Sediments of the earliest Eocene Fur Formation in the Skarrehage diatomite ('moler') quarry (Mors Island, NW Jutland, Denmark). The Fur Formation includes nearly 180 mainly black, basaltic volcanic ash layers which are recognised throughout the North Sea Basin and beyond. In Denmark, the ash layers have been divided into two numbered series, a lower negative series and an upper positive series. The photograph shows the upper part of the negative series and the entire positive series. The strong folding displayed by the Fur Formation in this quarry and throughout the area was caused by Quaternary glacial tectonics. The diatomite was formerly burnt for the production of insulating bricks. The reddish material seen in the road in the foreground is waste material from the burning process. Today the diatomite is quarried mainly for cat litter. For further reading see Pedersen (2008). Photo by Claus Heilmann-Clausen (1992).

Chapter 12 Cenozoic

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1 Introduction

Until the late Quaternary[1], the Cenozoic strata of the SPBA area were deposited within a single depositional area referred to as the Tertiary North-west European Basin (Vinken, 1988). Neotectonic restructuring in the Late Quaternary led to the present-day configuration (**Figure 12.1**) in which the North Sea Basin is separated from a shallow basin to the south-east, known as the East German – Polish Basin (see Figure 1.3).

The Cenozoic fill of the North Sea Basin has been the subject of especially intense investigation during the last 40 years due to the discovery of major oil and gas reserves in the Paleocene and Eocene rocks of the central and northern North Sea. There are no significant hydrocarbon reserves in the Cenozoic of the SPBA area, but the changing patterns of Cenozoic subsidence and sedimentation have exerted an important control on the generation of hydrocarbons in older parts of the stratigraphic column (e.g. Rasmussen et al., 2005).

A detailed account of the Tertiary succession in the SPBA area has been given in Vinken (1988), which presents a series of structural, thickness and facies maps, together with a wealth of local lithostratigraphic and biostratigraphic details. It also provides a comprehensive record of the older published literature. Since then, palaeogeographical maps of the SPBA area have been published by Ziegler (1990a), Ziegler & Horváth (1996), Clemmensen & Thomsen (2005), Heilmann-Clausen (2006) and Rasmussen et al. (2008). The 'Peri-Tethys' Atlas (Dercourt et al., 2000) also includes the SPBA area.

The last two decades have also seen the publication of Cenozoic maps for certain parts of the SPBA area. These include the works of Cameron et al. (1992), Knox & Holloway (1992), Murray (1992), Lott & Knox (1994), Knox (1996) and King (2006) for the UK; De Batist & Henriet (1995) and Jacobs & De Batist (1996) for Belgium, Van Adrichem Boogaert & Kouwe (1993), De Lugt et al. (2003) and Wong et al. (2007b) for the Netherlands; Berger et al. (2005) and Sissingh (2006) for the Upper Rhine Graben; Michelsen & Danielsen (1996), Danielsen et al. (1997) Gregersen et al. (1998), Michelsen et al. (1995, 1998), Clausen et al. (1999), Huuse (2002), Nielsen et al. (2002), Rasmussen et al. (2004a) and Japsen et al. (2007) for the central and eastern North Sea areas; Michelsen & Nielsen (1993), Danielsen et al. (1997), Clausen & Huuse (2002), Rasmussen (2005, 2006), Heilmann-Clausen (2006) and Schiøler et al. (2007) for Denmark; Lange et al. (1990), Baldschuhn et al. (1991), Stackebrandt & Manhenke (2002), Brückner-Röhling et al. (2005), Rascher et al. (2005), Standke (2006, 2008a) and Blumenstengel & Krutzsch (2008) for Germany; Kasiński (1985, 2000a, 2000b, 2004, 2005), Piwocki et al. (1985), Ciuk & Piwocki (1990), Piwocki (1992, 1998a, 1998b, 2004), Kramarska (1995, 1999, 2000, 2004, 2006), Piwocki & Kasiński (1995), Badura & Przybylski (2004) and Badura et al. (2006) for Poland. Details of a set of 1 : 50 000 Tertiary maps of the Flanders region of Belgium may be found on the website dov.vlaanderen.be. Maps of the adjacent northern North Sea area were published in Isaksen & Tonstad (1989), Gatliff et al. (1994), Jordt et al. (1995), Gregersen et al. (1998), Jordt et al. (2000) and in the 'Millennium Atlas' (Ahmadi et al., 2003 for the Paleocene; Jones et al., 2003 for the Eocene; Fyfe et al., 2003 for the post-Eocene). Maps of the Neogene of central and eastern Europe are provided by Hámor (1988).

Significant publications that specifically focus on Quaternary maps include the report of IGCP Project 346 (Stackebrandt et al., 1981; Garetsky et al., 2001), which describes eastern parts of the SPBA area; Stoker et al. (1985a, 1985b), Cameron et al. (1987) and Graham & Straw (1992) for the UK; Binzer & Stockmarr (1994) for Denmark; Eißmann & Litt (1994) and Streif (1996) for Germany and Mojski (2005) for Poland.

Following the widespread uplift, inversion and erosion that accompanied the termination of chalk sedimentation during Mid-Paleocene times, the deeper parts of the Tertiary North-west European Basin experienced more or less continuous subsidence, with the accumulation of more than 3000 m-thick sediments in the central North Sea (**Figure 12.1**). Sedimentation extended far beyond the present-day limits, which are largely a reflection of Neogene uplift of the basin margins and intensive Quaternary erosion. The principal phases of regional uplift, accompanied by inversion of Mesozoic basins, took place in the late Early to early Mid-Paleocene (Laramide Phase of Ziegler, 1990a), in the latest Eocene (Pyrenean Phase) and in the latest Oligocene to Mid-Miocene (Savian Phase) (**Figure 12.2**). These phases of regional uplift are generally attributed to successive Alpine-Carpathian compressional events associated with the convergence of Africa and Europe (e.g. Ziegler et al., 1995). However, some authors (e.g. Nielsen et al., 2005) have proposed that the associated Mid-Paleocene inversion tectonics took place under a regime of stress relaxation.

The influence of salt movement on Cenozoic thicknesses is also evident from **Figure 12.1**, especially in northern Germany where sediments more than 3500 m-thick were deposited in some rim-synclines (e.g. Scheck et al., 2003a). Much of the halokinesis in the east of the region and around the Sole Pit inversion took place during the Savian tectonic phase in latest Oligocene to Early Miocene times (Chapter 3).

Another important factor in the evolution of the basinal fill of the SPBA area was the progressive deterioration in climate that began in the Mid-Eocene, reflecting expansion of the Antarctic ice-sheet (Berggren & Prothero, 1992). This change in climate contributed to an overall but irregular increase in sedimentation rate. Warmer phases, which were superimposed on this long-term trend, are reflected in major eustatically controlled transgressions in the Early Oligocene and Mid-Miocene.

The principal structural elements that influenced the palaeogeography and facies distribution within and around the SPBA area are shown in **Figures 12.3a** & **b**. The term 'swell' is used to identify long-lived basement highs that were temporarily emergent and over which successions are attenuated and incomplete.

A key question in the reconstruction of Mid-Paleocene to Eocene palaeogeography is the extent to which the platform areas to the north-east and east of the North Sea Basin acquired a sedimentary cover. Previous regional reconstructions have shown the Baltic Platform as largely nondepositional (e.g.Vinken, 1988; Ziegler, 1990a; Ziegler & Horváth, 1996). However, it is likely that sea-level rises in the Eocene and perhaps also in the Late Paleocene led to marine inundation of much of the Fennoscandian Platform (Jordt et al., 1995), whereas the Caledonide belt marking the western edge of the Baltic Platform is believed to have remained emergent from the Mid-Paleocene onwards. This interpretation is based on evidence of a former marine Eocene sediment cover in northern Sweden (Cleve-Euler, 1941) and northern Finland (Hirvas & Tynni, 1976; Fenner, 1988) and on the occurrence of deep-marine Paleocene and Eocene sediments in Denmark at the present limit of deposits close to the Sorgenfrei-Tornquist Zone (Heilmann-Clausen et al., 1985; see also Rasmussen et al., 2008). Further evidence for the Eocene sediment cover on the southern Fennoscandian Platform is provided by reworked Eocene dinocysts and mudstone clasts in north-easterly derived Miocene sediments in Denmark (Dybkjær, 2004; Rasmussen, 2004a). Large areas of the Fennoscandian Platform are therefore thought to have been covered by the sea at times of high relative sea level in the Eocene and possibly in the Late Paleocene. The platform may have formed a low-lying land area at times of low relative sea level, particularly during the Mid-Paleocene and around the time of the Paleocene-Eocene transition.

Evidence for an early advance of the sea into the southern Baltic region and the North Polish Platform is provided by remnants of Middle Paleocene marine sediments in southern Sweden (Brotzen, 1948; Gustaffson & Norling, 1973) and north-west Poland (Słodkowska, 2004). However, subsequent uplift of the North Polish Platform is indicated by the widespread nonmarine Upper Paleocene sediments in northern Poland. Apart from a brief incursion in the late Early Eocene, the platform appears to have remained emergent until the late Mid-Eocene. Little is known of the palaeogeographical evolution of the eastern Baltic region during the Paleocene and Early Eocene, but evidence for sediment supply from the north in the Eocene of north-eastern Poland (Kosmowska-Ceranowicz, 1988; Kramarska et al., 2004; Kramarska, 2006) indicates that land existed in the areas of present-day Estonia and Latvia. It therefore seems likely that the Late Paleocene uplift of the North Polish Platform was related to uplift of the Baltic Platform. The Paleocene to Eocene tectonic evolution of the Polish and Baltic platforms, which form the south-western end of the East European (or Russian) Platform (e.g. Artemieva, 2007), was therefore distinct from that of the Fennoscandian Platform, which together with the Scandinavian Caledonides forms part of the Baltic Shield.

The North Polish Platform was bounded to the south-east by the Mid-Polish High, which developed as a result of Early to mid-Paleocene (Laramide) inversion of the Mid-Polish Trough (Ziegler, 1990a). This formed a conspicuous palaeogeographical feature for much of the Paleocene, but was progressively eroded during Early to Mid-Eocene times and largely inundated during the Late Eocene such that the platform no longer formed a significant topographic feature by the Early Oligocene. Long-term subsidence of the North Polish Platform began in the late Mid-Eocene and continued into the Mid-Pleistocene, when a regional change in stress pattern caused uplift along the southern basin margin.

The Fennoscandian Platform underwent combined progressive uplift and southward tilting from the Oligocene onwards, resulting in the establishment of a pronounced north to south palaeoslope in the present-day Baltic region. This fundamental change in tectonic configuration appears to have been associated with a reorganisation of sea-floor spreading axes in the Norwegian-Greenland Sea, together with developments in the convergence of Africa and Europe that led to the destruction of part of the Tethys Ocean and the formation of the Paratethys Ocean. Climatic deterioration from the Mid-Miocene onwards has resulted in a progressive increase in the volume of sediment supply to the south-eastern part of the North Sea Basin.

Regional uplift of the Fennoscandian Platform was accompanied by differential uplift of individual structural elements. The onset of southward deltaic progradation into the eastern North Sea Basin during the Early Oligocene therefore reflects the relative uplift of southernmost Norway (Michelsen et al., 1995, 1998; Riis, 1996). The alternative interpretation that these changes were solely due to climatic deterioration (e.g. Huuse, 2002) is not followed here, as explained below. Japsen et al. (2002, 2007) proposed that relative uplift of the South Swedish Dome took place in the Late Oligocene to Early Miocene and in the Early Pliocene. As discussed below, evidence of sediment supply from southern Sweden in the earliest Oligocene indicates that the onset of uplift took place earlier in association with the Pyrenean tectonic phase.

On the eastern margin of the present-day North Sea Basin, the Ringkøbing-Fyn High was an area of substantial uplift and erosion during the Laramide, Pyrenean and Savian tectonic phases (**Figure 12.3**). However, the high has not had a significant effect on the subsidence pattern since Mid-Miocene times. The Sorgenfrei-Tornquist Zone underwent major inversion during mid-Paleocene times (Nielsen et al., 2005) and further uplift in the earliest Miocene (Rasmussen, 2009). There is no evidence that these structures had a significant influence on the palaeogeography or facies distribution in the intervening quiescent phases of the Late Paleocene and Eocene. Following the period of Pyrenean uplift and inversion in the latest Eocene, the structures became incorporated into an area of intermittent and relatively shallow-marine sedimentation, here referred to as the Danish Shelf. Prior to this, bathyal water depths had existed along the axis of the Norwegian-Danish Basin. To the west in the Danish central North Sea, inversion of the Mesozoic Central Graben took place in the earliest Miocene (Rasmussen, 2009).

The SPB was bordered to the south by a complex series of structural highs located in present-day Germany, here collectively referred to as the Mittelgebirge Highs (**Figure 12.3**). A conspicuous feature of the southern coastline was the narrow peninsula formed by the Flechting Swell, which remained more or less emergent (though low-lying) until Late Eocene times (Lotsch, 1969). The Harz Swell is here shown as separating the paralic to nonmarine successions of the Hessian and Helmstedt-Halle embayments although it is possible that the uplift of the Harz Massif occurred later and that sedimentation was originally continuous between the two areas (König & Blumenstengel, 2005a). Subsidence of the Lower Rhine Graben led to the development of a long-lasting embayment in the western margin of the Rhenish Massif (Hiss et al., 2005). The Upper Rhine Graben was initiated during the Lutetian (Berger et al., 2005). Inversion of Mesozoic basins in the central Netherlands led to the development of a complex structure referred to as the 'Early Tertiary High'. The inversion involved parts of the Broad Fourteens, West Netherlands and Central Netherlands Mesozoic basins. Although inversion was most pronounced in the latest Eocene (Pyrenean tectonic phase) (De Lugt et al., 2003; De Jager, 2007), Worum & Michon (2005) argue that this was the culmination of an inversion process that began in the Early Eocene.

The tectonic and palaeogeographical evolution of the south-western margin of the basin has been discussed in detail by King (2006). Sediments of the present-day London, Hampshire and Dieppe basins were laid down in a single depositional area during most of the Paleocene and Eocene. Connection between the

1 In June 2009, the Executive Committee of the International Union of Geological Sciences (IUGS) formally ratified a proposal by the International Commission on Stratigraphy to equate the base of the Quaternary and the Pleistocene to coincide with the base of the Gelasian Stage (2.588 Ma), which was previously included in the Pliocene (Gibbard et al., 2009). The base of the Quaternary as thus defined is very close to that of a widely recognised North Sea seismic marker and to the base of the Quaternary as traditionally applied onshore in north-west Europe. Retention of the term 'Tertiary' has also been proposed (Head et al., 2008), but an official decision has yet to be taken. For this reason, the use of the term Tertiary in this atlas should be regarded as informal.

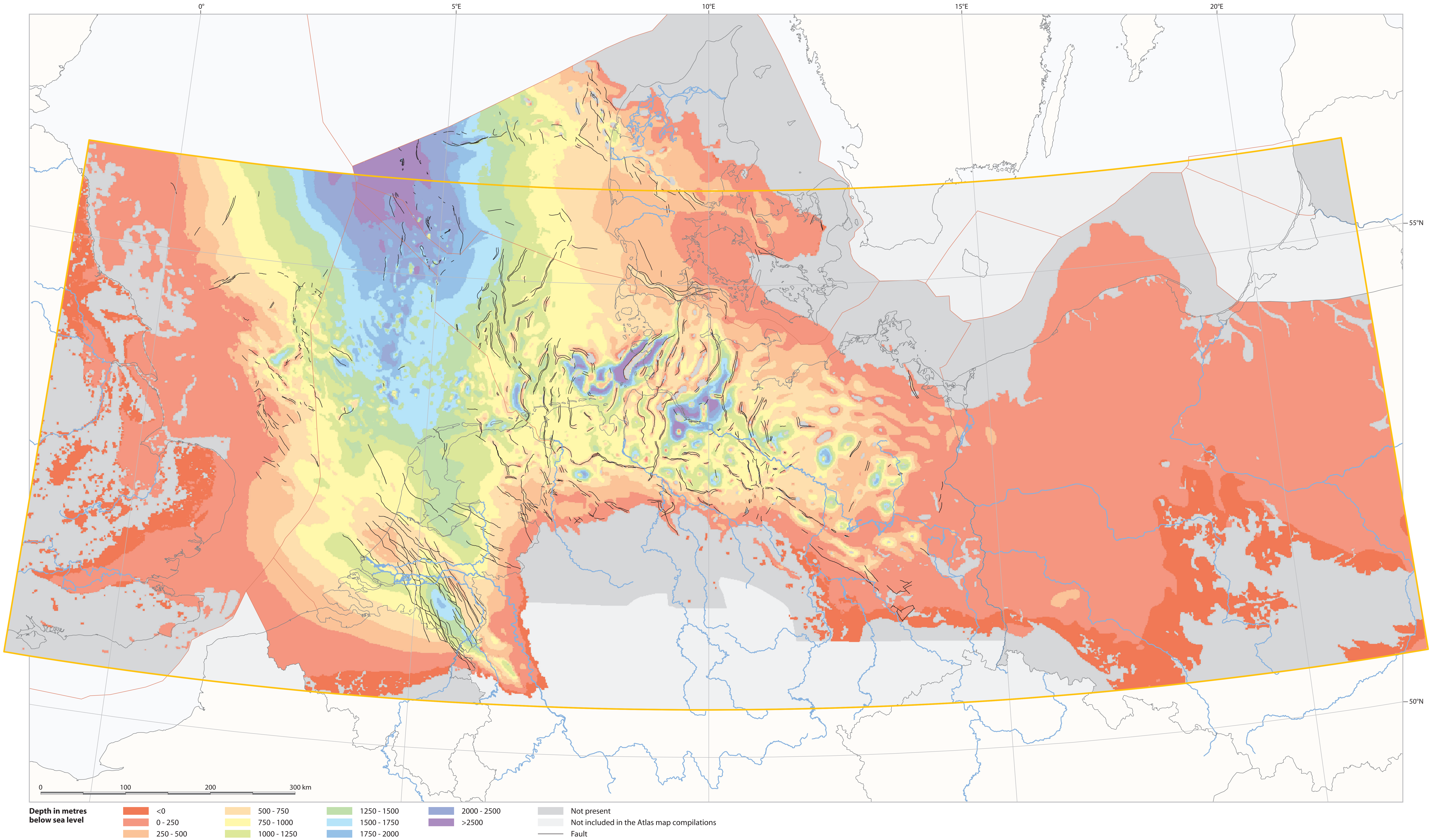


Figure 12.1 Depth to near base of the Tertiary (top of the Chalk Group, top Danian). This lithostratigraphic horizon is shown as Horizon 1 on Figures 1.5 and 12.5.

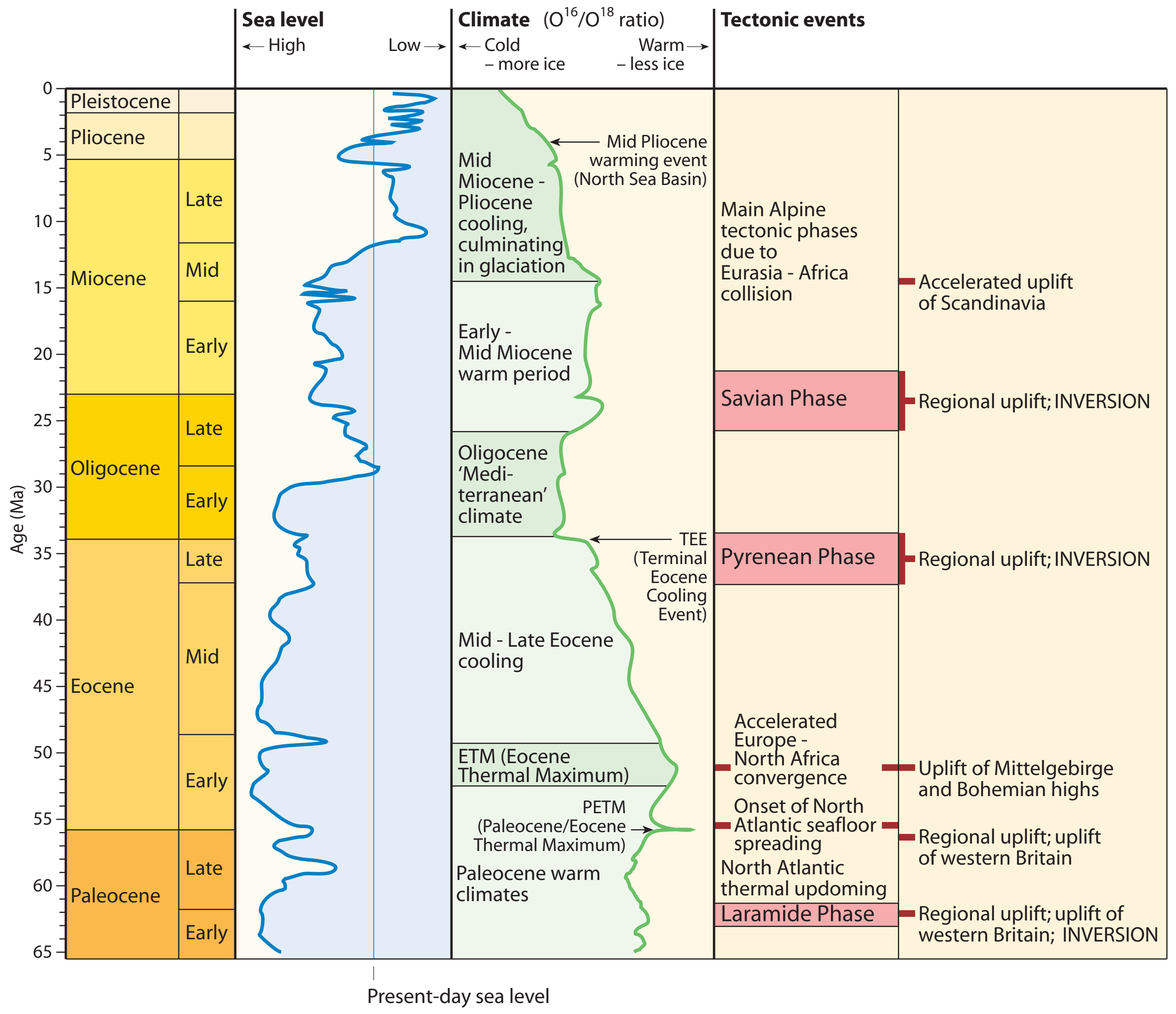


Figure 12.2 Cenozoic sea-level, tectonic and climatic events (modified from King, 2006, Figure 16.5).

Paris Basin and the North Sea is often regarded as having been restricted by the structural high commonly referred to as the 'Artois Sill' or even isolated by a 'Weald-Artois' axis. However, whereas the Artois structure appears to have acted as a swell with a thin and incomplete sediment cover, there is no direct evidence for it having formed a true physical barrier between the two areas during the Paleocene and Eocene (King, 2006). Similarly, there is no evidence for emergence of a Weald land area during the Paleocene, Eocene or earliest Oligocene. Despite their similar trends, the Artois and Weald structural highs have very different origins, the former is a basement high and the latter a product of Mid- to Late Cenozoic inversion of the Mesozoic Weald Basin. The Early Tertiary palaeogeography of the Channel area was more significantly influenced by the Start-Cotentin basement high, which acted as a swell that restricted connection between the North Sea Basin and the Western Approaches Basin during much of the Paleocene and Eocene (King, 2006). Exposure of the Start-Cotentin swell during periods of low sea level resulted in the Channel connection being temporarily severed.

The timing of inversion of the Mesozoic Weald Basin is still the subject of debate (see King, 2006). Although it has been suggested that it was substantially inverted during the Pyrenean (latest Eocene) tectonic phase (e.g. Ziegler, 1990a; Ziegler & Dèzes, 2007), King (2006) has pointed out that there is no evidence for a break in sedimentation at the Eocene-Oligocene boundary in the Hampshire Basin and that faunas in the youngest preserved sediments (earliest Oligocene) are of typical North Sea type. Both Chadwick (1993) and King (2006) consider a Miocene age for the inversion to be the most likely. Inversion of the nearby Mesozoic Central Channel Basin may have taken place earlier, in the Oligocene (Bray et al., 1998; King, 2006), and it is possible that the Weald Basin also underwent an early phase of inversion at that time. However, the strong contrast in present-day relief within the two inversion structures suggests that the main phase (or phases) of inversion of the Weald Basin took place significantly later than that of the Central Channel Basin. The presence of Upper Miocene to Lower Pliocene marine sediments (Lenham Beds) at an elevation of 180 m on the southern flank of the Weald Anticline points to relatively recent uplift (perhaps even inversion) in the Pliocene or Early Pleistocene.

The western SPB margin generally coincided with the eastern margin of the present-day English Pennine Hills during the Paleocene and Eocene. Eastern England and the adjacent offshore area appear to have been a relatively non-subsiding area, here referred to as the Eastern England Shelf, with the Sole Pit inversion zone marking its basinward limit (**Figure 12.3**). Uplift and exposure of this shelf appears to have taken place during earliest Eocene times (Knox, 1996; King, 2006). Inversion of the Mesozoic Sole Pit Basin began during the Late Cretaceous, with subsequent inversion pulses during the latest Eocene (Pyrenean tectonic phase) and more substantially during the Miocene (Savian Phase) (Van Hoorn, 1987; De Jager, 2007). The Mesozoic Cleveland Basin may have had a comparable Cenozoic inversion history, but any sedimentary evidence for the timing of its inversion has been lost due to Neogene erosion. However, like the Weald inversion, the Cleveland inversion has retained substantial relief, indicating that it too has undergone a relatively recent phase of uplift.

The marine waters of the Tertiary North-west European Basin and those of neighbouring basins were connected via seven seaways (**Figure 12.4**). The Norwegian Seaway, which connected the North Sea with the Arctic Ocean, has persisted throughout the Cenozoic. The other seaways were open for more limited periods, reflecting changes both in sea level and in the pattern of subsidence.

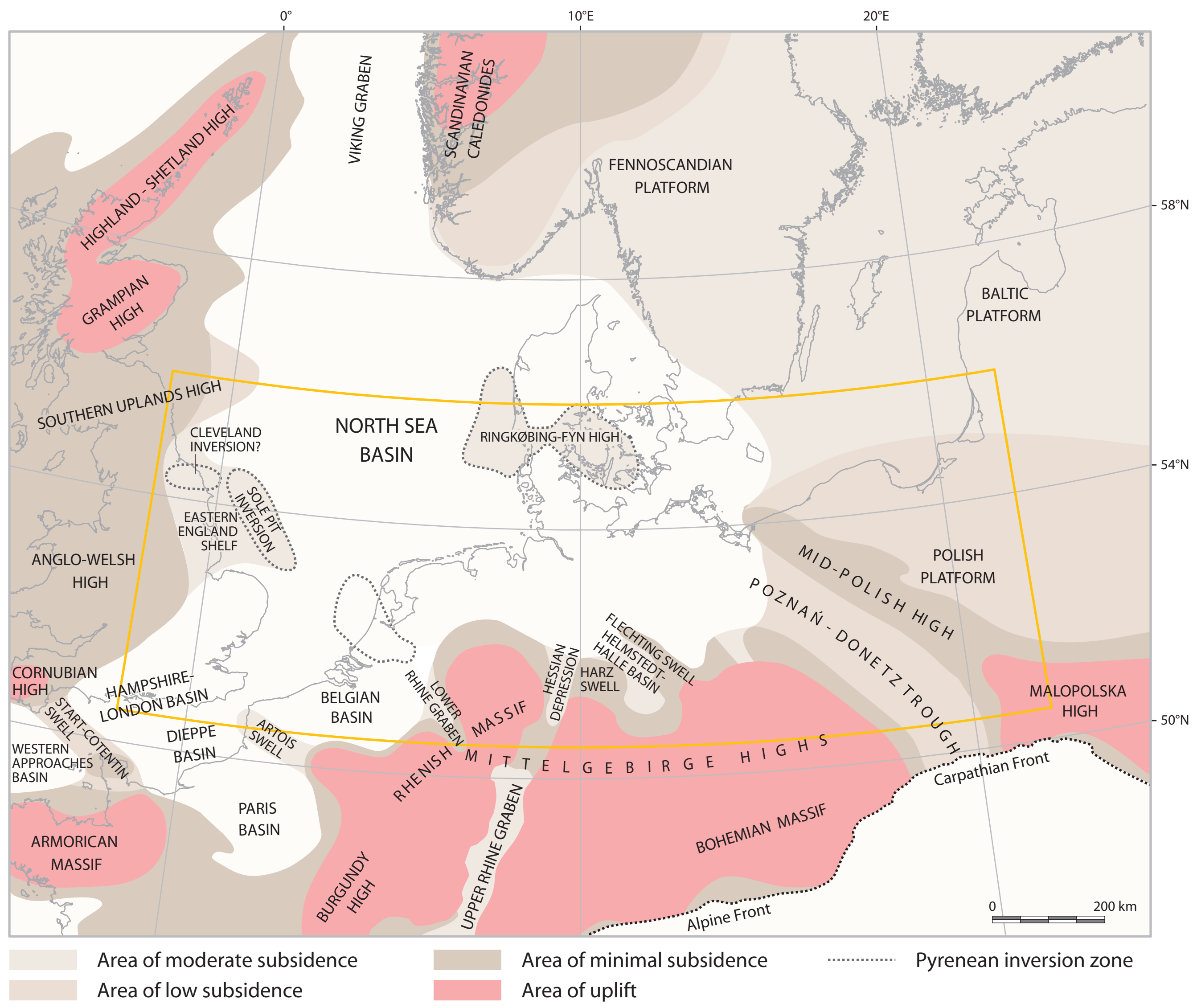


Figure 12.3a Early Tertiary structural elements.

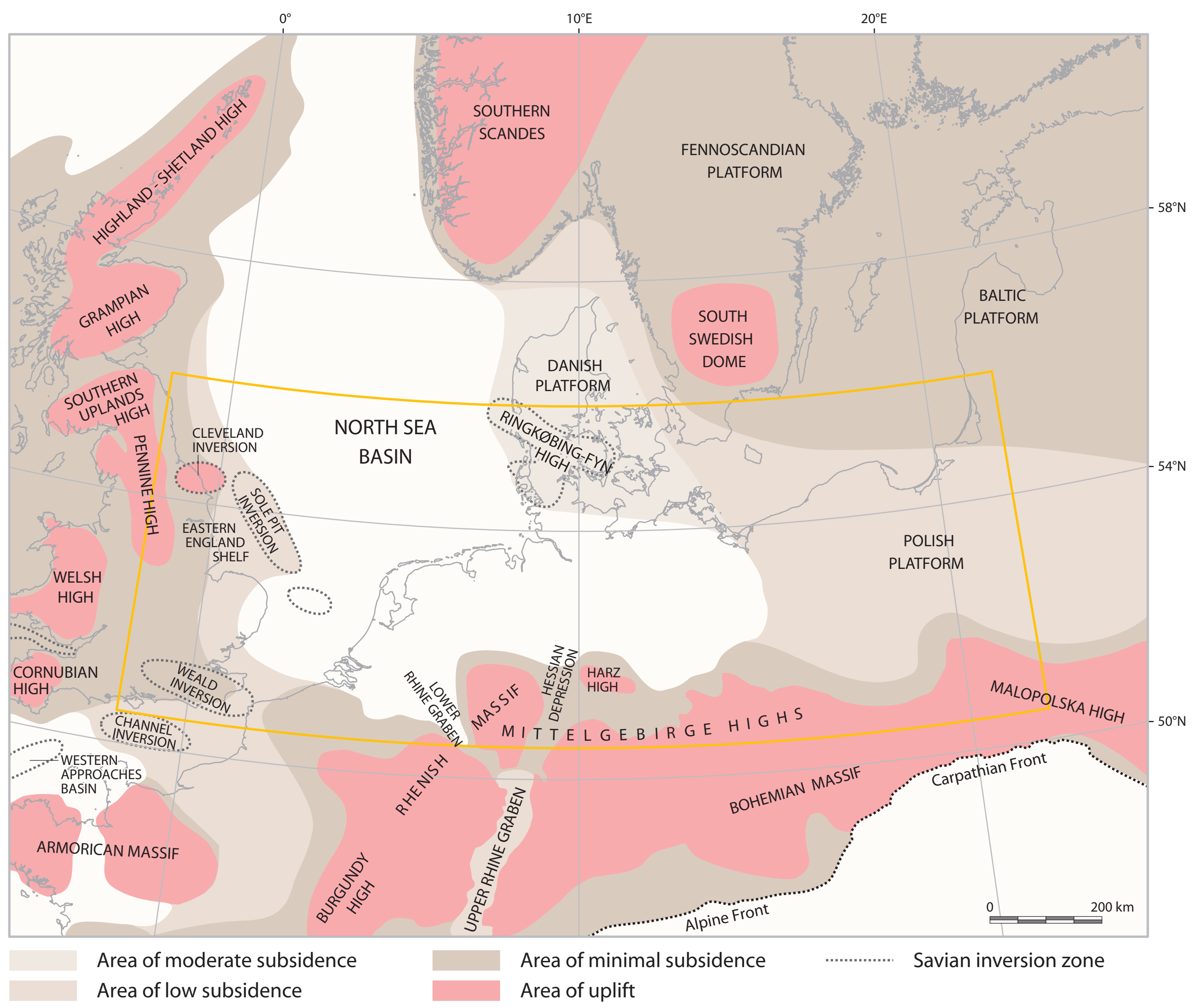


Figure 12.3b Late Tertiary structural elements.

There was a connection with the Tethys Ocean via the Moravian Seaway (Schnetler, 2001; Clemmensen & Thomsen, 2005) in mid-Paleocene times, but this closed during the mid- to Late Paleocene due to uplift of the North Polish Platform. The Moravian Seaway was re-established during the late Mid-Eocene, Late Eocene (Gramann & Kockel, 1988; Ziegler, 1990a), Early Oligocene (Popov et al., 2004) and possibly in the Late Oligocene (Janssen, 1979). An early Mid-Miocene connection has also been considered (Gramann, 1988, Gramann & Kockel, 1988, von Daniels, 1986), but is not supported by the sedimentary record. There was a connection with basins to the east via the Baltic Seaway during the Early and Mid-Eocene (Iakovleva et al., 2004; Iakovleva & Heilmann-Clausen, 2006; C. King, C. Heilmann-Clausen, A.I. Iakovleva & E. Steurbaut, pers. comm., 2008). Unpublished data (C. King, pers. comm., 2008) suggest that this connection continued until the Late Eocene, after which it was re-established for only a brief period in the Early Oligocene.

Connection with the Upper Rhine Graben via the Hessian Seaway was established during the Early Oligocene (Berger et al., 2005; Sissingh, 2006), but the endemic nature of the faunal assemblages in the Rupelian of the Upper Rhine Graben indicates that the marine connection did not extend to the Alpine Foreland Basin (Grimm, 2006). The Hessian Seaway appears to have been closed from the Chattian onwards.

Connection with the eastern Atlantic via the Channel Seaway existed for much of Early and Mid-Eocene times and probably during the Late Paleocene (King, 2006). There also appears to have been a connection with the Atlantic during the Early Oligocene, possibly via the Loire Seaway, which connected the Ligurian Basin (Sissingh, 2006) with the North Sea via the Paris Basin. Faunal evidence (Janssen, 1979) suggests that there was an intermittent connection during Early to Mid-Miocene times, probably via the Channel Seaway. Closure of the Atlantic connection probably took place in the Late Miocene due to inversion of the Mesozoic Weald Basin. The resulting barrier may have been breached in the earliest Pliocene, but was subsequently reinstated through uplift until it was breached in the Late Quaternary by overspill of the proglacial lake that occupied the southern North Sea (Gibbard, 1995; Gupta et al., 2007).

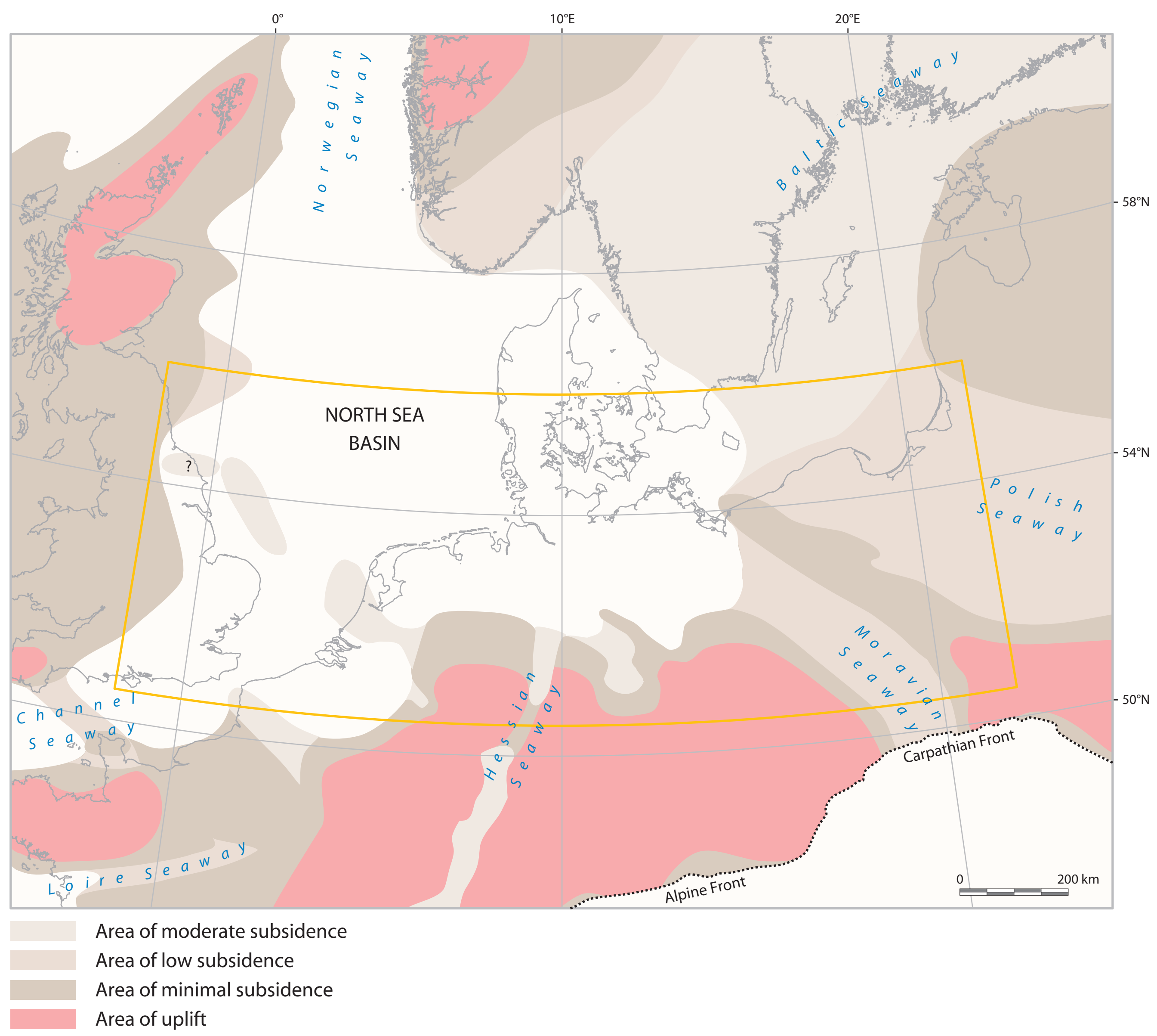


Figure 12.4 Early Tertiary seaways that connected the Cenozoic North Sea to adjacent areas of marine sedimentation: Norwegian Seaway to the Arctic and North Atlantic oceans; Baltic Seaway (via the Pripyat Strait) to the north-eastern Tethys (Early to early Middle Eocene) and eastern Peritethys (Early Oligocene); Polish Seaway, to the north-eastern Tethys (late Middle to Late Eocene) and eastern Peritethys (earliest Oligocene); Moravian Seaway, to the Tethys (Eocene) and central Peritethys (earliest Oligocene and Late Oligocene); Hessian Seaway, to the Upper Rhine Graben (early Oligocene); Loire and Channel seaways, to the eastern Atlantic Ocean. See Figure 3.23 for regional palaeogeography during the Tertiary.

2 Stratigraphy

A regional stratigraphic correlation chart is presented in **Figure 12.5**. The column order has been designed to emphasise stratigraphic continuity across national boundaries. Correlation has been achieved largely by means of biostratigraphy. A detailed account of the biostratigraphy of the succession has been provided by Vinken (1988). Further developments in the biozonation of the north-west European Cenozoic succession have been proposed by Heilmann-Clausen & Costa (1989), King (1989), Gradstein et al. (1992), Krutzsch et al. (1992), Powell (1992), Bujak & Mudge (1994), Mai (1995), Mudge & Bujak (1996a, 1996b), Köthe (2003, 2005a) and De Man et al. (2004). A summary of the regional stratigraphic zonations is provided by Rasser et al. (2008).

Significant developments in regional correlation have also been achieved through the application of sequence stratigraphy, particularly in the identification and correlation of hiatuses. Studies relevant to the succession in the SPBA area include those of Standke et al. (1993), Michelsen (1994), De Batist & Henriet (1995), Jordt et al. (1995), Jacobs & De Batist (1996), Knox (1996), Neal (1996), Danielsen et al. (1997), Gregersen et al. (1998), Michelsen et al. (1998), Vandenberghe et al. (1998, 2003, 2004), Clausen et al. (1999), Rasmussen (2004a, 2004b), Schäfer et al. (2004), Kasiński (2005), Schäfer (2005) and Standke (2006).

Magnetostratigraphy has also proved to be a useful tool in correlation and chronostratigraphical assignment in the Tertiary of southern England (Ali et al., 1993; Ali & Jolley, 1996; Ellison et al., 1996),

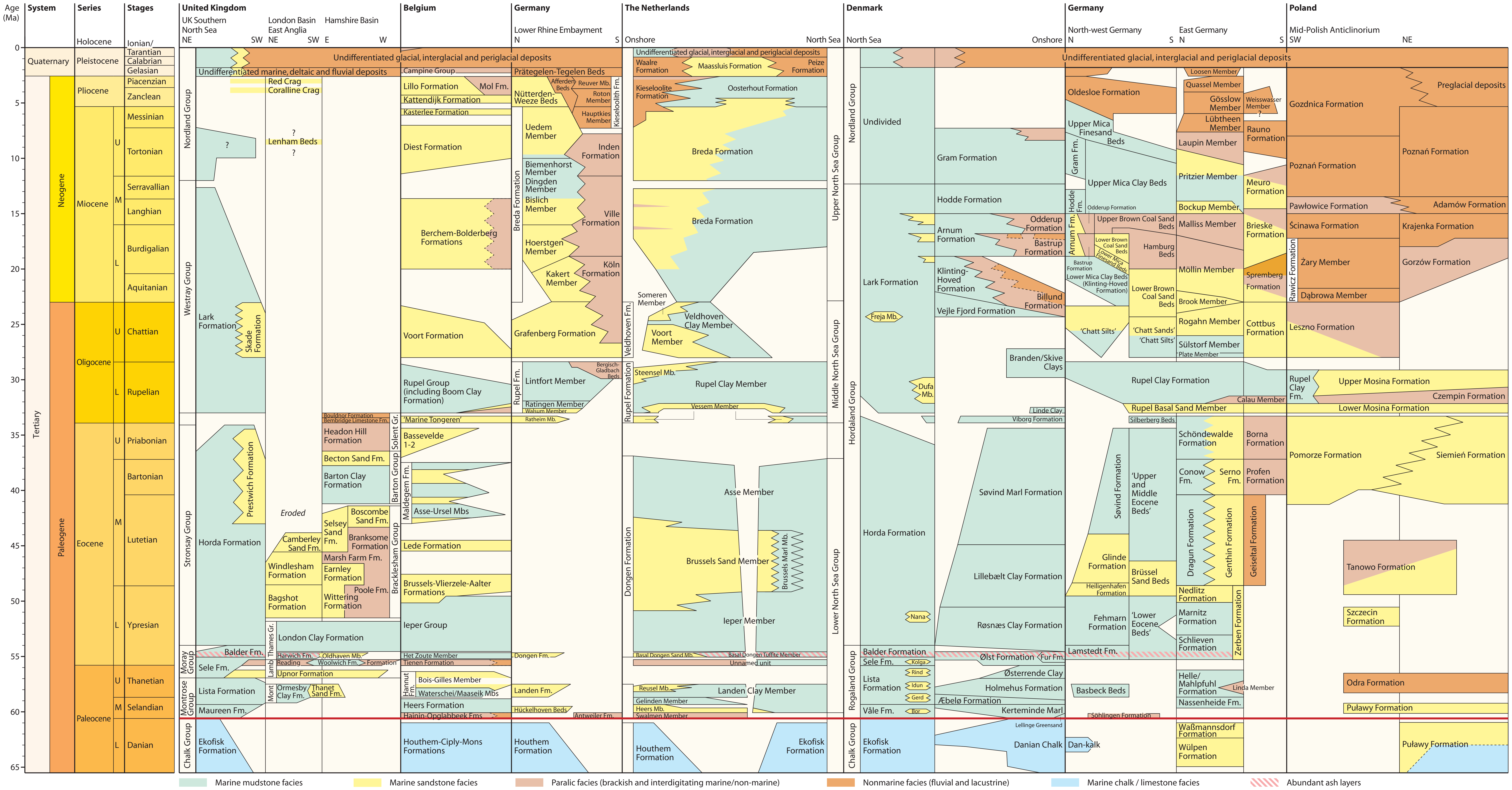


Figure 12.5 Tectonostratigraphic chart for the Cenozoic. The red line at the top of the Danian (1) is the lithostratigraphic horizon used to map the depth to the near base Tertiary (top of the Chalk Group). See Figures 1.5 & 12.1. Lithostratigraphic terminology taken from: Ellison et al. (1994), Lott & Knox (1994), Daley & Balson (1999) and King (2006) for the UK, Laga et al. (2001) for Belgium, Van Adrichem Boogaert & Kouwe (1993) for the Netherlands, Eißmann (1970, 1994), Lotsch (1981), von Bülow (2000), Krutzch (2000), Deutsche Stratigraphische Kommission (2002), Standke (2002, 2006, 2008a, 2008b), Gürs (2005), Hiss et al. (2005), Standke (2002), Standke et al. (2005), Gürs et al. (2008) and Blumenstengel & Krutzsch (2008) for Germany, Larsen & Dinesen (1959), Rasmussen (1961), Heilmann-Clausen et al. (1985), Heilmann-Clausen (1995, 2006), Schiøler et al. (2007) and Rasmussen et al. (2005) for onshore and offshore Denmark, and Dyjor (1970, 1986), Kramarska (1995), Piwocki & Ziembińska-Tworzydło (1995, 1997), Piwocki & Olszewska (1996), Piwocki (1998a, 1998b, 2001, 2004), Kasiński et al. (2003) and Kasiński & Piwocki (2008) for Poland. A recent history of the Tertiary is published by Rasser et al. (2008).

Belgium (Lagrou et al., 2004), Denmark (Beyer et al., 2001) and Germany (Menning & German Stratigraphic Commission, 2002) and in the Quaternary of Germany (Schwarz, 1996).

In the following stratigraphic account, post-Danian Cenozoic time is divided into four intervals representing distinct phases in the tectonic and depositional history of the basin (**Figure 12.6**). The Danian (Early Paleocene) interval, which was characterised by carbonate sedimentation, is described in Chapter 11.

3 Mid-Paleocene to earliest Eocene

The base of this interval is defined by the base of the middle Paleocene succession, which over much of the area rests unconformably on the Cretaceous to Lower Paleocene chalk succession. This unconformity was generated by regional uplift in Early to mid-Paleocene times (the 'Laramide' Phase of **Figure 12.2**), perhaps accompanied by a eustatic sea-level fall (Clemmensen & Thomsen, 2005); however, the contact is conformable in the deepest parts of the basin. The top of the interval is taken in basinal sections at the top of a unit with abundant volcanic ash layers, which marks the end of a major phase of North Atlantic subaerial volcanism. In south-western onshore sections, this level corresponds to the base of the London Clay Formation in England and the base of the Ieper Clay Formation in Belgium. The 'Paleocene to earliest Eocene' interval therefore equates with the 'Middle to Upper Paleocene' of Vinken (1988) and with the 'Paleocene' interval of Evans et al. (2003). Both the upper and lower boundaries are associated with prominent seismic reflectors in the North Sea succession.

The predominantly siliciclastic Late Paleocene sedimentation was in marked contrast to the carbonate-dominated sedimentation of the Early Paleocene (see Chapter 11). This reflects the increased land area that developed from regional uplift associated with the rise of the Iceland mantle plume combined with north-westward-directed compressional stresses (e.g. Ziegler et al., 1995; Hillis et al., 2008). At the same time, relative uplift of the East Shetland Platform and the Scottish Highlands led to the shedding of large volumes of sand-rich sediment eastwards into the Northern North Sea Basin. More than 1000 m-thick sediments accumulated in the Outer Moray Firth Basin during the Late Paleocene and earliest Eocene interval (**Figure 12.6a**). In contrast, the thickness of the succession in the SPBA area rarely exceeds 100 m.

The uplift at the end of the Early Paleocene was followed by a period of regional subsidence and transgression that spanned most of mid- and Late Paleocene times. This ended with a second period of regional uplift in the latest Paleocene, shortly before the onset of sea-floor spreading between Greenland and Scotland (**Figure 12.2**). The two uplift phases have been associated with discrete stages in the emplacement of the Iceland mantle plume (Knox, 1996; White & Lovell, 1997).

The oldest middle Paleocene (Selandian) sediments were deposited during a sea-level lowstand following the initial late Danian sea-level fall (Clemmensen & Thomsen, 2005). Calcareous mudstones accumulated in deeper parts of the SPB (Maureen and Våle formations: **Figure 12.7a**), while deep-water sands, locally accompanied by reworked chalk, accumulated along the north-western margin of the North Sea Basin. Marls and greensands up to 150 m thick accumulated in intermediate (~50-200 m) water depths near the eastern SPB margin, in present-day eastern Denmark. Selandian sediments are also preserved in a series of outliers along the margins of the Sole Pit inversion zone and along the southern basin margin (Vinken, 1988). The oldest beds are of nonmarine and paralic facies, but the overlying marine strata indicate that there was a shallow sea over much of the Southern North Sea Basin, although significant sediment accumulation was restricted to relatively small structural basins. The strongly calcareous nature of many Selandian sediments can be partly attributed to reworking of Cretaceous chalk exposed on the adjacent nondepositional shelf area.

A progressive rise in sea level extended the area of Selandian marine sedimentation into much of the southern North Sea area, with chalk reworking continuing to generate highly calcareous mudstone facies in marginal areas (e.g. Heers Formation, Gelinden Member). Noncalcareous mudstones accumulated farther offshore in deeper waters (lower part of Lista Formation, Æbelø Formation). The sea also extended eastwards into Poland (Słodkowska, 2004, 2009) where faunal similarities indicate a connection with the Tethys Ocean via the Moravian Seaway. This connection would have been closed in the late Selandian as a result of uplift of the Polish Platform.

According to Schnetler (2001) and Clemmensen & Thomsen (2005) a sea-level rise in the early Thanetian led to widespread transgression, with marine sedimentation extending into south-east England, Belgium, the Netherlands and much of Germany (**Figure 12.7a**). Hemipelagic clays accumulated in the deepest parts of the basin. The southern limit of early Thanetian sedimentation is thought to have been close to the present-day outcrop/subcrop limit. In contrast, sedimentation along the western and eastern margins most probably extended well beyond the present-day limits, which are a result of uplift and erosion in both Paleogene and Neogene times.

The Thanetian sea appears to have extended over much of eastern England, with the coastline running north–south down the eastern side of the present-day Pennines (Knox, 1996; King, 2006). The local preservation of Selandian and Thanetian sediments to the west of the Sole Pit inversion zone indicates that the Eastern England Shelf was depositional at that time (Stewart & Bailey, 1996). There was a restricted-marine connection to the eastern Atlantic at the time of maximum transgression, probably via the Channel Seaway (King, 2006).

The Thanetian sediments of the southern margin are mostly of shallow-marine facies. Paralic sedimentation took place in two small embayments separated by the Flechting Swell, which formed a narrow peninsula of low relief (Lotsch, 1969). The continental deposits found to the east are evidence of continued relative uplift of the North Polish Platform.

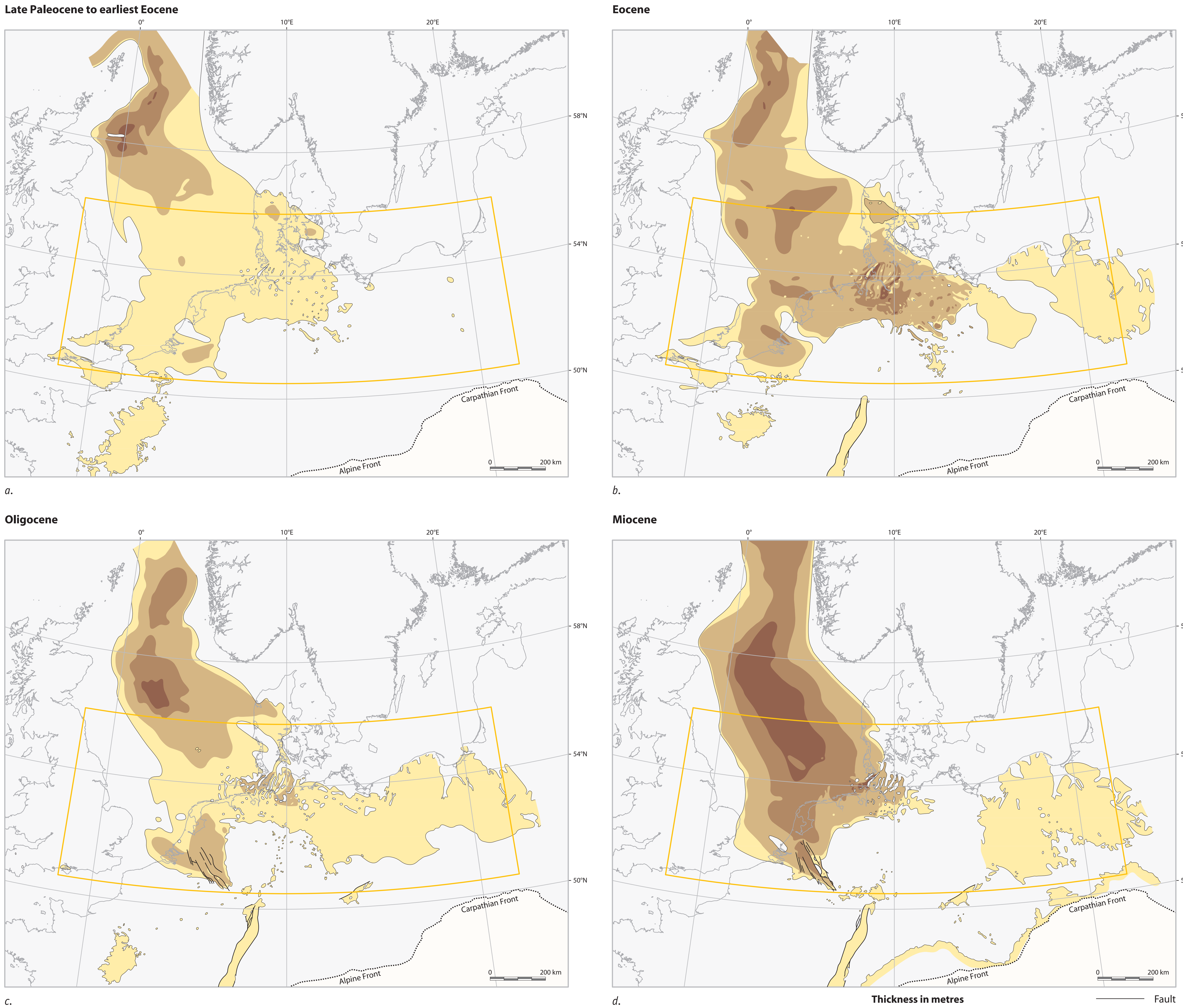


Figure 12.6 Distribution and thickness maps (after Vinken, 1988) for: a. Late Paleocene to earliest Eocene; b. Eocene; c. Oligocene; d. Miocene. Note that the thicknesses displayed in 12.9d are an approximation based on the base 'Mid Miocene' structure contour map of Vinken (1988).

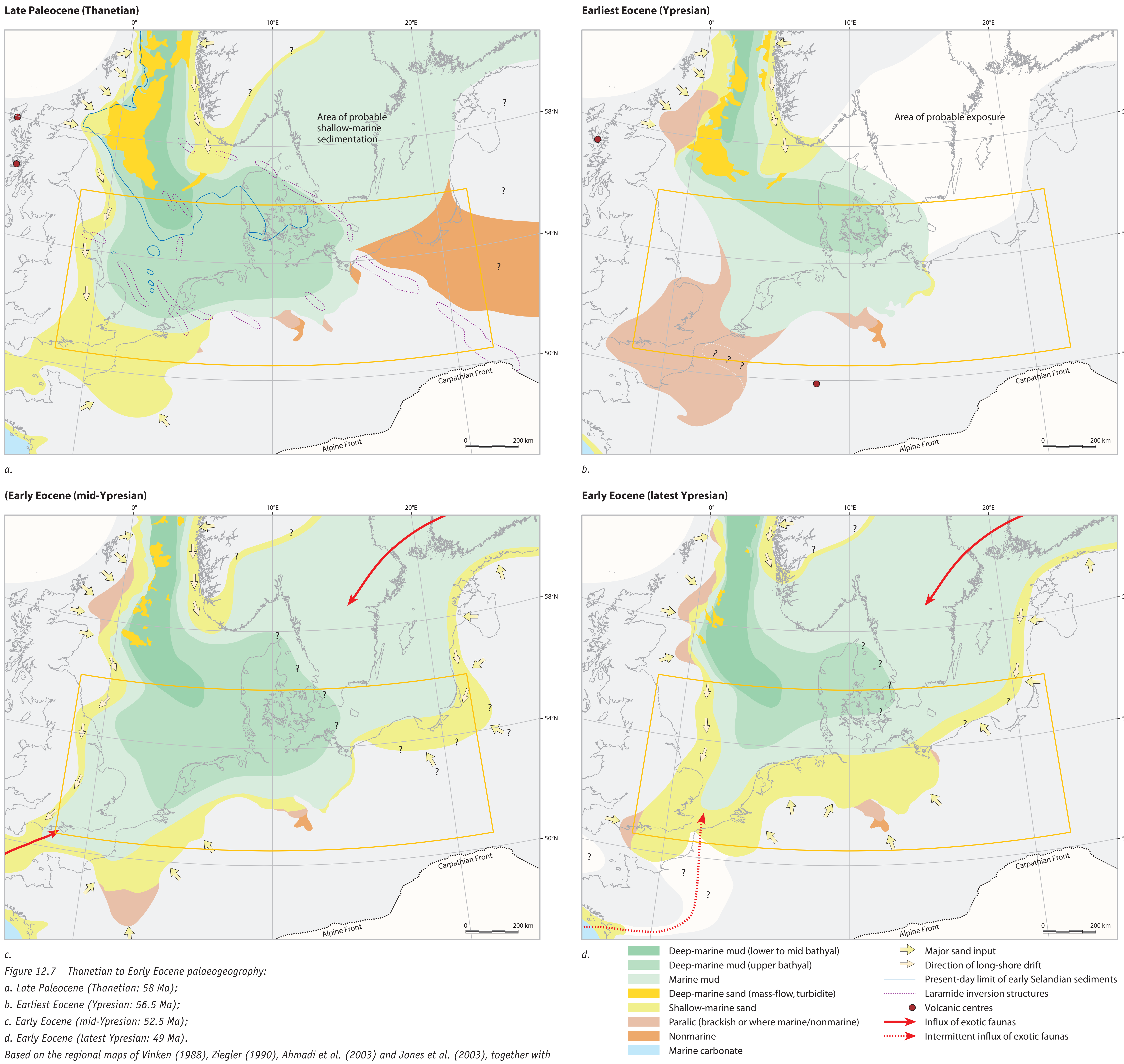


Figure 12.7 Thanetian to Early Eocene palaeogeography:
a. Late Paleocene (Thanetian: 58 Ma);
b. Earliest Eocene (Ypresian: 56.5 Ma);
c. Early Eocene (mid-Ypresian: 52.5 Ma);
d. Early Eocene (latest Ypresian: 49 Ma).
Based on the regional maps of Vinken (1988), Ziegler (1990), Ahmadi et al. (2003) and Jones et al. (2003), together with maps of Lotsch (1969, 2002), Thiry & Dupuis (1998), Martiklos (2002), Piwocki (2004), Gürs (2005), Heilmann-Clausen (2006), King (2006), Standke (2008a), Lustrino & Wilson (2007). The location of Laramide inversion structures in Figure 12.10a are modified from Nielsen et al. (2005). Bathyal limits are from C. King (unpublished data, 2009).

In contrast, the succession in Denmark indicates an increase in water depth, with the relatively shallow-marine facies of the Selandian being replaced by the deeper-water facies of the Thanetian. The clays deposited during the late Selandian to mid-Thanetian are extremely fine grained, with no indication of clastic input from a nearby landmass. This indicates that the sea extended across southern Sweden and probably onto the Baltic and Scandinavian platform areas.

The long period of early to mid-Thanetian transgression was brought to an abrupt end by regional uplift, which led to subaerial exposure and erosion of previously deposited Paleocene sediments in marginal areas. In the central North Sea and Denmark, this regression is marked by an upward change from grey-green mudstone facies with rich and diverse microfauna to grey mudstone with an impoverished microfauna. The regression is also associated with a renewed influx of deep-water sands. Any Thanetian sediments that had accumulated in the Fennoscandian and Baltic areas were probably removed at that time. In south-western marginal areas, truncated Lower Paleocene sandstones are locally overlain by shallow-marine sandstones of latest Paleocene age.

A final pulse of Late Paleocene tectonism led to uplift of western Britain, resulting in the near isolation of the North Sea Basin from oceanic waters (**Figure 12.7b**). Reduced circulation led to the development of anoxic bottom-waters in deeper parts of the basin, where the earliest Eocene sediments consist of finely laminated organic-rich mudstones (Sele Formation) and local submarine-fan sandstones. High concentrations of the dinoflagellate cyst *Apectodinium* coincide with the global Paleocene-Eocene Thermal Maximum (PETM) and probably reflect nutrient-enriched, warmer surface waters in the North Sea Basin. Relative subsidence in the south-western embayment of the North Sea Basin led to the widespread accumulation of marginal-marine to nonmarine, locally lignite-bearing sediments. In south-east England, these sediments display a reversal of the northward-deepening facies of the early Thanetian, indicating that the Eastern England Shelf underwent uplift at that time. The original extent of these Lower Eocene sediments is uncertain, as evidence from south-east England suggests that they underwent significant erosion shortly after deposition. However, there are equivalent marine sediments in Denmark and over much of the Netherlands and Germany. The Polish, Baltic and Fennoscandian platform areas were probably emergent at that time.

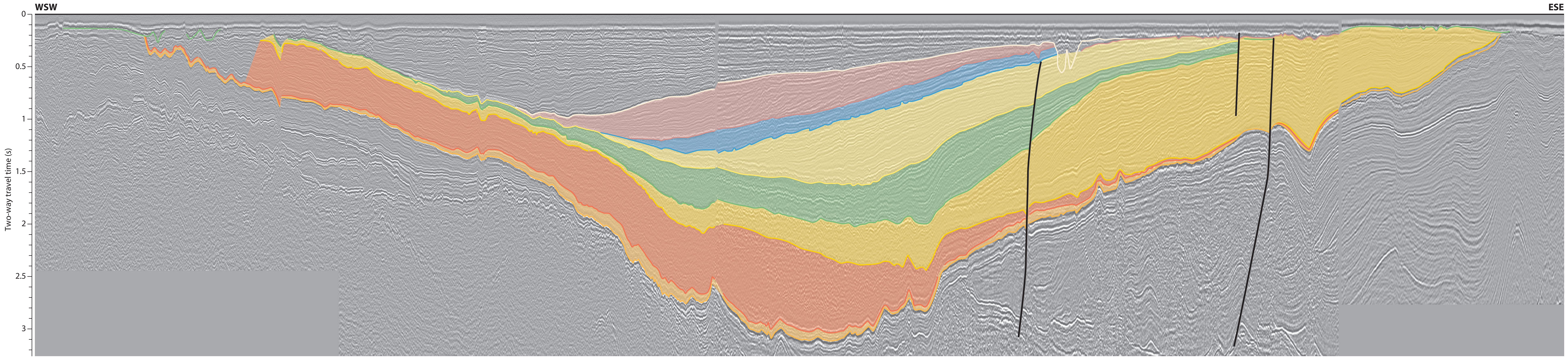
Earliest Eocene sedimentation ended with a further short-term phase of regional uplift that immediately preceded the onset of sea-floor spreading between Greenland and Scotland. This led to widespread erosion along the southern and south-western margins of the North Sea Basin with the development of an unconformity, as for example at the base of the Harwich Formation in south-east England. At the same time, uplift of the Scottish source areas was accompanied by the rapid eastward progradation of a major (up to 500 m thick) delta complex (Dornoch Formation) in the Outer Moray Firth embayment. Anoxic laminated muds continued to accumulate in the central North Sea while non-laminated muds were deposited in onshore Denmark (middle and upper Ølst Formation). Marine diatomites up to 60 thick were deposited (Fur Formation) in a narrow belt of north-west Denmark and the adjacent eastern North Sea.

Renewed sedimentation in the south of the basin was associated with a marked reduction in differential tectonic movement, reflected in the development of uniform depositional facies over much of the North Sea Basin. The change in tectonic regime and the associated rise in sea level mark the resumption of thermal subsidence following the onset of sea-floor spreading between Greenland and Scotland. The spreading ridge above the Iceland plume initially remained above sea level and was the site of intense subaerial pyroclastic activity. This is reflected by the abundant, predominantly basaltic ash layers in all marine mudstone and diatomite formations (see **Figure 12.5**). The spreading ridge eventually became submerged as sea level continued to rise, so that pyroclastic activity was largely suppressed.

4 Early to Late Eocene

The base of the Early to Late Eocene interval is defined in basinal sections by the top of an interval with abundant ash layers and in onshore successions by a minor hiatus. The top is defined by a widespread unconformity of latest Eocene to earliest Oligocene age.

Following the onset of North Atlantic sea-floor spreading, the Tertiary North-west European Basin underwent renewed thermal subsidence. Whereas previously the focus of sedimentation had been along the north-western margin of the basin (Outer Moray Firth Basin and Viking Graben), thick Eocene successions were more widely distributed, with the principal depocentres in the Viking Graben, the central North Sea and northern Germany (**Figure 12.6b**). The prograding shelf-margin wedge that developed along the western margin of the Viking Graben was more mud-prone than during the Paleocene, and individual deep-water sandstone bodies were deposited on a smaller scale (**Figure 12.7c**). Eastward progradation from the western margin of the basin is also evident in the southern North Sea (**Figure 12.8**). Relative subsidence of the central North Sea and Viking Graben maintained the deep-water environments established during the Late Paleocene. Deep-water environments also extended eastwards into the Danish area where



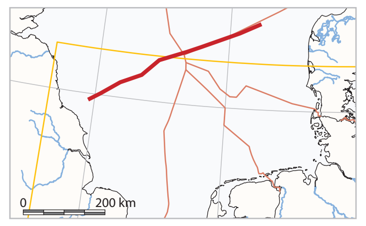


Figure 12.8 Seismic section across the southern central North Sea. The basin fill is dominated by marine mudstones. A thick pile of eastward-prograding Eocene sediments dominates the western part of the basin. This was sourced from the uplifted Scotland-Shetland Platform in response to the opening of the North Atlantic. There was a distinct change at the Eocene-Oligocene boundary when prominent outbuilding from the Fennoscandian Shield took place; this continued into the Pleistocene. Shallow-marine sediments are first recognised in the Gelasian. Seismic data courtesy of TGS-Nopec.

sediments were initially dominated by relatively thin, bathyal mudstone deposits. The mudstones were gradually replaced in the Middle and Upper Eocene successions by calcareous nannofossil oozes deposited in intermediate water depths.

The Viking Graben continued to provide a link to Arctic waters via the Norwegian Seaway and, following subsidence of the spreading ridge, a link to the north-east Atlantic. An Atlantic link was also established from time to time via the Channel Seaway (King, 2006), although faunal migration was commonly restricted by shallowing over the Start-Cotentin Swell. The Start-Cotentin Swell appears to have been emergent for brief periods, forming a barrier to oceanic connection. Eocene sediments are missing from much of eastern England as a result of uplift and erosion since Late Oligocene times, although it is likely that this area was depositional during most of the Eocene (King, 2006).

Progressive transgression of the basin margins during the early to mid-Ypresian led to the extension of marine mudstone facies over much of the SPBA area. Marine sands fringed the basin margins, with paralic and terrestrial deposits confined to the Hessian and Helmstedt-Halle embayments (**Figure 12.3a**). Connection with the North Atlantic via the Channel Seaway was established in mid-Ypresian times, as indicated by the appearance of warm-water foraminifera, including *Nummulites* (King, 2006) in the south-western embayment of the North Sea. Microfossil evidence suggests that there was also a marine connection with western Siberia (Iakovleva et al., 2004; C. King, C. Heilmann-Clausen, I.A. Iaklova & E. Steurbaut, pers. comm. 2009). This marine connection must have been established via the Baltic Seaway as the Moravian Seaway does not appear to have been open at that time. The idea that the Baltic area was occupied by the sea is supported by the presence of marine mudstones in the Eocene succession of the Kaliningrad area (Kramarska, et al., 2004; Kramarska, 2006). Epidote-rich heavy-mineral assemblages in the associated sands suggest a source area to the north. The likely source rocks are the Devonian sandstones of present-day Estonia and Latvia as these have epidote-rich heavy-mineral assemblages (see Rattas & Kalm, 2001).

This phase of sedimentation ended in latest Ypresian times by a major influx of sand into the southern basin-marginal areas (**Figure 12.7d**) and a basinward shift in facies in the Hampshire Basin and along the western margin of the southern North Sea. This sand influx, which persisted into the late Lutetian, cannot be attributed to a sustained eustatic sea-level fall (see **Figure 12.2**). It therefore presumably represents uplift of the southern and western marginal highs. This uplift may have been associated with stresses set up by the renewal of Africa-Europe convergence, dated at around 51 Ma by Dewey & Windley (1988). However, not all of the southern margin was involved in this uplift, as the latest Ypresian is also marked by the reappearance of *Nummulites* in the southern North Sea area (King, 2006), indicating re-establishment of a marine connection with the eastern Atlantic. The paralic facies in the Hampshire Basin indicates emergence of the Start-Cotentin Swell. It is therefore likely that a connection with the Atlantic was established via the Loire Seaway, although there is a lack of direct evidence as any upper Ypresian sediments in the Paris Basin have been removed beneath the base-Lutetian disconformity (e.g. Vinken, 1988).

Further uplift in the early Lutetian is indicated by a seaward extension of paralic facies in the Hampshire Basin, hiatuses in the Belgian succession, the replacement of marine by paralic facies on the North Polish Platform and by a loss of the connection with the eastern Atlantic. The Upper Rhine Graben started to subside about the same time (**Figure 12.9a**), accompanied by basalt extrusion in the Eifel area at about 45 Ma (Lippolt, 1983; Lustrino & Wilson, 2007). Following these events, subsidence of the southern and western marginal highs is indicated by a progressive transgression of the southern and south-western margins and a return to predominantly muddy sedimentation. The reappearance of *Nummulites* indicates a further renewed connection with the eastern Atlantic via the Loire Seaway. A sharp demarcation between the marine-carbonate facies of the Paris Basin and the sandy facies of the Belgian Basin suggests that the Artois Swell was emergent at that time. By the late Lutetian, the sea had extended across much of the North Polish Platform.

Significant palaeogeographical changes took place during late Mid-Eocene times as a result of uplift of western Britain and France, superimposed on a eustatic sea-level fall. Emergence of the Start-Cotentin Swell in Bartonian times had led to closure of the connection with Atlantic oceanic waters (King, 2006) with consequent loss of the associated warm-water faunas from the North Sea Basin. Temporary isolation of the Paris Basin led to the establishment of a hypersaline lake, while paralic environments extended over much of southern England and northern France (**Figure 12.9b**). Along the western margin of the basin, shallow-marine sands extended eastwards beyond the Sole Pit inversion zone. Conversely, the North Polish Platform continued to subside, leading to progressive inundation of the Mid-Polish High. Sediments in this region are dominated by high-energy sand facies. A connection with the warm waters of the Alpine-Carpathian Foreland Basin was established in late Mid- to Late Eocene times via the Moravian Seaway (Gramann, 1988; Gramann & Kockel, 1988; Ziegler, 1990a). Late Middle to Late Eocene faunas also indicate continued connection via the Baltic Seaway with the cool waters of the Donets-Caspian Basin (C. King, pers. comm., 2008). However, this interpretation requires a palaeogeographical reconstruction that is at odds with the model proposed by Jaworowski (1987) for the Late Eocene of northern Poland. In this model, the amber-bearing Upper Eocene sands of northern Poland are considered to be associated with a major delta that prograded southwards from a Fennoscandian landmass.

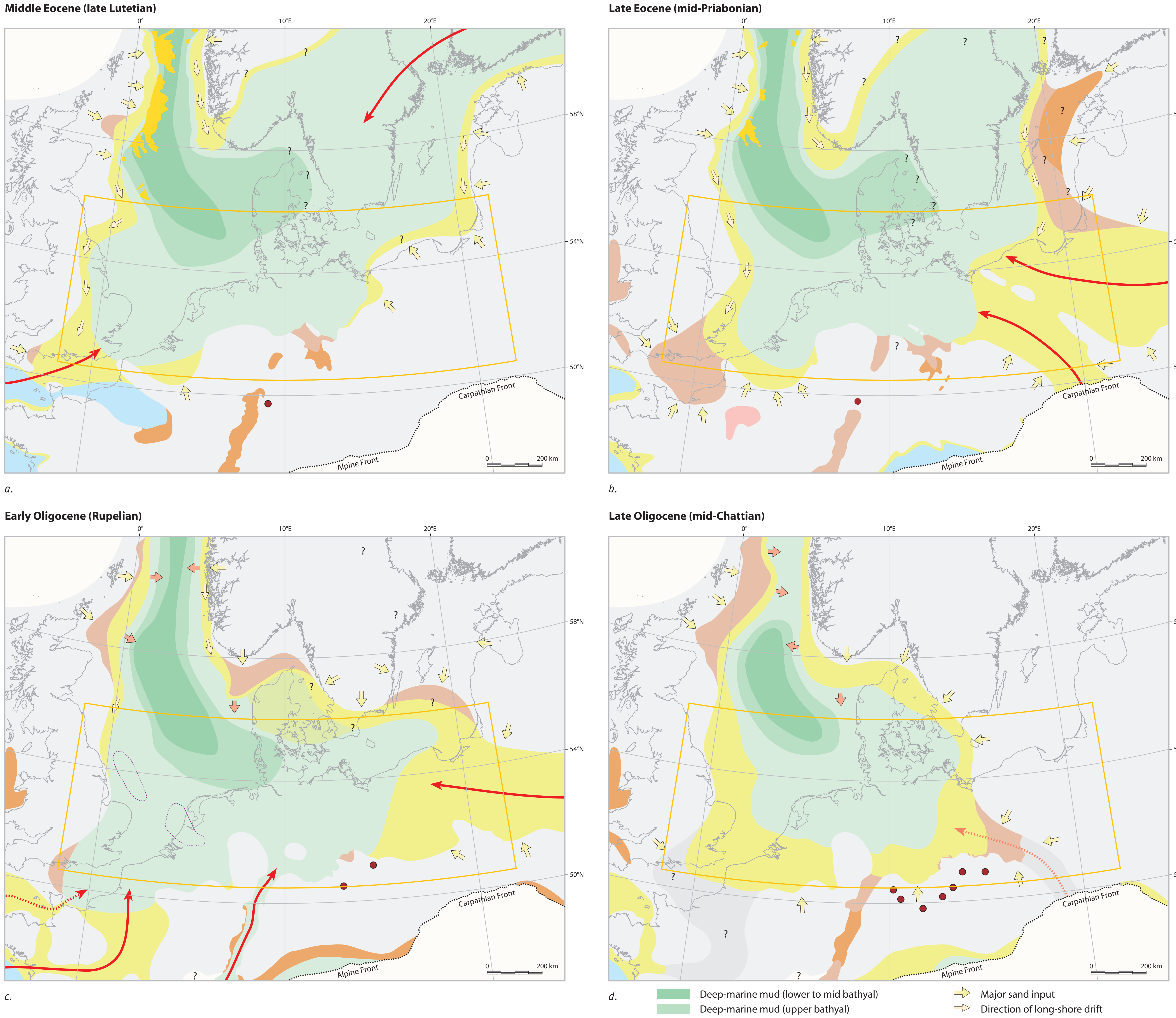
The latest Eocene was marked by regional uplift associated with the Pyrenean tectonic phase. Uplift was accompanied by local inversion of Mesozoic basins, which led to widespread regression in marginal areas. Sedimentation continued in the offshore North Sea Basin, except over areas of inversion.

5 Oligocene

The transition from the Eocene to the Oligocene was associated with a distinct and long-lasting change in the pattern of uplift and subsidence in north-west Europe, reflecting a change in the regional stress regime. The complex pattern of sediment accumulation that had characterised the Eocene within the SPB area (**Figure 12.6b**) was replaced by a more uniform pattern of basin-centred sedimentation (**Figure 12.6c**). This change was associated with uplift of the western and north-eastern basin margins. Uplift of the western margin was accompanied by the development of a series of fault-bounded basins in western Britain. Uplift of the Fennoscandian Platform is reflected in a distinct change from eastward to predominantly westward progradation in the North Sea (**Figures 12.8**). Uplift of the eastern Norwegian-Danish Basin took place at that time, forming the Danish Shelf. Inversion tectonics led to the development of a marked angular unconformity at the Eocene-Oligocene boundary in the central Netherlands area (De Lugt et al., 2003) (**Figure 12.10**) and locally in the Sole Pit area (Lott & Knox., 1994; De Jager, 2007). The Central Channel Basin may also have been inverted at that time (King, 2006).

The Eocene-Oligocene boundary is marked by an unconformity of latest Eocene to earliest Oligocene age in southern onshore areas and in adjacent offshore inversion zones. Oxygen isotope studies on the Belgian succession show that the oldest Oligocene deposits have a warm-water signature (De Man et al., 2004), indicating that they were deposited before the onset of the major Early Oligocene cooling event (Oi-1 of Miller et al., 2008). The hiatus seen at the Eocene-Oligocene boundary in Belgium and other marginal successions is therefore considered to be of tectonic origin, reflecting regional uplift and inversion associated with the Pyrenean tectonic phase. The major sea-level fall induced by the Oi-1 cooling event is estimated by De Man et al. (2004) to have taken place about one million years later, and led to widespread erosion of the previously deposited Lower Oligocene sediments.

Sedimentation resumed along the margins following the period of Eocene-Oligocene boundary tectonism. The facies distribution of the lowermost Oligocene succession is broadly similar to that of the uppermost Eocene (where preserved; see **Figure 12.5**). However, on the Danish Shelf, a marked reduction in water depth is indicated by a change from upper bathyal mudstone facies (Søvind Marl Formation) in the Upper Eocene to sublittoral mudstone facies (Viborg Formation) in the lowermost Oligocene (Heilmann-Clausen et al., 1985). In the eastern North Sea, deltaic deposits including the Dufa Sandstone Member (Schiøler et al., 2007) prograded southwards into deeper waters to the west of the Danish Shelf. This development provides the first evidence for uplift of southernmost Norway (Michelsen & Nielsen, 1993; Michelsen et al., 1998; Rundberg & Eidvin, 2005). Prior to this, uplift appears to have been confined to the Scandinavian Caledonide belt, as reflected in westward progradation into the Viking Graben. These two areas clearly acted independently during the Paleogene, as the onset of uplift of southernmost Norway in the Early Oligocene was associated with the end of uplift of the western Norwegian Caledonides (Riis et al., 2008).



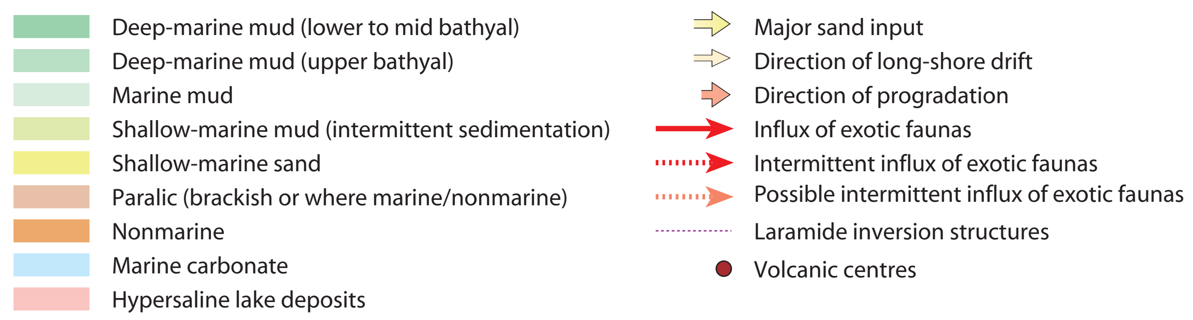


Figure 12.9 Mid-Eocene to Late Oligocene palaeogeography: a. Middle Eocene (late Lutetian: 42.5 Ma); b. Late Eocene (mid-Priabonian: 36Ma); c. Early Oligocene (Rupelian: 31 Ma); d. Late Oligocene (mid-Chattian: 26 Ma). Based on the regional maps of Vinken (1988), Ziegler (1990a), Jones et al. (2003) and Fyfe et al. (2003), together with maps of Lotsch et al. (1969), Geißler et al. (1987, 1988), Lotsch (2002), Martiklos (2002), Piwocki (2004), Rasmussen (2004a), Berger et al. (2005), Gürs (2005), Hiss et al. (2005), Kuster (2005), Rascher et al. (2005), Ritzkowski (2005), Heilmann-Clausen (2006), King (2006), Sissingh (2006), Van Simaeys (2004), Lustrino & Wilson (2007), De Man (2006), Standke (2008a). The location of Pyrenean inversion structures in Figure 12.9c are modified from Nielsen et al. (2005). Bathyal limits are from King (unpublished data, 2009).

Other areas of the Scandinavian Platform probably underwent further uplift at that time, as sands with a metamorphic heavy-mineral assemblage dominated by amphibole and epidote are seen for the first time in the lowermost Oligocene sediments of the Szczecin area of north-west Poland (Kozmowska-Ceranowicz, 1988). The similarity of this heavy-mineral assemblage with that reported from the lowermost Oligocene of the Viborg Formation of Denmark (Vinken, 1988) suggests derivation from southern Sweden. This sand influx is therefore interpreted as marking the onset of uplift of the South Swedish Dome. Combined with continued influx of epidote-rich sands from the north-east, the uplift led to a wider extension of epidote-rich sands onto the Polish Platform than at any other time in the Tertiary (Morton et al., 1988).

The similarity of some microfaunal elements in the lowermost Oligocene sediments of Poland and Germany with those of the succession in Hungary suggest that a connection existed with the eastern Paratethys Ocean via the Moravian Seaway (Odrzywolska-Bieńkowa & Pożaryska, 1984; Gramann, 1988; Gramann & Kockel, 1988; Popov et al., 2004). In the south-west, continued paralic sedimentation in the Hampshire Basin indicates that the Start-Cotentin Swell (and possibly the Central Channel inversion) remained exposed, while emergence of the Paris Basin probably precluded any connection with the Atlantic Ocean to the west.

This brief phase of earliest Oligocene sedimentation was terminated by a climatically induced sea-level fall (see above), which led to renewed erosion around the basin margins. The effects of this sea-level fall were short-lived, as an increase in global temperatures in mid-Rupelian times led to a rapid eustatic sea-level rise that was reflected in widespread transgression of marginal areas (**Figure 12.9c**). Sedimentation recommenced on the Danish Shelf, on the Polish Platform and along much of the southern basin margin, extending at times into the Upper Rhine Graben. Shallow-marine sands were deposited in and around the Paris Basin. No information is available for south-east England due to Neogene erosion, but it seems likely that the facies distribution was very similar to that during the earliest Rupelian, with paralic sediments passing eastwards into marine mudstones.

The mid-Rupelian sea-level rise led to the re-establishment of shallow-marine sand sedimentation over much of the Polish Platform. However, in the far north of Poland, the sands are replaced by marine mudstones, indicating that deeper water lay to the north. As there is faunal evidence for renewed connection with basins to the east (C. King, pers. comm., 2009), it is likely that the mid-Rupelian sea-level rise led to a temporary reopening of the Baltic Seaway.

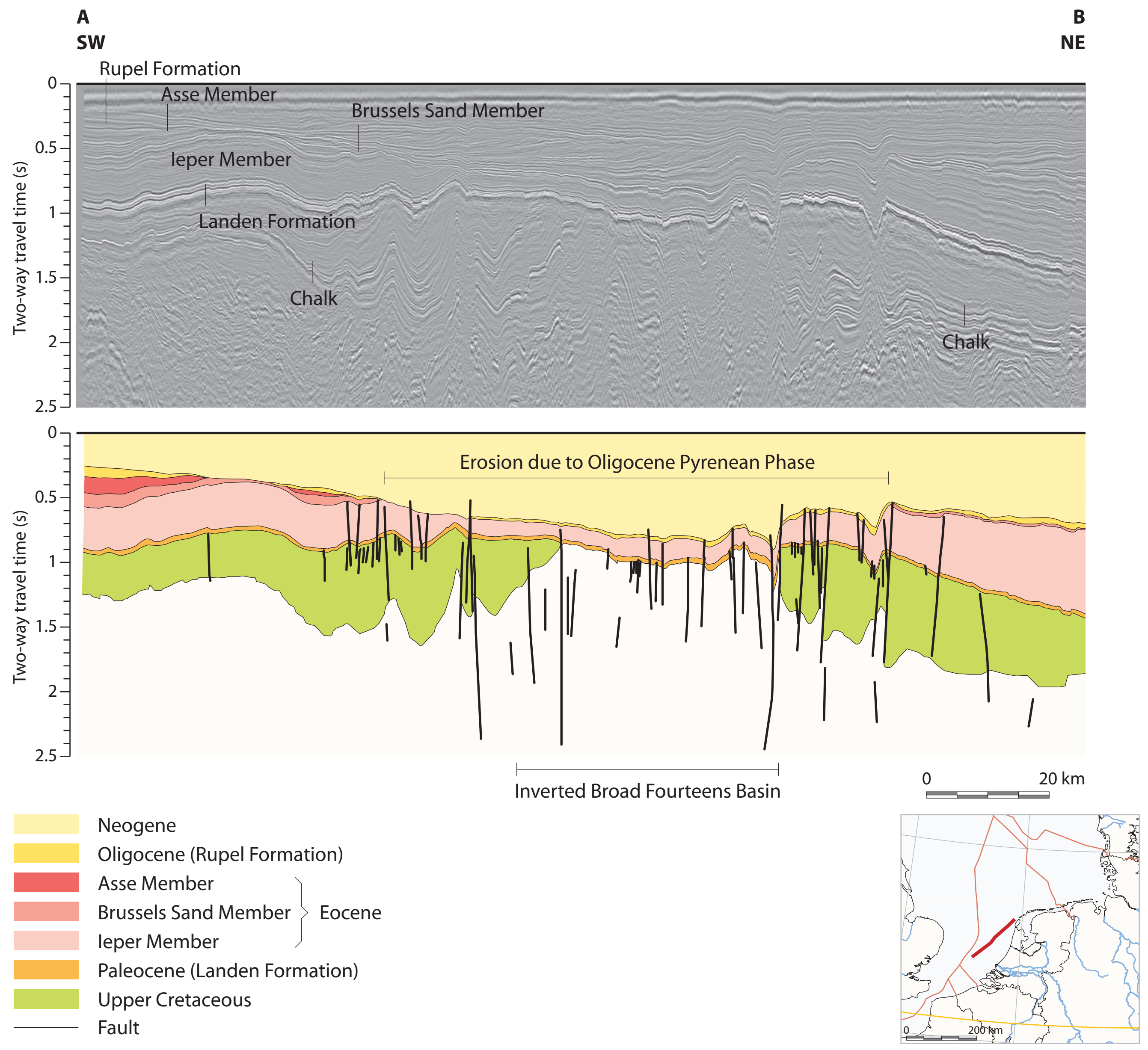


Figure 12.10 Seismic line SNST-83-02 and interpretation showing the distribution of Paleogene formations and members and the base of the Upper Cretaceous Chalk Series. The width of the Mesozoic Broad Fourteens Basin, and the area inverted during the Pyrenean Phase are shown. From De Lugt (2007).

It has long been recognised that there was an intermittent marine connection between the North Sea and the Upper Rhine Graben via the Hessian Seaway (see Berger et al., 2005; Sissingh, 2006), although Grim (2006) has doubted a connection with the Paratethys Ocean because of the endemic nature of the Upper Rhine Graben microfaunas. A seaway probably existed in the south-west, where the middle Rupelian succession is represented in the Paris Basin by tidal sands of the Fontainebleau Sands. The connection with the Atlantic was probably via the Loire Seaway, as the paralic sediments in the western Hampshire Basin suggest exposure of the Start-Cotentin Swell.

Renewed tectonic activity at the time of the Rupelian-Chattian transition, coupled with a glacially induced sea-level fall (Oi-2b event of Miller et al., 1998), amplified the palaeogeographical changes caused by the Eocene-Oligocene boundary tectonism. Emergence of the entire Fennoscandian area was accompanied by erosion over the Danish Shelf. Although the initial fall in sea level must have had a substantial eustatic component, the persistence of the new palaeogeographical configuration during subsequent Late Oligocene and Neogene sea-level highstands suggests an underlying tectonic cause. The absence of any major sediment influx along the eastern margin of the North Sea Basin during the Late Oligocene indicates that the newly formed land area had low relief.

Another effect of mid-Oligocene tectonism was the closure of the short-lived Hessian Seaway, which was associated with uplift and increased volcanic activity along the southern basin margin. Emergence in the Paris Basin area was probably accompanied by loss of connection with the eastern Atlantic. In the north, a shallowing of the Viking Graben resulted in bathyal environments becoming restricted to the central North Sea area.

Following the base-Chattian tectonic event, a progressive, probably eustatic, sea-level rise led to widespread marine transgression. Sandy facies are predominant along the south-western basin margin and muddy facies in eastern and south-eastern marginal areas (**Figure 12.9d**). Warm-water faunas with affinities to those of both the Atlantic and Paratethys oceans (Janssen, 1979) indicate renewed connections with marine waters to the west and south. Connection with the Paratethys Ocean via the Upper Rhine Graben can be ruled out, as paralic and nonmarine environments prevailed in the graben throughout Chattian times (Sissingh, 2006). However, a connection with the eastern Paratethys via the Moravian Seaway seems possible, as sediments of Chattian age in south-west Poland consist of marine glauconitic sands (lower Lesczno Formation). As seen in the Rupelian, it is likely that the Channel Seaway was closed as a result of exposure of the Start-Cotentin Swell. Marine connection via the Paris Basin and Loire Seaway is also unlikely as the reworked chalk microfossils in the Chattian of Belgium suggest that land lay to the south-west. Coastal regression in the south-east of the area since mid-Chattian times led to a change from mud-dominated to sand-dominated facies, and eventually to the establishment of paralic facies in the Lower Rhine Graben and on the Polish Platform, indicating closure of the Moravian Seaway. Following a period of nondeposition, renewed deposition of marine mudstones took place on the Danish Shelf in the latest Chattian, and the deep-water sandstones of the Freja Sandstone Member were deposited (Dybkjær & Rasmussen, 2007).

6 Miocene and Pliocene

The base of the Miocene is marked by a hiatus along much of the southern basin margin, reflecting a combination of tectonic activity related to the Savian Alpine phase and a eustatic sea-level fall caused by an increase in the volume of polar ice caps. Sedimentation appears to have been more or less continuous in deeper parts of the basin. The Savian tectonic phase was also marked by renewed inversion of the Sole Pit Basin (Van Hoorn, 1987) and the Sorgenfrei-Tornquist Zone (Rasmussen, 2009), and by inversion on the southern flank of the Ringkøbing-Fyn High and in the Danish Central Graben (Rasmussen, 2009) (**Figure 12.11**). It is probable that the Weald and Cleveland basins were also affected by inversion at that time. The inversion of the Danish Central Graben has been dated as Early Miocene (Rasmussen, 2009) and a similar age has been suggested for the Sole Pit inversion (King, 2006).

The Oligocene-Miocene unconformity is less distinct in the eastern SPBA area than in the west, reflecting enhanced subsidence following the Savian tectonic phase. Increased sediment supply in the eastern SPB was associated with the development of a major river system, the Baltic River, which drained a large area of Fennoscandia (**Figure 12.11a**). Heavy-mineral data from the Polish succession show a marked reduction in the number of epidote-bearing sands from the Oligocene into the Miocene (Vinken, 1988; Kramarska, 2006). The amphibole and epidote-rich sands that had been deposited in the north-western Polish area during earliest Oligocene times are found farther west in the Miocene (Vinken, 1988), indicating that the Baltic River flowed westwards along the trend of the present-day southern Baltic Sea. This is consistent with Bijlsma's (1981) record of the stratigraphic and geographical distribution of the distinctive Baltic Gravel Assemblage (see also Overeem et al., 2001), which largely consists of sedimentary rock types derived from the Lower Paleozoic rocks of southern Scandinavia. There was a marked progradation on the Danish Shelf in the Early Miocene as a result of uplift and inversion combined with increased sediment supply from

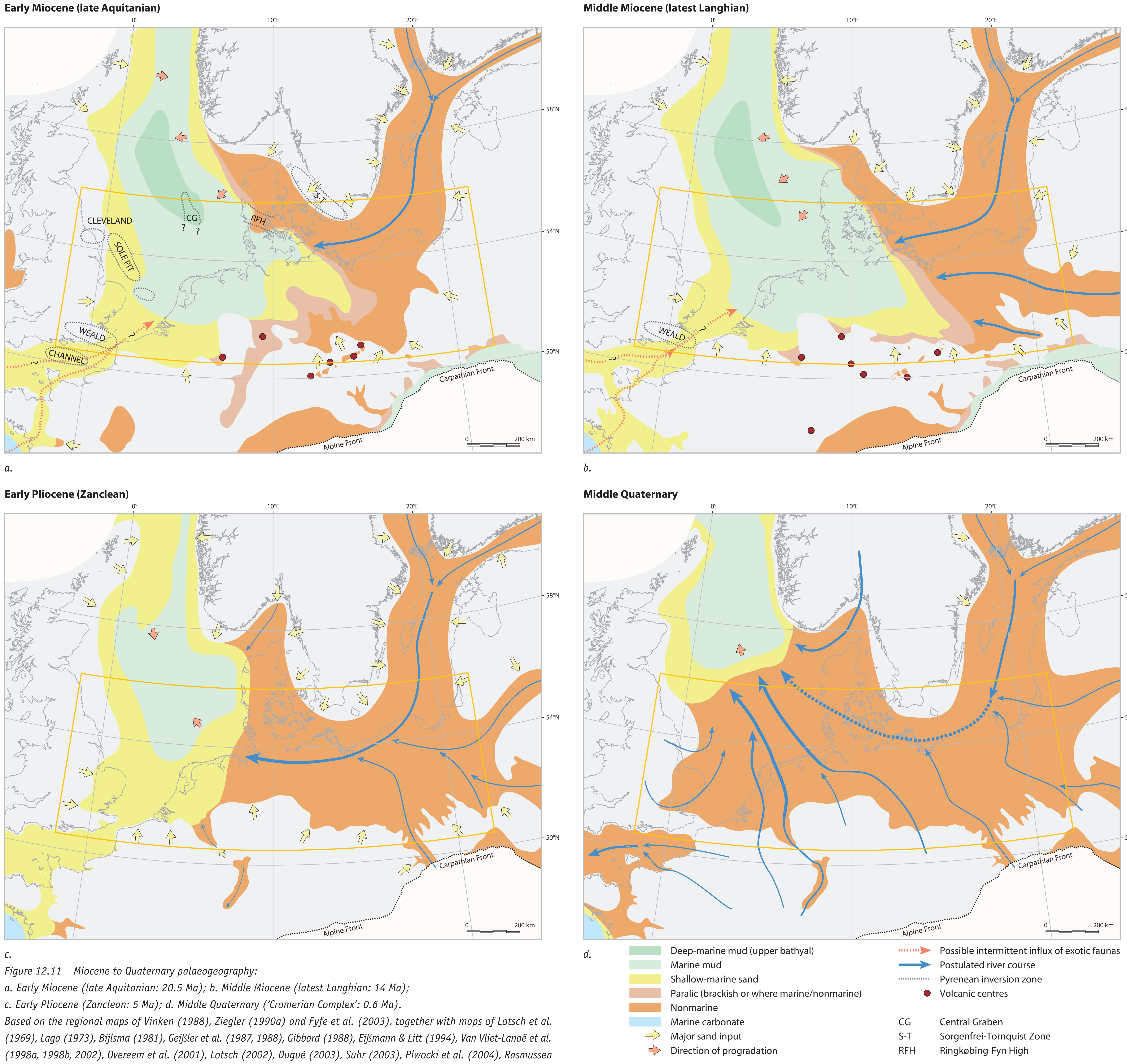


Figure 12.11 Miocene to Quaternary palaeogeography:
a. Early Miocene (late Aquitanian: 20.5 Ma); b. Middle Miocene (latest Langhian: 14 Ma);
c. Early Pliocene (Zanclean: 5 Ma); d. Middle Quaternary ('Cromerian Complex': 0.6 Ma).
Based on the regional maps of Vinken (1988), Ziegler (1990a) and Fyfe et al. (2003), together with maps of Lotsch et al. (1969), Laga (1973), Bijlsma (1981), Geißler et al. (1987, 1988), Gibbard (1988), Eißmann & Litt (1994), Van Vliet-Lanoë et al. (1998a, 1998b, 2002), Overeem et al. (2001), Lotsch (2002), Dugué (2003), Suhr (2003), Piwocki et al. (2004), Rasmussen (2004a), Berger et al. (2005), Hiss et al. (2005), Gürs (2005), Kuster (2005), Rascher et al. 2005, Ritzkowski (2005), Standke (2006, 2008b), Lustrino & Wilson (2007), Wolf & Alexowsky (2008), Rasmussen (2009). The location of Savian inversion structures in Figure 12.13A is modified from Nielsen et al. (2005). Bathyal limits are from King (unpublished data, 2009).

southern Norway and Sweden. Coastal progradation also took place to the south due to uplift of the Bohemian Massif and, to a lesser extent, in the Lower Rhine Graben. Higher energy conditions appear to have prevailed in the south-west of the basin, with widespread deposition of shallow-marine sands.

There is little information available for the western basin margin because of later Neogene uplift and erosion. However, the reworked marine Miocene fossils of East Anglia suggest that sedimentation may have extended into south-east England. There is faunal evidence for a marine connection with the Atlantic (Janssen, 2001; Janssen & Gürs, 2002) which must have been via the Channel Seaway as Lower Miocene deposits in the Paris Basin are nonmarine. This implies that any relief generated by inversion of the Central Channel and Weald basins must have been substantially reduced before the Early Miocene transgression. In this context it may be noted that comparably rapid erosion must have taken place over the Pyrenean inversion structures of the central Netherlands prior to the mid-Rupelian transgression.

A widespread transgression took place during Mid-Miocene times, with marine facies extending over much of the Danish Shelf and south-west Poland by the latest Langhian (**Figure 12.11b**). This transgression was caused by a eustatic sea-level rise associated with the Mid-Miocene climatic optimum (~17 to 14 Ma: Zachos et al., 2001), but in the south-eastern embayment of the North Sea it appears to have been enhanced by subsidence associated with increased southward tilting of the Fennoscandian Platform. In the northern and eastern Polish areas, there was a marked increase in the area of nonmarine sedimentation, with increased fluvial supply mainly from the east and north-east.

Faunal similarities with the Paratethys Ocean (Janssen & Zorn, 1993; Gürs & Janssen, 2002) suggest a connection via the Moravian Seaway, but no such marine connection is evident in the Polish succession. A marine ingression from the Paratethys Ocean into south-west Poland is known to have taken place somewhat later in the Mid-Miocene (Gedl & Worobiec, 2005), but appears not to have extended into the North Sea. As both the Upper Rhine Graben and Paris Basin were then areas of nonmarine sedimentation, the connection with southern waters must have been to the west via the Channel Seaway, as it was during the Early Miocene.

There was a distinct change in the tectonic regime of the North Sea region during the late Mid-Miocene, with accelerated uplift of Britain and Fennoscandia. Uplift of Fennoscandia, coupled with a marked deterioration in climate, led to a major increase in sediment supply to the south-eastern embayment of the North Sea via the Baltic River (Overeem et al., 2001). The South Swedish Dome also appears to have undergone relative uplift (Japsen & Bidstrup, 1999), while subsidence accelerated in the North Sea region. The pattern of uplift and subsidence established at that time has persisted to the present day, with a 1500 m-thick accumulation of sediment in the central North Sea since the Mid-Miocene (**Figure 12.6d**). Uplift along the Weald-Artois axis appears to have led to closure of the Channel Seaway, as warm-water faunas disappear from the North Sea Basin. Whether this was entirely due to regional uplift or to renewed inversion of the Weald Basin is not certain. The Baltic River deposits, as characterised by the Baltic Gravel Assemblage, extended farther west during the Late Miocene (Bijlsma, 1981). The absence of northerly derived epidote-bearing sands in the Upper Miocene succession of the Szczecin and Gdańsk areas (Vinken, 1988) indicates that the Baltic River flowed directly into present-day Germany.

Coastal regression around the North Sea margins was brought to a close by sea-level rise in the latest Miocene (see **Figure 12.2**). This is reflected in the occurrence of Late Miocene marine sediments with faunas of Atlantic affinity on the southern flank of the Weald-Artois uplift (Lenham Beds: Daley & Balson, 1999; King, 2006). At the time of maximum sea level in the Early Pliocene, it is likely that the Weald-Artois barrier was temporarily breached (**Figure 12.11c**). Within the North Sea Basin itself, sedimentation continued to be dominated by the Baltic River, which supplied vast amounts of sediment to the south-eastern embayment, leading to continued offshore progradation (Overeem et al., 2001; Kuhlmann & Wong, 2008). Elsewhere, the effects of sea-level rise were countered by continued uplift, most notably of the Scottish source areas, as shown by a major phase of southward progradation. Although no sediments of this age are preserved on the Danish Shelf, it seems likely that it was largely transgressed. Shortly after, the shelf underwent uplift and erosion associated with a major phase of exhumation of Fennoscandia including the South Swedish Dome (Japsen et al., 2007).

7 Regional Tertiary correlation panels

Regional stratigraphic correlation in the SPBA area is illustrated by two well-correlation panels. **Figure 12.12** shows a section across the Tertiary succession in the North Sea Basin, which is dominated by marine mudstones. The section in **Figure 12.13** shows a correlation between the late Eocene to Pliocene successions of the eastern North Sea Basin and the East German – Polish Basin, a conspicuous feature being the south-eastward increase in the proportion of paralic and nonmarine facies.

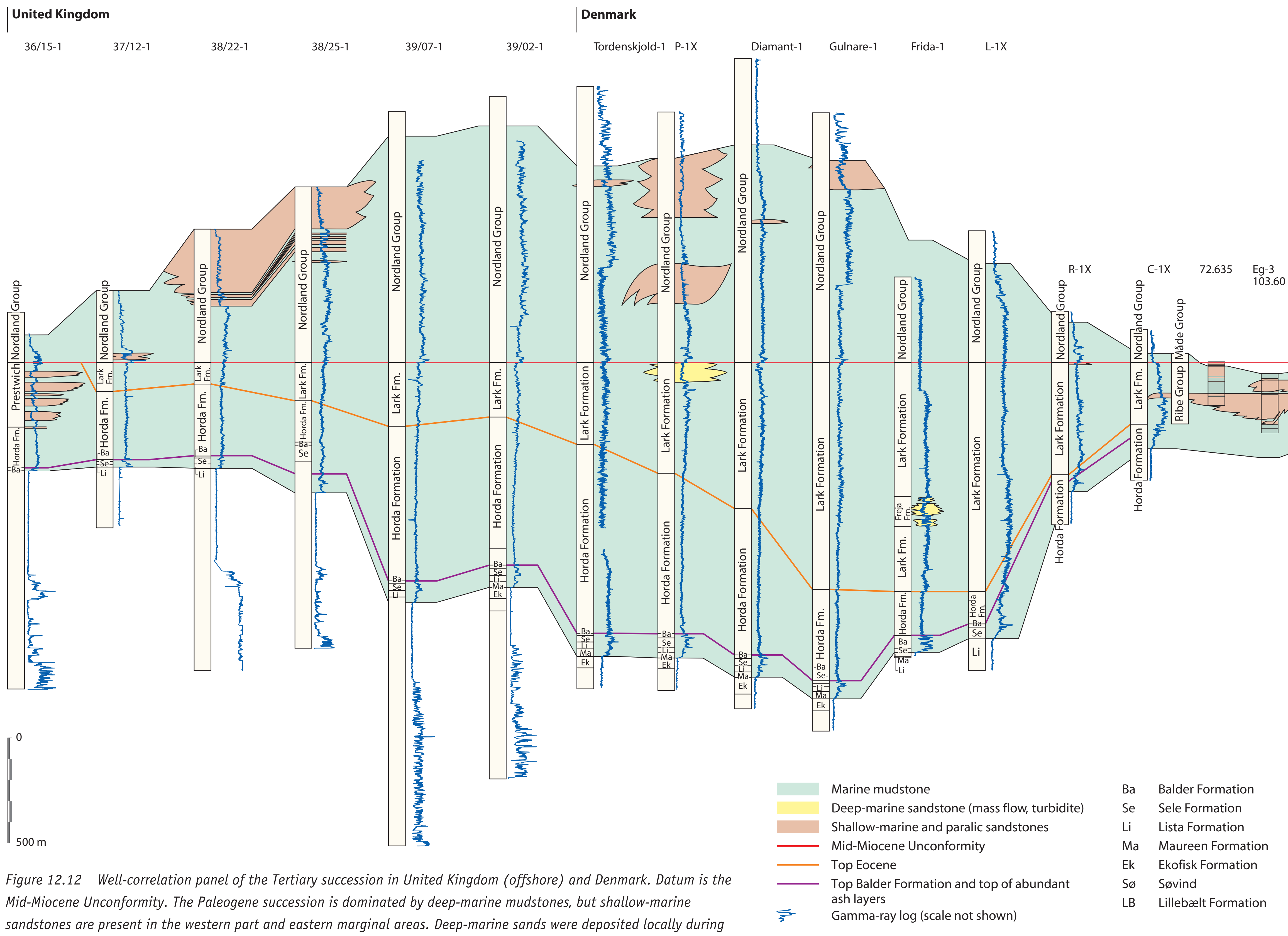
8 Quaternary

As outlined in the footnote on the first page of this chapter, the base of the Quaternary is now formally defined as corresponding to the base of the Gelasian (2 588 Ma). This level is close to that traditionally used to define the base of the Quaternary in north-west Europe and is the level used for the base-Quaternary structure contour map (**Figure 12.14**).

The proposed age for the base of the Quaternary is particularly relevant for the SPBA area as it marks the onset of a period of climatic cooling that led to the rapid disappearance of many tree species that are found today in subtropical areas of North America and South-east Asia (Donders et al., 2007) and led eventually to the extension of ice over much of the SPBA area. Traditionally, four phases of ice extension have been recognised in mainland north-west Europe, referred to as Elsterian, Saalian and Weichselian ice ages. Apart from the glacial stages, a higher number (about 14) of interglacial stages has been identified in the course of palynological investigations during the last 50 years. However, subsequent studies on deep-sea successions have shown that the onshore record is very incomplete and that there were more than 50 warm-cold cycles during the Quaternary (Shackleton et al., 1995). These cycles had an initial duration of about 41 ka, but about 700 ka BP the duration changed to approximately 100 ka. In north-west Europe, the more intense cold periods were associated with the last 400 ka. During these cold periods, the largest ice sheet was centred on Scandinavia, while smaller ice sheets were established in Scotland and north-west England.

The pattern of sedimentation established during the latest Tertiary (**Figure 12.11c**) persisted into the Early Quaternary, with large amounts of sediment derived from the areas of southern Scandinavia, Finland, the Baltic states and Poland entering the south-eastern embayment of the North Sea via the Baltic River System (see Gibbard, 1988), known as the Eridanos River System (Overeem et al., 2001). This led to continued westward progradation, which is marked on seismic profiles by prominent delta-slope foresets (e.g. Cameron et al., 1993; Overeem et al., 2001), and to the eventual accumulation of about 62 000 km^3 of sediment (Overeem et al., 2001). Whereas no change in foreset morphology is apparent at the transition from the Pliocene to Quaternary, a massive increase in the rate of sediment accumulation is believed to have taken place from about 6 km^3/Ma at the end of the Pliocene to about 30 km^3/Ma in the earliest Quaternary (Gelasian Stage) (Kuhlmann & Wong, 2008). This increase is attributed to a deterioration in climate causing breaches in the plant cover and a considerable increase in the rate of erosion. The Baltic River deposits consist of quartz-rich sands and the distinctive Baltic Gravel Assemblage (see above), which includes silicified limestone clasts derived from the Lower Paleozoic succession of the Baltic region (Bijlsma, 1981).

The phase of accelerated delta progradation came to an end about 900 ka and the Baltic Gravel Assemblage became mixed with gravel and sands originating from the Mittelgebirge Highs to the south (Bijlsma, 1981). There is no direct indication as to whether or not the Baltic River continued to supply sediment at that time, or if the Baltic River components represent reworking of earlier deposits (Bijlsma, 1981). However, because the provenance change was associated with the first of the major glaciations to affect north-west Europe at that time, as reflected by ice-rafted Scandinavian erratics in the 'Hattem Beds' (e.g. Zandstra,



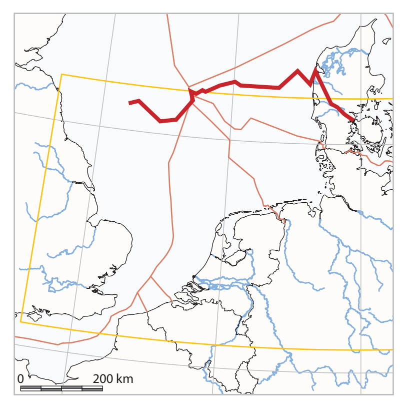


Figure 12.12 Well-correlation panel of the Tertiary succession in United Kingdom (offshore) and Denmark. Datum is the Mid-Miocene Unconformity. The Paleogene succession is dominated by deep-marine mudstones, but shallow-marine sandstones are present in the western part and eastern marginal areas. Deep-marine sands were deposited locally during the latest Oligocene and Early Miocene. In the eastern part, shallow marine sands of the Lower Miocene Ribe Group were deposited in association with Early Miocene inversion tectonism. Deposition of shallow-marine sands began to dominate in the Early Pliocene and from the Gelasian onwards.

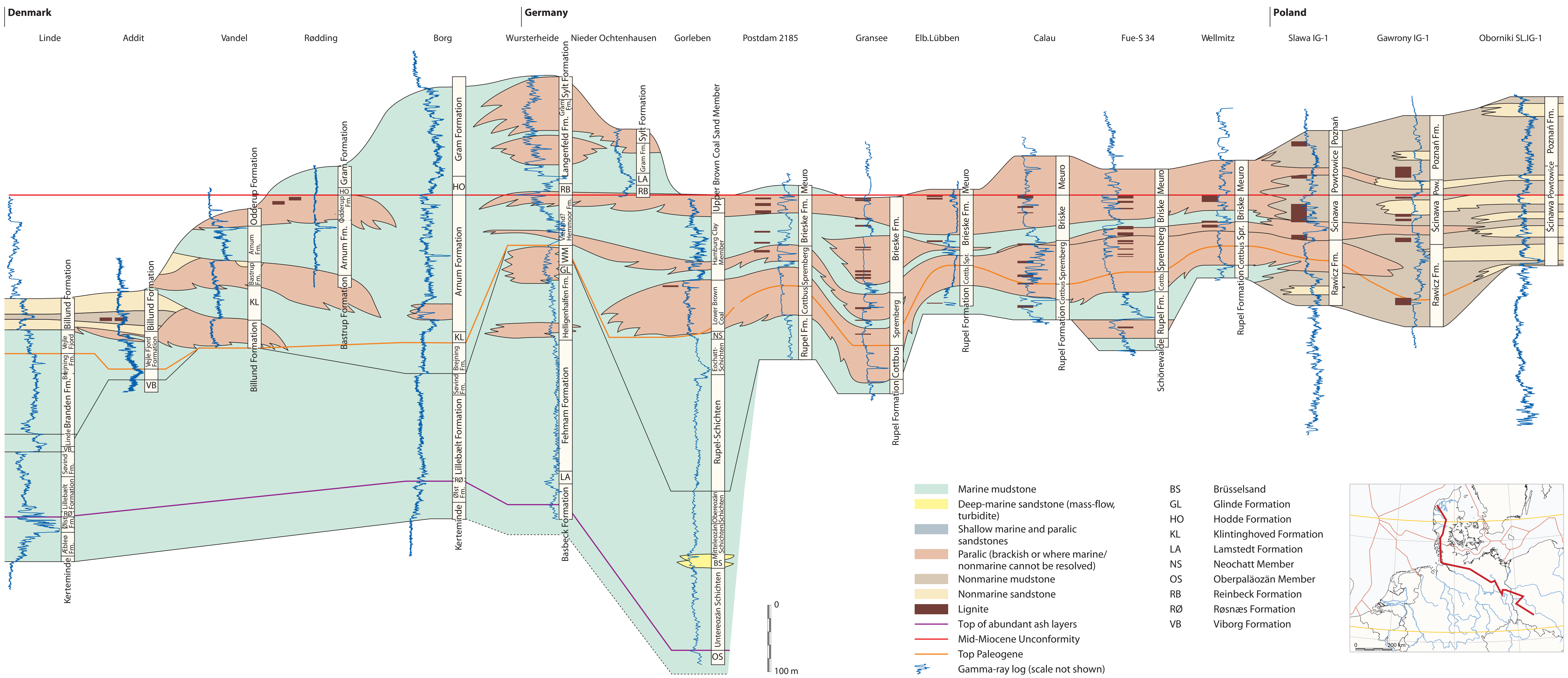


Figure 12.13 Well-correlation panel of the Tertiary succession in Denmark, Germany and Poland. Datum is the Mid-Miocene Unconformity. The north-western area is dominated by Paleogene marine mudstones deposited in a bathyal depositional environment. This is abruptly overlain by Early Miocene shallow-marine deltaic deposits. The marked change was the result of Early Miocene inversion tectonism. An initial phase of progradation of a fluviodeltaic system took place during the Late Oligocene, which continued into the Neogene with widespread lignite formation. Note that the Neochatt Member, Oberpaläozän Member and Reinbeck Formation represent older published names that are not shown on Figure 12.5.

1971), it is likely that a fundamental change in the physiography of the Baltic area had taken place. Destruction of the upper reaches of the Baltic River drainage system (Bijlsma, 1981) would have reduced the potential for sediment output, whereas glacial scouring in the southern Baltic and Kattegat areas could have provided an alternative route for the course of the Baltic River. These geographical changes set the scene for the remainder of the Pleistocene, as sediments of Baltic River derivation are entirely missing from the sedimentary record of the Netherlands and Germany (Bijlsma, 1981).

Another factor that may have contributed to the disappearance of Baltic River sediments from onshore northern Europe during the Mid-Pleistocene is the accelerated uplift of the Ardennes-Rhenish and Bohemian massifs (e.g. Van Balen et al., 2000; Tyráček et al., 2004). The establishment of a regional palaeoslope to the north, coupled with climatic deterioration, led to increased sediment supply from the south, with the rivers Saale, Elbe, Weser, Rhine, Meuse and Thames providing the bulk of the sediment that accumulated in the southern North Sea area. Despite the diminished contribution from the Baltic River, the delta is thought to have occupied much of the southern North Sea area (**Figure 12.11d**).

During the Elsterian (~450 ka BP), land ice blocked northward drainage from the southern North Sea into the Norwegian Sea (e.g. Huuse & Lykke-Andersen, 2000). The existence of a landbridge between France and the British Isles (the Weald-Artois landbridge) caused a large freshwater lake to develop in the area to the south of the ice front. During this period, glacial meltwater eroded deep valleys under the ice sheet, some cutting as much as 400 m into the subsurface and forming prominent features on seismic sections in the North Sea (Praeg, 1997). These valleys have been studied in detail using 3D-seismic data (Kristensen et al., 2007). In the example from the southern North Sea (**Figure 12.15**), an infill showing northward-dipping reflectors was caused by sedimentation from fast-flowing meltwater. Similar valley systems can be traced southwards onshore. Here, the succession with northward-dipping reflectors has been shown to consist of very thick upward-fining sand layers deposited by water flowing to the south (Bosch et al., 2009). The valley-fill sequence is locally capped by a stiff glaciolacustrine clay unit that is more than 100 m thick in places.

Overspill of water from the Elsterian southern North Sea lake carved a deep channel in the Weald-Artois landbridge, which was subsequently widened by marine erosion to form the Strait of Dover. This channelling was thought by Gibbard (1988) to have taken place during successive periods of lake overspill, but Gupta et al. (2007) have proposed that it was formed in a single catastrophic breaching.

At the start of the Holocene 10 000 years ago, a large area of the present-day southern North Sea was land. The susbsequent postglacial sea-level rise flooded the area, isolating the British Isles from the rest of the European continent. There has been little change in the configuration of the North Sea coastline or drainage pattern of the land areas since about 5 ka BP.

Several phases of volcanic activity have been documented in the Eifel area during the last 500 ka (Bogaard & Schmincke, 1990). The most recent large eruption took place in the Laacher See area about 12.9 ka BP. Tephra deposits resulting from this eruption have been found over large parts of north-west Europe, reaching eastwards as far as western Poland.

9 Fossil fuels

The Cenozoic deposits of the onshore SPB area contain the world's largest commercial reserves of brown coal (lignite) (Dill et al., 2008). Due to their low rank, the Cenozoic coals have not generated significant quantities of gas either onshore or offshore. No oil accumulations are known within the Cenozoic of the SPBA area, although between 1859 and 1971 oil was extracted from Eocene bituminous shales in the Messel district south of Frankfurt (Schaal & Schneider, 1995; Raab, 1998). These shales are now better known for the remarkable preservation of their vertebrate fauna (e.g. Schaal & Ziegler, 1992), which are now thought to include the earliest known primate (Franzen et al., 2009). Shallow gas, believed to be of biogenic origin, is encountered widely in the offshore southern North Sea, and occurs in commercial quantities in the northern part of the Dutch offshore sector (see Chapter 13).

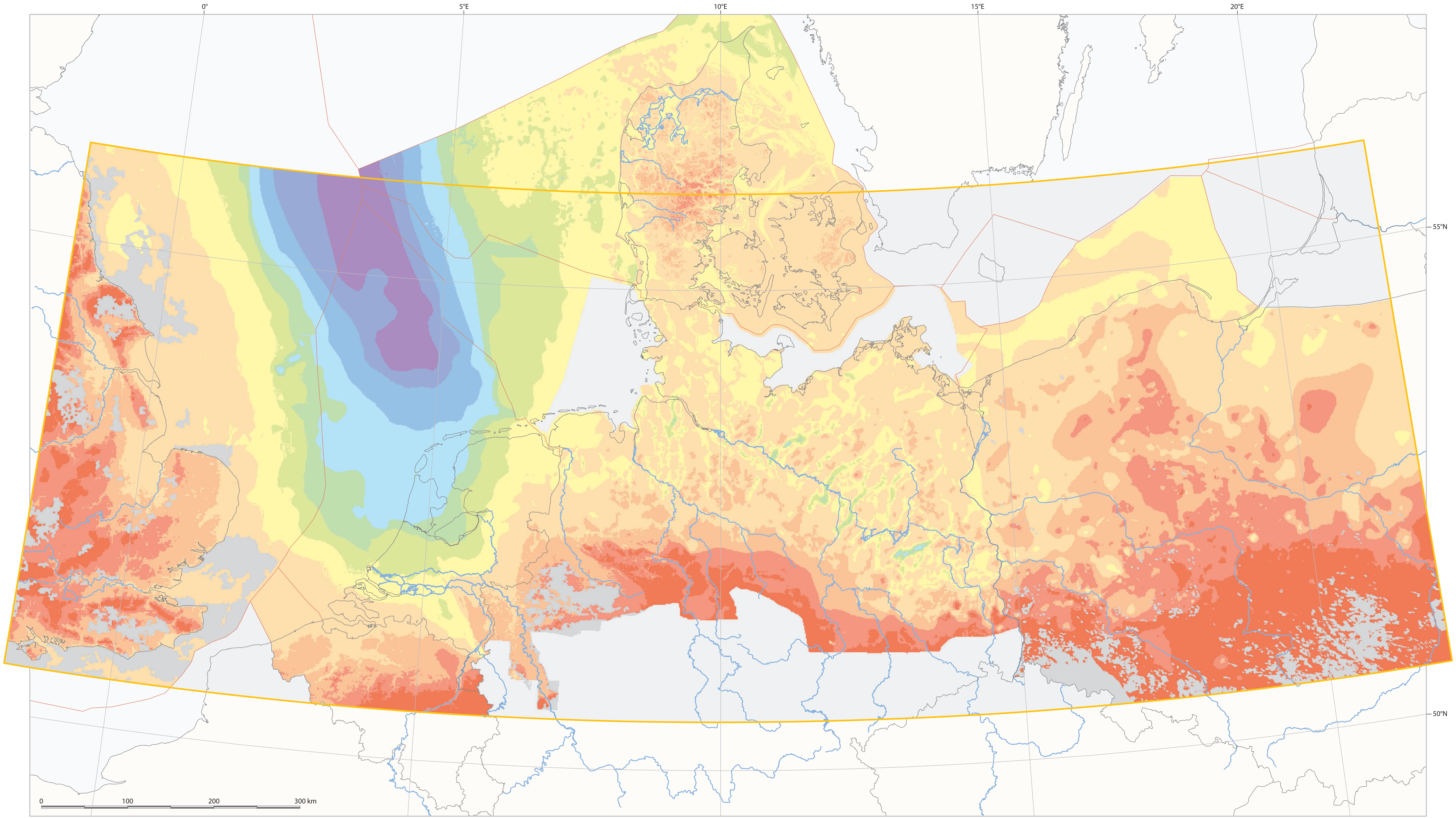
9.1 Cenozoic coals

Low-rank coals are found at many levels in the Cenozoic of the SPBA area, but present-day commercial exploitation is confined to the latest Paleocene and Lower Eocene deposits of north-west Germany, the Middle and Upper Eocene of eastern Germany, and the Miocene of the Lower Rhine Embayment, eastern Germany and Poland. Except for the Lower Rhine Embayment, the stratigraphic distribution of coals (**Figure 12.16**) reflects the progressive eastward shift in the focus of paralic and terrestrial sedimentation through time (see **Figure 12.5**). A recent summary of the stratigraphic distribution and economic history of the Cenozoic coals is given by Dill et al. (2008). Although the coals are the same throughout the region, they have traditionally been described as 'brown coals' in the Lower Rhine Embayment, north-west Germany and Denmark and as 'lignites' in east Germany and Poland (see Chapter 16).

The Miocene brown coals of Denmark occur in the Fasterholt Member of the Odderup Formation, where they consist of three seams with individual thickness up to about 2 m (Koch, 1989). The coal was once extracted from several opencast mines in the Søby-Fasterholt area, but production at the main Søby mine ended in 1970.

The highest brown coal/lignite production in Europe is from the Cenozoic deposits of the Lower Rhine Embayment (Dill et al., 2008). The coals occur in a north-west–south-east-trending graben, about 100 km long and 50 km wide. The seams that are currently exploited include the Main Seam (Hauptflözgruppe) of the Miocene Ville Formation and several thinner seams within the overlying Inden Formation. Further details are given in Hager (1993) and Schäfer et al. (2004).

The Paleocene to Eocene coals of the Helmstedt and Egeln areas are found in long, narrow rim-synclines around salt structures. The Main Seam at Helmstedt (related to the 'Lower Eocene Beds') is still being mined at the Schöningen mine. The Eocene (Lutetian) succession at Geiseltal is characterised by several thick lignite seams and particularly by a remarkable vertebrate fauna, which has an even more diverse

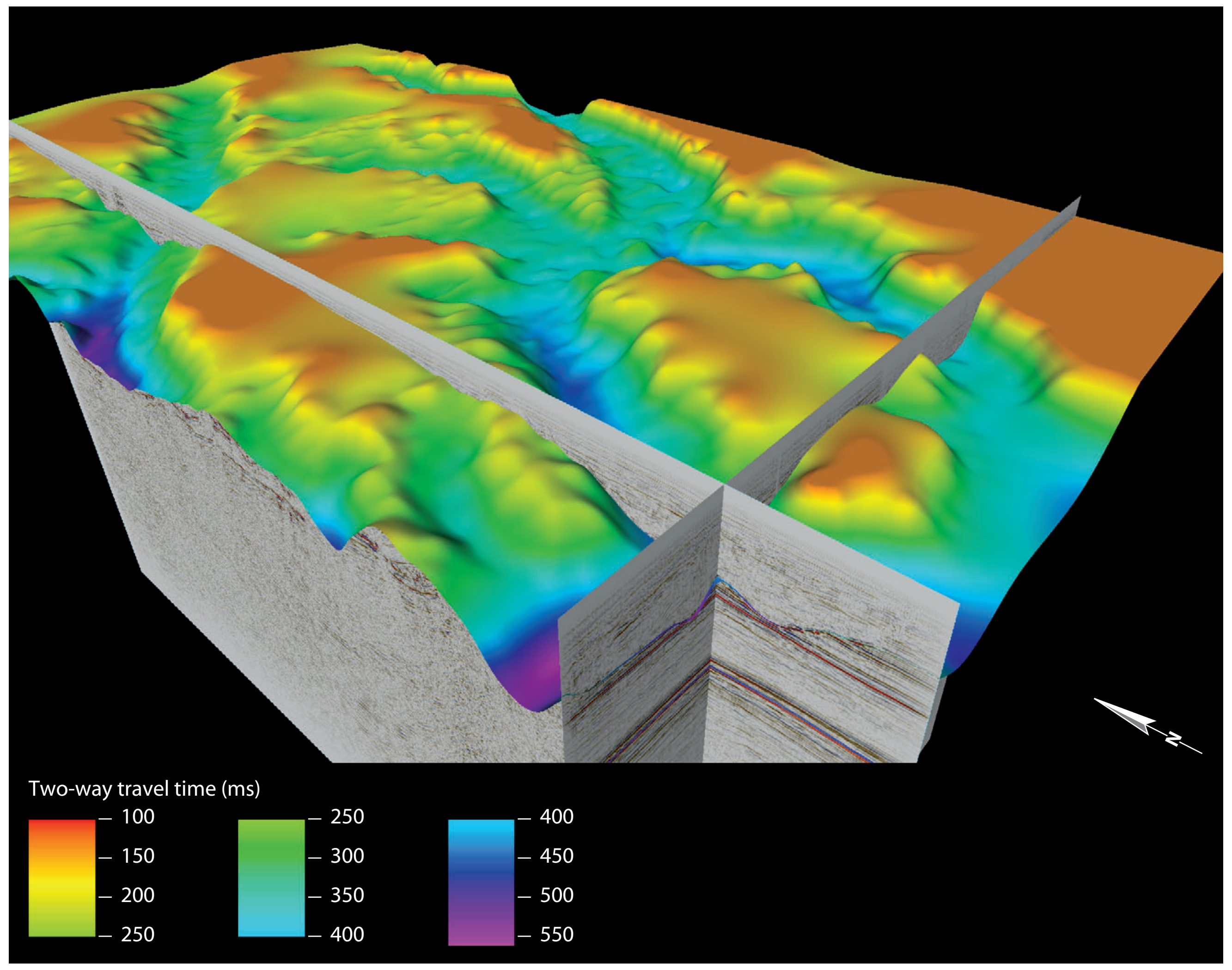


Height in metres above sea level
- >100
- 50 - 100
- 0 - 50

Depth in metres below sea level
- 0 - 100
- 100 - 200
- 200 - 300
- 300 - 400
- 400 - 600
- 600 - 800
- 800 - 1000
- >1000

- Not present
- Not included in the Atlas map compilations

Figure 12.14 Depth to the base of the Quaternary. The base of the Quaternary is at a depth of over 1000 m in the North Sea Basin. The deposits have a maximum thickness of 900 m. These deposits are also thick in the Roer Valley Graben in the southern part of the Netherlands. In general they have a mean thickness of 300 m, reducing towards the rim of the basin. The main infill of the North Sea Basin came from the Baltic (Eridanos) River until ~700 000 years ago and thereafter the North German rivers and the rivers Rhine, Meuse and Thames. The surface mapped by Overeem et al. (2001) is the base of seismostratigraphic unit D4, dated at ~7.5 Ma. By studying dinoflagellates, Kuhlmann & Wong (2008) demonstrated this surface to be the base of the Gelasian, i.e. the base of the Quaternary. The available maps for the UK offshore (unpublished compilation by P.S. Balson, British Geological Survey, 2008) and for the German offshore (Brückner-Röhling et al., 2005) have been fitted at the national boundaries by adjusting the mapped surface to the base of the Gelasian. Data for the onshore areas has been provided by the national geological surveys, whereas the map for Poland has been taken from Garetsky et al. (2001). Data for the Polish offshore area are from Kramarska (2006).



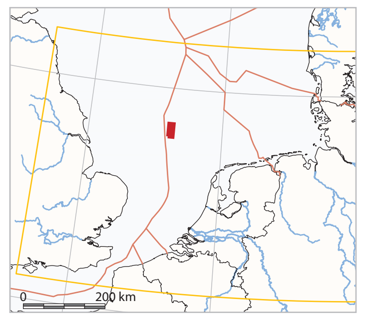


Figure 12.15 Interpreted Elsterian glacial valleys in a 3D-seismic survey in the K10 and K13 blocks of the Dutch North Sea (Survey WIN1990C, see location map). The valleys locally incise the base-Miocene unconformity to a depth of more than 500 m below sea level. On the 3D-seismic profiles the valley (channel) fill deposits display an internal structure of northward dipping reflectors. These are believed to have been generated by fast-flowing meltwaters from the north. (Courtesy of Serge van Gessel, TNO).

range than at Messel. Unfortunately, the deep mines and their unique fossils have been flooded in recent years. Lower and Upper Eocene lignites are found in the Amsdorf and Halle areas.

The Eocene to Lower Miocene lignites of the Bitterfeld-Leipzig area of east Germany are more extensive than those of the Helmsted and Egeln areas. Individual seams are typically 10 to 15 m thick, but are locally more than 50 m thick as a result of salt movement. The two seams that are currently exploited occur within the Profen and Borna formations (**Figure 12.5**). Farther east, in the Lausitz (Lusatia) area, the lignite seams are mostly of Miocene age; the only seam currently being exploited is in the Middle Miocene succession (Welzow Member of the Brieske Formation). Further details are given in Baumann & Vulpius (1991), Schneider (1995), Rascher (2002, 2009), Standke et al. (2005), Präger et al. (2003), Standke (2006, 2008a, 2008b) and Bachmann et al. (2008).

The Cenozoic lignite deposits of Poland are mostly found in the western and central parts of the country, especially in the Polish Lowlands area. They range in age from Late Paleocene to Late Miocene, but commercial exploitation is limited to three seams in the Lower to Middle Miocene Ścinawa and Poznań formations. These seams extend over areas ranging from 30 000 to 70 000 km^2 and are typically up to 35 to 40 m thick. Much greater thicknesses are found in tectonic depressions such as the Bełchatów deposit in the Kleszczów Trough, where the clastic sediments and associated seams are up to 250 m thick (Kasiński et al., 2000a) (see Chapter 16 frontispiece). Further details are given in Ciuk & Piwocki (1990), Piwocki (1992, 1998a), Kasiński & Piwocki (2002), Kasiński (2004) and Kasiński et al. (2008).

9.2 *Cenozoic shallow gas*

Shallow-gas accumulations are found widely in Upper Cenozoic (mainly Plio-Pleistocene) sediments of the offshore SPBA area, where they form distinct bright spots on seismic profiles (e.g. Appel, 2007). The gas is probably of both biogenic (microbial) and thermogenic origin, as explained in Chapter 13. Most of the shallow-gas accumulations are of no commercial value, but since potentially commercial production rates were encountered in 1988 (De Jager & Geluk, 2007), several fields are now in production in the northern Dutch offshore sector (A and B blocks: see Chapter 15, Figure 15.13).

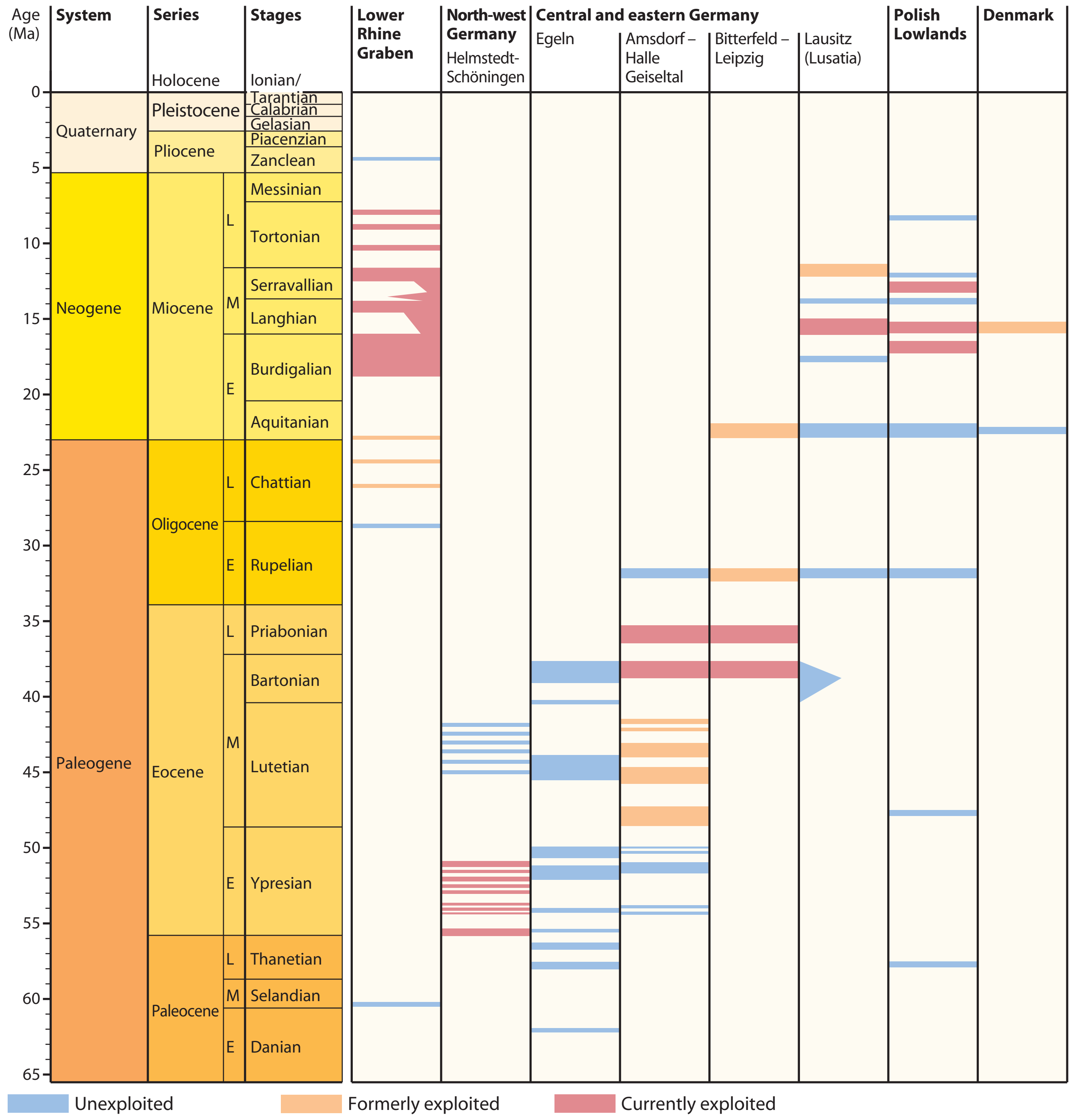


Figure 12.16 Stratigraphic distribution of coals and lignite in the Cenozoic of the Southern Permian Basin area (after Kuhlmann et al., 2006 and Standke, 2008c). Timescale from Gradstein et al. (2004).

10 Hydrocarbon field example

10.1 *A15-A gasfield, offshore Netherlands*

The A15-A gasfield (**Figure 12.17**) is located offshore in the northern Dutch sector about 250 km from the mainland in a shallow anticlinal dip-closed structure (see Section 5.4 of Chapter 15). Appraisal well A15-3 drilled in 1999 by Wintershall tested dry gas at over 10 MMscf/d. It is planned to develop the field using vertical wells with sand-exclusion measures to avoid sand production.

Table 12.1 Properties of the A15-A field.

Reservoir	Quaternary sands
Lithology	Sandstone
Depth to top (m)	400
GWC/GOC.OWC (m)	644
Maximum column height (m)	244
Net reservoir thickness (m)	43
Net to gross ratio	18
Porosity (%)	29
Gas saturation	40%
Permeability (mD)	10mD
Fluid type	Gas
Gas composition	CH_4 99%, N_2 0.4%, CO_2 0.02%
Initial pressure (bar)	800
Temperature (°C)	15-25
Source rock	Biogenic gas
Seal	Upper North Sea Group shales

The stacked reservoir intervals can be seen on seismic records as high-amplitude reflections (bright spots; **Figure 12.18**) with each interval having a slightly different areal extent, suggesting that the combination of gas-column thickness and gas saturation are having an impact on the seismic response. The gas in the A15-A field is structurally trapped, as reflectors show a 4-way dip closure on depth-converted seismic profiles. As the gas is inferred to be of biogenic origin, the area of gas production may also be limited.

The reservoir consists of seven stacked Upper North Sea Group sandstone units at depths between 400 m and 650 m total vertical depth (TVD). The reservoir sands are Quaternary in age and represent deposits of fluvial/deltaic/paralic origin (Kuhlmann et al., 2006) and are predominantly fine grained and well sorted, which combined with the lack of compaction and cementation result in high porosities (**Table 12.1**).

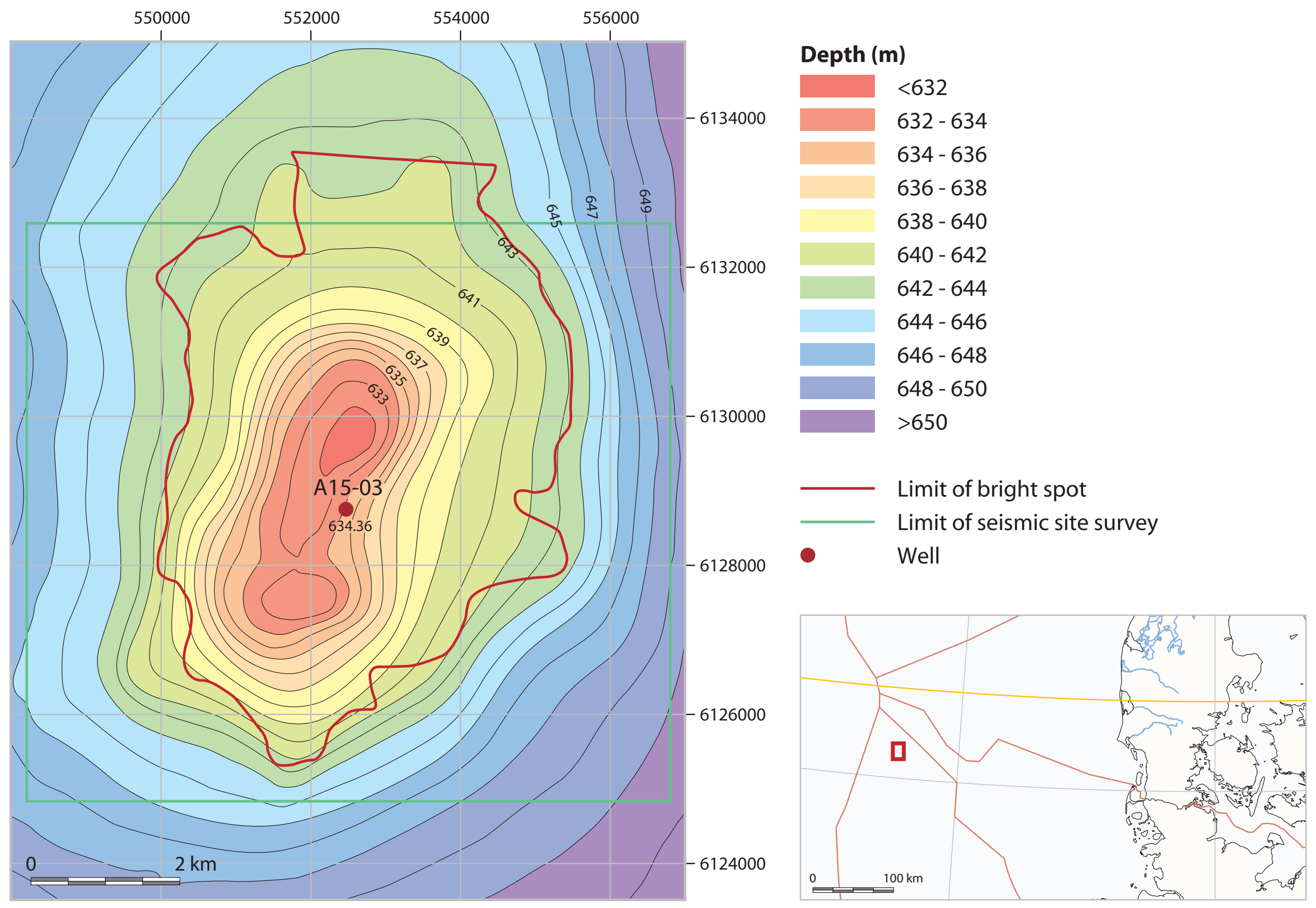


Figure 12.17 Depth of the A70 reservoir zone in the A15-A gasfield. (Courtesy of Centrica Energy).

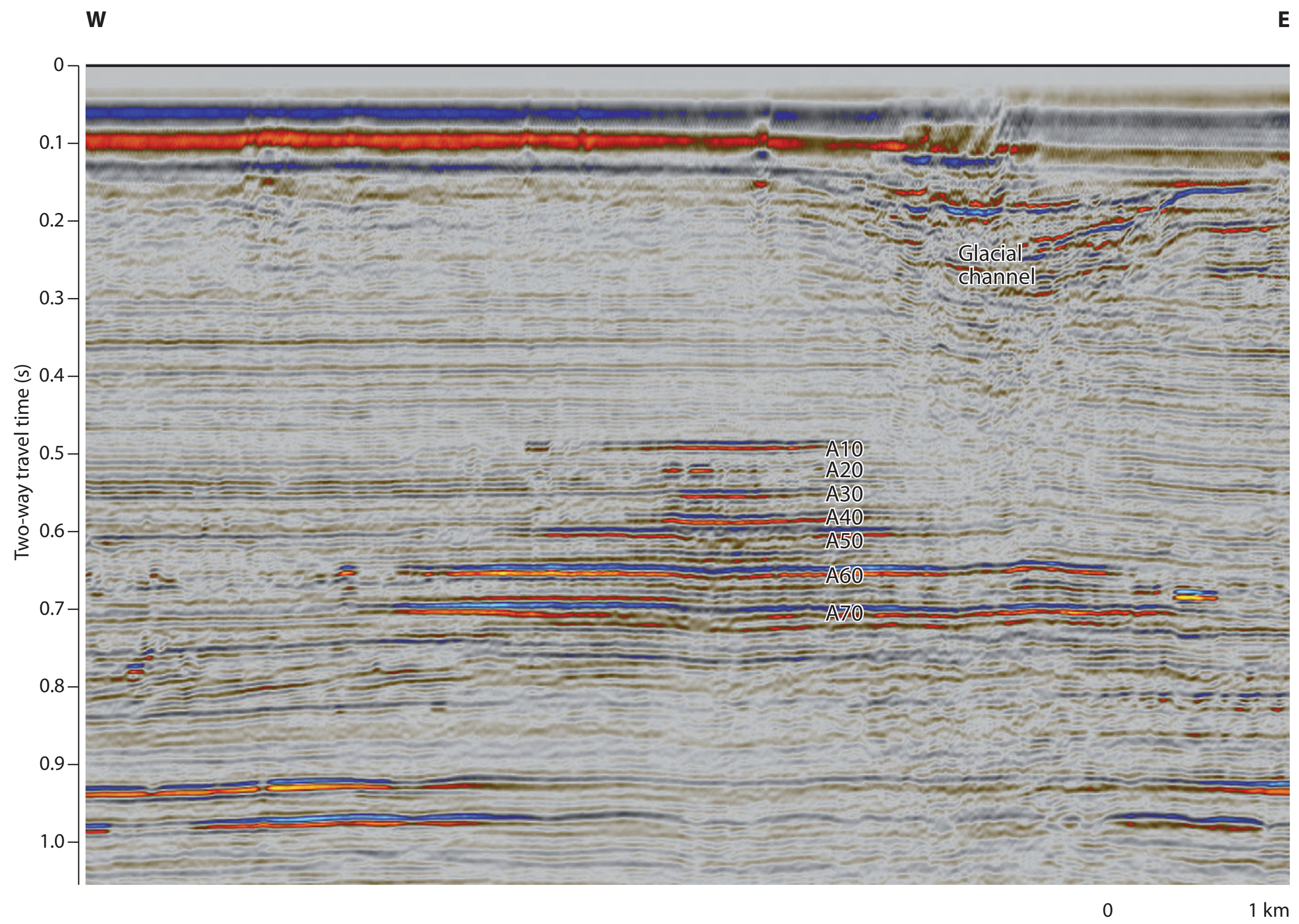


Figure 12.18 Seismic section through the A15-A gasfield showing high-amplitude events of gas-bearing reservoir zones. Note that because the seismic profile is in two-way time, the reflectors appear to be flat. When depth converted, however, they show a 4-way dip-closed structure. (Courtesy of Centrica Energy).