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

1 Introduction

Until the late Quaternary, sedimentary rocks within the SPBA area were deposited within a single depocenter 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 1.1).

The Cenozoic 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 reservoirs in the Palaeocene and Eocene rocks of central and northern North Sea. There are no significant hydrocarbon reservoirs 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 by Ziegler (1991a, 1991b) and Cameron et al. (1992). The palaeogeography of the SPBA area has been summarized by Cameron et al. (1985a, 1985b, 1987) and Cameron & Norling (1973) for North-eastern Poland (Kosmowska-Ceranowicz, 1988; Kramarska et al., 2004; Kramarska, 2006) indicates that the onset of uplift took place earlier in association with the Pyrenean tectonic phase. However, some authors (e.g. Håland et al., 2005) have proposed that the associated Mid-Paleozoic inversion tectonics took place under a regime of strong relaxation.

A key question in the construction of Mid-Paleozoic to Eocene palaeogeography is the extent to which the platform areas to the north-west and north of the North Sea Basin acquired a sedimentary cover. Previous regional reconstructions have shown the Baltic Platform as a largely nondepositional (e.g. Ziegler, 1988; Ziegler, 1991a; Ziegler & Horváth, 1996). However, it is likely that sea-level rise in the Eocene and also in the Late Cenozoic led to marine inundation of much of the Fennoscandian Platform (Johannes et al., 1995), whereas the Caldogna belt marking the western edge of the Baltic Platform is believed to have remained emergent from the Mid-Eocene onwards. This interpretation is based on evidence of a substantial uplift and erosion during the Laramide, Pyrenean and Savian tectonic phases (Chapter 3). On the eastern margin of the present-day North Sea Basin, the Ringkøbing-Fyn High was an area of emergent land at this time (Rasmussen et al., 2002). The position of these areas at this time is not known for the north-eastern North Sea Basin, but the onset of uplift took place in the late Miocene to Pliocene period (Japsen et al., 2002, 2007) and further uplift in the earliest Miocene (Rasmussen, 1992). There is no evidence that these structures had a significant influence on the palaeogeography of the Baltic or southern Baltic regions. The structures are shown as emergent (though low-lying) until the Late Eocene (Lotsch, 1969). The Harz Swell is here shown as an emergent area from the Middle Miocene onwards, but the evidence for sediment supply from the north of the Harz region is limited to the late Miocene (Dyke et al., 2003 for the post-Messinian). Maps of the Neogene of central and eastern Europe are provided by Hain (1998).


The North Polish Platform was bounded to the south-west by the Mid-Paleozoic high, which developed as a result of the loss of a large number of deep marine clastics during the Early to mid-Palaeozoic (Larsson, 2005). In the late Cretaceous and Early Tertiary (Middle Eocene) a series of major inversions led to the formation of a pronounced palaeogeographical feature for much of the Palaeocene, but was progressively eroded during Early to Mid-Eocene times and largely transgressed during the Late Eocene such that the platform no longer formed a significant topographical feature by the Early Eocene. Long-term subsidence of the North Polish Platform began in the late Eocene and continued into the Miocene, when a regional change in stress patterns uplifted along the southern basin margin.

The Fennoscandian Platform underwent combined progressive uplift and southern tilting from the Oligocene onwards, resulting in the establishment of a pronounced north to south palaeoapex in the present-day Baltic region. This fundamental change in tectonic configuration appears to have been associated with a reorganization 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 Tethyan Ocean and the formation of the Paratethys Ocean. Clastic deflection from the Mid-Paleozoic 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 south-eastern deflection of palaeoflow towards the northern North Sea Basin during the Early Miocene therefore reflects the relative uplift of southwestern Norway (Michaelis et al., 1995, 1996, 1998; Riis, 1996). The alternative interpretation that these changes were solely due to climatic deterioration (e.g. Håland, 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 Eocene to Early Miocene and in the Early Oligocene. 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 Lutetian, Palaeocene and Eocene tectonic phases (Figure 12.4). However, the high has had a significant effect on the subsidence pattern since Mid-Miocene times. The Sverdrup Trough Zone underwent major inversion during Mid-Miocene times (Skou et al., 1988) and further uplift in the earliest Miocene (Rasmussen, 1992). There is no evidence that these structures had a significant influence on the palaeogeography of the Baltic or southern Baltic regions. The structures are shown as emergent (though low-lying) until the Late Eocene (Lotsch, 1969). The Harz Swell is here shown as an emergent area from the Middle Miocene onwards, but the evidence for sediment supply from the north of the Harz region is limited to the late Miocene (Dyke et al., 2003 for the post-Messinian). Maps of the Neogene of central and eastern Europe are provided by Hain (1998).

The SPB was bordered to the south by a complex series of structural highs located in present-day Germany, here referred to collectively as the Mittelgebirge Highs (Figure 12.3). One conspicuous feature of the northern coastline was the narrow peninsula formed by the Flodvalling Shallow, which remained more or less continuous throughout the last 40,000 years and supplied much of the Late Cenozoic sediments that fill the North Sea Basin.

The BSP was bordered to the south by a complex series of structural highs located in present-day Germany, here referred to collectively as the Mittelgebirge Highs (Figure 12.3). One conspicuous feature of the northern coastline was the narrow peninsula formed by the Flodvalling Shallow, which remained more or less continuous throughout the last 40,000 years and supplied much of the Late Cenozoic sediments that fill the North Sea Basin.
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.
The marine waters of the Tertiary North-west European Basin and those of neighboring 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 physical occurrence.

There was a connection with the Faroe-Iceland Basins via the North Atlantic Ocean (Schmitz, 2002; Grammenos & Thomas, 2005) in mid-Paleocene times, but this closed during the end-Oligocene due to uplift of the North Polish Platform. The Norwegian Seaway was re-established during the late Middle-Eocene, Late Eocene (Grammenos & Kirkbride, 1988; Ziegler, 1990a), Early Oligocene (Popov et al., 2004) and possibly in the Late Oligocene (Jansen, 1979). An early Middle-Miocene connection has also been considered (Grammenos, 1988; Grammenos & Kirkbride, 1988; von Dania, 1988), but is not supported by the palaeontological record. There was a connection with basins to the east of the Baltic Seaway during the Early and Mid-Eocene (Söderblom et al., 2004; Söderblom & Heilmann-Clausen, 2005; C. King, pers. comms., 2006) that supported 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 Rhine Seaway was established during the Early Oligocene (Becker et al., 2005; Söderblom, 2006), but evidence of the fauna assemblages in the Rhine Seaway indicates that the marine connection did not extend to the Alpine Foreland Basin (Görres, 2006). The Rhine Seaway appears to have been closed from the Oligocene 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 Thames Seaway, which connected the Liassic Basin (Söderblom, 2006) with the North Sea via the Pasie Basin. Fossil evidence (Jansen, 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 World Basin. The resulting basins may have been formed in the earliest Pliocene, but was subsequently reactivated through uplift until it was breached in the Late Oligocene by over-spill of the progradational lobe that occupied the southern North Sea (Gillibrand, 1999; Gupta et al., 2007).

The timing of inversion of the Mesozoic World Basin is still the subject of debate (see King, 2006). Although it has been suggested that it was substantially inverted during the Pyrenean (Late Eocene) tectonic phase (e.g. Ziegler, 1990a; Ziegler & Dünn, 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 (1994) and King (2006) consider a Mesozoic age for the inversion to be the most likely. Evidence of the nearby Rheno-Maas Central Channel Basin may have taken place earlier, in the Oligocene (Bray et al., 1988; King, 2006) and it is possible that the World Basin was also underway on an earlier 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 World Basin took place significantly later than that of the Central Channel Basin. The presence of Upper Miocene to Lower Pliocene marine sediments (Lahnian Beds) at an elevation of 180 m on the southern flank of the World Anticline points to relatively recent uplift (perhaps even inversion) in the Flensburg or Early Pleistocene.

The eastern SIF margin presently coincides with the eastern margin of the present-day English Channel Hills during the Paleocene and Eocene. Eastern England and the adjacent offshore area appear to have been a relatively non-erosive area, here referred to as the Eastern Shelf, with the Sola Pit inversion zone marking its boundary. (Figure 12.3). Uplift and exposure of this shelf appears to have taken place during earliest Eocene times (King, 1998; King, 2001). 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 (Serra Phase) (Van Born, 1987; De Jager, 2007). The Mesozoic Cleveland Basin may have had a comparable Cenozoic inversion history, but any 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.
A regional stratigraphic correlation chart is presented in Figure 12.5. The column order has been designed to emphasize stratigraphic continuity across national boundaries. Correlation has been achieved largely by means of biostratigraphy. A detailed account of the biostratigraphic succession has been provided by Pabst & Gaden (2002), Skrbek (2005, 2006) and De Batist et al. (2008). A summary of the regional stratigraphic nomenclature is provided by Rauzer et al. (2008).


Sequence stratigraphy has also proved to be a useful tool in correlative and chronostratigraphical assignment to the Treaty of Southern England (Al et al., 1991; Ali & Jelfey, 1989; Eilson et al., 1990).
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 (Roux, 1986; King, 2006). The local preservation of Thanetian sediments to the west of the Sole Pit inversion zone indicates that the Eastern England Shelf was depositional at that time (Dixon & Bailey, 1964). There was a restricted-marine connection to the eastern Atlantic at the time of maximum transgression, probably via the Channel Sessuy (Eng, 2006).

The predominantly siliciclastic Late Paleocene sediments were deposited during a period of regional subidence and transgression that spanned most of mid- and Late Paleocene times. This ended with a second period of regional uplift in the Late Paleocene, shortly before the start of sea-floor spreading between Greenland and Scotland (Figure 12.6b). The two uplift phases have been associated with distinct stages in the emplacement of the Iceland mantle plume (Koon, 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 SPA (Figure 12.7a), while deep-water sands, locally accompanied by reworked chalk, accumulated along the north-western margin of the 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 12.7a). In contrast, the thickness of the succession in the SPA area rarely exceeds 100 m.

The Thanetian sediments of the northern margin are mostly of chalky-marine facies. Paralic sediments took place in two small embayments separated by the Trumming fault, which formed a narrow peninsula of low relief (Sossick, 1966). The continental deposits found to the east are evidence of continued relative uplift of the North Polish Platform.
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 indications 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 by regional uplift, which led to substantial erosion and deposition of previously deposited Paleocene sediments in marginal areas. In the central North Sea and Denmark, this was marked by an increase in deposition of grey-green mudstone facies with rich and diverse microfaunas to grey mudstone with impoverished microfaunas. The regression in sandbox also associated with a renewed influx of deep-water sands. Any Thanetian sediments that had accumulated in the Fenno-Scandian and Baltic areas were probably removed at this time. In north-western marginal areas, truncated Lower Paleocene sandstones are locally overlain by shallow-marine sandstones of latest Paleocene age.

A final pulse of Late Paleocene deposition 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-water in deeper parts of the basin, where the earliest Eocene sediments consist of fine-grained organic-rich mudstones (Mølke Formation) and local subaqueous fan sandstones. High concentrations of the dioxiflagellate cyst Actinaplanis coincide with the global Palaeocene-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 marine, locally subaqueous sandstones. 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 Fenno-Scandian 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 northern and south-western margins of the North Sea Basin with the development of an unconformity, as for example at the base of the Hamnir Formation in north-east England. At the same time, uplift of the Scottish source areas was accompanied by the rapid eastward propagation of a major (up to 500 m thick) Anoxic complex (Sverdrup 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 Ilmen Formation). Marine distomites up to 80 m thick were deposited (For 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 inception 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 increased subaerial pyroclastic activity. This is reflected by the abundant, predominantly basaltic ash layers in all marine mudstone and distomite formations (see Figure 12.3). 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 successions by the top of an interval with abundant ash layers and onshore successions by a major 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 margins of the basin (Outer Moray Firth Basin and Viking Graben), the North Sea Basin underwent a more widely distributed, with the principal depocentres in the Viking Graben, the central North Sea and northern Germany (Figure 12.8b). The prograding shelf-margin wedge that developed along the western margins of the Viking Graben was more rapid than during the Palaeocene, and internal deep-water sandstone bodies were deposited on a smaller scale (Figure 12.7c). Eastward progradation from the western margins of the basin is also evident in the southern North Sea (Figure 12.8c). Relative subsidence of the central North Sea and Viking Graben maintained the deep-water environments established during the Late Palaeocene. Deep-water environments also extended outwards into the Danish area where...
stresses set up by the renewal of Africa-Europe convergence, dated at around 51 Ma by Dewey & Windley represents uplift of the southern and western marginal highs. This uplift may have been associated with eustatic sea-level fall (see Rattas & Kalm, 2001). Sandstones of present-day Estonia and Latvia as these have epidote-rich heavy-mineral assemblages. The Kaliningrad area (Kramarska, et al., 2004; Kramarska, 2006). Epidote-rich heavy-mineral assemblages occupied by the sea is supported by the presence of marine mudstone facies over much of the Eocene succession of the Baltic Sea Basin, including the Liassic carbonates, the replacement of marine by paralic facies on the North Polish Platform and by a loss of the connection with the eastern Atlantic. The further renewal of the Baltic Sea (Kramarska, et al., 2004; Kramarska, 2006). This marine connection must have been established via the Baltic Seaway with the cool waters of the Donets-Caspian Basin (C. King, 2006). It therefore presumably provides the first evidence for uplift of southernmost Norway (Michelsen & Nielsen, 1993; Michelsen et al., 2007) prograded southwards into deeper waters to the west of the Danish Shelf. This development continued in the offshore North Sea Basin, except over areas of inversion. The latest Eocene was marked by regional uplift associated with the Pyrenean tectonic phase. Uplift was with consequent loss of the associated warm-water faunas from the North Sea Basin. Temporary isolation of the eastern Norwegian-Danish Basin started to subside about the same time (Figure 12.8a), accompanied by basin extension in the central North Sea that prograded southwards from a Fennoscandian landmass. The complex pattern of sediment accumulation that had characterised the Eocene within the SPB area was replaced in the Late Eocene by renewed north-west Europe, reflecting a change in the regional stress regime. The Eocene-Oligocene boundary is marked by an unconformity of latest Eocene to earliest Oligocene age (Figure 12.10). The Eocene-Oligocene boundary is marked by a uniform pattern of basin-centred sedimentation (Figure 12.10). In the Baltic Sea, the basinal sands fringed the basin margins, with paralic and terrestrial deposits confined to the Mesozoic and post-Mesozoic sediments (Figure 12.2a). Connection with the North Atlantic via the Channel Swing was established in mid-Eocene time, as indicated by the appearance of warm-water facies successions, including Nummulites (Kling 2006) in the south-western embayment of the North Sea. Microfossil evidence suggests that there was also a marine connection with western Siberia (Jakobson et al., 2001; C. King, C. Baltussen-Glasson, I.A. Jakobov & E. Daams, pers. comms. 2000). This marine connection must have been established via the Baltic Sea as the Northern Sea 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 mudstone facies in the Eocene successions 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 evident heavy-mineral assemblages (see Rattas & Kalm, 2001). This phase of sedimentation ended in latest Oligocene time by a major influx of sand into the southern basin-marginal areas (Figure 12.7f) and a basinward shift in facies in the Hamptons Basin and along the western margins 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 strains set up by the renewal of Africa-Europe convergence, dated at around 51 Ma by Dewey & Windley which was involved in this uplift, as the latest Tertiary is also marked by the upbuilding of Nummulites in the southern North Sea (Kling, 2006), indicating re-establishment of a marine connection with the eastern Atlantic. The paralic facies in the Hamptons Basin indicates emergence of the Start-Cotentin Swing. It is therefore likely that a connection with the Atlantic was established via the Lüne Seaway, although there is a lack of direct evidence in upper Tertiary sediments in the Paris Basin have been removed beneath the lower-Lutetian disconformity (e.g. Vinken, 1988). Further uplift in the early Lutetian is indicated by a seaward extension of paralic facies in the Hamptons Basin, facies in the Belgian Basin, the replacement of marine by paralic facies on the North Polish Platform and by a loss of the connection with the eastern Atlantic. The Elbe-Schleswig Graben started to subside about the same time (Figure 12.8a), accompanied by basin extension in the central North Sea that prograded southwards from a Fennoscandian landmass. Following these events, subsidence of the southern and western marginal highs is indicated by a progressive transgression of the southern and western margins of the Baltic Sea Basin, with a return to predominantly muddy sedimentation. The upbuilding of Nummulites indicates a further renewed connection with the eastern Atlantic via the Lüne Seaway. A sharp demarcation between the marine-carbonate facies of the Paris Basin and the sandy facies of the Belgian Basin suggests that the Baltic Sea 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 latest Eocene-earliest Oligocene time as a result of uplift of western Britain and France, superimposed on a eustatic sea-level fall. The latest Eocene facies in the Hamptons Basin at this time had died out the connection with Atlantic oceanic waters (Kling, 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 12.8a). Along the western margins 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 Algero-Cantabrian Province Basin was established in late Mid- to Late Eocene times via the Norwegian Seaway (Grammas, 1988; Grammas & Emslie, 1988; Ziegler, 1990a). Late Middle to Late Eocene facies also indicate continued connection via the Baltic Seaway with the cool waters of the Benbecula-Caplan Basin (C. King, pers. comms. 2000). However, this interpretation requires a palaeogeographical reconstruction that is at odds with the model proposed by Siemieniec (1987) for the Late Eocene of northern Poland. In this model, the amber-hued Upper Eocene sands of northern Poland are considered to be associated with a major delta that predated mudflats 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 Nummulites facies, which led to widespread reworking in marginal areas. Sedimentation continued in the offshore North Sea Basin, except over areas of inversion. 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 12.10). 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 predominately westward propagation in the North Sea (Figure 12.8b). 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 eastern North Sea basin (De Lape et al., 2003). Figures 12.10 and 19). The former Channel Basin may also have been inverted at that time (King, 2006). The Eocene-Oligocene boundary is marked by a change in the regional stress regime. 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 (Second Mat Formation) in the Upper Eocene to additional mudstone facies (Viking Formation) in the lowermost Oligocene (Halmann-Clausen & Clausen, 2006). In the eastern North Sea, dolomitic deposits including the Dols Sandstone Member (Schubert et al., 2007) prograded seaward into deeper waters to the west of the Danish Shelf. This development provides the first evidence for uplift of southwestern Norway (Nicholas & Watkins, 1993; Nicholas et al., 1996; Rødberg & Ødeby, 2005). Prior to this, uplift appears to have been confined to the Scandinavian Caledonides, as reflected in westward propagation into the Viking Graben. These tectonic events clearly pre-date the Palaeogene, as the onset of uplift of southwestern Norway in the Early Oligocene was associated with the end of uplift of the western Norwegian Caledonides (Røt et al., 2006).
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Bathyal limits are from King (unpublished data, 2009). Standke (2008a). The location of Pyrenean inversion structures in Figure 12.9c are modified from Nielsen et al. (2005).

Late Oligocene (mid-Chatian)

Other areas of the Scandinavian Platform probably underwent further uplift at that time, as sands with a metazoan/foraminiferal heavy-mineral assemblage dominated by amphibolite and epidote are seen for the first time in the lowermost Oligocene sediments of the Sarrecois area of north-west Poland (Kozierowski-Czeczotowa, 1988). The similarity of this heavy-mineral assemblage with that reported from the lowermost Oligocenesequences of the Viborg Formation of Denmark (Nikolai, 1985) suggests derivation from southern Sweden. This sand influx is therefore interpreted as marking the onset of uplift of the South Swedish Zone. Combined with continued influx of epiphyte-rich sands from the north-east, the uplift led to a wider extension of epiphyte-rich sands onto the Polish Platform than at any other time in the Tertiary (Morton et al., 1988).

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 no fossil evidence for renewed connections with basins to the east (C. King, pers. comm., 2000), it is likely that the mid-Rupelian sea-level rise led to a temporary re-uplifting of the Baltic Swell.

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It has long been recognized that there was an intermittent marine connection between the North Sea and the Upper Rhine Graben via the Hanian Seaway (see Berger et al., 1996; Sinningh, 2001), although Grön (2004) has doubted a connection with the Paratethys Ocean because of the endemic nature of the Upper Rhine Graben microfauna. A seaway probably existed in the south-west, where the middle Miocene succession is represented in the Paris Basin by tidal sands of the Fontainebleau Sands. The connection with the Atlantic was probably via the Ile de Sein, as the paralic sediments in the western Hampshire Basin suggest exposure of the Start-Cottiaen Shell.

Removal of tectonic activity at the time of the Rupelian-Chattian transition, coupled with a gradually induced sea-level fall (12–28 million years of Miller et al., 1998), amplified the palaeogeographical changes caused by the Eocene–Oligocene boundary tectonics. Emergence of the entire Fennoscandian area was accompanied by inversion 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 Miocene 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 Hanian 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 (Figures 12.2–4). Marine facies 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 reworked offshore phenomena prevailed in the grabbing throughout Chattian times (Sinningh, 2004). 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 pelagic sediments (v. Loewen, 1923; Tschopp, 1928). As seen in the Rupelian, it is likely that the Channel-Swayne was closed as a result of exposure of the Start-Cottiaen Shell. Marine connections via the Paris Basin and Ile de Sein are also unlikely as the overlying chalk mudrocks 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 land-dominated to sea-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 mudrocks took place on the Danish Shelf in the latest Chattian, and the deep-water sandstones of the Paas Sandstone Member were deposited (Björklund & Rasmussen, 2007).

6 Miozene and Pliocene

The base of the Miozene is marked by a hiatus along most of the southern basin margin, reflecting a combination of tectonic activity related to the Iberian Alp stage 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 Iberian tectonic phase was also marked by renewed inversion of the Solean tectonic phase (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 pelagic sediments (v. Loewen, 1923; Tschopp, 1928). As seen in the Rupelian, it is likely that the Channel-Swayne was closed as a result of exposure of the Start-Cottiaen Shell. Marine connections via the Paris Basin and Ile de Sein are also unlikely as the overlying chalk mudrocks 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 land-dominated to sea-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 mudrocks took place on the Danish Shelf in the latest Chattian, and the deep-water sandstones of the Paas Sandstone Member were deposited (Björklund & Rasmussen, 2007).

The Oligocene-Miocene unconformity is less distinct in the eastern SPB area than in the west, reflecting enhanced subsidence following the Iberian 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. The Baltic River valley evolved along the trend of the present-day southern Baltic Sea. This is consistent with Björklund’s (1981) record of the stratigraphic and geophysical distribution of the distinctive Baltic Gravel Assemblage (see also Swinnerton et al., 2001), which largely consists of sediments that derived from the Lower Palaeozoic rocks of southern Scandinavia. There was a marked postglacial rise in the Danish Shelf in the Early Miozene as a result of uplift and inversion combined with increased sediment supply from

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**Figure 12.11: Miozene to Quaternary palaeogeography.**

- **a. Early Miozene (Late Aquitanian: 20 Ma):** Black Miozene (Late Langhian: 14 Ma).
- **c. Early Pliocene (Zanclean: 5 Ma):** Black Quaternary (‘Cimmerian Complex’ 0.6 Ma).

Based on the regional maps of Miller et al. (1998), Ziegler (1990a) and Fyfe et al. (2003), together with maps of John et al. (1998), Bari et al. (1998), and Roberts et al. (1998).
Regional stratigraphic correlation in the SPBA area is illustrated by two well-correlation panels. The pattern of sedimentation established during the latest Tertiary (Figure 12.11b) persisted into the Early Quaternary, with large amounts of sediment derived from the areas of northeastern Scandinavia, Poland, the Baltic states and Poland entering the south-eastern embayment of the North Sea via the Baltic River system (see Glikson, 1986), known as the Embalse River system (Overeem et al., 2001). This led to continued westward propagation, which is marked on seismic profiles by prominent delta-levee sequences (e.g. Cameron et al., 1993; Overeem et al., 2001), and to the eventual accumulation of about 62 000 km³ of sediment (Overeem et al., 2001). Whereas no change in faunal assemblages 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 4 ka (N) at the end of the Pliocene to about 50 ka (N) in the earliest Quaternary (Gelasian Stage) (Kolliarkopulos & Wong, 2008). This increase is attributed to a deterioration in climate causing breaks in the plant cover and a considerable increase in the rate of erosion. The Baltic River deposits consist of pebbly-sand and the distinctive Baltic Gravel Assemblage (see above), which includes silicified limestone clasts derived from the Lower Palaeozoic succession of the Baltic region (Björn, 1981).

8 Quaternary

The phase of accelerated delta propagation came to an end about 900 ka and the Baltic Gravel Assemblage became mixed with gravel and sands originating from the Mittelpleistozän (El K 2) to the south (Björn, 1981). There is no direct evidence 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, 1991), it is inferred that the Baltic River continued to supply sediment at that time, if not the Baltic River components represent reworking of earlier deposits (Bijlsma, 1981). In northernmost and north-west England.

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1971), it is likely that a fundamental change in the physiography of the Baltic Sea area had taken place. Destruction of the upper reaches of the Baltic River drainage system (Bijlsma, 1981) would have induced the potential for sediment output, whereas glacial cutting 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 Palaeogene, 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 the mid-Palaeogene is the accelerated uplift of the Ardennes-Rhenish and Bohemian massifs (e.g. van Baren et al., 2000; Synal et al., 2004). The establishment of a regressive palaeo-sea to the north, coupled with climatic deterioration, led to increased sediment supply from the north. The influence of the Baltic Sea and the North Sea on denudation in the interior of Europe could have provided an alternative route for the course of the Baltic River. These geographical changes set the scene for the remainder of the Palaeogene, as sediments of Baltic River derivation are entirely missing from the sedimentary record of the Netherlands and Germany (Bijlsma, 1981).

At the start of the Holocene 10 000 years ago, a large area of the present-day northern North Sea was land. The subsequent post-glacial sea-level rise flooded the area, isolating the British Isles from the rest of the European continent. This has been little change in the configuration of the North Sea coastline or drainage pattern of the land area since about 5 ka BP. Several phases of volcanic activity have been documented in the EDS area during the last 500 ka (Regourd & Schmincke, 1999). The most recent large eruption took place in the Laacher See area about 12.8 ka BP. Eruption deposits resulting from this eruption have been found over large parts of north-west Europe, marking seawards 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) (Jöhl et al., 2008). Due to their low rank, the Cenozoic coals have not generated significant quantities of gas either on-land or offshore. No oil accumulations are known within the Cenozoic of the SPB area, although between 1859 and 1971 oil was extracted from Eocene bituminous shales in the Messel district north of Frankfurt (Schulz & Schröder, 1995; Bau, 1988). These shales are now better known for the remarkable preservation of their vertebrate fauna (e.g. Schulp & Deger, 1948), which are now thought to include the earliest known primates (Frisancho et al., 2000). Shale 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).
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 500 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 Elbe, Meuse and Thames. The surface mapped by Overeem et al. (2001) is the base of seismo-stratigraphic 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 Kranczulska (2004).
shallow-gas accumulations are of no commercial value, but since potentially commercial production rates
is probably of both biogenic (microbial) and thermogenic origin, as explained in Chapter 13. Most of the
Shallow-gas accumulations are found widely in Upper Cenozoic (mainly Plio-Pleistocene) sediments of the
9.2 Cenozoic shallow gas
range than at Mesel. Unfortunately, the deep mines and their unique fossils have been flooded in recent
years. Lower and Upper Eocene lignite deposits are located in the Auerstedt and Halle areas.
The Eocene 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 and Middle Miocene Scierow and Poznań
formations. These seams extend over areas ranging from 30 000 to 70 000 km2 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
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 (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 antitaxial dip-closed structure (see Section 5.6 of Chapter 15). Appraisal well
A15-1 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-screen techniques to avoid sand production.

Table 12.1 Properties of the A15-A field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithology</td>
<td>Sandstone</td>
</tr>
<tr>
<td>Depth to top (m)</td>
<td>605</td>
</tr>
<tr>
<td>OWC/GWC (m)</td>
<td>644</td>
</tr>
<tr>
<td>Maximum caliper height (mm)</td>
<td>244</td>
</tr>
<tr>
<td>Net reservoir thickness (m)</td>
<td>63</td>
</tr>
<tr>
<td>Net to gross ratio</td>
<td>16</td>
</tr>
<tr>
<td>Porosity (%)</td>
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</tr>
<tr>
<td>Gas saturation</td>
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</tr>
<tr>
<td>Permeability (mD)</td>
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</tr>
<tr>
<td>Fluid type</td>
<td>Gas</td>
</tr>
<tr>
<td>Gas composition</td>
<td>CH4: 89%, N2: 0.6%, CO2: 0.03%</td>
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<tr>
<td>Initial pressure (psi)</td>
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<tr>
<td>Temperature (°C)</td>
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</tr>
<tr>
<td>Source rock</td>
<td>Biogenic gas</td>
</tr>
<tr>
<td>Seal</td>
<td>Upper North Sea Group shales</td>
</tr>
</tbody>
</table>