Int J Earth Sci (Geol Rundsch) (2005) 94: 621–639
DOI 10.1007/s00531-005-0499-7

ORIGINAL PAPER

A. Schäfer · T. Utescher · M. Klett
M. Valdivia-Manchego

The Cenozoic Lower Rhine Basin – rifting, sedimentation, and cyclic stratigraphy

Received: 6 October 2003 / Accepted: 28 March 2005 / Published online: 21 June 2005

Abstract In the Cenozoic, the Lower Rhine Basin formed as a rift at the southeastern terminus of the Dutch German Central Graben, while the Rhenish Massif was uplifted. The study focusses on the marginal marine and fluvial fill of the Lower Rhine Basin. A basin model is developed. Support for this study was given by extensive industry outcrop and well data, by new stratigraphical and sedimentological observations. The ingression and subsequent regression of the Cenozoic North Sea is analysed using the concept of base level cyclicity. As the geohistory of the basin was complex, a subsidence curve is constructed. Furthermore, an attempt is made to trace the simultaneous uplift of the Rhenish Massif.

Keywords Tertiary · Rift basin · Sedimentology of marginal marine sediments · Lignite brown coal · Base level cycles · Subsidence of Lower Rhine Basin · Uplift of Rhenish Massif

Introduction

The Lower Rhine Basin forms a marginal marine rift basin in the southern part of the Dutch German Central Graben (Zagwijn 1989). It is cut into the northwestern headlands of the Rhenish Massif (Fig. 1a and b), morphologically forming an 'embayment' (Schäfer 1994; Schäfer et al. 1997). The basin extends towards the North and forms part of the Dutch German Central Graben, a rift system that is connected to the Upper Rhine Graben in the South (Sissingh 2003). The German part of the basin contains about 1300 m of Oligocene to Pleistocene siliciclastic sediments with intercalated brown coal layers attaining a thickness of almost 100 m (Hager 1986). The brown coal (consisting of lignite; Hager 1986; Schneider 1995) has been exploited in open-cast mines for many years starting in the 19th century, at locations where the seams were easily accessable. Since then, the exploitation of the coal has formed the basis for regional power supply. Surface access to the basin fill of the Lower Rhine Basin is possible in open-casts, where the structural position of the brown coal seams allows for mining (RWE Power AG, formerly Rheinbraun AG). Moreover, numerous wells provide insight to the depth of the basin. Using the combination of surface exposures and well-logs, the Lower Rhine Basin has been studied intensely (Schneider and Thiele 1965; Teichmüller 1974; Zagwijn and Hager 1987; Hager and Prüfert 1988; Zagwijn 1989; Boersma 1991; Utescher et al. 1992; Schäfer et al. 1996; Hager et al. 1998). Many biostratigraphical, palaeoecological, sedimentological, palaeoclimatological, and structural studies have been made (e.g. von der Brelie 1968, 1981, 1988; von der Brelie et al. 1981; Ashraf and Mosbrugger 1995, 1996; Heumann and Litt 2002; Mörs 2002; Mörs et al. 1998, 2000; Utescher and Mosbrugger 2000; Klett et al. 2002; Schäfer and Siehl 2002). More recently, a sequence stratigraphical approach provided a time frame for the fill of the Lower Rhine Basin (Schäfer et al. 2004).

Standke et al. (1993) and Standke (2002) investigated Miocene coastal environments in the Lausitz brown coal deposits at the southeastern shore of the Central European Tertiary basin (cf. Fig. 1b). Here, a moderately inclined, more or less stable ramp provided the structural frame for the development of the depositional systems. Thus, the relative sea level exclusively originated the sedimentary cycles. They cover a time span equivalent to those of the Lower Rhine Basin. Yet, the lignite seams in this stratigraphic range from the Rupelian (Early Oligocene) to the Serravallian (Middle Miocene) are preserved to form five individual seams. The seams are separated from each other by coastal marine sands and clays. The entire succession can be

---

A. Schäfer (✉) · T. Utescher · M. Klett · M. Valdivia-Manchego
Geologisches Institut, Universität Bonn,
Nussallee 8, 53115 Bonn, Germany
E-mail: schaefer@uni-bonn.de
Tel.: +49-228-732430
Fax: +49-228-739037

differentiated into an initial transgressive unit, followed by a regressive unit. Offshore, this is suspected to represent a third-order cyclicity. Close to the coast, a fourth- to fifth-order allocyclicity with relevance for stratigraphic use can be shown. Autocyclic smaller-scaled cycles are also encountered in places.

Vandenberghe et al. (1998) provided a sequence stratigraphic framework for Paleogene sediments mostly from the western shore of the Central European Tertiary basin (cf. Fig. 1b). A comprehensive summary of this was published by Vinken (1989). Hager et al. (1998) reported on the Rupelian of this basin, while Vandenberghe and Hardenbol (1998) focused on the Neogene.

In the present contribution, a base level control for the marginal marine and fluvial depositional sequences in the Lower Rhine Basin is derived from wells and their geophysical data (kindly provided by RWE Power, formerly Rheinbraun AG, Köln). With help of new stratigraphic data (Schäfer et al. 2004) the concept of sequence stratigraphy can be applied. As the development of the rift basin is closely related to the uplift of the Rhenish Massif (Fuchs et al. 1983), a geohistory curve will be constructed depicting the subsidence of the basin and the uplift of the massif.

Methods and data acquisition

Our field work focusses on three open-cast mines that are active today in exploiting brown coal; these are the Inden, Hambach, and Garzweiler mines (Fig. 2). The Vereinigte Ville, Fortuna, and Bergheim mines were closed recently, after the work of Hermanns (1992), Abraham (1994), Petzelberger (1994), Valdivia-Manchego (1994, 1996), Schäfer et al. (1996) and Klett (2000) was completed. The Frechen and Zukunft-West mines are only known to us from the publications of Boersma et al. (1981) and Boersma (1991).

In the open-cast mines, measured sections for paleontological investigations were taken (Utescher et al. 1992, 2000; Ashraf and Mosbrugger 1995, 1996; Ashraf et al. 1997a, 1997b; Mörs et al. 1998, 2002; Mörs 2002; Heumann and Litt 2002, Heumann 2001). Sedimentological analyses from measured sections in open-cast mines and from well and geophysical logs provided the means for the interpretation of sediment models (Abraham 1994, Petzelberger 1994, Schäfer et al. 1996, Klett 2000).

Well data were kindly provided as copies of the original analog readings from the archives of Rheinbraun AG (Köln) and Erftverband (Bergheim). Additionally, well data were provided by the Staatliches Umweltamt (Bonn). The lithological logs were digitized, and the geophysical logs were interpreted as facies logs by mathematical interpretation methods developed from Klett and Schäfer (1997), Klett (2000) and Klett et al. (2002). As a result, it was possible to specify sedimentological models even at a subenvironment scale (Schäfer et al. 2004).

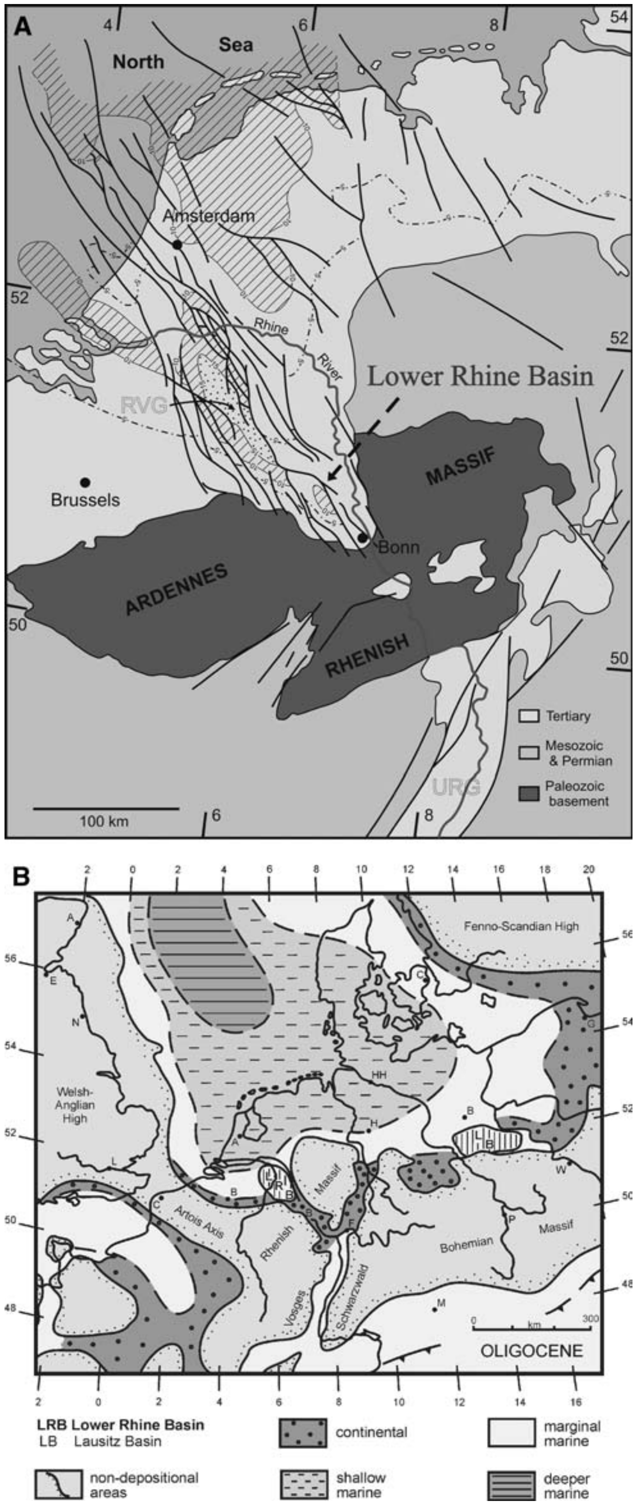


Fig. 1 **a** The Lower Rhine Basin and the Roer Valley Graben (RVG) both form the Dutch-German Central Graben, a rift that deeply cuts into the Rhenish Massif and is assumed to continue to the Upper Rhine Graben (URG). **b** Palaeogeographical map of Northern Germany and neighbouring areas in the Oligocene. Redrawn after Ziegler (1990). LRB: Lower Rhine Basin; LB: Lusatian Basin (each with vertical hatchures)

Forming the basin

The southeastern part of the Dutch German Central Graben (Zagwijn 1989) cuts into the north-western headlands of the Rhenish Massif (Hager and Prüfert 1988; Schäfer and Siehl 2002), forming the 100 km long and 50 km wide lowland area of the Lower Rhine Embayment in Germany ('Niederrheinische Bucht') (cf. Fig. 2). The rift system consists of a mosaic of NE-ward tilted half grabens and horst blocks separated by NW–SE-trending and SW-ward dipping synthetic faults and NE-ward dipping antithetic faults in the SW (Fig. 3a and b). In the half grabens, the maximum thickness of the Tertiary and Quaternary siliciclastic basin fill is attained along the north-eastern faults of the Roer Valley Graben and the Erft Block (Schäfer and Siehl 2002). Up to 2000 m of sediments accumulated in the Roer Valley Graben at the SW side of the Peel Fault, whereas up to 1300 m were deposited in the Lower Rhine Basin along the SW side of the Erft Fault, separating the Erft Block and the Köln Block (Zagwijn et al. 1985). In the Lower Rhine Basin, rich brown coal seams with a total thickness of about 100 m in the SE and close to the Erft Fault formed (Hager 1986).

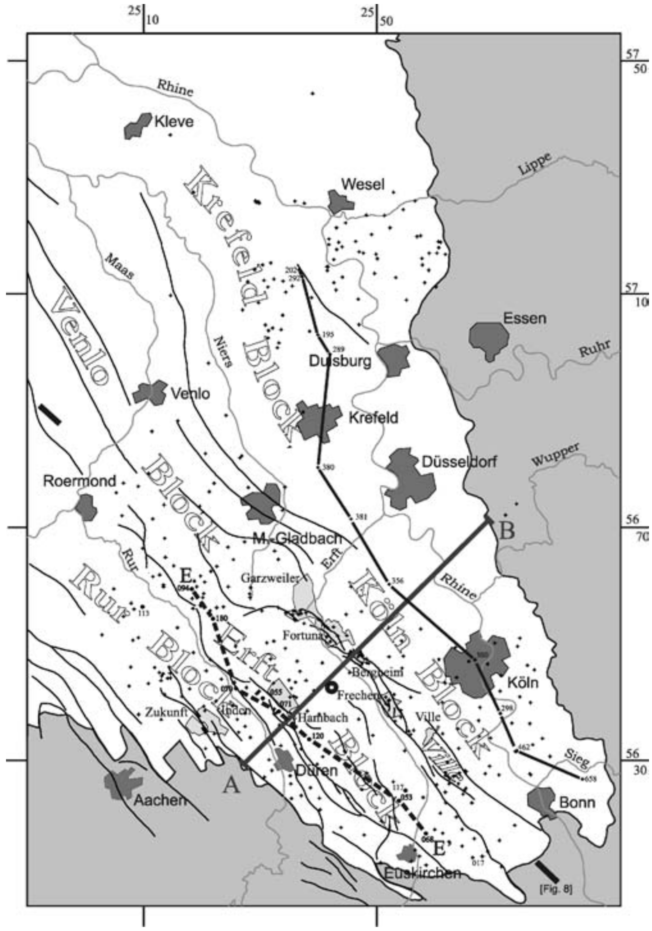


Fig. 2 The surface area of the Lower Rhine Basin (white) – cut into the Rhenish Massif (medium grey) – shows structural blocks that are separated by faults (thin black lines). Open cast mines on lignite brown coal are indicated, both active and inactive (light grey). A cross section A–B is redrawn from the 'Rosettenschnitt' (courtesy of Rheinbraun AG) to show the general structure of the basin (cf. Fig. 3 b). Two cross-sections (dashed line E–E′ for Fig. 6 and thin continuous line for Fig. 11) follow numbered well locations. Extraordinary well locations are also named, in addition. The position of the stratigraphic standard section (cf. Fig. 4) is marked by a bold circle

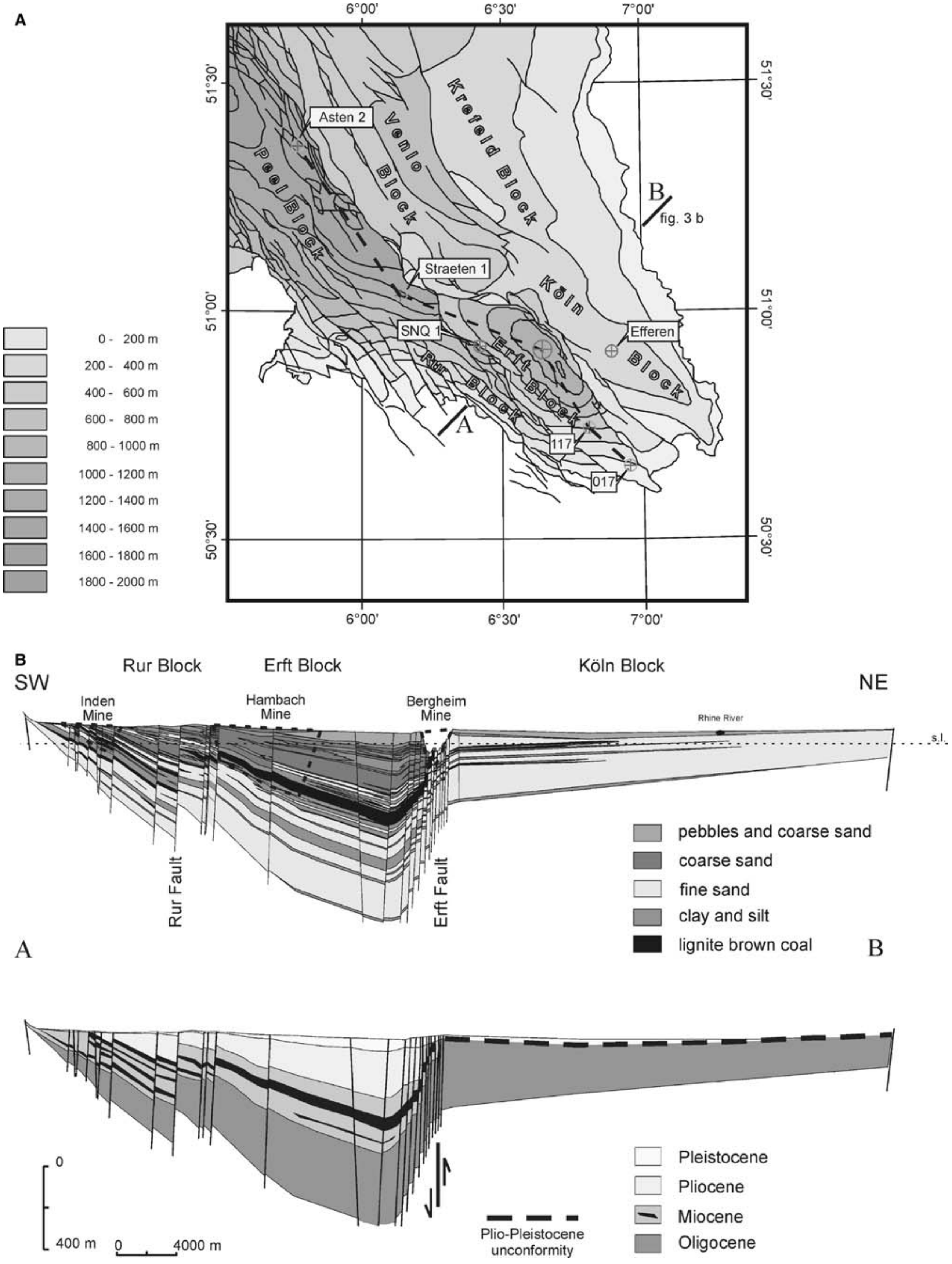
NW–SE trending faults define individually subsiding structural blocks. These are subsiding with different velocities. The Erft Block in the central part of the Lower Rhine Basin is the deepest (cf. Fig. 3a). The Rur Block in the West is relatively shallow. Both blocks are gently inclined towards the East. The Köln Block with the Ville Ridge at its western margin forms the hangingwall. These tectonic units continue towards the N, to the western Krefeld Block and the eastern Venlo Block. W of the Venlo Block, the Roer Valley Graben forms the deepest block of the Dutch German Central Graben. Beneath the Tertiary strata, rocks of Devonian, Carboniferous, and Triassic age form local subcrops (Hilden 1988).

The Erft and Rur Faults join towards the NW, to form the Peel Fault, which can be traced towards the NW along the eastern side of the Dutch German Central Graben. These faults are inclined westward and have a dip of 70–80°. In the W of the Dutch German Central Graben, the Feldbiss Fault forms the opposite fault system, dipping to the East with about the same angle. The Lower Rhine Basin developed by extension forming an asymmetric half graben. Close to the surface, the faults are planar in shape. In the shallow subsurface, as far as the Cenozoic sediment fill allows, the basin was formed by SW–NE directed orthogonal extension. At a crustal scale, a listric fault might have developed. The Erft and the Peel faults, at depth, are suspected of having a widely curved and W-ward oriented detachment (although there is no deep seismic control at present).

Plein et al. (1982) performed a satellite image analysis on the Krefeld and Venlo blocks and concluded that there was a strike slip component to the formation of the Lower Rhine Basin. The E-ward displacement of the Lower Rhine Basin with respect to the Roer Valley Graben suggests a sinistral strike-slip origin of the basin configuration (Schreiber and Rotsch 1998; Schäfer and Siehl 2002). Recently, Michon (2003) and Michon et al. (2003) pointed out that the Dutch-German Central Graben formed by a N–S-ward oriented compression leading to a strike-slip combined with a sinistral rotation.

Seismicity has been active up to the present day. On April 13th 1992 an earthquake occurred, with magnitude 5.8 and an epicentre located underneath Roermond (Ahorner 1992; Pelzing 1992; Paulssen et al. 1992; Plenefisch and Bonjer 1997).

During the Cenozoic, the Lower Rhine Basin subsided at a rate of up to 2 mm per year, predominantly along the northeastern margins of the individual sub-


A
6°00'
6°30'
7°00'
51°30'
51°00'
50°30'
Asten 2
Peel Block
Venlo Block
Krefeld Block
B
fig. 3 b
Straeten 1
Köln Block
SNQ 1
Efferen
Rur Block
Erft Block
A
117
017
0 - 200 m
200 - 400 m
400 - 600 m
600 - 800 m
800 - 1000 m
1000 - 1200 m
1200 - 1400 m
1400 - 1600 m
1600 - 1800 m
1800 - 2000 m
B
Rur Block
Erft Block
Köln Block
SW
NE
Inden Mine
Hambach Mine
Bergheim Mine
Rhine River
s.l.
Rur Fault
Erft Fault
pebbles and coarse sand
coarse sand
fine sand
clay and silt
lignite brown coal
A
B
0
400 m
0
4000 m
Plio-Pleistocene unconformity
Pleistocene
Pliocene
Miocene
Oligocene

◀

Fig. 3 **a** Faulted blocks of the base of Tertiary of the Lower Rhine Basin, separated by major faults and inclined toward the NE. Bold broken line marks the well section of Fig. 7a. The wells SNQ 1 and Efferen are used for the compilation of the stratigraphic standard section of Fig. 4 (virtual location at the encircled big cross). **b** The 'Rosettenschnitt' cross-section A to B through the Lower Rhine Basin is redrawn from an early construction of Rheinbraun AG to verify the sediments and the tentative stratigraphy of its basin fill. Steeply dipping normal faults separate the structural blocks shown in Fig. 2. The Plio-Pleistocene unconformity on the Köln Block is marked by a dashed line. The interpretation of the basin's subsidence and uplift will be presented in Fig. 12

grabens (Quitzow and Vahlensieck 1955; Zijerveld et al. 1992). Due to the deep groundwater drainage with respect to the mining of the brown coal, mining-related subsidence is at least 30 mm per year (in some places even more). The present day horizontal extension in an E–W direction is up to 2 mm per year (inferred from GPS measurements; Campbell et al. 2002). The present day seismic activity is closely associated with structural activity along the main fault systems (Ahorner 1997; Klostermann 1983).

On a SW–NE cross-section through the Lower Rhine Basin (cf. Figs. 2, 3a and b) it is evident that its eastern block, consisting of Oligocene strata, is directly overlain by terrace gravels of the Rhine River. The uplift of this eastern block presumably occurred after the deposition of the Pliocene Reuver strata.

The structural development of the Lower Rhine Basin has been discussed by Plein et al. (1982), Knufinke and Kothen (1997), Plenefisch and Bonjer (1997), Schreiber and Rotsch (1998), Schäfer and Siehl (2002), Michon (2003), Michon et al. (2003), Hinzen (2003). The uplift of the Rhenish Massif during the Pleistocene (Fuchs et al. 1983) was recently discussed by a number of studies on the terraces of the River Rhine and its major tributaries in the Rhenish Massif (Meyer and Stets 1998, 2002) and also in the Ardennes (Garcia-Castellanos et al. 2000; Van Balen et al. 2002).

Sediment fill of the basin

The Cenozoic rocks of the Lower Rhine Basin are exposed at various sites. Palaeocene and Eocene deposits are locally preserved along the southeastern margin of the basin, to the South of the city of Euskirchen, and in the Antweiler Graben (Oehms 1980). The fill of the Lower Rhine Basin dominantly consists of Oligocene, Miocene, and Pliocene sediments (Fig. 4). Pleistocene sediments were mostly derived from the Rhenish Massif, and form only a thin veneer. Following the Rhine and Maas tributaries towards the North, Holocene deposits increase in thickness.

The basin fill forms three units, marine beds in the deepest part of the basin, brown coal seams interfingering with marine deposits in the middle, and fluvial and lacustrine sediments at the top. The maximum thickness of the Rhenish Main Seam in the eastern part of the central Erft Block (Fig. 5) is about 100 m (Hager 1986). Towards the NW, it subdivides and forms three separate smaller seams, the Morken, Frimmersdorf, and Garzweiler seams (Minnigerode and Richter 1986). In the western Lower Rhine Basin, the Upper Seam developed during the Late Miocene. The Bergheim seam in the E of the basin is of Early Pliocene age (cf. Fig. 4). In the NW part of the Dutch German Central Graben, the Oligocene to Miocene sediment fill of the basin is marine, bearing glauconite, and no brown coal was formed (Verbeek et al. 2002).

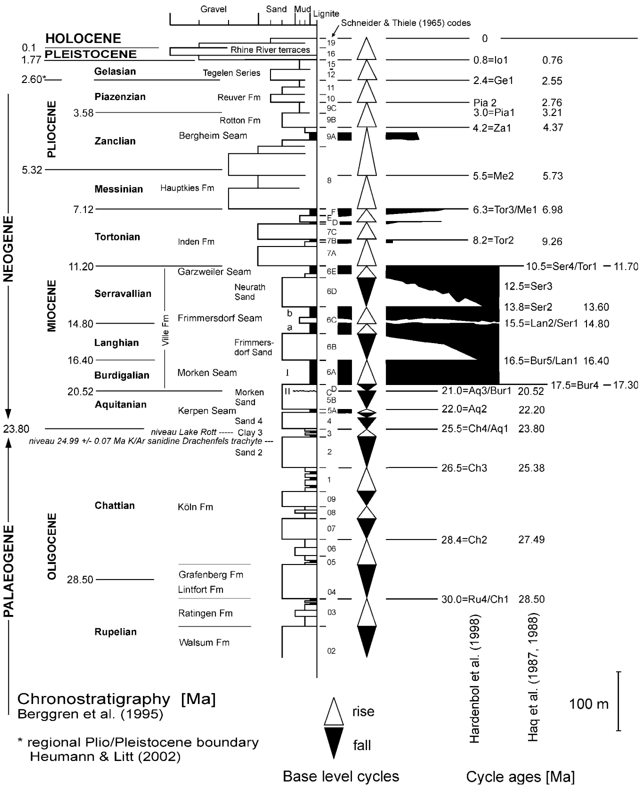


Fig. 4 Stratigraphic standard section, compiled from two wells (Schäfer et al. 2004) and virtually located in the centre of the Erft Block (cf. Fig. 2). Formation names and the lithostratigraphic number code from Schneider and Tiele (1965) are inserted along the section. Stratigraphic ages are from Berggren et al. (1995), Heumann and Litt (2002), cycle ages from Haq et al. (1987, 1988) and Hardenbol et al. (1998) as compiled by Schäfer et al. (2004)

Sediment thickness and stratigraphy in the Lower Rhine Basin are shown in the stratigraphic standard section (cf. Fig. 4). This was compiled from two wells, one in the western part of the Erft Block and the other on the Köln Block, corrected with help of industry cross-sections through the basin (Schäfer et al. 1997, 2004). The virtual location of the stratigraphic standard section found its location in the centre of the Erft Block, where the Rhenish Main Seam should have been drilled completely (cf. Fig. 2: black bold circle; cf. Fig. 5).

Stratigraphic code numbers, marked on the profile, were developed for industry purposes (Schneider and Thiele 1965). The formation names do not strictly obey

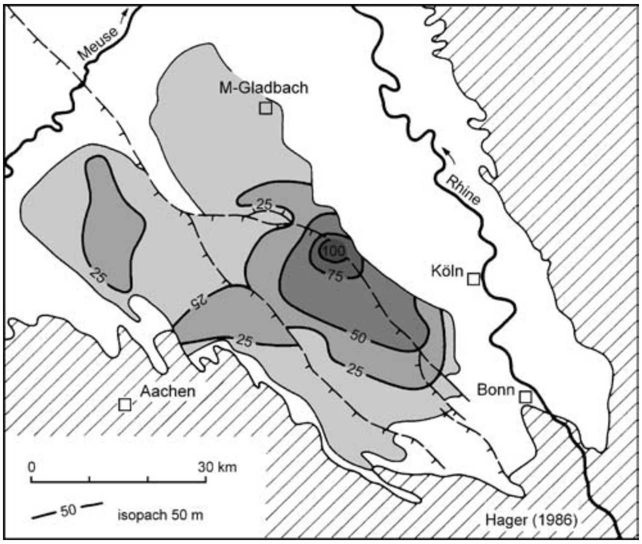


Fig. 5 Stratigraphical thickness of the lignite brown coal seams of the Lower Rhine Basin (adopted from Hager 1986). The centre of the Rhenish Main Seam is on the eastern Erft Block (cf. Fig. 3) at almost 400 m below the present surface

the actual stratigraphical nomenclature, but have been in common use as 'Schichten'. Nevertheless, they form the basis for synthesizing a consistent chrono- and sequence-stratigraphic standard for the region (cf. Fig. 4). The biostratigraphical ages presented are derived from Berggren et al. (1995), while the sequence stratigraphy ages were adopted from Haq et al. (1987, 1988) and Hardenbol et al. (1998).

Deposition in the Lower Rhine Basin began in the Early Oligocene times. The most complete sedimentary record was in the northern Rur Block (Walsum Fm, Ratingen Fm, Grafenberg Fm, and Lintfort Fm) and in the southern Venlo Block (Boom Clay, *Nucula* Clay and Sand). In the SE Lower Rhine Basin, the Bergisch-Gladbach Fm is the stratigraphical equivalent of those formations. The beds of the Schneider–Thiele code numbers 02–04 (Schneider and Thiele 1965) represent the transgressive basal series of the basin forming marginal marine shaley sands rich in organic material.

This transgressive series extends to the upper Oligocene to lower Miocene Köln Formation (Schneider–Thiele code numbers 05–5), the deposits of which were high-energy coastal marine sands and contain tidal bedding features. South of these sands, lagoonal and/or back-barrier fine-grained depositional environments formed. The sediments are rich in organic material, contain mostly wood, which today is preserved as brown coal. Towards the sea in the North, shales deposited in environments below the wave base predominate. The upper part of the Köln Fm (from sand 2 to the base of strata 6) has been interpreted as a model of a stacked high-energy coast (Schäfer et al. 1996).

Along the southernmost margin of the Lower Rhine Basin, the depositional systems are dominated by flood plain sedimentation, rich in fine-grained siliciclastics, and thin brown coal seams. In the Siebengebirge, in the SE of the Lower Rhine Basin, explosive volcanism led to the deposition of extensive trachyte tuffs some hundreds of metres in thickness into which trachyte, latite, and basalt was intruded (Vieten et al. 1988; Meyer 1994). The Drachenfels trachyte intrusives have an age of 24.99 ± 0.07 Ma (Wijbrans et al. 1995).

Above these tuffs, in the northern promontories of the Siebengebirge, the Rott Lake formed during the uppermost Oligocene (Mörs 1996, 2002). Thus, the Rott Lake sequence is correlated with Clay 3, consisting of lagoonal to lacustrine clay and brown coal (cf. Fig. 4). Clay 3 forms a stratigraphic marker horizon throughout the Lower Rhine Basin, at a posititon close to the Oligocene/Miocene transition (Schäfer et al. 2004).

The Ville Fm (Schneider–Thiele code number 6) in the centre of the Lower Rhine Basin is represented by the Rhenish Main Seam (cf. Fig. 4). It has a thickness of about 100 m. Prior to its compaction, the Rhenish Main Seam is estimated to have had a thickness of 300 m of peat (Hager 1986, 1993). Its age is Early to Middle Miocene, and it formed within a time span of 17.5–10.5 Ma (according to cycle ages of Hardenbol et al. 1998; Schäfer et al. 2004). In Middle Miocene times, the marine Frimmersdorf and Neurath sands intercalate with the growing peats and demonstrate major flooding events in the subsiding embayment (Petzelberger 1994). The marine sands deposited along the seaward side of the coastal lowlands contained salt marshes, peats, and bush forests. At back-barrier positions, tidal and lagoonal clays accumulated. Many of the coastal marine sands were capped by aeolian dunes and sheet sands (Clemmensen 1976; Petzelberger 1994).

In the W of the Lower Rhine Basin, the Inden Fm preserved the Upper Seams with a cumulative thickness of almost 40 m. Towards the north, these split into three separate seams, the Friesheim (7B), Kirchberg (7D), and Schophoven (7C) seams. Their biostratigraphical age is Late Miocene. Further details are provided by Schäfer et al. (2004). In the eastern part of the basin, only minor brown coal deposits above the Rhenish Main Seam were preserved. Instead, there are fluvial coarse-grained greyish sands and clays of the Inden Fm (here called Fischbach Fm) deposited by northward flowing meandering rivers that drained the fluvial plain. Considerable erosion of the Rhenish Main Seam underneath can be observed, and intraclasts of various sizes are abundant (Abraham 1994). Williams and Flint (1990) reported on major collapse structures due to exposed river bank reliefs, which they observed in the Inden Fm.

The Hauptkies Fm (Schneider–Thiele code number 8) is interpreted as having been deposited as a coarse-grained mixed-load braided-river system containing numerous well-rounded white vein quartz and black chert clasts from the Maas River system in the SW. Additionally, Cretaceous silicified oolites are also noted. These beds on top of the Rhenish Massif are named the 'Kieseloolith' (Boenigk 1981, 1990, 1995, 2002; Boersma et al. 1981). In part, the underlying Inden Fm was eroded considerably (Abraham 1994). The top of the Hauptkies Fm (8/9A transition) exposes fine-grained sediments, alternately bedded sands and muds, that were interpreted as representing an estuarine facies (Valdivia-Manchego 1996). The Hauptkies Fm was deposited close to the Miocene/Pliocene boundary, however, as biogenic remains are sparse, the stratigraphic control is not precise.

In the Rotton Fm (Schneider–Thiele code number 9), the input of coarse-grained sediments was reduced. Sandy braided rivers provided coarse-grained sands partially rich in coarse organic debris (wood, fruits, and seeds), and also lacustrine clays (Ashraf et al. 1997a; Schäfer et al. 1997). Minor brown coal is preserved.

The Upper Pliocene Reuver Fm (Schneider–Thiele code numbers 10–11) started with braided rivers delivering coarse-grained sediments. Sands of meandering rivers and lacustrine clays contain reworked palynomorphs (Ashraf et al. 1997 b).

According to the regional chronology of the Lower Rhine Basin, the Pleistocene begins with the deposition of the Older Pleistocene Terraces, followed by the so-called Tegelen Complex (Schneider–Thiele code numbers are 12–15; the Tegelen s.str. is 13). The sediments of the Older Pleistocene Terrace are predominantly fluvial sands of braided rivers (Boenigk 2002), but also consist of lake deposits. The overlying Younger Main Terrace of the Rhine River (Schneider–Thiele code number 16) is rich in heterolithic bolders, gravels, and coarse-grained sands from nearby sources in the Rhenish Massif (Boenigk 1981, 1990, 1995, 2002; Brunnacker 1978; Klostermann 1995), and formed a high-energy fluvial fan (Schirmer 1995). As the source area of the Main Terrace widened towards the South, the sediments delivered also originate from beyond the Rhenish Massif. Younger terraces developed due to the incision of the Rhine River and its tributaries, when the Rhenish Massif was uplifted in the Pleistocene (Meyer and Stets 1998, 2002). Heumann (2001) and Heumann and Litt (2002) have provided a sedimentological and biostratigraphical analysis on a Pleistocene section taken from the Hambach mine. Stratigraphical ages resulting from this investigation have been incorporated into the stratigraphic standard section (cf. Fig. 4).

Eleven thousand years ago, the phreatomagmatic Maria Laach volcano exploded, and spread windborne ash towards the NE and SE (Schmincke 2000). This volcanic ash was reworked by the River Rhine and is suspected of having formed a stratigraphic marker horizon in the terrace sediments (Meyer 1994). However, up until now, no ash has been found in the Lower Rhine Basin. This is probably due to the fact that it was intensely reworked in the high-energy fluvial environments and also altered by postdepositional weathering.

From the Paleogene onward, the Cenozoic North Sea transgressed onto the lowlands of present-day Belgium, The Netherlands, and Germany. Initial subsidence of this area commenced in Early Oligocene times with the onset of the Rupelian (Vandenberghe et al. 2001). The ingression of the Cenozoic North Sea led to the formation of early coastal marine environments. The subsidence of the Lower Rhine Basin during the Rupelian and the Early Chattian was due to late activities of the Hercynian Aachen Thrust. Late Variscan thrust movements are suspected to be probably responsible for differential subsidence of the faulted blocks (Nickel 2003). In the Chattian, cyclic marginal marine sediments formed in the southern part of the basin, individually overlain by marshland clays and peats. In the Early Miocene, a wide coastal plain was vegetated by swamps, bushlands, and forests.

The North Sea retreated again during late Miocene and Pliocene times. Fluvial systems recovered the wide marshland plain, once the coastline prograded seaward. The early precursors of the rivers Maas, Rhine, Sieg, and Wupper delivered sediments to the subsiding basin (Abraham 1994; Petzelberger 1994; Valdivia-Manchego 1996). A gradual decrease in temperature has been documented by analysis of the floral record (Utescher et al. 2000, 2002). Finally, the Rhenish Massif was uplifted in the Pleistocene and attained its present elevation. This uplift provided the source for detritus to the Lower Rhine Basin. The River Rhine deposited a thick and coarse-grained fluvial fan (Boenigk 2002). In the Rhenish Massif, fluvial terraces developed by the incision of the river network and due to the structural uplift, showing the complex interaction of tectonics, sea level, and climatic change (Meyer and Stets 2002).

Base level cycles

A selection of wells representative of the fill of the Lower Rhine Basin were interpreted in terms of their base level cyclicity. Base level cycles are correlative to the basin volume by the ratio A/S, i.e. Accommodation space versus Sediment supply (Cross et al. 1993; Cross and Lessenger 1997, 1998; Ramón and Cross 1993, 2002). Depending on the tectonic subsidence of the basin and/or the rise or fall of the relative sea level, the accommodation space of a basin increases or decreases. In general, sediment supply is from an uplifted source, forming a climate dependent drainage network of erosion and transport paths to the basin. Thus, the base level provides information on the complex interaction of tectonics, sediment transport, and the variation of sea level. In this study (cf. Fig. 4) base level half cycles are marked along field and well sections as base level rise (white peak-up triangles) and base level fall (black base-up triangles).

In coastal regimes, the base level is correlated with the storm wave base, above which reworking of the coastal profile may occur. Landward from the shore, the base level is the undulating ideal surface, above which no deposition is possible, and below which sediments may accumulate (Wheeler 1964; Galloway 1989a, 1989b). Close to the sea, base level cycles correlate with the sea level. Landward they change to show an intense interrelation with depositional systems in continental sedimentary basins, their drainage pattern and structural style (Ramón and Cross 1993, 2002; Aigner et al. 1999; Huggenberger and Aigner 1999; Klingbeil et al. 1999; Hornung and Aigner 2002a and 2002b). Base levels provide a more specific signal to the depositional record of individual measured sections and well profiles. Base level cycles also faciliate the correlation between sections and profiles over long distances, even without a precise identification of their environments and subenvironments (Cross and Lessenger 1998). With respect to sequence stratigraphy, flooding surfaces (tips of triangles) mark the inundation of a preceding depositional sequence. On the other hand, sequence boundaries (base of triangles) mark subaerial erosion of exposed sections and landscapes. They need not be specifically attributed to sequence stratigraphic orders but demand a thorough interpretation of the depositional environment.

The stratigraphy of the early sediment fill of the Lower Rhine Basin consists of base level fall and rise cycles (cf. Fig. 4). They represent the marine sections below the Morken Seam (the basal seam of the Rhenish Main Seam). The Rupelian forms the base of the stratigraphic record of the Lower Rhine Basin (Hager et al. 1998). Since this major flooding event (the Rupelian transgression, verified in European basins), individual flooding events are recorded in well sections of the Lower Rhine Basin. They occurred rapidly, initiating sediment supply from sources in the hinterland, presumably from the S of the Rhenish Massif. So, together with some minor ravinement, the flooding events started with base level fall cyclicity. The marine sections show a shallowing-upward trend. Base level fall is representative for all marine sections. When the sections extended into non-marine environments, they were topped by base level rise. The progradation of the coastal environments was from the SE towards the NW, parallel to the basin axis.

As is shown in one of the profile sections of Klett (2000), Sand 2 was closest to the maximum marine flooding in the early Oligocene (Fig. 6) (Klett et al. 2002; modified). In the following, the extension of Sand 4, Morken Sand, and Frimmersdorf Sand (cf. Fig. 4) slowly reduced. The Neurath Sand was deposited, while the Lower Rhine Basin was inundated for the last time.

From the Lower Miocene onward, the North Sea retreated from the Lower Rhine Basin. As the groundwater table was still high and the subsidence of the basin favourable, a thick peat layer formed from wood

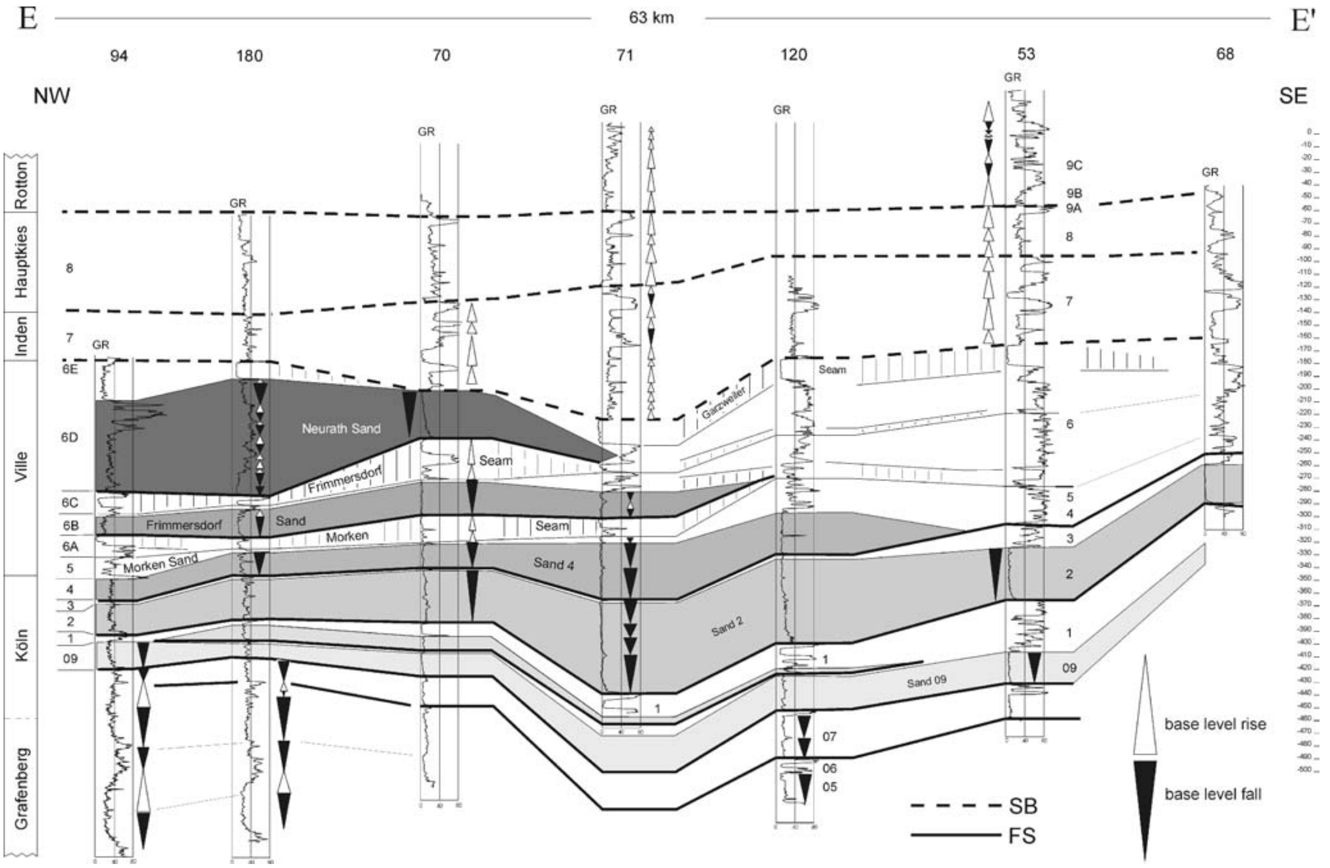


Fig. 6 The NW-SE oriented well section, compiled from well profiles compiled as facies code profiles (Klett 2000; Klett et al. 2002). The lignite brown coal seams are vertically hatched, and their names indicated. The section shows marine sands (grey colours) intercalated to the depositional record of the Lower Rhine Basin. These sands slowly retreated towards the NW, the younger they became with stratigraphy. Base level cycles are shown as triangles in black and white, symbolizing their fall and rise (for location of the section cf. Fig. 2)

fragments and leaves of extensive bush forests (Hager 1986; Huhn et al. 1997). Rivers drained the lowlands and partially eroded the topmost horizons of the peats. Thus, erosion surfaces on the tops of the coal seams are present in many sedimentary sequences of the Lower Rhine Basin, both in well profiles and measured field sections (Abraham 1994).

The fluvial Inden Fm (7) represents the first marked regressive event in the Lower Rhine Basin (Fig. 7). In places, intense reworking of the underlying Garzweiler Seam can be observed (Schäfer et al. 2004). Lags of clay intraclasts, brown coal and wood fragments were interbedded in the basal fluvial layers of the Inden Fm. The Inden Fm formed a meandering river environment and ended with lacustrine beds rich in lignites.

From the top of the Rhenish Main Seam onward, base level rise cycles are representative for the upper stratigraphic unit of the basin. They mostly contain marked basal erosion features. The rivers were oversupplied by sediments, and their sedimentary sequences have small A/S ratios. Due to a widening and deepening of the basin later on, the A/S ratios increase, and the sections end with lacustrine beds. The individual sections of the strata 7, 8, 9, and 10 are depositional systems correlative over wide parts of the Lower Rhine Basin. Sequence 7 is of a meandering facies. The sequences of 8, 9, and 10 each started with major braided rivers, then changed to form meandering rivers, and ended with lacustrine environments (Abraham 1994). This is summarized in the stratigraphic standard section (cf. Fig. 4) and individually shown by the base level rise motifs of the geophysical logs in the wells B 71 and 53 (cf. Fig. 6). The lacustrine facies each followed preceding major fluvial stages (transitional 8/9A, 9C, 11) and represent a wide variety of lake bed and swamp environments having had a minimal sediment supply. The corresponding log motifs form the base of the stratigraphic correlation (as is shown in Fig. 7).

The facies section lengthwise through the Lower Rhine Basin and the southern part of the Roer Valley Graben (Fig. 8) shows a tentative summary of a base level correlation from the SE to the NW of the Dutch German Central Graben (Zagwijn et al. 1985; Klett et al. 2002; Schäfer et al. 2004). The section is mostly based on well profiles, while details from its SE interior are from the brown coal open-cast mines along the Ville Ridge.

The Rupelian transgression is documented by the Boom Clay (for stratigraphic details refer to Vandenberghe et al. 1997, 1998), achieved a highstand and is then followed by a slow retreat of the marine sands from sand 2 to Neurath Sand (6D). The subsequent regression during the fluvial unit on top of these shows a base level rise trend.

The fluvial beds of the Inden Fm contain stacked channels with medium- to coarse-grained sands and a reduced amount of overbank clay layers. In places, the Inden Fm started with a marine flooding horizon placed on top of the Garzweiler Seam (where *Pholas* sp. borings often can be encountered; Bertling et al. 1995), then changing to meandering fluvial conditions within a metre of section. The sinuosity of the river beds was of a medium-sinuosity meandering style with a reduced amount of flood basin clays. It may be characterized as a perennial river system with a continuous water course, rich in sediment freight, and stacked channels, as well as abandoned meander loops of oxbow lakes, which are filled by clay plugs (Abraham 1994). Overall, the fluvial environment of the Inden Fm was that of a lowland river, confined by the structure of the basin and forced to form a stacking pattern. The structural subsidence of the Lower Rhine Basin at this time was dominated by the initial compaction of the peats of the underlying Ville Fm.

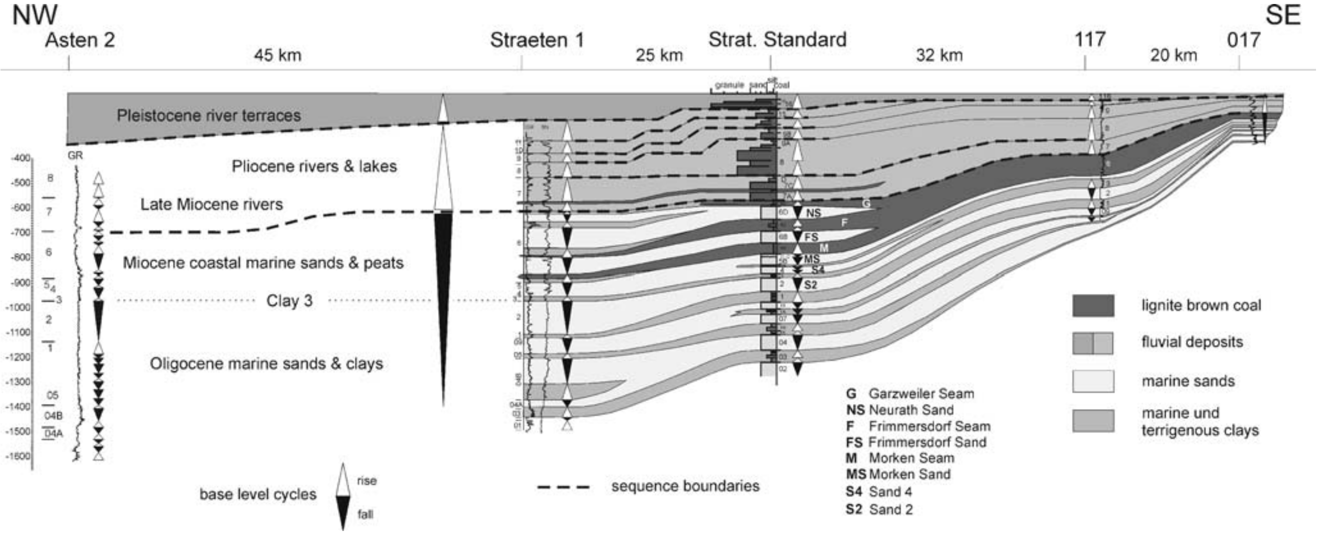


Fig. 7 Section from the Roer Valley Graben in the NW to the SE of the Lower Rhine Basin (cf. Fig. 2). Compiled from well profiles and the stratigraphic standard section (cf. Fig. 4). Stratigraphical correlation was made by use of base level cycles. The fluvial erosion surface on top of the Rhenish Main Seam is the first major sequence boundary starting the progradation of Late Miocene and Pliocene rivers towards the North. In the Pleistocene, the river terraces rapidly gained thickness towards positions distant of the Rhenish Massif

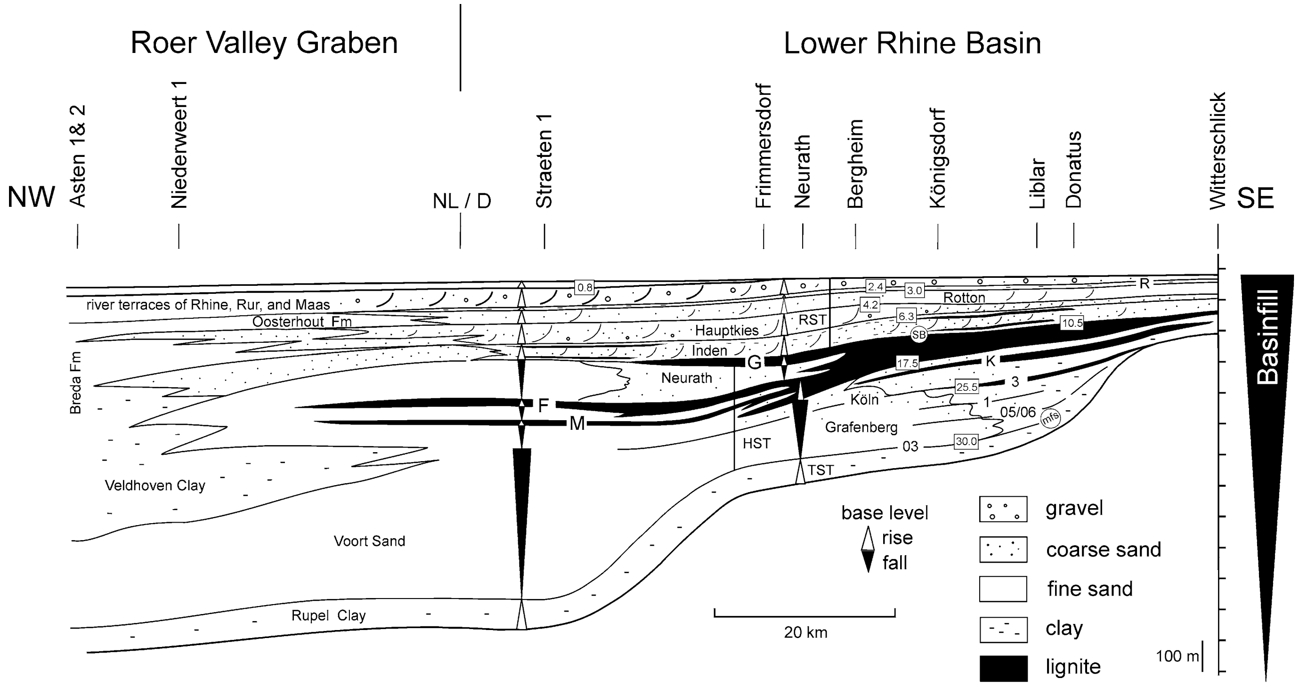


Fig. 8 Southeastern part of a NW-SE running facies section (cf. Fig. 2), showing the facies relationships from the Rupelian to the top of the Rhenish Main Seam (black). First compiled by Zagwijn et al. (1985), then completed by Schäfer et al. (2002), to schematically show the younger strata above the Rhenish Main Seam. Corrected by Schäfer et al. (2004) for stratigraphical thicknesses. Base level cycle symbols are included to visualize the interpretation of the depositional environments. Numerical ages (of a 3rd-order hierarchy) and a tentative systems tract nomenclature are inserted. The Lower Rhine Basin underwent a long-lasting base level fall when it was filled by Cenozoic deposits. The ratio of accommodation space vs. sediment supply was reduced especially due to the uplift of the Rhenish Massif

The sediments of the Hauptkies Fm were deposited in a deeply channelized braided river environment. Well developed channels contain transverse trough cross-bedding and channel-bar islands with downstream oriented plane-shaped cross-bed sets. In places, these two cross-bed features show tightly arranged sets. Both are well organised and suggest ample accommodation space while they were formed. The Hauptkies Fm is the stratum that shows the richest sediment input to the basin. Basal erosion on the underlying Inden Fm is significant and forms a clear-cut sequence boundary that can be traced throughout the Lower Rhine Basin. The Hauptkies Fm consists of two major fluvial cycles and a final transition to meandering, estuarine and lacustrine conditions on top (transition 8 to 9A).

The Rotton Fm sands (9B) were deposited in a sand-rich braided river environment, showing numerous stacked channels and confined by abundant unconformities. The channels carried a sand-rich freight with a large amount of wood remains, fruits, and seeds from nearby forests. Nevertheless, the depositional sequences of the Rotton Fm show a transition to meandering environments, that ended with a well developed lake bed environment (9C).

The Reuver Fm (sands 10 and clays 11) were also deposited under similar environmental conditions demonstrating that the basin repeated the change from low to high accommodation space.

Finally, the deposition of the Pleistocene terrace sediments of the River Rhine began under conditions of low-accommodation space. Coarse-grained and boulder-rich sediments forming stream-channel environments were provided. A widening of the accommodation space then followed, and the sediment freight was gradually reduced. The deposits contain numerous unconformities, cutting and reworking preceding deposits. The unit is about 20 m in thickness, and mainly forms the Younger Main Terrace of the River Rhine (Heumann and Litt 2002).

The Holocene deposits also show fining-upward sequences, and demonstrate a widening of the accommodation space of the basin together with a reduction in sediment transport.

The overall base level tendency of the Lower Rhine Basin has to be understood as a general base level fall, because the fill of the Lower Rhine Basin has to be correlated with the uplift history of the Rhenish Massif. This uplift initiated erosion and a rich fluvial freight. As a consequence, the base level fall trend is marked by rich sediment supply and dramatic loss of accommodation space. The uplift of the Ardennes also delivered sediments that were deposited in the Roer Valley Graben (Van Balen et al. 2002; Garcia-Castellanos et al. 2000).

Geohistory

The subsidence history of the Lower Rhine Basin was recorded by compiling geohistory curves for the region. This is shown with a plot of stratigraphical thicknesses versus stratigraphical age (Fig. 9). The stratigraphical thicknesses of the strata are derived from the stratigraphic standard section (cf. Fig 4). This contains an isotope age datum from the Drachenfels trachyte (Wijbrans et al. 1995) and was corroborated by biostratigraphical ages from Berggren et al. (1995). Cycle ages (Schäfer et al. 2004) were provided using sequence stratigraphic concepts from Haq et al. (1987, 1988), Mitchum et al. (1993), and Hardenbol et al. (1998).

Since the brown coal is compacted by a ratio of about 3:1 (Hager 1986), some uncertainty with the continuity of the basin subsidence history remains. The siliciclastic sediments mostly consist of sands, with only thin layers of intercalated sandy muds. The sedimentary sequence under consideration has a total thickness of 1 km or less. The coastal marine to fluvial sediments were deposited in, or close to, sea level and thus the differences between a tectonic and a total subsidence history could be ignored. On the other hand, Kooi et al. (1991), Zijerfeld et al. (1992), Michon (2003), Michon et al. (2003) have published backstripped subsidence curves from the Roer Valley Graben that were calculated with corrections for compaction and environment.

The subsidence history of the Lower Rhine Basin presented here (cf. Fig. 9) shows a continuous curve – a period of rapid subsidence in the Oligocene marine unit, followed by a period of reduced subsidence, in much of the Miocene, and again, finally, a phase of rapid subsidence which began in the Messinian (Upper Miocene) and extends to the Present. The fluvial unit above the Rhenish Main Seam had a very high sediment input. Except for the Inden Fm, the fluvial facies patterns preferentially comprise braided systems and coarse-grained sediments. This would mean, that in the fluvial unit the ratio of accommodation space to sediment supply was rather small, i.e. more sediment was delivered than the basin could accommodate. The fluvial facies patterns also indicate that most of the rivers were proximal systems. Thus, a large amount of the fluvial freight that must have bypassed the Lower Rhine Basin, was transported towards the Cenozoic North Sea.

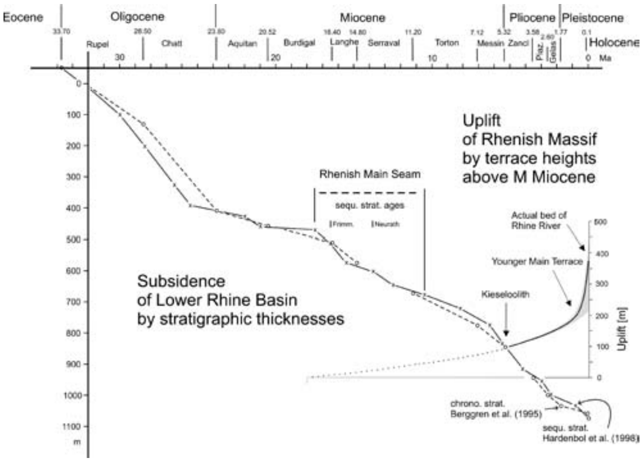


Fig. 9 The geohistory curve showing the subsidence of the Lower Rhine Basin is compiled by stratigraphical thicknesses versus stratigraphical ages as they are given in the stratigraphic standard section (cf. Fig. 4) with respect to Berggren et al. (1995) and Hardenbol et al. (1998). The uplift of the Rhenish Massif is calculated from height positions of the Younger Main Terrace of the Rhine River tributary system (Meyer and Stets 1998, 2002), in relation to the top of the Rhenish Main Seam. Initiation of the uplift of the Rhenish Massif is indicated by 'Kieseloolith', a wide river terrace element at the Miocene/Pliocene boundary

The Lower Rhine Basin subsided during the Tertiary, especially from the Oligocene (in the Rupelian and the Early Chattian; Nickel 2003). The Rhenish Massif was markedly uplifted coincident with the initiation of fluvial sedimentation in late Miocene. The overlying Tertiary deposits were mostly removed and are only locally preserved. Thus, the uplift history of the Rhenish Massif was calculated on the basis of Plio-Pleistocene fluvial sediments of the Rhine River tributary system, preserved today in terrace positions (Meyer and Stets 1989, 2002).

Most of the Tertiary deposits in the Lower Rhine Basin were derived from the Rhenish Massif consisting of the weathered Devonian bedrocks, late Paleozoic and Mesozoic cover rocks, and Cenozoic sediments transported northward in wide river systems (Sissingh 2003). As Tertiary strata on top of the Rhenish Massif were only locally preserved (Meyer 1994), their deposition and subsequent removal must have been balanced by the concomitant subsidence of the Lower Rhine Basin, and also of the Roer Valley Graben (Zijerveld et al. 1992; Van Balen et al. 2002).

Hermanns (1992) differentiated two types of clay-mineral assemblages in the Tertiary fill of the Lower Rhine Basin. The Lower Miocene Kaolinite-Illite zone and the Upper Miocene to Pliocene Kaolinite-Illite-Smectite-Vermiculite-Chlorite zone can be correlated with the erosion of the weathering crust of the Rhenish Massif. The denudation of the deeply weathered Rhenish Massif began in the Miocene. The thickness of its weathered zone is estimated to have been between 50 and 100 m (Spies 1986; Felix-Hennigsen 1990). However, it is difficult to calculate its precise former thickness, since it was often completely removed or only preserved in tectonic traps (Meyer 1994).

With the onset of the Pleistocene, the ratio of the sediments supplied to the Lower Rhine Basin changed significantly, when the Rhenish Massif (Meyer and Stets 1998, 2002) and the Ardennes (van Balen et al. 2002; Garcia-Castellanos et al. 2000) were uplifted (Fig. 10a and b). Rivers deeply cut into the Devonian rocks and structures. In the Lower Rhine Basin, the uplift was marked by the deposition of the Rhine River fluvial fan, consisting of a mixed-load of gravel and coarse-grained sands, transported and deposited in a wide braided river system. The Rhine River fluvial fan was laterally interconnected with the Maas fluvial fan.

The uplift of the Rhenish Massif was of an order of about 250 m above a maximum anomaly in the Eifel volcanic field as can be shown by the present-day elevation of the Rhine River terraces and those of its confluents (Meyer and Stets 1998, 2002). The Lower Rhine Basin formed the sink to which the detritus of the Rhenish Massif was delivered. The Maas and its tributaries mainly contributed material to the Roer Valley Graben (Van Balen et al. 2002). Both systems together formed the wide Maas-Rhine Fan (Boenigk 2002).

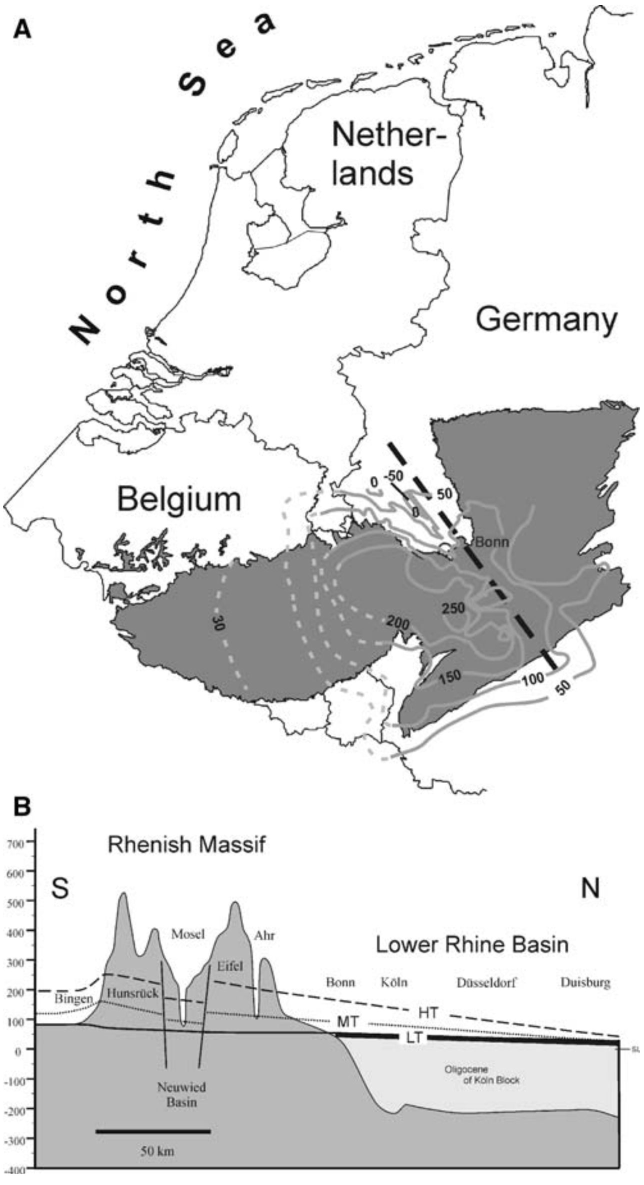


Fig. 10 a The Pleistocene uplift of the Rhenohercynian block, demonstrated by river terrace heights, as compiled by Meyer and Stets (1998, 2002) along the Rhine River system in the Rhenish Massif, and by Garcia-Castellanos et al. (2000) and Van Balen et al. (2002) along the Maas River system in the Ardennes. The isopachs verify the uplift of the younger main terrace (jHT) during the last 800000 years. The bold interrupted line running SE–NW shows the position of the cross section. **b** SE–NW section through the Rhenish Massif and the eastern part of the Lower Rhine Basin. The Köln and Krefeld blocks consist of Oligocene strata, deeply eroded during the Pleistocene uplift. Miocene and Pliocene deposits were removed, and close to the Rhine River remnant Oligocene strata are capped by the Low Terrace (LT) and Holocene deposits (for details cf. Fig. 11). The Pleistocene HT and MT terraces are present in other areas of the basin only. In the Rhenish Massif, the terraces can be traced along the modern Rhine river system (Meyer and Stets 1998, 2002)

The terrace bodies in the Rhenish Massif were deposited during a period of lateral erosion at the end of the Menap cold stage (Early Pleistocene). As the uplift of the massif continued into the following Cromer stage, the rivers vertically cut into the bedrocks. This incision was only interrupted by short cold stages each corresponding with terrace remnants that have been classified as Lower Younger Main Terrace and High Middle Terrace (Hilden 1988).

During warm stages the transport of gravels, accumulated during the cold stages, took place. The river systems cut down into the bedrock and by this balanced the continuous uplift of the Rhenish Massif. Thus, a prominent increase in sediment supply and river slope towards the Lower Rhine basin can be observed, especially during the transition from cold stages to warm stages.

During the Saale Glaciation, the sediments of the Middle Terrace developed in the Lower Rhine Basin. Braided rivers formed and were entrenched into the underlying Main Terrace sediment bodies of the Rhenish Massif.

As is evident from the uplift curve (cf. Fig. 9; right hand side of the diagram), the uplift of the Rhenish Massif commenced with the development of the early Pliocene fluvial unit in the Lower Rhine Basin (as indicated by the Hauptkies Fm, equivalent to the position of 'Kieseloolith'). Yet, the maximum uplift of the Rhenish Massif occurred in the Pleistocene leading to the development of a series of terraces along the major rivers (Meyer and Stets 1998, 2002). With respect to the thickness of the Pleistocene sediments in the Lower Rhine Basin, it may be assumed that much of the detritus bypassed due to the basin's lack of subsidence. A mixed-load fluvial fan formed, prograding from the Rhenish Massif towards the North. A section of it is well documented in the Hambach mine by Heumann (2001) and Heumann and Litt (2002). The fluvial deposits in the Lower Rhine Basin are organized as a system of High, Middle, and Low Terraces correlated with the Pleistocene glacial/interglacial cyclicity (Boenigk 1981, 1990, 1995, 2002). On the Köln/Krefeld Block and close to the Rhine River, a profile section based on well logs extending from NE of Bonn to NNW of Duisburg was constructed (Fig. 11). This shows strata of the Köln Fm in the South and Grafenberg Fm to Walsum Fm (equivalent to the Berg Sand in Fig. 8; pers. comm. Noel Vandenberghe 2004) in its North. The entire section exposes Oligocene strata, which were deposited during the transgression of the Tertiary North Sea. These are unconformably overlain by Pleistocene Low Terrace deposits. Below the section, prominent thrust systems, known from surface outcrops on either sides of the Lower Rhine Basin, dissect the Devonian basement of the Rhenish Massif (Hilden 1988). The Aachen thrust probably was active during the Palaeogene, since

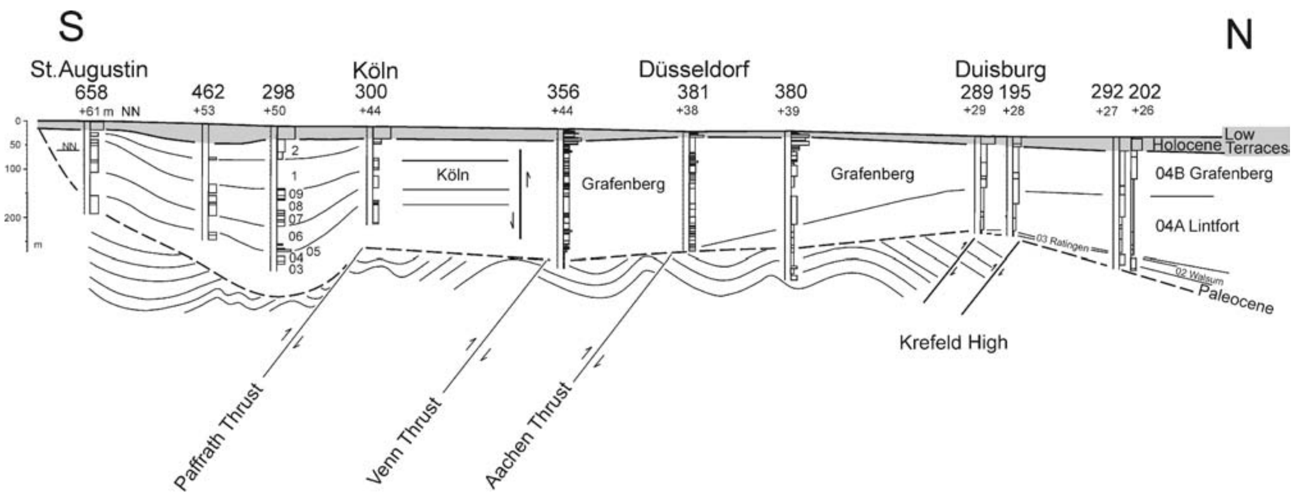


Fig. 11 A N-S well section through the eastern blocks of the Lower Rhine Basin (position indicated in Fig. 2 as a thin line running from well 658 in the SE to well 202 in the NW) on the uplifted Köln Block shows that only the Oligocene is preserved. Oligocene is unconformably overlain by Pleistocene sediments of the Rhine River Low Terrace. The Devonian basement of the Rhenish Massif underneath the Oligocene is given with structural elements as proposed by Hilden (1988)

differences in depositional facies and bed thicknesses on either sides of the thrust can be observed (Nickel 2003).

The cross-section of the basin shows a tilt in its strata towards the NE (cf. Fig. 3a and b). This asymmetry is preserved only in the blocks to the W of, and close to, the Erft and Peel faults. The strata of the Köln, Venlo and Krefeld blocks have a more or less horizontal position. Subsidence of the Lower Rhine Basin was as a result of right-angle extension leading to faults showing a vertical to steep inclination (cf. Fig. 3 b). This was also noted by Knufinke and Kothen (1997) and Jentzsch and Siehl (2002). Michon et al. (2003) provided evidence of a 60° inclination of the Peel Fault based on their interpretation of a seismic section through the central Roer Valley Graben.

From the cross-sections of Fig. 3 an interpretation of the basin formation of the interior Lower Rhine Basin was made (Fig. 12). From the inclination of the Cenozoic strata in the Lower Rhine Basin and surface maps it is assumed that the easternmost border fault (east of the Rhine River; position B) was the most active one during the subsidence of the basin from Oligocene to Pliocene. Moreover, this boundary fault is a prolongation of the Middle Rhine River valley, dissecting the Rhenish Massif. From the surface it is expected that the faults in the Lower Rhine Basin are steep. However, with greater depth, the right-angle extension could have provided a listric shape in an example of Leeder and Gawthorpe (1987) from elsewhere. While the uplift of the Rhenish Massif started in the Pliocene, and accelerated during the early Pleistocene, a reactivation of the faults is assumed. Presumably, the eastern boundary fault renewed its movement, contributing to major uplift of the eastern part of the basin. In addition, the today Ville Ridge (the border region between the Köln and the Erft blocks) is a position with a bundle of numerous faults (Jentzsch and Siehl 2002; cf. Fig. 3b) that altogether are named Erft

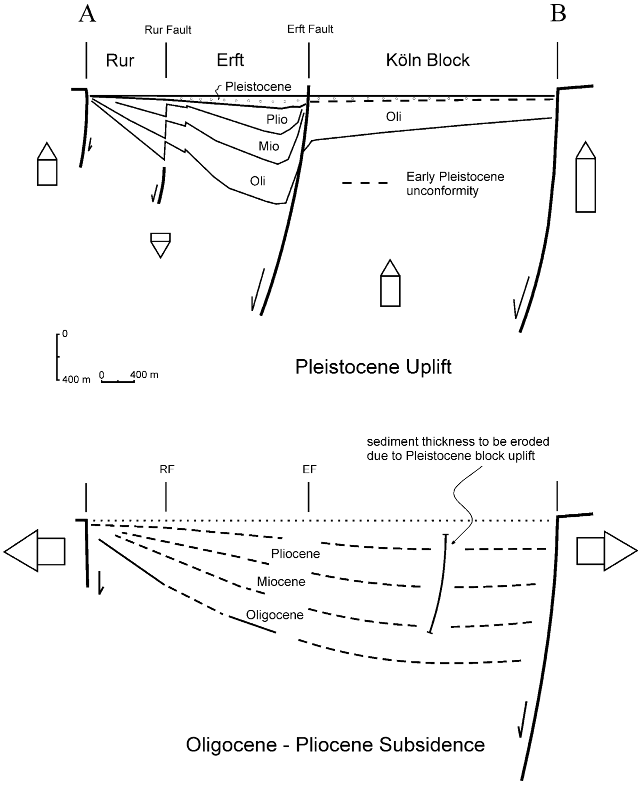


Fig. 12 Two interpretative SW–NE sections through the Lower Rhine Basin (A to B in Figs. 2 and 3), showing the asymmetry of its basin fill. The extension of the basin led to accentuated subsidence during the Oligocene, Miocene, and Pliocene. The most important normal fault during the subsidence phase was at the eastern margin of the basin, bordering the Rhenish Massif east of the Rhine River (Position B). The uplift of the Rhenish Massif became marked in early Pleistocene. Within the basin, the Köln Block was also uplifted, by repeated activation of the eastern fault (at position B) and, most importantly, also of the Erft Fault that shows major seismicity and movement until today. The Pleistocene and a thin veneer of Holocene strata covering the entire basin are only dissected by some of the faults.

Fault. This Erft Fault faciliated major uplift of the Köln Block leading to the erosion of the Neogene strata on top of it. Therefore, the Oligocene of the Köln Block is unconformably overlain by Pleistocene and some Holocene.

Discussion

Basin subsidence, geohistory, and sequence stratigraphy

The Lower Rhine Basin forms the southeastern part of the Dutch-German Central Graben and is strongly correlated with the uplift of the Rhenish Massif and the Ardennes (Schäfer and Siehl 2002). The geohistory curve (cf. Fig. 9) shows that the subsidence of the basin was steady from the Oligocene – which was the beginning of the stratigraphic control on the fill of the Lower Rhine Basin (Schäfer et al. 2004).

From Late Miocene time onward, the basin subsidence became marked. The uplift of the Variscan massifs (Ardennes and Rhenish Massif) can be monitored since the latest Miocene times. In early Pleistocene especially, the uplift of the Rhenish Massif accelerated and formed a staircase-like arrangement of river terraces along the valleys of the Rhine River and Lower Mosel River (Meyer and Stets 1998, 2002).

The Rupelian transgression (Boom Clay; Stratum 03) led to maximum flooding and the deposition of rich clays in many basins of Central Europe (Vandenberghe et al. 1997, 1998; Vandenberghe and Hardenbol 1998; Hager et al. 1998), and also in the Lower Rhine Basin (Nickel 2003). The marine sands overlying Rupelian clays were deposited under a relative sea level highstand (HST). Several trans- and regressions in the Lower Rhine Basin are estimated as broad regional events of higher order. During this highstand, when the freshwater level was high and the growth conditions of the vegetation in the coastal lowlands were favourable (cf. McCabe and Shanley 1992), the peats of the Rhenish Main Seam and its sub-seams developed. This was from 30 to 10.5 Ma sequence stratigraphic cycle age (sensu Hardenbol et al. 1998) (cf. Fig 4).

Highstand conditions with a maximum in the Langhian changed to fluvial sequences and by this initiated the regressive phase after the Serravallian. The fluvial sequences were stacked and are separated by relatively thin lacustrine sandy clays.

The stratigraphy of the basin fill of Cenozoic strata in the Lower Rhine Basin is in the time range of the third-order cyclicity of the sequence stratigraphic concept (Schäfer et al. 2004). The depositional cycles of the Grafenberg and the Köln formations both commenced with flooding surfaces. With only little reworking, so that a marked ravinement surface was preserved, the peats were flooded and followed shallowing upward with coastal tidal environments and ended with onshore peats (Minnigerode 1985; Petzelberger 1994; Schäfer et al. 1996). While flooded again, most often there was time enough for lamellibranchiate larvae to occupy the peat substrate to start dwelling there, as borings of *Pholas* sp. may prove (Bertling et al. 1995). In some cases, these flooding surfaces were reworked to form intraformational clasts of brown coal and mud fragments (e.g. Frimmersdorf seam at Garzweiler mine). In some places, the flooding provided delicate features as are storm sand layers by which the marine environment regained the exposed topstratum of the peats (basal Neurath Sand on Frimmersdorf seam at Hambach mine). The flooding process was rapid and resulted in depositional environments of about the lower shoreface or the transition zone of the coast. Tidal bundles show at least a mesotidal, or even a macrotidal range (Schäfer et al. 1996).

The coastal sequences may be subdived to form a series of sub-sequences. These are smaller-scaled and follow on top of each other with intense erosion unconformities that are formed in stacked high-energy sand-rich shoreface environments, e.g. in the Fortuna mine (Schäfer et al. 1996). These sub-sequences are below the resolution limit of dating, presumably higher than the fourth-order range. On the other hand, some of them have stratigraphical relevance.

In the Lower Rhine Basin, the regressive fluvial cycles overlying the brown coal each begin with erosive sequence boundaries (cf. Fig. 7). The erosional features at the base of the fluvial sequences are generally well developed. Thus, fluvial erosion unconformities can be used for stratigraphic correlation of the depositional sequences. The Hauptkies Fm, in particular, shows a prominent sequence boundary at its base throughout the Lower Rhine Basin. This sequence boundary erodes major parts from the topstratum of the Inden Fm below (Abraham 1994). Also, the sequence boundary at the base of the Pleistocene Rhine River terraces is significant.

The sequences in the Lower Rhine Basin can be correlated with those of the Cenozoic basinfill of the Roer Valley Graben, forming the centre of the Dutch German Central Graben (Verbeek et al. 2002).

As sequence stratigraphy allows for overregional correlations with separate basins, the drop of the sea level in Late Miocene particularly, (Serravallian/Tortonian, 10.5 Ma sequence age according to Hardenbol et al. 1998) is such an event. It marks a dramatic change in the depositional record of various Cenozoic marginal marine environments, even world-wide. In the Lower Rhine Basin (Schäfer et al. 2004), the base of the Inden Fm cut a significant sequence boundary into the top of the Rhenish Main Seam (cf. Figs. 6, 7, 8).

In southern Belgium, the Tortonian Diest Sands transgressed into a large scale gully structure that was deeply cut into the Rupelian Boom Clay underneath. There are arguments that major erosion suggesting a considerable drop of the late Miocene sea level occurred prior to the deposition of the marginal marine sands containing glauconites (Vandenberghe et al. 1998).

The Northwest European Tertiary Basin was only open towards the northern higher latitudes (Vinken

1989), so that a significant drop in temperature according to the palaebotanical record at the beginning of the Tortonian could be realized (Schäfer et al. 2004). Close to the southeastern margin of this Northwest European Tertiary Basin with respect to the Miocene, the stratigraphic record of the Wursterheide well (south of Cuxhaven; Benda et al. 1989) does not give any hint that the Cenozoic sea level might have dropped with the beginning of the Tortonian (Gram Fm). On the other hand, Michelsen et al. (1995) and Clausen et al. (1999) reported about westward oriented progradational and aggradational seismic patterns in the East of the Danish North Sea sector in late Miocene. These presumably belong to the Eridanos Delta that prograded westward into the southern Cenozoic North Sea, fed by a huge fluvial tributary trailing along southern Scandinavia (Overeem et al. 2001). Below its progadational stacking patterns, the delta was bounded by a major unconformity about 10.7 Ma in age, which elsewhere marks the Late Miocene fall of the sea level.

In the Upper Rhine Graben (Sissingh 1997, 1998, 2003), the Late Miocene Serravallian/Tortonian boundary also forms a marked erosion feature. The fluvial Dinotherium Sands unconformably rest on lacustrine beds of Upper Tertiary I.

On the Ragusa carbonate ramp of the Hyblean Plateau, SE Sicily, Italy, a Serravallian rhodalgal (red algae) biotic community was unformabely overlain by a Tortonian chloralgal to chlorozoan lithofacies, giving proof of a major lowering of the sea level (Ruchonet and Kindler 2005). As a consequence, an increase in the Mediterranean water temperature was argued due to a change of the water circulation from an anti-estuarine to an estuarine regime within the relief of the Mediterranean water basin.

Recently, John et al. (2004) quantified the late Middle Miocene sea level drop at the Marion Plateau (ESE-ward offshore Townsville, NE Australia) having been of 50 ± 5 m. This obviously may explain the above observed environmental changes to be due to a worldwide rapid fall of the eustatic sea level.

Base level stratigraphy and accommodation space

Base level stratigraphy has been demonstrated to be an excellent field method for small-scale correlation of depositional cycles (Cross and Lessenger 1998; Mjos et al. 1998; Ramón and Cross 1993, 2002). The use of this concept faciliated the tracing of the structural and depositional history in sedimentary basins in many details, for instance in the Upper Rhine Graben (Derer et al. 2003; Derer 2003). This approach was also used here for the study on the Lower Rhine Basin.

Base level cycles form the basis for the interpretation of marginal marine and fluvial sedimentary sequences; the time concept for the Lower Rhine Basin was recently published by Schäfer et al. (2004). The ingressive phase (the Rupelian Boom Clay) coincides with base level rise (cf. Fig. 8). The subsequent sedimentary sequences of the basal fill of the Lower Rhine Basin are strongly cyclic. They each show initial flooding of the preceding terrestrial environments (marshlands with peats and nearshore bush forests forming the present-day lignite brown coal seams). This then was followed by a rapid drowning that led to the establishment of coastal marine conditions, most often starting with a lower shoreface environment. Shallowing-upward developed beach, lagoonal, salt marsh, and finally fresh-water environments. As is evident in length sections through the Lower Rhine Basin, the marine ingressive sands (from Sand 2 upwards to Neurath Sand) reduced their landward extent with rising stratigraphic niveau (cf. Fig. 6). The coastal marine sands provided each a slow but accentuated offlap, although their base level motives remained identical (cf. Fig. 7).

Base level cycles can be correlated with the structural development of the Lower Rhine Basin. The marine fill of the Lower Rhine Basin dominantly shows base level fall patterns. Its fluvial fill consists of cycles showing base level rise. Particularly during the fluvial unit, the cycles not only indicate that they are controlled by the relative sea level of the distant Cenozoic North Sea, but they also show that the subsidence of the Lower Rhine Basin was coeval with the uplift of the Rhenish Massif (cf. Fig. 9).

A good correlation between the subsidence of the Lower Rhine Basin and the uplift of the Rhenish Massif is obvious as the A/S ratio diminished (Accommodation space vs. Sediment supply; Cross and Lessenger 1998). This drop in the A/S ratio was due to the increasing input of erosion products from the massif while it was uplifted. Although the fluvial strata individually show base level rise cycles, the 'Basinfill' pattern of the entire Lower Rhine Basin (on the right hand alongside the section of Fig. 8) demonstrates an overall base level fall while the basin was filled during the Cenozoic.

The Inden Fm at the beginning of the fluvial unit of the Lower Rhine Basin developed a meandering architecture (Abraham 1994). All subsequent fluvial horizons – the Hauptkies, Rotton, Reuver, Tegelen formations, together with the Pleistocene terraces – show dominantly braided river patterns. These Pliocene fluvial sections individually transformed from a braided to a short-lived meandering pattern and finally to a lacustrine style. The sands and clays formed individual base level rise cycles. The fluvial horizons differ much in their individual outlook. This reflects the changing A/S ratio of the Lower Rhine Basin. Whenever the basin subsided, the increase in accommodation space allowed a free formation of heterogenous fluvial features. When the accommodation space decreased, numerous discordances confining the crossbed sets indicate a wide fluvial plain with bypass of most of the sediments, resulting in the deposition of stacked fluvial sequences. Comparable observations were first specified by Ramón and Cross (1993) in fluvial intracontinental environments elsewhere.

The fluvial beds of the Inden Fm developed their bedding features in a style suggesting that there was ample accommodation space. The Hauptkies Fm shows a good balance between basin subsidence and sediment supply from pebbly braided rivers. The Rotton Fm achieved rather small accommodation space as the sandy downstream accreting bedform sets expose numerous reactivation surfaces and unconformities. The Reuver Fm regained accommodation space, and the fluvial bedforms enlarged their shape still having downstream accretion surfaces of a sandy braided river system. A complete change in fluvial architecture is evident with the Pleistocene sequences. Coarse-grained stream channel and bedload systems formed a widespread fluvial fan of Rhine River terraces in the Early Pleistocene.

While the Rhenish Massif was further uplifted, the Elsterian fluvial fan was eroded by younger terraces exposed along the course of the today Rhine River through the Rhenish Massif (Meyer and Stets 1998, 2002). It is important to realize that the thickness of the Pleistocene and Holocene alluvial beds in the Lower Rhine Basin is only about 20 m. These erosion products were provided from the Rhenish Massif during its uplift. Thus, an intense bypass of the erosion products should be taken into consideration.

Conclusions

Base level cycles are used in the Cenozoic Lower Rhine Basin to subdivide sedimentary sequences. They are subordinate in length and duration with respect to sequences and systems tracts in a sequence stratigraphic terminology. They illustrate seaward and landward shifts of the coastline at a much smaller scale. Nevertheless, they can be correlated with the third-order sequence stratigraphic cyclicity.

The Cenozoic continuous subsidence of the Lower Rhine Basin provided three groups of base level cycles throughout the period the basin was filled.

1. Base level rise together with the ingression of the Cenozoic North Sea to the southern end of the Dutch-German Central Graben, the Lower Rhine Basin being the southward termination of it. In sequence stratigraphic nomenclature, this section is understood as a transgressive systems tract (TST).
2. Base level fall cycles are significant across the lower part of the fill of the Lower Rhine Basin, including the Rhenish Main Seam. This is interpreted as a highstand systems tract (HST). An elevated table of fresh groundwater was necessary for the continuous generation of the bush forests and peats.
3. Several base level rise cycles constitute the regressive systems tract (RST) during the upper unit of the Lower Rhine Basin.

Overall, the basin fill of Lower Rhine Basin shows a pattern that developed from marine flooding to coarse-grained fluvial input, as a result of the structural extension of the Dutch German Central Graben in the Cenozoic, coeval with the uplift of the Rhenish Massif.

Acknowledgements Rheinbraun AG (today RWE Power) (Köln), Erftverband (Bergheim), and Staatliches Umweltamt (Bonn) are kindly appreciated for the gratitude to use their well data, also thanks are due to Rheinbraun for their generous permission and help to enter their brown coal open-cast mines, where Gerhard Gross, Bertram Wutzler, and especially Fritz von der Hocht were altruistic guides for many years. The Deutsche Forschungsgemeinschaft (DFG) granted splendid financial support for all of us (SFB 350 – Bonn), for which we are deeply grateful. The paper benefitted from a DFG supported travel of A.S. to Tim A. Cross (Golden, Col., USA) some years ago, and from discussions with Tom Aigner, Volker Mosbrugger and Rahman Ashraf (Tübingen), with Agemar Siehl and Niko Froitzheim (Bonn), also and especially from many improvements suggested by the reviewers, who were Noel Vandenberghe (Leuven, Belgium) and Adam Vecsei (Leipzig). The late Hans Hager (Krefeld) initiated early steps into our research work. Tom McCann (Bonn) did the final reading; he not only corrected the English writing, but also suggested numerous valuable improvements to the manuscript. We thank all much for their help.

References

Abraham M (1994) Untersuchungen zur sedimentologischen Entwicklung der fluviatilen Deckschichten (Miozän Pliozän) der Rheinischen Braunkohle. Bonner Geowiss Schr 15, pp 227

Ahorner L (1992) Das Erdbeben bei Roermond am 13. April 1992 und die daraus zu ziehenden Lehren für das Erdbebengefährdungspotential im Rheinland. Mitt Deutsch Geophys Ges 1992:51–57

Ahorner L (1997) Niederrheinische Bucht. Das Erdbeben von Roermond am 13. April 1992. Erdbeben in Deutschland

Aigner Th, Hornung J, Junghans WD, Poeppelreiter M (1999) Baselevel cycles in the Triassic of the South-German Basin: a short progress report. In: Bachmann GH, Lerche J (eds) Epicontinental Triassic 1. Zbl Geol Paläont I 1998: 537–544

Ashraf AR, Mosbrugger V (1995) Palynologie und Palynostratigraphie in der Niederrheinischen Bucht Teil 1 Sporen. Palaeontographica B 235:61–173

Ashraf AR, Mosbrugger V (1996) Palynologie und Palynostratigraphie in der Niederrheinischen Bucht. Teil 2 Pollen. Palaeontographica B 241:1–98

Ashraf AR, Mosbrugger V, Utescher T (1997 a) Palynological studies in the Neogene of the open pit mines Inden and Bergheim. Lower Rhine Embayment (Germany). Courier Forsch Inst Senckenberg 201:29–46

Ashraf AR, Utescher T, Mosbrugger V (1997 b) Tertiary palynostratigraphy – how reproducible are the results? Meded Nederl Inst Toeg Geowetensch TNO 58:163–170

Benda L (ed) (1989) Forschungsbohrung Wursterheide. Geol Jb A111:1–542

Berggren WA, Kent DV, Swisher CC, Aubry MP (1995) A revised Cenozoic geochronology and chronostratigraphy. SEPM Spec Publ 54:129–212

Bertling M, Hermanns K, von der Hocht F (1995) Sedimentologie und Palaeontologie autochthoner Muschel-Bohrungen in Kohleflözen (Neogen der Niederrheinischen Bucht). N Jb Geol Paläont Mh 12:711–736

Boenigk W (1981) Die Gliederung der tertiären Braunkohlendeckschichten in der Ville (Niederrheinische Bucht). Fortschr Geol Rheinld u Westf 29:193–263

Boenigk W (1990) Die pleistozänen Rheinterrassen und deren Bedeutung für die Gliederung des Eiszeitalters in Mitteleuropa. In: Liedtke H (ed) Eiszeitforschung. Darmstadt, pp 130–140

Boenigk W (1995) Terrassenstratigraphie des Mittelpleistozän am Niederrhein und Mittelrhein. Meded Rijks Geol Dienst 52:71–81

Boenigk W (2002) The Pleistocene Drainage Pattern in the Lower Rhine Basin. In: Schäfer A, Siehl A (eds) Rift tectonics and syngenetic sedimentation – the Cenozoic Lower Rhine Graben and related structures. Netherlands J Geosci, Geologie en Mijnbouw 81:201–209

Boersma JR (1991) A large flood-tidal delta and its successive spill-over apron. Detailed proximal-distal facies relationships. Miocene Lignite Suite Lower Rhine Embayment (Germany). In: Smith GD, Reinson GE, Zaitlin BA, Rahmani RA (eds) Clastic tidal sedimentology. Can Soc Petrol Geol Memoir 16:227–254

Boersma JR, Gelder AV, Groot TD, Puigdefabregas C (1981) Formen fluviatiler Sedimentation in neogenen und jüngeren Ablagerungen im Braunkohlentagebau Frechen (Niederrheinische Bucht). Fortschr Geol Rheinld u Westf 29:275–307

Brelie G von der (1968) Zur mikrofloristischen Schichtengliederung im rheinischen Braunkohlenrevier. Fortschr Geol Rheinld u Westf 16:85–102

Brelie G von der (1981) Neue Gesichtspunkte zur pollenstratigraphischen Gliederung des Pliozäns in der Niederrheinischen Bucht. Fortschr Geol Rheinld u Westf 29:265–274

Brelie G von der (1988) The Lower Rhine Embayment. In: Vinken R (ed) The Northwest European Tertiary Basin. Geol Jb A 100:316–317

Brelie G von der, Hager H, Weiler H (1981) Pollenflora und Phytoplankton in den Kölner Schichten sowie deren Lithostratigraphie im Siegburger Graben. Fortschr Geol Rheinld u Westf 29:21–48

Brunnacker K (1978) Der Niederrhein im Holozän. Fortschr Geol Rheinld u Westf 28:399–440

Campbell J, Kümpel HJ, Fabian M, Fischer D, Görres B, Keysers ChJ, Lehmann K (2002) Recent movement pattern of the Lower Rhine Embayment from tilt gravity and GPS data. In: Schäfer A, Siehl A (eds) Rift tectonics and syngenetic sedimentation – the Cenozoic Lower Rhine Graben and related structures. Netherlands J Geosci, Geologie en Mijnbouw 81:93–199

Clausen OR, Gregersen U, Michelsen O, Soerensen JC (1999) Factors controlling the Cenozoic sequence development in the eastern parts of the North Sea. J Geol Soc London 156:808–816

Clemmensen LB (1976) Eolian sandy lignite and associated sediments from the Miocene of the Lower Rhine Basin, Western Germany. Geologie en Mijnbow 55:73–82

Cross TA, Lessenger MA (1997) Correlation strategies for clastic wedges. In: Coulson EB, Osmond JC, Williams FT (eds) Innovative applications of petroleum technology in the Rocky Mountain area. Rocky Mountain Association of Geologists, 183–203

Cross TA, Lessenger MA (1998) Sediment volume partitioning rationale for stratigraphic model evaluation and high.resolution stratigraphic correlation. In: Gradstein FM, Sandvik KO, Milton NJ (eds) Sequence stratigraphy – concepts and applications. Norwegian Petroleum Society (NPF), Spec Publ 8:171–195

Cross TA, Baker MR, Chapin MA, Clark MS, Gardner MH, Hanson MS, Lessenger MA, Little LD, McDonough KJ, Sonnenfeld MD, Valasek DW, Williams MR, Witter DN (1993) Application of high-resolution sequence stratigraphy to reservoir analysis. In: Eschad R, Doligez B (eds) Subsurface reservoir characterisation from outcrop observations. Proceedings of the 7th Exploration and Production Research Conference Technip. Paris, 11–33

Derer ChE (2003) Tectono-sedimentary evolution of the northern Upper Rhine Graben (Germany), with special regard to the early syn-rift stage. pp 100, (electronically published) Dissertation, University of Bonn

Derer ChE, Kosinowski M, Luterbacher H, Schäfer A, Süss MP (2003) Sedimentary response to tectonics in extensional basins: the Pechelbronn Formation (late Eocene to early Oligocene) in the northern Upper Rhine Graben, Germany. In: McCann T, Saintot, A (eds) Tracing tectonic deformation using the sedimentary record. Geol Soc London Spec Publ 208: 55–69

Felix-Hennigsen P (1990) Die mesozoisch-tertiäre Verwitterungsdecke (MTV) im Rheinischen Schiefergebirge – Aufbau, Genese und quartäre Überprägung. Relief, Boden, Paläoklima 6, pp 192

Fuchs K, von Gehlen K, Mälzer H, Murawski H, Semmel A (eds) (1983) Plateau Uplift. The Rhenish Shield – a case history. Springer, Berlin Heidelberg New York Tokyo, 1–411

Galloway WE (1989 a) Genetic stratigraphic sequences in basin analysis – I. Architecture and genesis of flooding-surface bounded depositional units. AAPG Bull 73:125–142

Galloway WE (1989b) Genetic stratigraphic sequences in basin analysis – II. Application to Northwest Gulf of Mexico Cenozoic Basin. AAPG Bull 73:143–154

Garcia-Castellanos D, Cloetingh SAPL, Van Balen RT (2000) Modeling the Pleistocene uplift in the Ardennes-Rhenish Massif: thermo-mechanical weakening under the Eifel? Global Planet Change 27:39–52

Hager H (1986) Peat accumulation and syngenetic clastic sedimentation in the Tertiary of the Lower Rhine Basin, F.R. Germany. Mém Soc Géol France NS 149:51–56

Hager H (1993) The origin of the Tertiary lignite deposits in the Lower Rhine region, Germany. Int J Coal Geol 23:251–262

Hager H, Prüfert J (1988) Tertiär. In: Hilden HD (ed) Geologie am Niederrhein. GLA NRW: 32–40, Krefeld

Hager H, Vandenberghe N, Van Den Bosch M, Abraham M, von der Hocht F, Rescher K, Laga P, Nickel E, Verstraelen A, Leroi S, Van Leeuwen RJW (1998) The geometry of the Rupelian and Chattian depositional bodies in the Lower Rhine district and its border area implications for Oligocene lithostratigraphy. Bull Geol Soc Denmark 45:53–62

Haq BU, Hardenbol J, Vail PR (1987) Chronology of fluctuating sea levels since the Triassic. Science 235:1156–1166

Haq BU, Hardenbol J, Vail PR (1988) Mesozoic und Cenozoic chronostratigraphy and cycles of sea-level change. In: Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, van Wagoner JC (eds) Sea-level changes, an integrated approach. SEPM Spec Publ 42:71–108

Hardenbol J, De Graciansky C, Jacquin T, Vail PR (eds) (1998) Mesozoic and cenozoic sequence stratigraphy of European basins. SEPM Spec Publ 60:1–485

Hermanns K (1992) Untersuchungen in neogenen Tonschichten des Rheinischen Braunkohlenreviers südliche Niederrheinische Bucht. Bonner Geowiss Schriften 2, pp 203

Heumann G (2001) Stratigraphie und Paläoökologie des Jungpliozän und Altpleistozän im Tagebau Hambach (Niederrheinische Bucht). unpublished Dissertation, University Bonn, pp 109

Heumann G, Litt T (2002) Stratigraphy and palaeoecology of the Late Pliocene and Early Pleistocene in the open-cast mine Hambach (Lower Rhine Basin). In: Schäfer A, Siehl A (eds) Rift tectonics and syngenetic sedimentation – the Cenozoic Lower Rhine Graben and related structures. Netherlands J Geosci, Geologie en Mijnbouw 81:193–199

Hilden HD (ed) (1988) Geologie am Niederrhein. 4 ed. GLA NRW, Krefeld, p 142

Hilger D (1991) Zur Sedimentologie der Liegendschichten im Tagebau Fortuna. unpublished Diploma thesis, University of Bonn, pp 87

Hinzen KG (2003) Stress field in the Northern Rhine area, Central Europe, from earthquake fault plane solutions. Tectonophysics 377:325–356

Hornung J, Aigner T (2002 a) Reservoir architecture in a terminal alluvial plain: An outcrop analogue study (Upper Triassic, Southern Germany). Part I: Sedimentology and petrophysics. J Petroleum Geol 25:3–30

Hornung J, Aigner T (2002b) Reservoir architecture in a terminal alluvial plain: An outcrop analogue study (Upper Triassic, Southern Germany). Part II: Cyclicity, controls and models. J Petroleum Geol 25:151–178

Huggenberger P, Aigner Th (1999) Introduction to the special issue on aquifer-sedimentology: problems, perspectives, and modern approaches. Sediment Geol 129:179–186

Huhn B, Utescher T, Ashraf AR, Mosbrugger V (1997) The peat-forming vegetation in the Middle Miocene Lower Rhine Embayment, an analysis based on palynological data. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO 58:211–218

Jentzsch T, Siehl A (2002) Kinematic subsidence modelling of the Lower Rhine Basin. In: Schäfer A, Siehl A (eds) Rift tectonics and syngenetic sedimentation – the Cenozoic Lower Rhine Graben and Related Structures. Netherlands J Geosci, Geologie en Mijnbouw 81: 231–239

John CM, Karner DG, Mutti M (2004) Delta ^{18}O and Marion Plateau backstripping: Combining two approaches to constrain late middle Miocene eustatic amplitude. Geology 32:829–832

Klett M (2000) Sedimentologie des Tertiärs der Niederrheinischen Bucht – Interpretation anhand von Bohrungen und Bohrlochmessungen. Bonner Geowiss Schriften 28, pp 133

Klett M, Schäfer A (1997) Das Tertiär der Niederrheinischen Bucht. Interpretation der Sedimentfazies anhand von Bohrungen und Bohrlochmessungen. Zbl Geol Paläont Teil I 1996:443–456

Klett M, Eichhorst F, Schäfer A (2002) Facies interpretation from well-logs applied to the Tertiary Lower Rhine Basin fill. In: Schäfer A, Siehl A (eds) Rift Tectonics and Syngenetic Sedimentation – the Cenozoic Lower Rhine Graben and Related Structures. Netherlands J Geosci, Geologie en Mijnbouw 81:167–176

Klingbeil R, Kleineidam S, Asprion U, Aigner Th, Teutsch G (1999) Relating lithofacies to hydrofacies: outcrop-based hydrogeological characterisation of Quaternary gravel deposits. Sediment Geol 129:299–310

Klostermann J (1983) Die Geologie der Venloer Scholle (Niederrhein). Geol Jb A 66:3–115

Klostermann J (1995) Das Quartär Deutschlands. IV. Nordrhein-Westfalen. In: Benda L (ed) Das Quartär Deutschlands. Borntraeger, Berlin Stuttgart, 59–94

Knufinke HU, Kothen H (1997) Die Tektonik der Niederrheinischen Bucht vor, während und nach der Hauptflözbildung. Braunkohle, Surface Mining 49:473–479

Kooi H, Hettema M, Cloetingh S (1991) Lithospheric dynamics and the rapid Pliocene-Quaternary subsidence phase in the southern North Sea Basin. Tectonophysics 192:245–259

Leeder MR, Gawthorpe RL (1987) Sedimentary models for extensional tilt-block/half-graben basins. In: Coward MP, Dewey JF, Hancock PL: Continental Extensional Tectonics. Geol Soc Spec Publ 28:139–152

McCabe PJ, Shanley KW (1992) Organic control on shoreface stacking patterns. Bogged down in the mire. Geology 20:741–744

Meyer W (1994) Geologie der Eifel. 3rd ed. Schweizerbart, Stuttgart, pp 618

Meyer W, Stets J (1998) Junge Tektonik im Rheinischen Schiefergebirge und ihre Quantifizierung. Z dt geol Ges 149:359–379

Meyer W, Stets J (2002) Pleistocene to Recent Tectonics in the Rhenish Massif (Germany). In: Schäfer A, Siehl A (eds) Rift Tectonics and Syngenetic Sedimentation – the Cenozoic Lower Rhine Basin and Related Structures. Netherlands J Geosci, Geologie en Mijnbow 81, 217–221

Michelsen O, Danielsen M, Heilmann-Clausen C, Jordt H, Laursen GV, Thomsen E (1995) Occurence of major sequence stratigraphic boundaries in relation to basin development in Cenozoic deposits of the southeastern North Sea. In: Steel RJ, Felt VL, Johannessen EP, Mathieu C (eds) Sequence Stratigraphy on the Northwest European Margin. Norwegian Petroleum Society (NPF), Spec Publ 5:415–427

Michon L (2003) Role of the Alpine belt in the Cenozoic lithospheric deformation of Europe sedimentologic/stratigraphic/tectonic synthesis. Géologie de la France 1:115–119

Michon L, van Balen RT, Merle O, Pagnier H (2003) The Cenozoic evolution of the Roer Valley rift system integrated at a European scale. Tectonophysics 367:101–126

Minnigerode C (1985) Palaeoökologische Untersuchungen an der Basis des Rheinischen Hauptbraunkohlenflözes auf der Ville-Scholle. Paläont Z 59:43–49

Minnigerode C, Richter HG (1986) Holzanatomische Untersuchungen fossiler Wurzelhölzer aus dem Miozän der Niederrheinischen Bucht. Rev Paleobotany and Palynology 48:253–268

Mitchum RM, Sangree JB, Vail PR, Wornardt WW (1993) Recognizing sequences and systems tracts from well logs seismic data and biostratigraphy Examples from the Late Cenozoic of the Gulf of Mexico. In: Weimer P, Posamentier HW (eds) Siliciclastic Sequence Stratigraphy, AAPG Memoir, 58:163–197

Mjos R, Hadler-Jacobsen F, Johannessen EP (1998) The distal sandstone pinchout of the Mesa Verde Group, San Juan Basin, and its relevance for sandstone prediction of the Brent Group, northern North Sea. In: Gradstein FM, Sandvik KO, Milton NJ: Sequence stratigraphy – concepts and applications. Norwegian Petroleum Society (NPF), Special Publication, 8: 263–297

Mörs T (1996) Die Säugetiere der oberoligozänen Fossillagerstätte Rott bei Bonn (Rheinland). Decheniana 149:205–232

Mörs T (2002) Biostratigraphy and palaeoecology of continental Tertiary vertebrate faunas in the Lower Rhine Embayment (NW Germany). In: Schäfer A, Siehl A (eds) Rift tectonics and syngenetic sedimentation – the Cenozoic Lower Rhine Graben and Related Structures. Netherlands J Geosci, Geologie en Mijnbouw 81:177–183

Mörs T, von Koenigswald W, von der Hocht F (1998) Rodents (Mammalia) from the late Pliocene Reuver Clay of Hambach (Lower Rhine Embayment Germany). Meded Nederl Inst Toeg Geowetensch TNO 60:135–160

Mörs T, von der Hocht F, Wutzler B (2000) Die erste Wirbeltierfauna aus der miozänen Braunkohle der Niederrheinischen Bucht (Ville-Schichten Tagebau Hambach). Paläont Z 74:145–170

Nickel E (2003) Oligozäne Beckendynamik und Sequenzstratigraphie am Südrand des Nordwesteuropäischen Tertiärbeckens. Dissertation Universität Bonn, pp 151

Oehms EPN (1980) Schwermineralogische und mikropaläontologische Untersuchungen im marin beeinflussten Alttertiär des Antweiler Grabens (südliche Niederrheinische Bucht). Meded Werkgr Tert Kwart Geol 17:225–231

Overeem I, Bishop-Kay C, Weltje GJ, Kroonenberg SB (2001) The Late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? Basin Research 13:293–312

Paulssen H, Dost B, van Eck T (1992) The April 13, 1992 earthquake of Roermond (The Netherlands); first interpretation of the NARS seismograms. Geol en Mijnb 71:91–98

Pelzing R (1992) Das Erbeben von Roermond 13. April 1992. pp 16, GLA NRW, Krefeld

Petzelberger BEM (1994) Die marinen Sande im Tertiär der südlichen Niederrheinischen Bucht – Sedimentologie Fazies und stratigraphische Deutung unter Berücksichtigung der Sequenzstratigraphie. Bonner Geowissenschaftliche Schriften 14, pp 112

Plein E, Doerholt W, Greiner G (1982) Das Krefelder Gewölbe in der Niederrheinischen Bucht Teil einer grossen Horizontalverschiebungszone? Fortschr Geol Rheinld u Westf 30:15–29

Plenefish T, Bonjer KP (1997) The stress field in the Rhine Graben area inferred from earthquake focal mechanisms and estimation of frictional parameters. Tectonophysics 275:71–97

Quitzow HW, Vahlensieck O (1955) Über pleistozäne Gebirgsbildung und rezente Krustenbewegungen in der niederrheinischen Bucht. Geol Rundschau 43:56–67

Ramón JC, Cross TA (1993) Characterization and prediction of reservoir architecture and petrophysical properties in fluvial channel sandstones middle Magdalena Basin Colombia. CT &F – Ciencia Technologia y Futuro 1:19–46

Ramón JC, Cross TA (2002) Correlation strategies and methods in continental strata middle Magdalena Basin Colombia. [home page TACross: http://www.mines.edu, http://www.platte.com]

Ruchonet C, Kindler P (2005) Climate change at the Middle/Late Miocene boundary: Evidence from the Ragusa carbonate ramp (SE Sicily, Italy). In: Homewood P (ed) Abstracts, 24th IAS Meeting of Sedimentology, January 10–13 2005, p 146, Muscat/Oman

Schäfer A (1994) Die Niederrheinische Bucht im Tertiär – Ablagerungs- und Lebensraum. In: Koenigswald W, von Meyer W (eds) Erdgeschichte im Rheinland. Fossilien und Gesteine aus 400 Millionen Jahren, 155–164, München

Schäfer A, Siehl A (eds) (2002) Rift Tectonics and Syngenetic Sedimentation – the Cenozoic Lower Rhine Basin and Related Structures, Utrecht. Netherlands J Geosci, Geologie en Mijnbouw 81:145–256

Schäfer A, Hilger D, Gross G, von der Hocht F (1996) Cyclic sedimentation in Tertiary Lower Rhine Basin (Germany) – the 'Liegendrücken' of brown coal open-cast Fortuna mine. Sed Geol 103: 229–247

Schäfer A, Utescher T, von der Hocht F (1997) Klastische Sedimentsysteme im Tertiär der Niederrheinischen Bucht. In: Ricken W (ed) Exkursion E 4 Sediment '97, 12. Sedimentologentreffen 21–24 Mai 1997 am Geologischen Institut der Universität zu Köln. Terra Nostra 1997:68–113

Schäfer A, Utescher T, Mörs Th (2004) Stratigraphy of the Cenozoic Lower Rhine Basin northwestern Germany. Newsletter Stratigr 40:73–110

Schirmer W (ed) (1995) Quaternary field trips in Central Europe (Rhine Traverse). XIV International Congress 3.-10.8.1995, Berlin. International Union for Quaternary Research 9:475–558

Schmincke HU (2000) Vulkanismus. Wissenschaftliche Buchgesellschaft, Darmstadt, pp 264

Schneider W (1995) Palaeohistological studies on Miocene brown coal of Central Europe. Int J Coal Geol 28:229–248

Schneider H, Thiele S (1965) Geohydrologie des Erftgebietes. Ministerium für Ernährung Landwirtschaft und Forsten NRW, Düsseldorf, pp 185

Schreiber U, Rotsch S (1998) Cenozoic block rotation according to a conjugate shear system in central Europe – indications from paleomagnetic measurements. Tectonophysics 299:111–142

Sissingh W (1997) Tectonostratigraphy of the North Alpine Foreland Basin correlation of Tertiary depositional cycles and orogenic phases. Tectonophysics 282:223–256

Sissingh W (1998) Comparative Tertiary stratigraphy of the Rhine Graben, Bresse Graben and Molasse Basin: correlation of Alpine foreland events. Tectonophysics 300:249–284

Sissingh W (2003) Tertiary paleogeographic and tectonostratigraphic evolution of the Rhenish Triple Junction. Palaeogeogr Palaeoclimatol Palaeoecol 196:229–263

Spies ED (1986) Vergleichende Untersuchungen an präpleistozänen Verwitterungsdecken im Osthunsrück und an Gesteinszersatz durch aszendente (Thermal-) Wässer in der Nordeifel (Rheinisches Schiefergebirge). (unpublished) Dissertation, University of Bonn, pp 182

Standke G (2002) Palaeogeographisch-fazielle Modellierung des Unter-/Mittelmiozän-Grenzbereichs in der Lausitz (Briesker Folge/Formation). pp 9, Thesen Dissertation, Technische Universität Bergakademie Freiberg

Standke G, Rascher J, Strauss C (1993) Relative sea-level fluctuations and brown coal formation around the Early-Middle Miocene boundary in the Lusatian Brown Coal District. Geol Rundschau 82:295–305

Teichmüller R (1974) Die tektonische Entwicklung der Niederrheinischen Bucht. In: Illies JH, Fuchs K (eds) Approaches to Taphrogenesis, Schweizerbart, Stuttgart, 269–285

Utescher T, Ashraf AR, Mosbrugger V (1992) Zur Faziesentwicklung im Neogen der Niederrheinischen Bucht. In: Kovar-Eder J (ed) Palaeovegetational Development in Europe, 235–243, Wien

Utescher T, Mosbrugger V, Ashraf AR (2000) Terrestrial climate evolution in northwest Germany over the last 25 million years. Palaios 15:430–449

Valdivia-Manchego M (1994) Rechnergestützte stereophotogrammetrische Aufnahme und Auswertung fluviatiler Sedimentstrukturen im Tertiär der Niederrheinischen Bucht. Zbl Geol Paläont Teil I 1993:1011–1026

Valdivia-Manchego M (1996) Stereophotogrammetrisch-sedimentologische Aufnahme und 3D-Modellierung von Schrägschichtungsgefügen am Beispiel einer pliozänen fluvialen Abfolge in der Niederrheinischen Bucht. Bonner Geowiss Schriften 21, pp 152

Van Balen RT, Houtgast RF, Van der Wateren FM, Vandenberghe J (2002) Neotectonic evolution and sediment budget of the Meuse catchment in the Ardennes and the Roer Valley Rift System. In: Schäfer A, Siehl A (eds) Rift Tectonics and Syngenetic Sedimentation – the Cenozoic Lower Rhine basin and related structures. Netherlands J Geosci, Geologie en Mijnbouw 81:211–215

Vandenberghe N, Hardenbol J (1998) Introduction to the Neogene. SEPM Spec Publ 60:83–85

Vandenberghe N, Laenen B van, Echelpoel E, Lagrou D (1997) Cyclostratigraphy and climatic eustasy Example of the Rupelian stratotype. CR Acad Sci Paris Sciences de la terre et des planetes, Earth Planetary Sci 325:305–315

Vandenberghe N, Laga P, Steurbaut E, Hardenbol J, Vail PR (1998) Tertiary sequence stratigraphy at the southern border of the North Sea Basin in Belgium. SEPM Spec Publ 60:119–154

Vandenberghe N, Hager H, van den Bosch M, Verstraelen A, Leroi S, Steurbaut E, Prüfert J and Laga P (2001) Stratigraphical correlation by calibrated well logs in the Rupel Group between North Belgium, the Lower-Rhine area in Germany and southern Limburg and the Achterhoek in the Netherlands. In: Vandenberghe N (ed) Contributions to the Paleogene and Neogene stratigraphy of the North Sea Basin. Proceedings of the 7th Biannual Meeting of the Regional Committees of northern Neogene and Paleogene stratigraphy. Aardkundige Mededelingen, 11:69–84

Verbeek JW, de Leeuw CS, Parker N, Wong ThE (2002) Characterization and correlation of Tertiary seismostratigraphic units in the Roer Valley Graben. In: Schäfer A, Siehl A (eds) Rift Tectonics and Syngenetic Sedimentation – the Cenozoic Lower Rhine Basin and Related Structures. Netherlands J Geosci, Geologie en Mijnbouw 81:159–166

Vieten K, Hamm HM, Grimmeisen W (1988) Tertiärer Vulkanismus des Siebengebirges. Fortschr Miner 66 Beih 2:1–42

Vinken R (1989) The Northwest European Tertiary Basin. Geol Jb A100, 1–508

Wheeler HE (1964) Base level lithosphere surface and time-stratigraphy. Geol Soc Amer Bull 75:599–610

Wijbrans JR, Pringle MS, Koppers AAP, Scheveers R (1995) Argon geochronology of small samples using VULKAAN argon laserprobe. Proc Kon Nederl Akad v Wetensch 98:185–218

Williams H, Flint S (1990) Anatomy of a channel-bank collapse structure in Tertiary fluvio-lacustrine sediments of the Lower Rhine Basin Germany. Geol Mag 127:445–451

Zagwijn WH (1989) The Netherlands during the Tertiary and the Quaternary. A case history of coastal lowland evolution. Geol en Mijnbouw 68:107–120

Zagwijn WH, Hager H (1987) Correlations of continental and marine Neogene deposits in the South-Eastern Netherlands and the Lower Rhine district. Meded Werkgr Tert Kwart Geol 24(1–2):59–78

Zagwijn WH, Beets DJ, van den Berg M, van Montfrans HM, van Rooijen P (1985) Atlas van Nederland in 20 delen. Deel 13 – Geologie. 23 pp, S'Gravenhage

Zijerveld L, Stephenson R, Cloetingh S, Duin E, Van Den Berg MW (1992) Subsidence analysis and modelling of the Roer Valley Graben (SE Netherlands). Tectonophysics 208:159–171