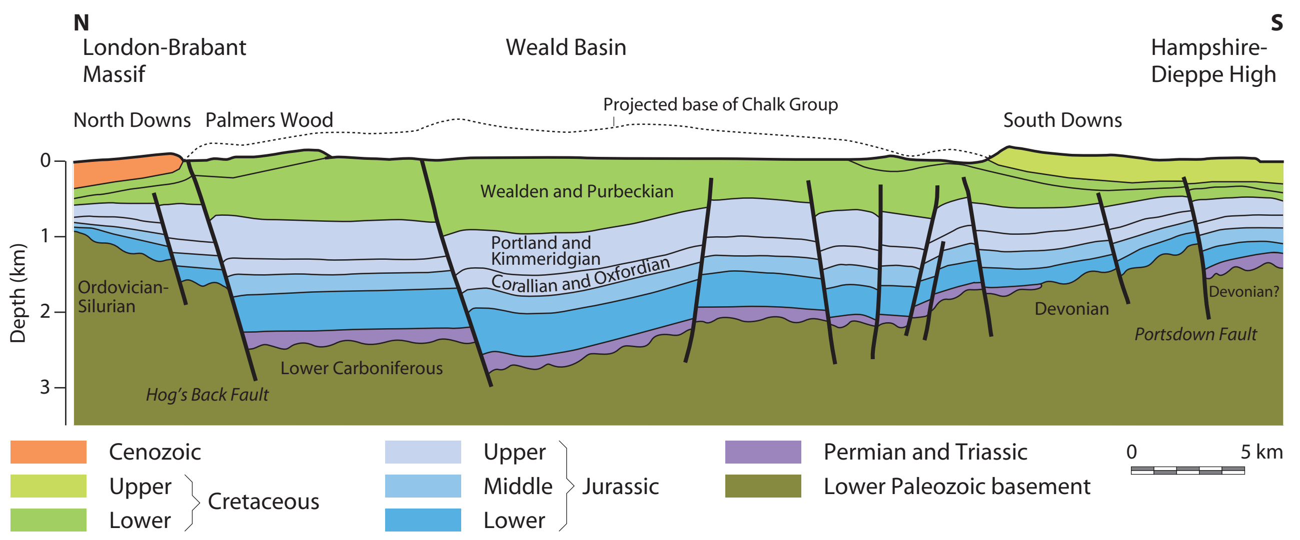



*Figure 10.16 Schematic cross-section through the Palmers Wood field. See Figure 10.15 for location.*

Prior to Tertiary uplift, the Weald Basin was an asymmetric, east–west-trending basin (**Figure 10.15**) that became a major depocentre early in the Jurassic. The northern margin of the basin is defined by a series of down-to-the-south normal faults in the Hog's Back area (**Figure 10.16**) becoming less well-defined in the south-east. The reservoir is sealed by a thick succession of Kimmeridge Clay Formation mudstones. The reservoir source rocks are probably of Early Jurassic (Lias Group) age (**Table 10.1**).

The Corallian succession is a sequence of interfingering bioturbated mudstones, shallow-marine ooidal and bioclastic limestones and detrital siliciclastic sandstones. The reservoir is an approximately 10 m-thick sandstone in the upper part of the Corallian Group (**Figure 10.17**), which comprises low-angled, cross-bedded, off-white, fine- to medium-grained, sporadically shelly, siliciclastic lithologies with traces of pyrite and glauconite. The sandstones are variably cemented by calcite and were deposited on a shallow-marine shelf as part of a mobile, offshore sand-wave belt. Sandstone porosities average 12.9% and the average permeability is 5 mD (Trueman, 2003).

*Table 10.1 Properties of the Palmers Wood field.*

| | |
|---|---|
| Reservoir | Corallian Group sandstone |
| Lithology | Sandstone |
| Depth to top (m) | 716 |
| GWC/GOC.OWC (m) | 844-854 |
| Maximum column height (m) | 55.8 |
| Net reservoir thickness (m) | 10 |
| Net to gross ratio | 16 |
| Porosity (%) | 12.9 |
| Permeability (mD) | 5 (0.05-1000) |
| Fluid type | Oil and gas |
| Initial pressure (bar) | 81.4 |
| Temperature (°C) | 100 |
| Source rock | Lias Group |
| Seal | Kimmeridge Clay Formation |

### *3.6.2 F03-FB gasfield, offshore Netherlands*

The F03-FB Upper Jurassic gas-condensate field is situated at the junction of the Dutch offshore blocks F02, F03, F05 and F06, approximately 210 km north of Den Helder (**Figure 10.18**). The field was discovered in 1974 by exploration well F03-3 and consists of three separate hydrocarbon accumulations with different free water levels (FWL's) in the Upper Jurassic Lower, Middle and Upper Graben formations. The Lower and Middle Graben reservoirs contain retrograde gas-condensate (significant amounts of condensate have dropped out of the gas phase in the reservoir as a result of pressure decline) and are classified as oil reservoirs (40-50° API). The Upper Graben reservoir has a lower condensate-gas ratio (CGR) and therefore is classified as a gas reservoir. Gas and condensate production started in 1993. The field was produced by a total of seven development wells, with current production from three wells. The production mechanism is mainly water drive with gas-depletion support in some blocks.

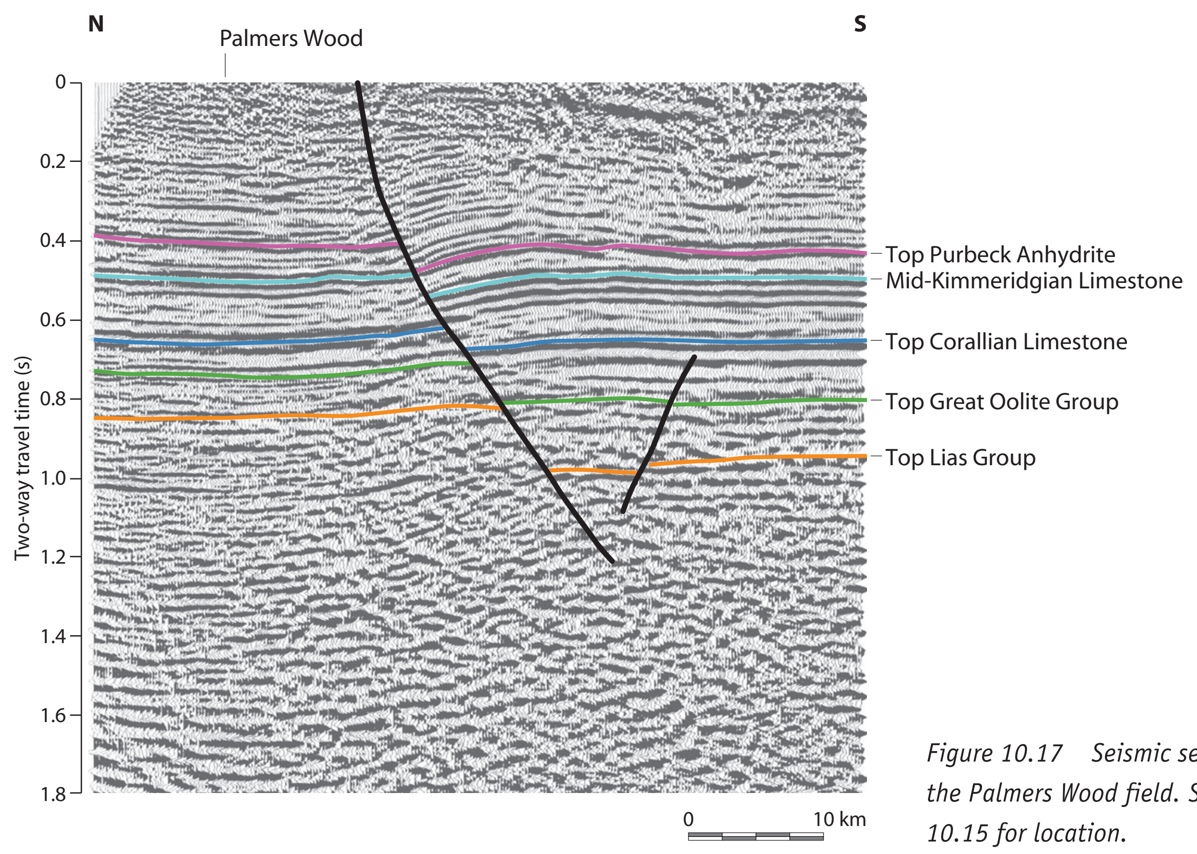



*Figure 10.17 Seismic section across the Palmers Wood field. See Figure 10.15 for location.*

The F03-FB field is located within the Central Graben, a Late Jurassic to Early Cretaceous rift structure, which forms the southern extension of the North Sea Jurassic rift system. The F03-FB structure is a north-west–south-east-trending faulted turtle-back anticline formed by Zechstein salt diapirism during the Late Cretaceous inversion (**Figure 10.19**). Two main fault trends cross-cut the field (west-north-west and north–south trending) with throws varying between 10 and 100 m. Many of the faults are open to flow as shown by production behaviour and acquired 4D-seismic data. The condensate-rich gas is sourced mainly from the Jurassic Posidonia shale (Toarcian age), which is mature for gas in large parts of the Central Graben area (**Table 10.2**). The gas seal is formed by intraformational shales.

The Lower to Upper Graben formation sandstones are of Callovian to Oxfordian age and belong to the Central Graben Subgroup, which in turn is part of the Schieland Group. The sediments were deposited in an estuarine environment. The east–west progradational tidal-flat sequences resulted in a complex facies distribution comprising a highly heterogeneous combination of sands, shales and coals that can not be generally correlated (**Figure 10.20**). The best reservoirs are tidal-channel and shoreface sands.

The Lower Graben Formation comprises alternating sandstones and shales of up to 550 m thick, with individual sandstone bodies between 10 and 20 m thick (**Figure 10.21**) The Middle Graben Formation consists of three stacked sand bodies with thicknesses up to 15 m, 11 m and 4 m respectively. The sand bodies are separated by shales and they pinch-out to the south-east. The Upper Graben Formation is up to 130 m thick and is a sequence of alternating sandstones and shales; individual sandstone bodies are up to 20 m thick. The Lower Graben reservoir is by far the most important accumulation as it contains 72% of all hydrocarbons.

*Table 10.2 Properties of the F03-FB field.*

| Reservoir | Lower Graben Formation | Middle Graben Formation | Upper Graben Formation |
|---|---|---|---|
| Lithology | Sandstone | Sandstone | Sandstone |
| Depth to top (m) | 3000 | 2850 | 2475 |
| GWC/GOC.OWC (m) | 3220 | 2935 | 2540 |
| Maximum column height (m) | 65 | | |
| Net reservoir thickness (m) | 110 | | 67 |
| Net to gross ratio | | | 0.6-0.8 |
| Porosity (%) | 12 | 21 | 21 |
| Permeability (mD) | 0.02-300 | 100-2000 | 0.02-2600 |
| Fluid type | Oil and gas | Oil and gas | Oil and gas |
| Gas composition | C1 69.5-75.4%, C2 8.7-8.8%, C3 5.4-11.5%, $N_2$ 0.5-0.6%, $N_2$ 0.5-0.6%, $CO_2$ 3.3-3.9% | | C1 79.9%, C2 6.8%, C3 4.6%, C4+ 6.7%, $N_2$ 1.2%, $CO_2$ 0.7% |
| Initial pressure (bar) | 41 | | |
| Temperature (°C) | 127 | | |
| Source rock | Posidonia Shale | Posidonia Shale | Posidonia Shale |
| Seal | Kimmeridge Clay Formation | Kimmeridge Clay Formation | Kimmeridge Clay Formation |

### *3.6.3 F15-B gasfield, offshore Netherlands*

The F15-B field is located in the F15 block approximately 140 km north of Den Helder (**Figure 10.22**). In 1986, the Triassic Volpriehausen sandstone was proven to be gas-bearing by discovery well F15-4. One of the appraisal wells of this Triassic F15-A field indicated a potential gas-bearing reservoir in the Jurassic Scruff Group sands. This was finally confirmed by the F15-9 exploration well, drilled in 1998. The F15-B field started production in the same year. The field is operated by Total (38.2%) with EBN (50%), Dyas (8.82%) and Lundin (2.98%) as partners.

The F15 block lies between the eastern limit of the Dutch Central Graben and the north-western limit of the Terschelling Basin on the south-eastern edge of the Schill Grund High (**Figure 10.22**). During Late Jurassic times, the area differentiated into rapidly subsiding basins, such as the Dutch Central Graben, and stable platforms such as the Schill Grund High. Thick packages of Upper Jurassic sediments were deposited in the deep basins whereas outside the basins they are rare, although where found they occur in thin sequences in rim-synclinal structures (**Figure 10.23**). The F15-B field is part of such a structure. It forms the eastern flank of a south-west–north-east-trending rim-syncline, which is indicated by the fan-shaped geometry of the Upper Jurassic succession. The structure is controlled by a south-south-west-trending salt diapir, and its top is cut by faults with relatively small displacements trending N 130 and N 160. Salt-swelling, and ultimately salt-piercing during Late Jurassic tectonic movements, led to thickness variations in the Upper Jurassic series with sequences pinching out to the east. The overlying Clay Deep Member forms an efficient seal for the Scruff reservoir. The source rocks are inferred to be the Carboniferous Coal Measures (**Table 10.3**).

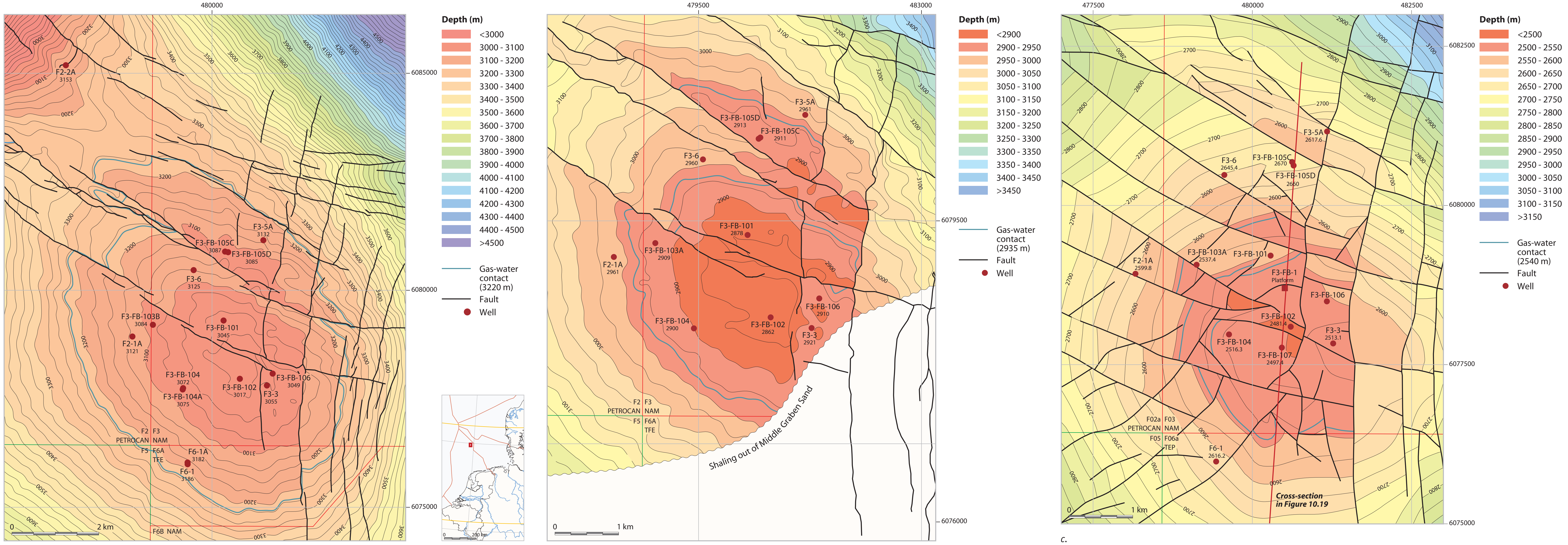



Figure 10.18 The F03-FB gas-condensate field showing depth contours to: a. the top of the Lower Graben Formation; b. the top of the Middle Graben Formation; and c. the top of the Upper Graben Formation.

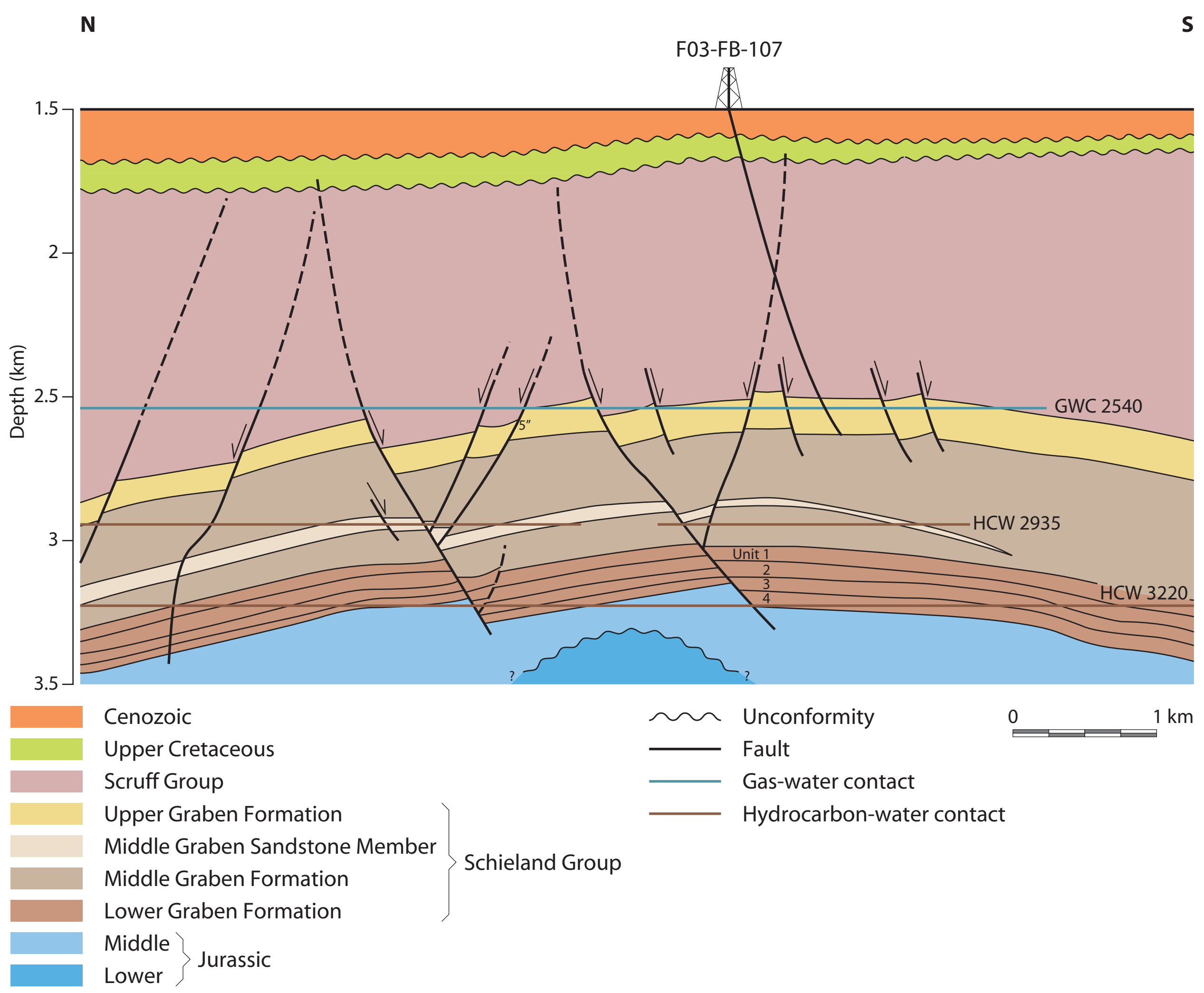



Figure 10.19 Schematic section through the F03-FB gas-condensate field. See Figure 10.18c for location.

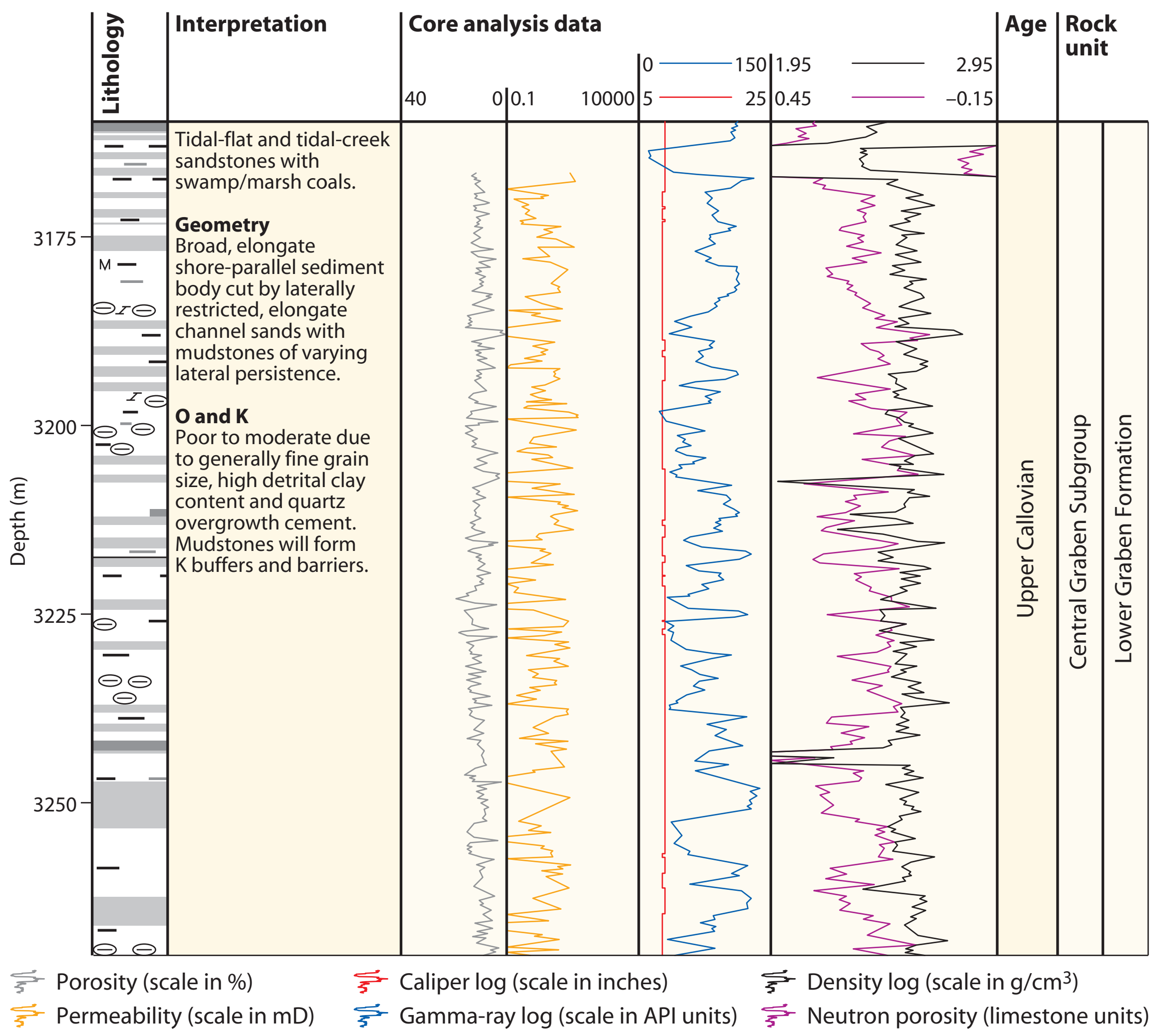



Figure 10.20 Well log and lithostratigraphy from representative well section F03-05-S1 in the F03-FB field.

Figure 10.21 Core photograph of sediments from the Lower Graben Formation.

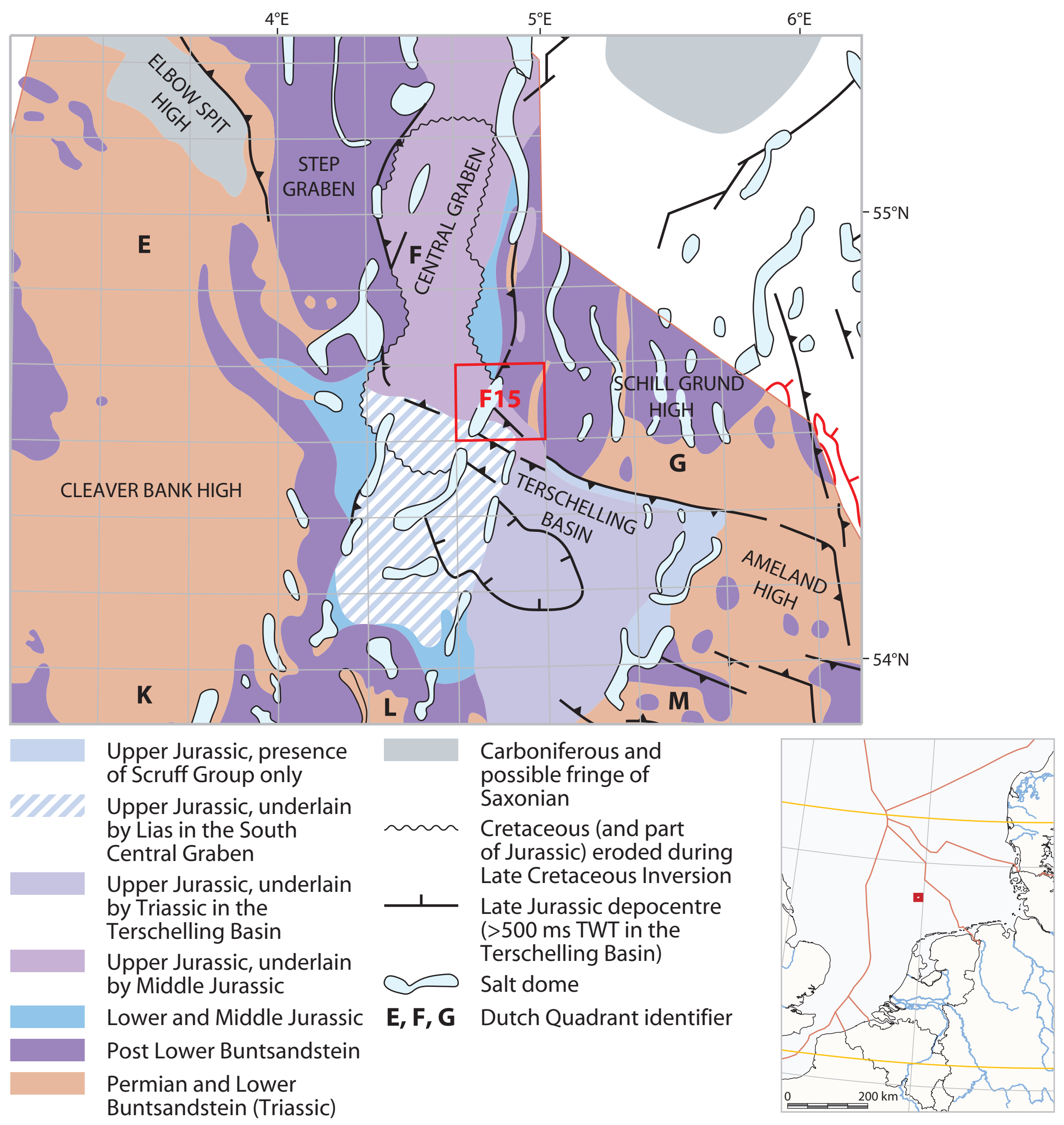



Figure 10.22 Structural elements of the F15-B gas-condensate field area.

The Scruff Group sandstones correspond to siliciclastic platform sediments deposited in a storm-controlled ramp to shelf setting. The sandstones are fine-grained and strongly bioturbated with glauconite and sponge spicules (**Figure 10.24**). Sponge colonies developed in the shallow water overlying the salt diapir and were later eroded to become a reworked product of the upper offshore transition zone. The basal part of the Scruff reservoir is more sandy and displays reservoir characteristics that are slightly poorer than the spiculite member that forms the main part of the reservoir. Porosity is linked mainly to the solution of the sponge spicules and therefore is better in the spiculite member. Despite the good porosities, permeabilities are highly variable, ranging between 0.04 and 23 mD.

*Table 10.3 Properties of the F15-B field.*

| | |
|---|---|
| Reservoir | Scruff greensand |
| Lithology | Glauconitic sandstone and argillaceous sandstone |
| GWC/GOC.OWC (m) | 3665 |
| Net reservoir thickness (m) | 88 |
| Net to gross ratio | 74.7 |
| Porosity (%) | 20.2 |
| Permeability (mD) | 0.04-23 |
| Fluid type | Gas |
| Gas composition | C1 86.23, C2 3.8%, $N_2$ 8.67%, $CO_2$ 0.95% |
| Source rock | Westphalian Coal Measures |
| Seal | Clay Deep Member |

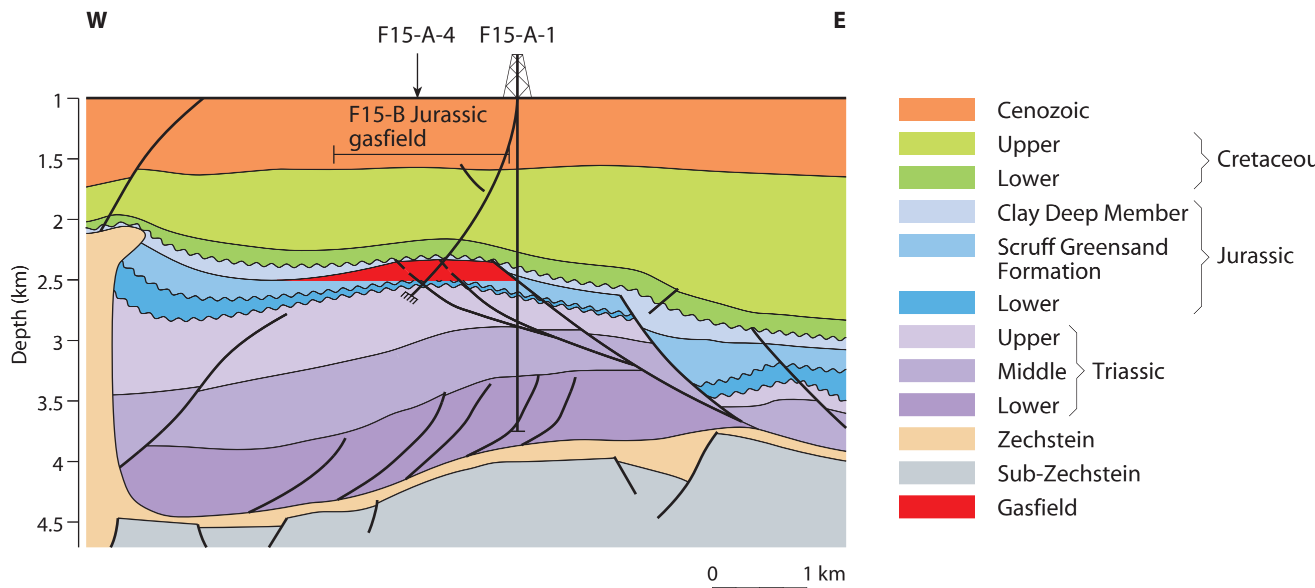



*Figure 10.23 Schematic section through the F15-B gas-condensate field.*

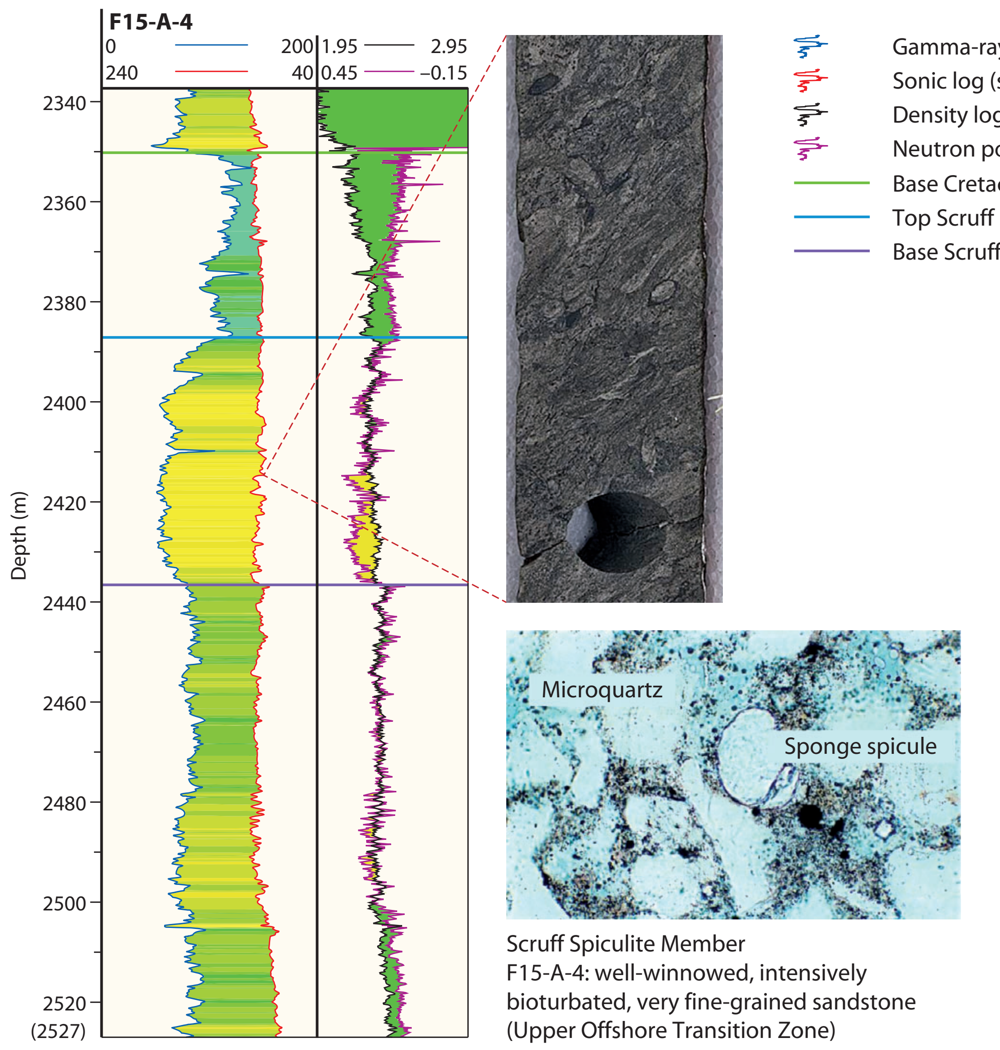



*Figure 10.24 Well log and core photograph from well F15-A-4 in the F15-B field.*

## 3.6.4 *Mittelplate oilfield, onshore Germany*

The Mittelplate field is located in the Jurassic West Holstein Trough in the German Wadden Sea (**Figure 10.25**) about 100 km north-west of Hamburg. It was discovered in 1980 by the Deutsche Texaco well Mittelplate 1, which penetrated oil-saturated Middle Jurassic sandstones. Two appraisal wells were drilled in 1981 and confirmed a large oil accumulation approximately 7 km wide (east–west) and 15 km long (north–south). Two separate hydrocarbon columns were found, one in the Middle Jurassic (Dogger) 'beta' sandstones and the other in the Middle Jurassic (Dogger) 'gamma', 'delta', and 'epsilon' sandstones. Production began in 1987 from the Dogger 'beta' and 'delta', in 1992 from the Dogger 'epsilon', and in 1997 from the Dogger gamma. The field is owned by RWE DEA AG (50%) and Wintershall AG (50%), with RWE DEA AG as the operator.

The Mittelplate oilfield is related to the structural evolution of the western part of the Büsum salt dome in the middle of the south-west–north-east-trending West Holstein Trough, the most northerly Jurassic trough of the North German Basin (**Figures 10.25** & **10.26**). The steeply inclined or overturned Dogger beds on the flank of the Büsum salt dome indicate that the diapiric salt movements post-date deposition of the Dogger sediments. The distribution of the Dogger sandstones within the West Holstein Trough also suggests that there was no breakthrough of the Büsum diapir during the time when they were deposited. Back-stripping and balanced 2D-modelling indicate that the Büsum salt dome was active from Early Jurassic times and that deposition of the reservoir sequences, structuring and trap formation in the Mittelplate oilfield took place during the upwelling of the salt dome. The reservoirs are sealed by Lower Cretaceous marls and the source rock consists of Upper Liassic bituminous Posidonia Shale.

Sequence-stratigraphic and eustatic events that took place during the Jurassic are shown in **Figure 10.27** together with a type-log from the vertical exploration well Mittelplate 1. Core descriptions from several wells are projected to the type-log, showing detailed lithological profiles of the different sedimentological environments of the deltaic and fluvial systems. The depth range of the oil-bearing section is from 1900 m to 3000 m TVD. The oldest reservoir, the Dogger 'beta' reservoir sandstone, despite being relatively thin with a maximum of 17 m true stratigraphic thickness, is the most important reservoir zone due to its widespread productive area, with oil down to 2975 m TVD below sea level. The thickest reservoir units, with more than 50 m true stratigraphic thickness, are found within the Dogger 'delta' sandstones.

*Table 10.4 Properties of the Mittelplate field.*

| Reservoir | Middle Jurassic Dogger 'beta' (prodelta) | Middle Jurassic Dogger 'gamma' (fluvial Delta) | Middle Jurassic Dogger 'delta' (prodelta - fluvial channel) | Middle Jurassic Dogger 'epsilon' (estuary delta) |
|---|---|---|---|---|
| Lithology | Sandstone | Sandstone | Sandstone | Sandstone |
| Depth to top (m) | 2400 | 1900 | 1900 | 1900 |
| Net reservoir thickness (m) | 6-17 | 30-50 | 40-60 | 20-30 |
| Porosity (%) | 15-24 | 22-25 | 17-27 | 22-25 |
| Permeability (mD) | 200-3000 | 60-5000 | 2000-10 000 | 2000-10 000 |
| Fluid type | Oil | | | |
| Source rock | Posidonia Shale | Posidonia Shale | Posidonia Shale | Posidonia Shale |
| Seal | Lower Cretaceous marl and limestone | Lower Cretaceous marl and limestone | Lower Cretaceous marl and limestone | Lower Cretaceous marl and limestone |

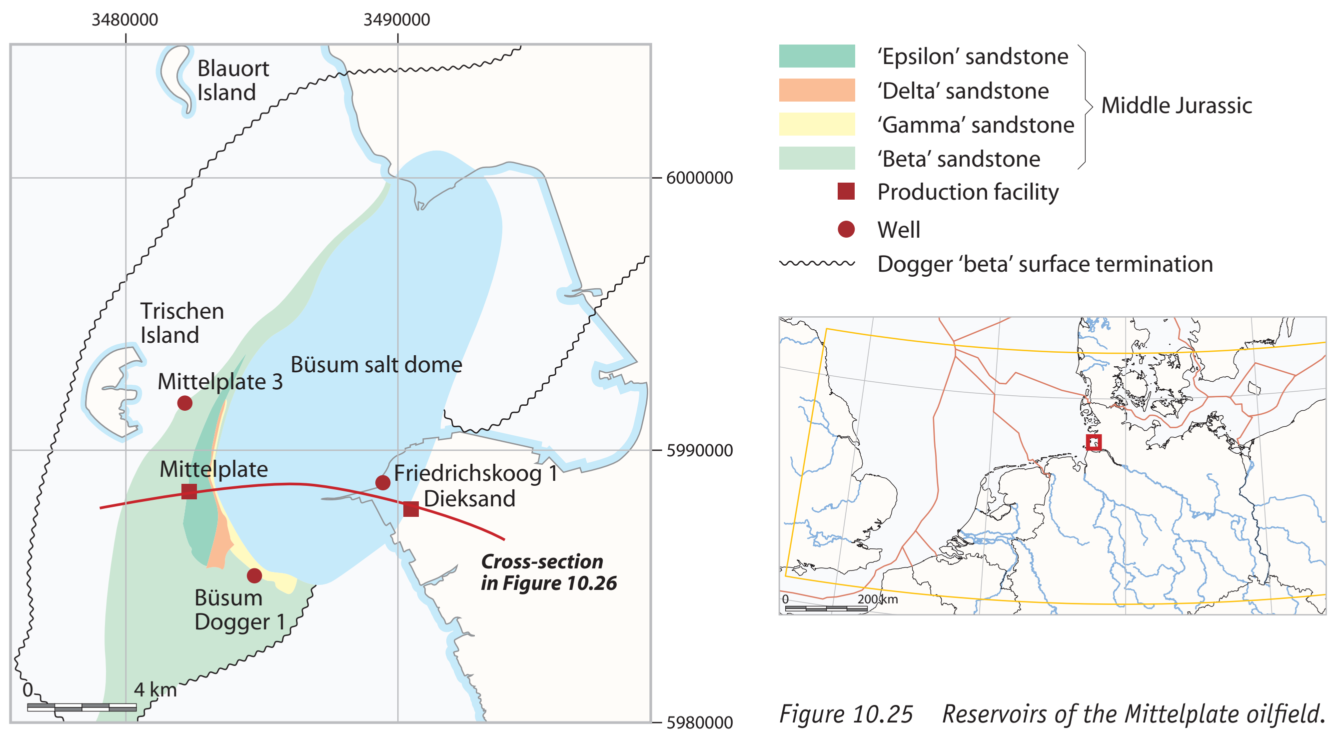



*Figure 10.25 Reservoirs of the Mittelplate oilfield.*

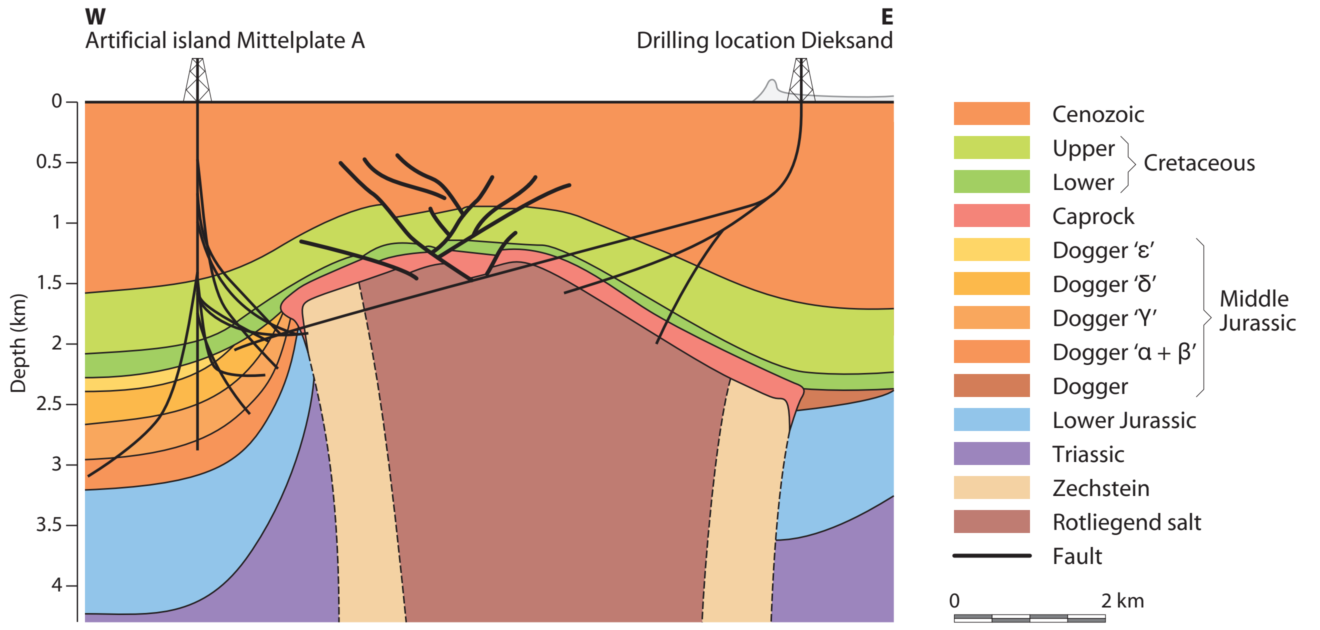



*Figure 10.26 Schematic section across the Mittelplate oilfield. See Figure 10.25 for location.*

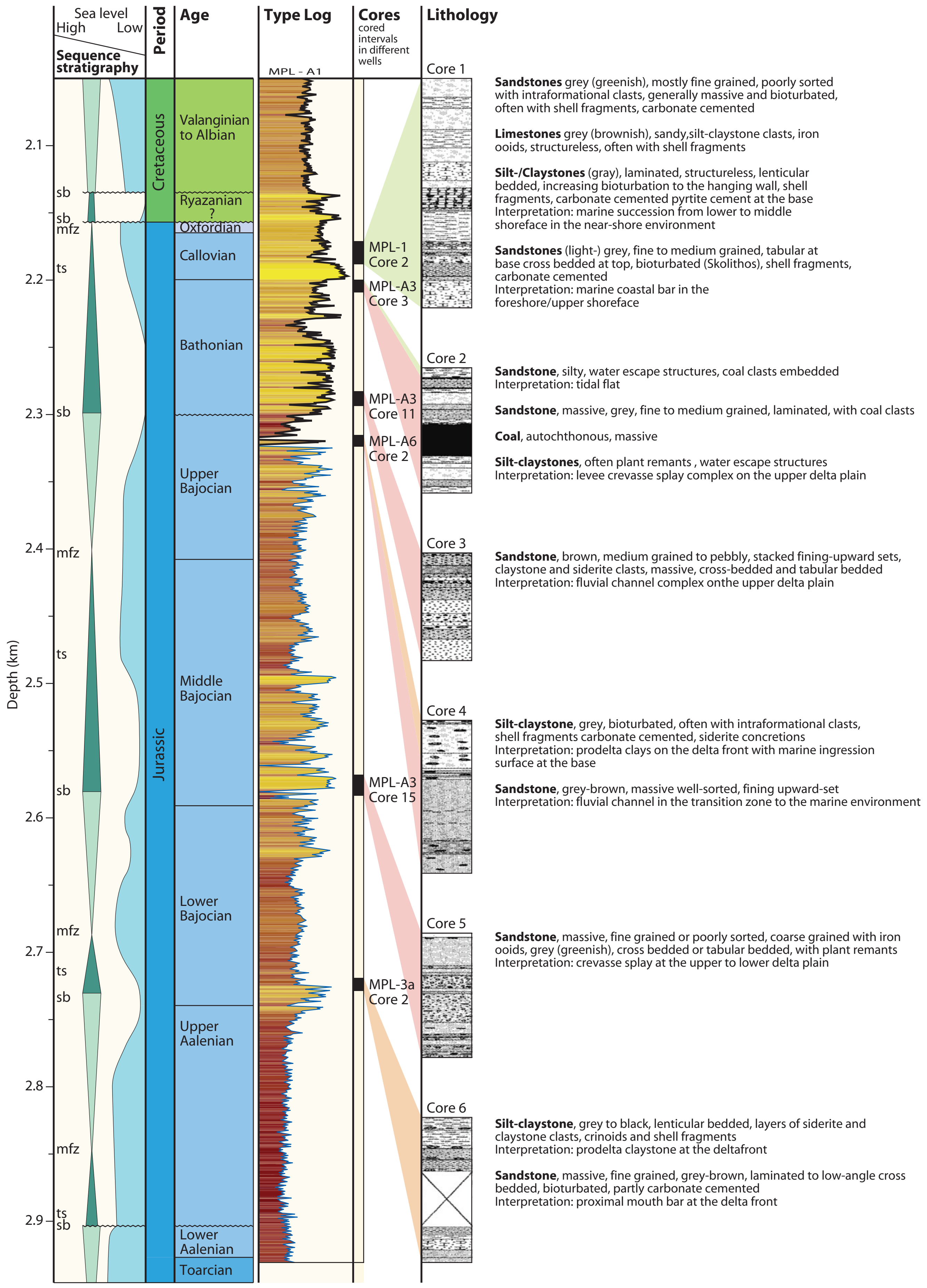



*Figure 10.27 Sequence stratigraphic and eustatic events in the Mittelplate oilfield succession.*