

**CORRELATIONS OF CONTINENTAL AND MARINE NEOGENE DEPOSITS IN THE
SOUTH-EASTERN NETHERLANDS AND THE LOWER RHINE DISTRICT**

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The lithostratigraphy of the Neogene continental deposits of the Lower Rhine Embayment (F.R.G.) is discussed, with special reference to the Miocene Lower Rhine Brown-coal Formation and its relation to marine deposits further to the West. The factors involved in the genesis of the exceptionally thick Main Seam of the Lower Rhine Brown-coal Formation are analysed. The bio- and chronostratigraphy of the neogene marine deposits is described. New data permit better correlation with the Miocene standard subdivision in the Mediterranean region than was hitherto possible. The boundaries defined as Early-Middle and Middle-Late Miocene, hitherto applied to the North Sea area, should be revised. The fairly precise correlations between the continental and marine sequences throw light on the role of sea-level movements. The role of climate as revealed by pollen analysis is briefly discussed.

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SAMENVATTING

Sedert het Laat Paleogeen vormden de Centrale Slenk en de Nederrijnse Bocht een snel dalend deel van het zuidelijke Noordzeebekken. Een dikke reeks van mariene afzettingen in de Centrale Slenk is vertand met zuidoostelijk ervan gelegen continentale lagen in het centrum van de Nederrijnse Bocht. In het Vroeg Neogeen namen dalingssnelheid en instroom van rivierafzettingen vanuit het zuiden af. Dit bevorderde het ontstaan van uitgestrekte veenmoerassen in de kustvlakte. In het centrale deel van de Nederrijnse bocht accumuleerde in het Mioceen ongeveer 300 m veen, dat door inklinking tot een laag van ruim 100 m zuivere bruinkool werd samengedrukt (Ville Formatie, Hauptflöz, Main Seam). Deze opeenhoping van veen in het bekkencentrum was mogelijk, doordat de riviersystemen lange tijd dit centrum meden. Later werd hier wel klastisch fluviatiel materiaal afgezet en ontstond verder zuidelijk een koollaag van 40 m (Inden Formatie, Oberflöz, Upper Seam). Daarna overheerste in het jongste Mioceen en het Plioceen klastische sedimentatie.

Op grond van nieuwe gegevens kunnen de mariene miocene afzettingen nauwkeuriger worden gecorreleerd met andere gebieden rond de Noordzee, maar met name ook is een correlatie met de standaardstratigrafie van het Mediterrane gebied mogelijk gebleken, in het bijzonder op grond van nannoplankton en dinoflagellaten. Hierdoor is een herziening nodig geweest van de traditionele afbakening tussen Vroeg, Midden en Laat Mioceen in het onderzochte gebied. Uit de correlaties blijkt, dat de belangrijke transgressie in het Midden Mioceen, die aanleiding gaf tot de vorming van het Neurather Sand en gedurende welke de zee ver (ruim 80 km) het veenmoeras binnendrong, te zelfder tijd ook elders langs de Noordzee optrad. Deze transgressie komt overeen met de hoogste zeestand in het Mioceen in de curve van Vail et al. (1977). Voorafgaand aan en volgend op deze episode vond regressie plaats. De laatste begon in het Laat Mioceen en zette zich, afgezien van enkele kleine schommelingen, voort in het Plioceen en vroegste Pleistoceen.

Uit pollenanalytische studies kan een indruk verkregen worden van klimaatschommelingen. In het algemeen blijkt veenvorming vooral gecorreleerd met warme en vochtige perioden.

INTRODUCTION

The Miocene lignites of the Lower Rhine Embayment (FRG) form what is one of the world's largest single occurrences of brown-coal. The geologically proven amount of exploitable lignites is no less than 55 billion tons. At present, the annual production amounts to about 120 million tons, most of this coal being used for the production of electricity, supplying more than 20% of the total demand in the Federal Republic of Germany.

The present discussion concerns the tectonic, palaeogeographic and palaeoclimatic conditions that led to the accumulation of such a huge amount of organic material in a relatively small area and, more specifically, the question of how a coal seam with a thickness of more than 100 metres could arise in the centre of that accumulation (fig. 1).

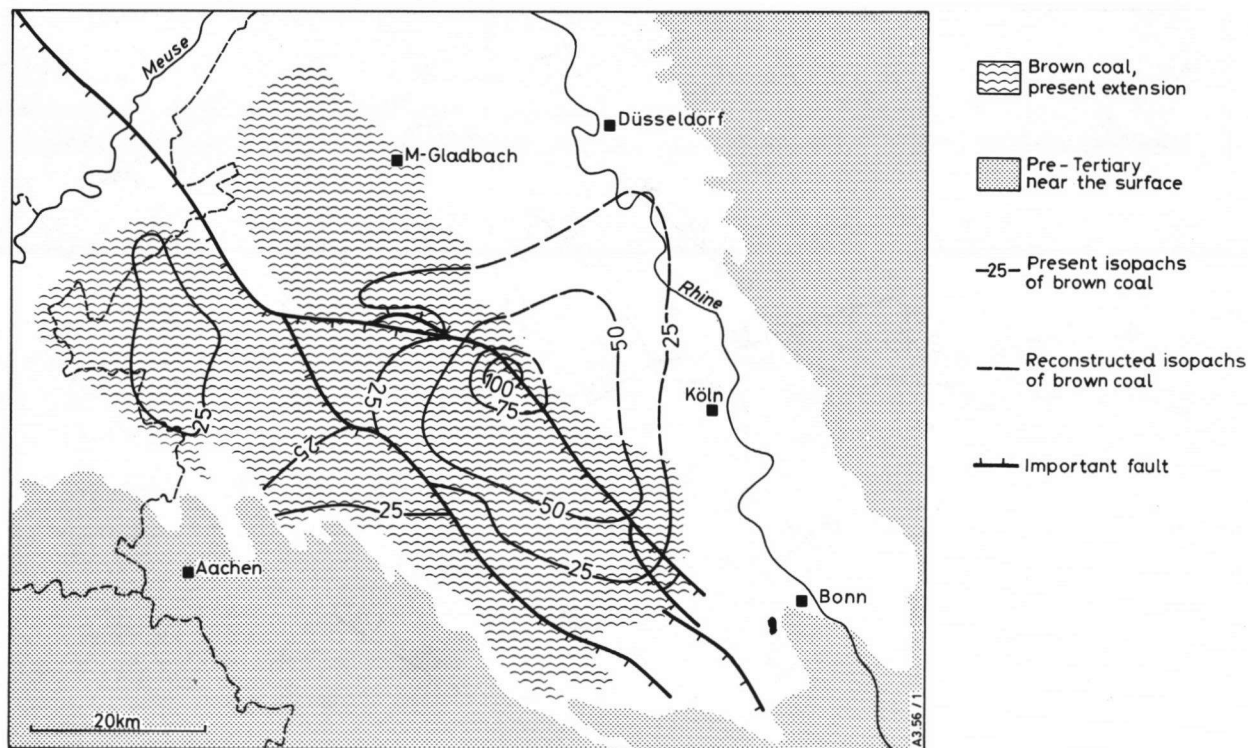


Fig. 1. Map showing the occurrence and thickness of brown-coal deposits in the Lower Rhine District and some important faults in this region.

The basis for this discussion is twofold. In the first place a detailed knowledge of the mineable deposits in question is needed, and secondly a thorough knowledge of the stratigraphic position of the coal beds in relation to beds from a different facies.

The second author is responsible for the interpretation of the geological setting of the Lower Rhine Lignites, which is based on the evaluation of a great amount of detailed information. Because in the area under discussion the border between the Federal Republic of Germany and The Netherlands roughly coincides with the boundary of predominantly continental Miocene deposits toward the South-East and predominantly marine deposits toward the North-West (fig. 2), close co-operation between research workers of the two countries was needed to solve the problems associated with stratigraphic correlation between the two facies. The data presented in this paper are the result of this collaboration between the Geological Survey of The Netherlands and the Geological Survey of Nordrhein-Westfalia. This co-operation was originally undertaken as part of IGCP Project 124 (NW European Tertiary Basin), but was continued after its completion.

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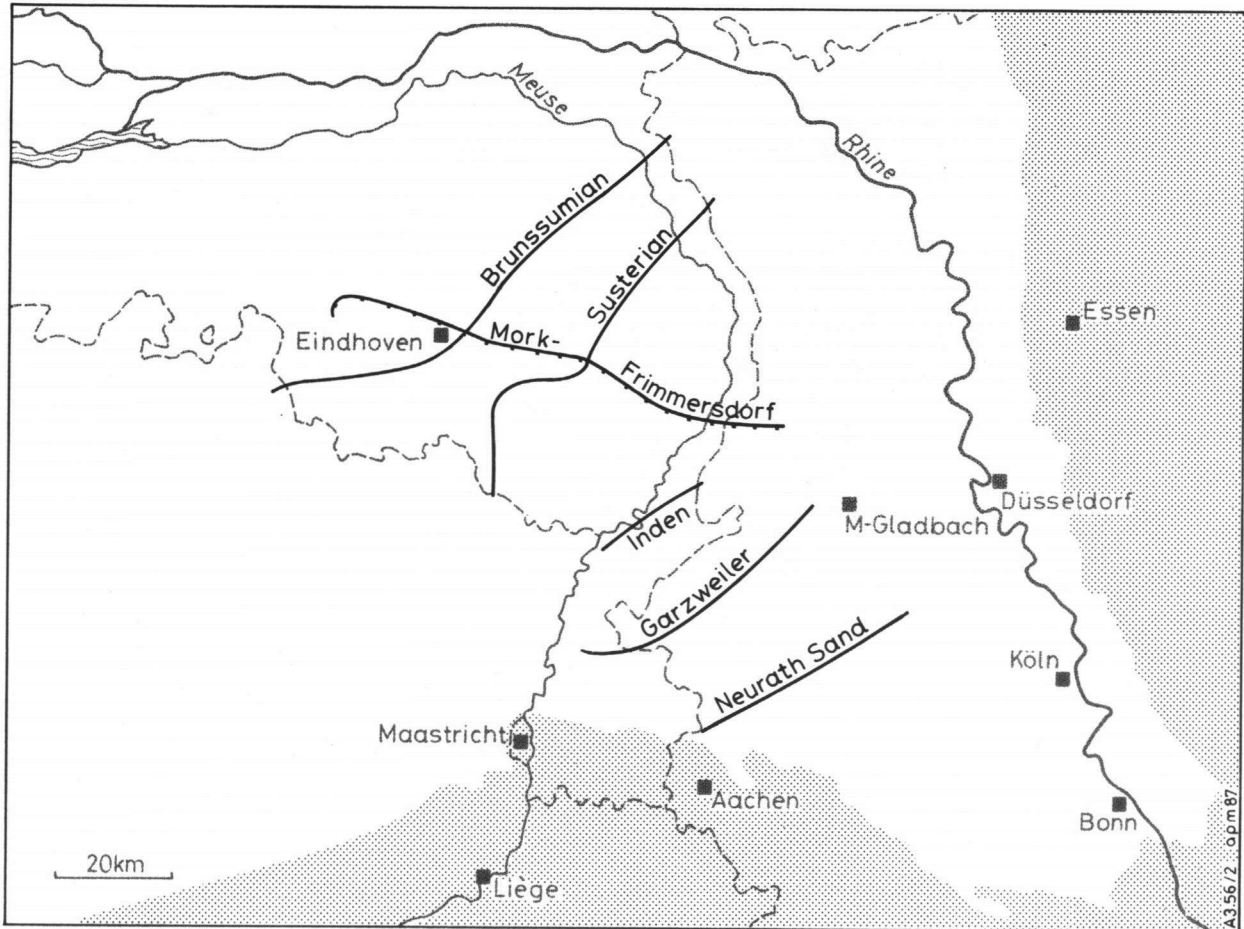


Fig. 2. Position of Miocene, and Pliocene coastlines.

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TECTONIC FRAMEWORK AND PALAEOGEOGRAPHY

The Lower Rhine Embayment is related to a SE-NW-running fault system which continues into the south-eastern part of The Netherlands (fig. 3). These faults became active at the end of the Eocene, when rifting gave rise to a horst and graben system in which the Erft fault block, the Rurgraben, the Central Graben, and the Erkelenz, Peel, and Venlo blocks are important features. In particular, thick accumulations of Neogene sediments are present in the grabens of this system.

The Lower Rhine Embayment is part of a western European rift system, to which the Upper Rhine Graben and the Bresse fault basin also belong. Shortly after the Lower Rhine Embayment was formed, most of it was invaded by the sea during the Early and Middle Oligocene (Rupelian) (fig. 2). Later, however, coastlines gradually shifted to the West, and continental beds of fluvial and coastal swamp facies were formed in the inner, south-eastern part of the Embayment (fig. 2). Since the onset

of the Neogene coastlines shifted strongly toward the West during the Early Miocene and they are now found in the Central Graben of The Netherlands as far West as Eindhoven and Oisterwijk.

During the same episode the lower part of what is called the Main Seam of the brown-coal Formation (Morken and Frimmersdorf seams) accumulated in the inner part of the Lower Rhine Embayment. Later, an important transgression toward the South-East occurred during the Middle Miocene and led to the formation of a transgressive body of sand which is called the Neurath Sand (Hager, 1981). This marine sand-body penetrates far into the coastal peat-bog facies, as shown by its south-eastern limit, which corresponds with a position of the coastline during the latter part of the Middle Miocene and the earlier part of the Late Miocene (fig. 2). Still later during the Miocene, a regressive westward movement of the coastline began, and this continued into the Pliocene (fig. 2).

As early as the Late Oligocene some periods of peat formation occurred in the coastal plain area in the inner parts of the Lower Rhine Embayment (fig. 4). However, during the later part of the Early Miocene and throughout the Middle Miocene peat formation was predominant in most of the coastal plain and, as already mentioned, it was during this period that the Main Seam (Ville Formation) accumulated (fig. 4). Still later, i.e. during the early part of the Late Miocene, peat accumula-

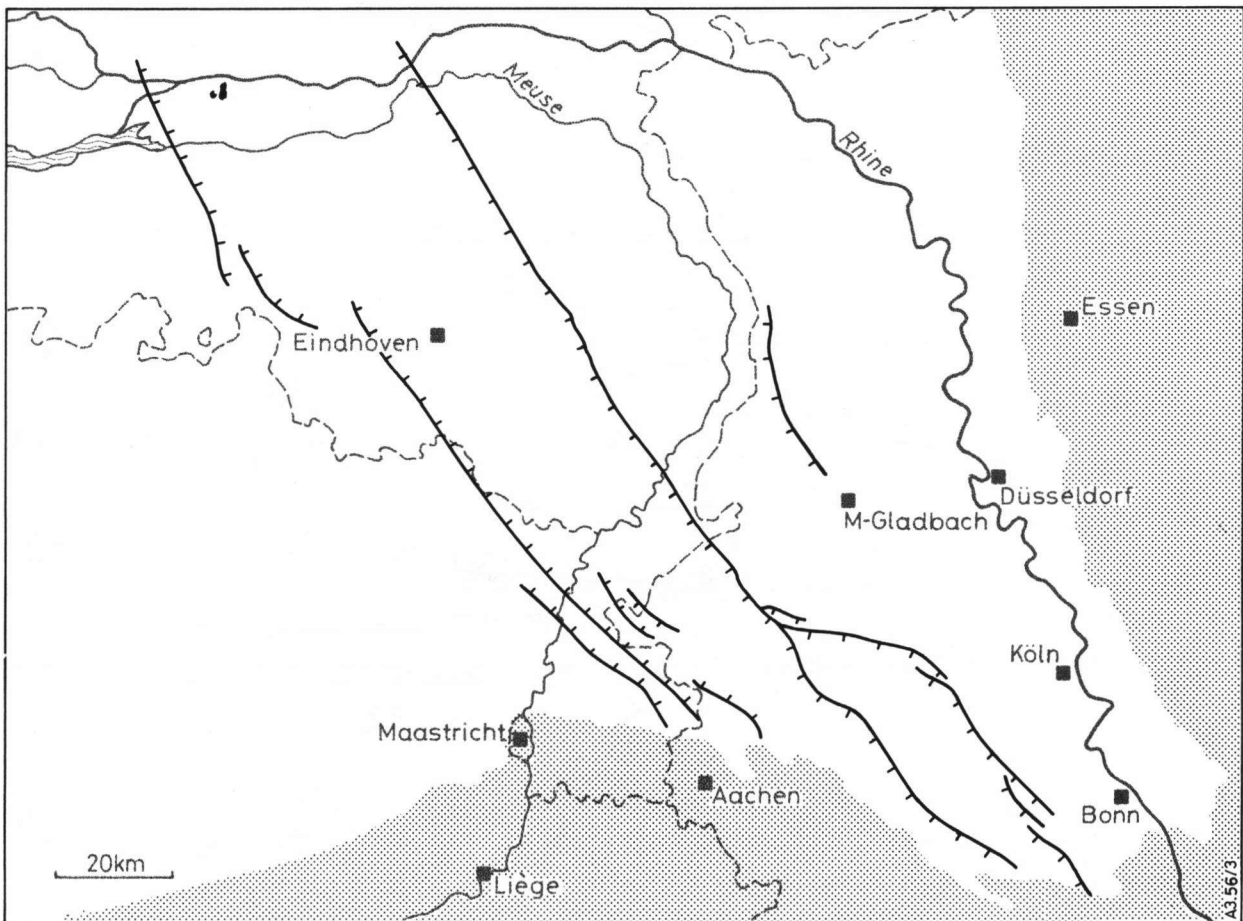


Fig. 3. Main structural features of the south-eastern part of The Netherlands and the Lower Rhine Embayment.

tion was less widespread and was restricted to the southern parts of the Lower Rhine Embayment, when what is called the Upper Seam was formed in that region. At the same time but further North fluvial clastics were laid down, which also belong to the Inden Formation. Even later in the Miocene, coarse fluvial clastic sedimentation predominated everywhere, and this is when the Main Gravel Series or Waubach Gravel was laid down.

In the Early Pliocene fine-grained fluvial sediments with several thin peat intercalations were formed (Brunssum Clay), but during this process no coal seams of economic importance were formed. Still later in the Pliocene, alternating coarse and fine fluvial sediments originated (fig. 4).

It may be concluded from all this evidence, that a first condition to be mentioned for this accumulation of coal was the presence of extensive coastal peat-bogs in the inner part of the Lower Rhine Embayment during certain periods. The second condition was tectonic in nature. During the first half of the Neogene, subsidence in this area became slower than it had been during the Late Oligocene, but it nevertheless continued steadily and slowly. At the same time, movements along

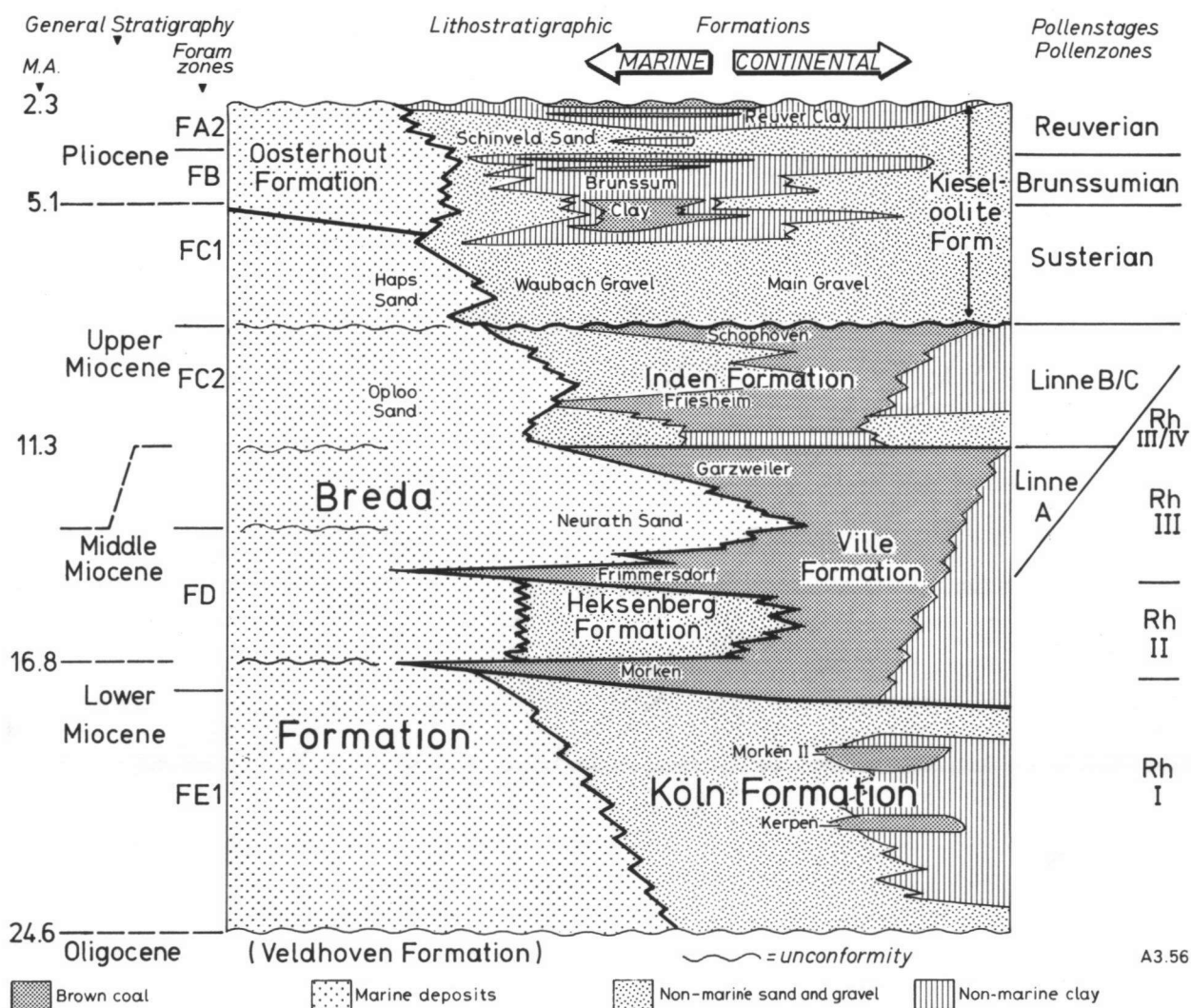


Fig. 4. Lithostratigraphy of the marine and continental Neogene beds.

faults were minimal and the influx of river-transported clastic material diminished too, probably as a result of diminishing tectonism.

The isopachs of the present Main Seam reflect these conditions (fig. 1). The coal accumulated in a basin, the original centre of which contains no less than 100 m of continuous pure brown-coal. As fig. 1 shows, much of the peat which had accumulated in the north-eastern part of the basin must have been eroded when this area was uplifted during the Late Miocene. It should be noticed that the faults do hardly influence the thickness of the lignite deposits, which indicates the absence of noteworthy faulting during accumulation of the deposit (Hager, 1986).

A third factor of importance with respect to the genesis of the thick lignites of the Main Seam was compaction. As Hager et al. (1981) pointed out, the present coal seam with a maximum thickness of about 100 m is interdigitated further to the West by a series of marine clastics, which is at present

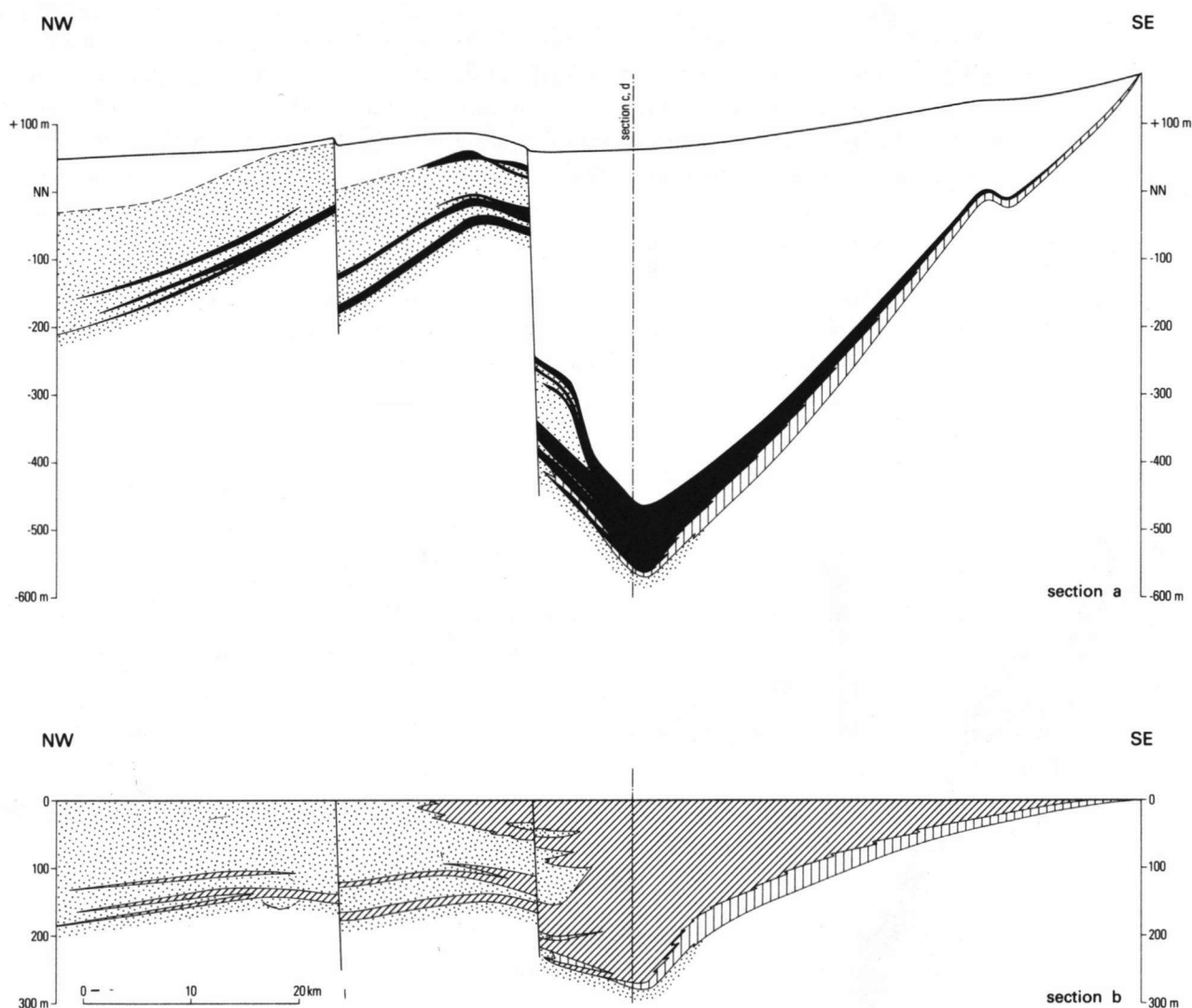


Fig. 5. SE-NW section through the Lower Rhine Embayment, showing the present location of the Main Seam and its equivalents (Ville Formation), compared with the situation before compaction began at the end of the Middle Miocene. (According to Hager, 1985). Legend see fig. 6.

about 260 m thick and was close to 300 m before compaction. Therefore, the latter must have been roughly the original thickness of the coastal peat. Fig. 5 shows a SE-NW section across the longest axis of the basin for comparison of the situations before and after compaction, the former at the end of the formation of the Main Seam. The continuous coal bed in the centre of the basin splits into several seams toward the North-West, i.e., in the direction of the ancient coastline. These seams are called (from bottom to top) Morken, Frimmersdorf, and Garzweiler. Locally, they can be further subdivided. The thick body of the Neurath Sand between Frimmersdorf and Garzweiler is a remarkable phenomenon which corresponds with a major marine invasion, as discussed below. Furthermore, this section indicates that much less vertical displacement along faults occurred during than after peat accumulation, and also that in the area of maximum thickness of the coal, the thickness of the overburden also reaches a maximum. This is due to a combination of two factors: compaction of the peat to about one-third of its original thickness and continued tectonic subsidence of the central part of the basin.

Fig. 6 shows a section perpendicular to the one in fig. 5. The main features are in general similar to those in the latter section, but the influence of a fourth condition can be seen: during the formation of the Main Seam fluvial clastic sedimentation occurred not in the centre of the basin but South of it. It is only in terms of this very special palaeogeographic situation that the exceptionally thick continuous peat accumulation in the basin centre can be understood (Gliese & Hager, 1978; Hager, 1986). Four palaeogeographic maps (fig. 8) showing the patterns of fluvial sedimentation in the basin during the Miocene illustrate this situation.

Initially (fig. 8a), at the very beginning of the formation of the Main Seam, a relatively small river system laid down clastic sediments near the centre of the basin, and peat accumulation took place on either side of the river, as can normally be expected. Later, however, the river was diverted

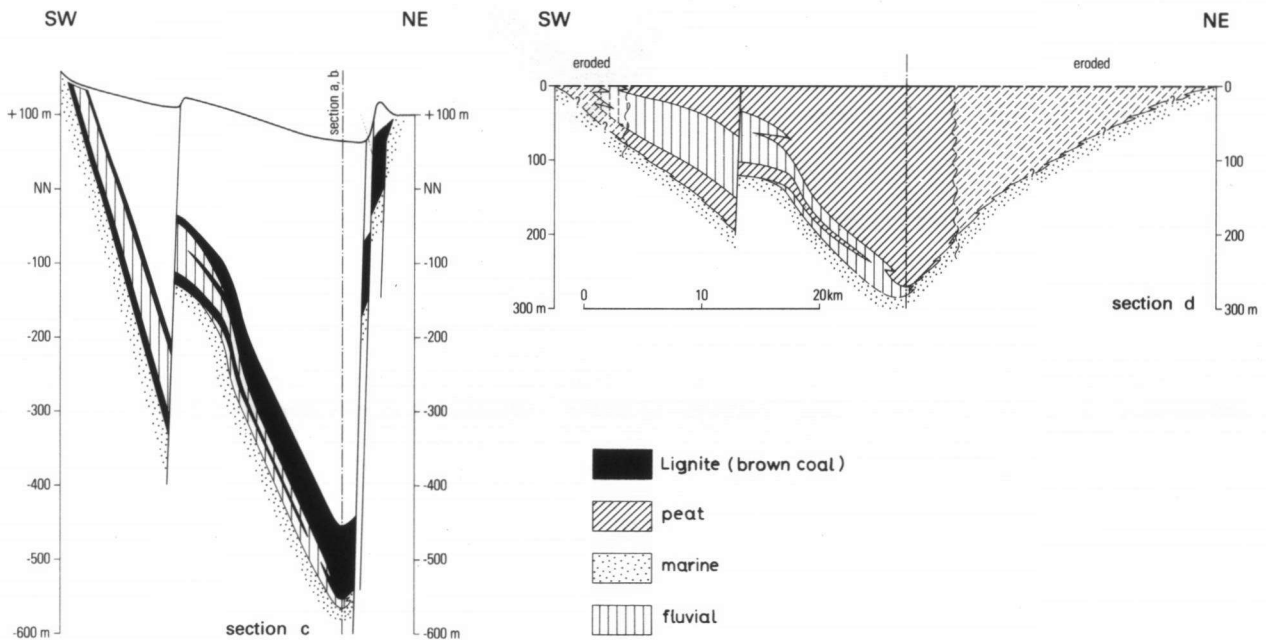


Fig. 6. NE-SW section through the Lower Rhine Embayment for comparison of the present situation with that at the end of the Middle Miocene. (According to Hager, 1985).

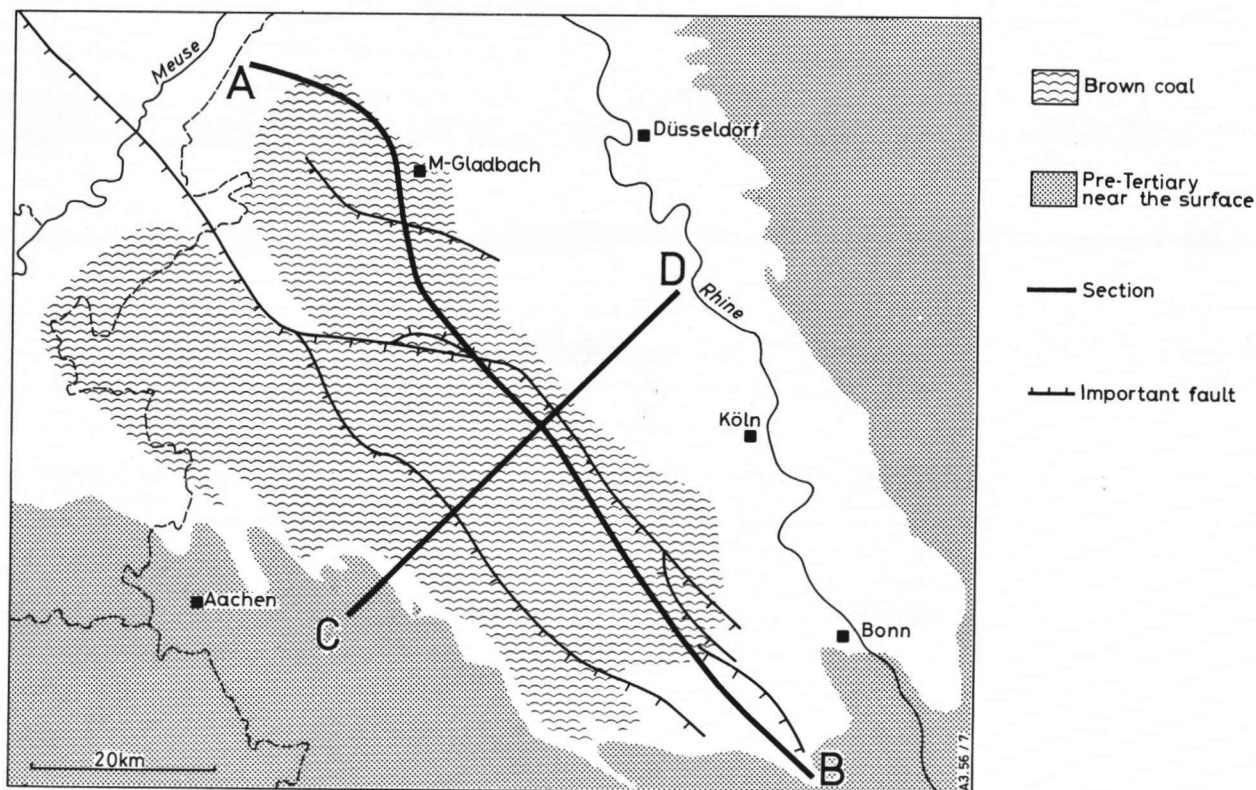


Fig. 7. Locations of sections in figs 5 and 6.

to the South (fig. 8, b and c) and did not stream in the centre of the basin. Only after completion of the Main Seam, when the Upper Seam (Inden Formation) came into existence, a major river system, probably a precursor of the present river Rhine, did again flow through the centre of deposition (fig. 8d). The Upper Seam proper was accumulated to the South of this river system. This seam too interdigitates with the fluvial clastic sediments. Three seams have been recognized and are called—in order of decreasing depth—Friesheim, Kirchberg, and Schophoven (fig. 4).

CORRELATION OF THE CONTINENTAL AND MARINE BEDS

Before we can deal with the influence of changes in sea-level, the fifth factor in order of importance, it will be necessary to discuss not only the correlation of the continental deposits, and particularly the coal beds, with the marine sequence but also the correlation of this marine sequence with those in other areas. We shall start with the latter problem.

A special problem in Neogene stratigraphy of the North Sea Basin is that the evidence provided by most marine groups of fossils does not permit direct correlation with the open ocean or the Mediterranean, for which a standard subdivision of the Neogene has been established. Only in recent years has this situation changed to some extent.

In the lower part of the Miocene some of the standard calcareous nannoplankton zones have been recognized (Verbeek, 1984; pers. comm.). For adjacent areas in the North Sea Basin a few data

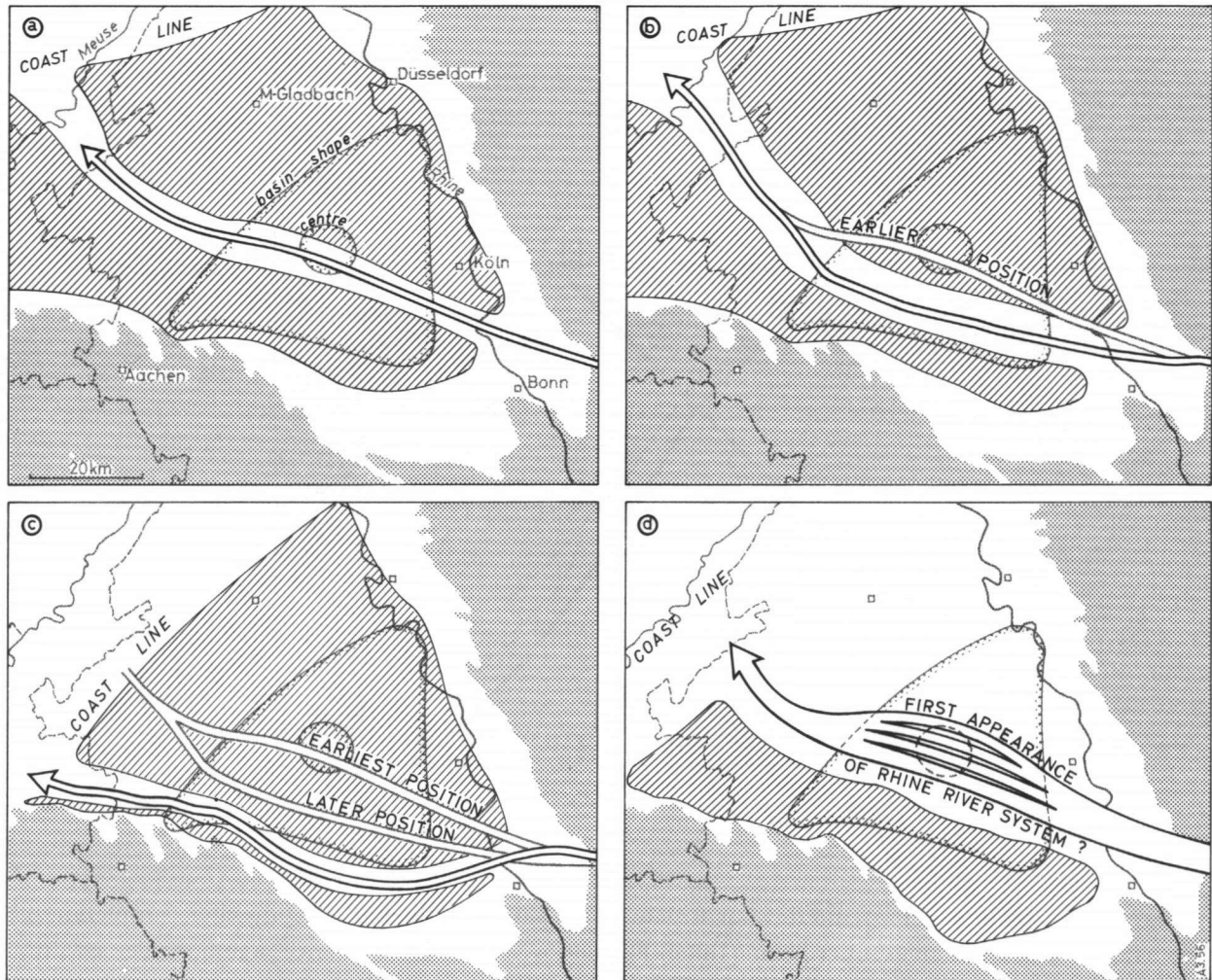


Fig. 8. Palaeogeography of the Lower Rhine Embayment during formation of the Main Seam (a-c) and that of the Upper Seam (d).

on planktonic Foraminifera and on the occurrence of *Uvigerina* species have provided information on the correlation in the Middle Miocene (Gramann & Spiegler, 1980) and dinoflagellate cysts recently provided a first-order correlation of Middle and Upper Miocene beds in the south-eastern Netherlands with the type area of the Mediterranean stages in northern Italy (Herngreen, 1987). For the uppermost Miocene and Pliocene beds of the North Sea Basin no such first- or second-order correlations are yet available, although pollen-analytical data made it possible to compare palaeoclimatic trends in the North with those in the western Mediterranean (Suc & Zagwijn, 1983; Diniz, 1984) and to derive correlations from this comparison.

Fig. 9 shows the local marine biostratigraphy for The Netherlands (Doppert, 1980; Sliggers & van Leeuwen, 1987; Verbeek, 1984; Herngreen, 1987) and the conventional age assignments as well as the correlation with Miocene pollen zonation and Miocene to Early Pleistocene palynological stages (Zagwijn, 1960, 1975). These subdivisions can be compared in fig. 9 with those for NW Germany (based on results of IGCP Project 124 and Piasecki, 1980) and with the standard stages for the Mediterranean (based on Martini & Müller, 1986).

N.W. Germany	The Netherlands				Mediterranean	M.A.		
Conventional Chronostr. assignment	Forams	Molluscs	Nanno pl. Dinoflag.*	Palynological Stages	Unconf.			
	Pleistocene	FA 1	MOL B		Praetiglian			
	Upper Pliocene	FA 2	MOL C		Reuverian	Plaisancien	Late Pliocene	
		Lower Pliocene	FB	MOL D	Brunssumian	Tabianian	Early Pliocene	
	Morsum	FC 1	MOL E		Susterian	Messinian		
	Upper Miocene	FC 2	MOL F		Linne B/C	Tortonian	Late Miocene	
Sylt				1			③	
Gram				2				
Langenfelde N14-16				3				
				4		②		
	5		①					
	Middle & Lower Miocene	FD U	MOL G		Rheinisch III	Serravallian	Middle Miocene	
N10/NN5 Reinbek					NN5	II		
					NN4	I	Langhian	
Upper Hemmoor								
Lower Hemmoor			MOL H			Burdigalian	Early Miocene	
		FE 1						
Vierland						Aquitanian		
							24.6	
Chatt	Upper Oligocene	FE 2	MOL I	NN3		Chattian		
			NP 25					

U = *Uvigerina tenuipustulata* *Herngreen 1987

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Fig. 9. Table showing the biostratigraphic zonations of the marine Neogene of The Netherlands and the palynological stages in relation to the subdivision for NW Germany and the standard stages of the Mediterranean. Dinoflagellates: 1. *Nematosphaeropsis aqueducta*, 2. *Palaeocystodinium golzowense*, 3. *Pentadinium laticinctum* et al.

With respect to the conventional age assignment hitherto used for the North Sea Basin, the following corrections must be applied. The Early-Middle Miocene boundary is within nannoplankton zone NN 4 and coincides with the Early-Late Hemmoor boundary in NW Germany and its correlative, the base of the range of *Uvigerina tenuipustulata* van Voorthuysen in The Netherlands. A substantial part of the deposits previously assigned to the lower part of the Upper Miocene have proved to be of Middle Miocene age (Herngreen, 1987), the Middle-Late Miocene boundary lying between mollusc subzones Mol F 4 and Mol F 3, a level which can be placed within the foraminiferal subzone FC 2. This means that in NW Germany the same boundary falls within the Langenfelde stage.

According to the new dinoflagellate correlation, the upper part of foraminiferal zone FC 2 and the mollusc zones Mol F 1, F 2 and F 3 belong to the Tortonian. According to the convention applied by the Geological Survey of The Netherlands, foraminiferal zone FC 1 and also part of mollusc zone E are placed together with the Susterian in the Late Miocene. Others, however, would prefer to place at least parts of it, such as the Kattendijk Sands of Belgium, in the Pliocene.

According to the palynological-palaeoclimatic correlation referred to above, the Brunssumian of The Netherlands correlates with the Zanclean of the Mediterranean (Suc & Zagwijn, 1983). With respect to the correlation of the Praetigian with the Mediterranean sequence, reference is made to the same paper.

Precise correlation of the Lower Rhine coal seams with the marine sequence was formerly difficult because in the region where these seams are intercalated with marine deposits, the latter often lack calcareous fossils. However, with the help of particularly gamma-ray logs, precise correlation has proved possible between fully marine fossiliferous sequences on the one hand and the continental deposits on the other. As an example, fig. 10 shows a section between Bergheim in the South-East, where there is a maximum development of the Main Seam, and Venlo in the North-West, where the

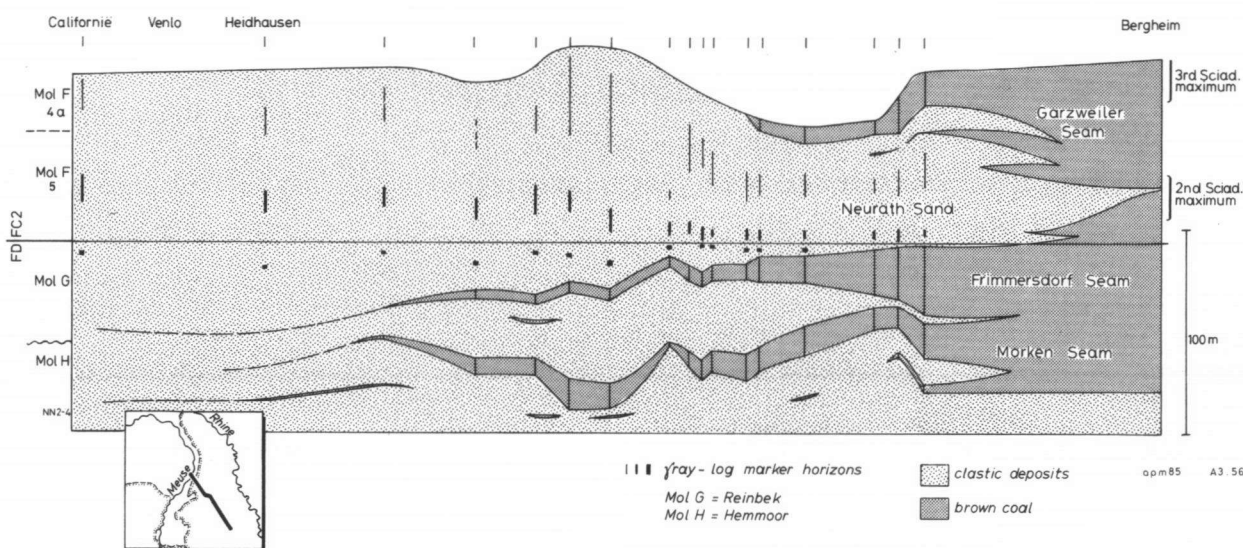


Fig. 10. Section through the Main Seam and its interdigitation with marine beds in the area between Bergheim (Federal Republic of Germany) and Venlo (The Netherlands). For convenience, the thickness of the coal seam in the Bergheim area has been corrected for later compaction. The reference horizon is the base of foram zone FC 2 and its correlatives, as established by gamma-log interpretation.

corresponding sequence is completely marine. This section made it possible to establish with a fair degree of precision the stratigraphic position of the transgressive sand wedge formed by the Neurath Sand as the upper part of foram zone FD (mollusc zone Mol G) and lower part of foram zone FC 2 (mollusc zones Mol F 5 and F 4). The maximum of the transgression near Bergheim lies in the early part of zones FC 2 and Mol F 5. This means that the Neurath Sand and its transgression are temporally equivalent to the Reinbek and the lower part of the Langenfelde Stage in the classification for NW Germany (fig. 9), and of the Serravallian in the Mediterranean region. The wedging-out of the Morken and Frimmersdorf seams in this section can be assigned to mollusc zone Mol H and the basal part of mollusc zone Mol G.

A number of wells, some of them in the deepest part of the Central Graben (fig. 11, the Veldhoven, Asten, Nederweert wells) have provided information on the position of the two lowermost seams, Morken and Frimmersdorf, in relation to the marine stratigraphy. The correlation between the seams in this part of the Central Graben, among which the Frimmersdorf seam in particular splits into several narrow seams, and other parts of the Central Graben further to the South-East, where the seams are thicker, can be seen in fig. 11. The correlation of the Morken and Frimmersdorf seams in the Straeten, Obspringen, Broeksittard, and Nieuwstadt wells with the hinterland is considered reliable. The data indicate that the Morken seam belongs to nannoplankton zones NN 2-4, and probably lies within NN 4, mollusc zone Mol H, and the part of foram zone FD predating the *Uvigerina*

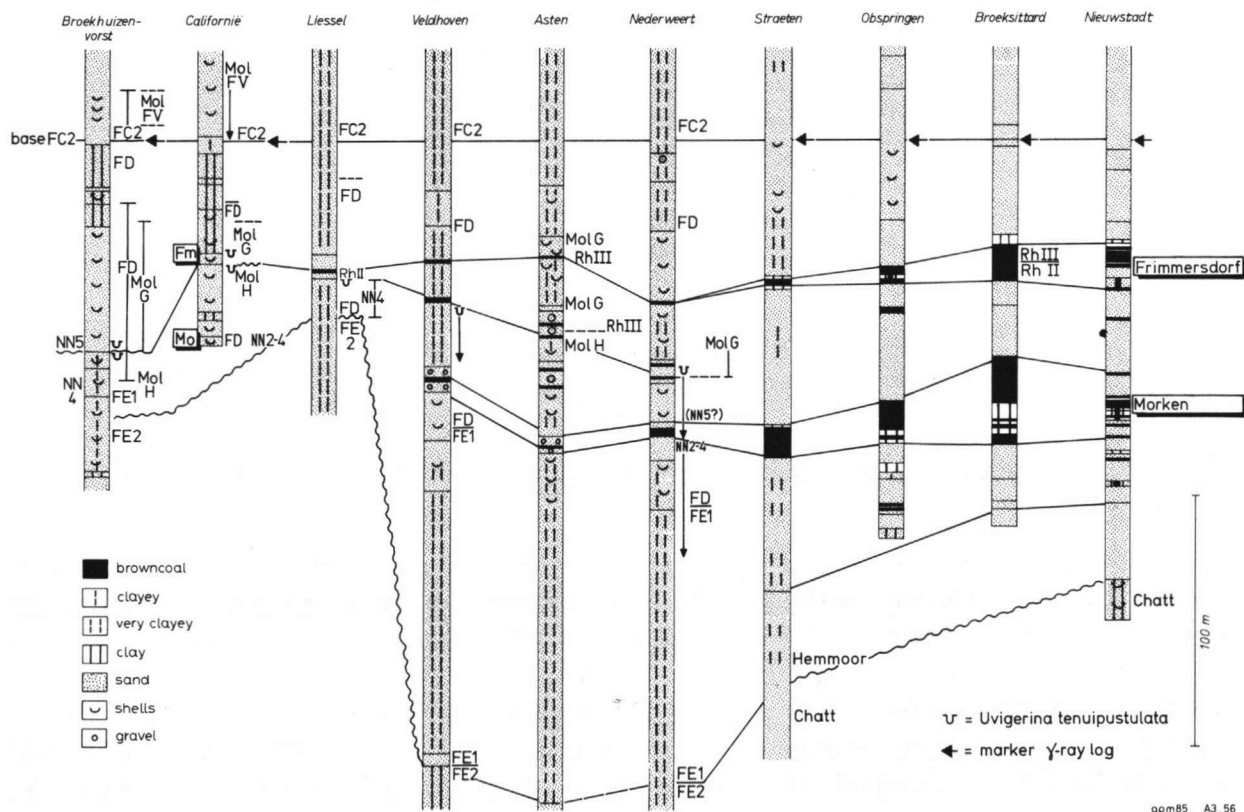


Fig. 11. Correlation of the Frimmersdorf and Morken coal seams in wells in the Central Graben (The Netherlands) with the adjacent Peel and Venlo fault blocks. The reference horizon is the base of foraminiferal zone FC 2.

tenuipustulata-Range Zone. Furthermore, the sands between Morken and Frimmersdorf belong to the upper part of Mol H, the *Uvigerina tenuipustulata*-Range Zone, and possibly the transition of NN 4 to NN 5; the Frimmersdorf seam belongs to mollusc zone Mol G and the part of foram zone FD postdating the *U. tenuipustulata*-Range Zone; and the lower part of the Neurath Sand also belongs to the same zones. These conclusions correspond fairly well with those obtained by the aforementioned correlation between Bergheim and Venlo, although the wells from the Peel and Venlo fault blocks (Liessel, Californië, and Broekhuizenvorst) show some unconformities in the lower part of the Miocene sequence that make the correlations less reliable. According to the terminology in use in NW Germany, this means that the Morken seam belongs to a relatively late period in the Hemmoor Stage, the sand between the Morken and Frimmersdorf seams to the last part of the Hemmoor Stage, and the Frimmersdorf seam to the earliest part of the Reinbek Stage (fig. 12).

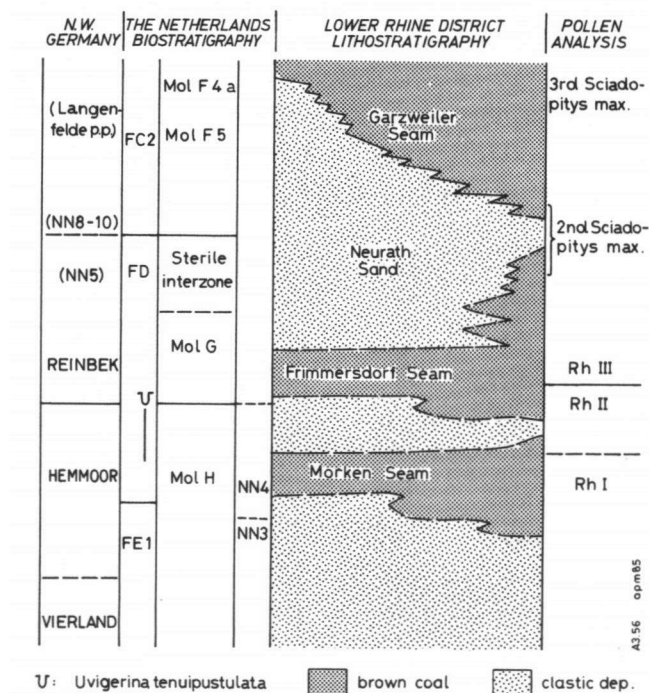


Fig. 12. Lithostratigraphy of the brown-coal deposits in relation to the bio- and chronostratigraphy.

Some brief remarks can be made on the age of the Inden Beds (Upper Seam) and the overlying deposits. Generally speaking, the Inden Beds can be shown to coincide in time with the upper part of foram zone FC 2 (mollusc zones Mol F 1-3) and the overlying Waubach Gravel of Susterian age with foram zone FC 1. In most areas outside the deepest part of the Central Graben, however, there is a hiatus between the two units, and more precise data are required. Similarly, the Brunssumian deposits correspond as to time with foram zone FB, but more precise information on the correlation of the stage boundaries is needed. More detailed information is available on the correlation of the Reuverian with foram zone FA 2 and of the Praetigian with the lower part of FA 1 (Zagwijn & Doppert, 1978). These correlations imply that time required for the formation of the approximately 100-metre thick Main Seam was of the order of at least 5.5 to 6 million years. The formation of the Upper Seam may have taken another two to three million years.

CORRELATION WITH SEA-LEVEL FLUCTUATIONS

The data discussed in the preceding section make comparison possible between the lithostratigraphic sequences of this area and those in two other parts of the southern North Sea Basin, i.e. NW Germany (Hamburg and Holstein area) and Denmark (fig. 13). In NW Germany (IGCP 124) there are two sand horizons with lignite beds, one intercalated in the Hemmoor and the other in the lower Reinbek deposits. This means that the formation of these lignitic horizons coincided with the formation of the Morcken and Frimmersdorf seams in the Lower Rhine area. The Brown-coal Seam of the Odderup Formation in Denmark has the same palynological characteristics as the lower half of the Main Seam of the Lower Rhine area, i.e. the Morcken and Frimmersdorf seams (Koch, 1984), and is overlain by the marine Hodde Formation, which according to its dinoflagellates and other marine fossils (Piasecki, 1980) has the same age as the lower part of the Neurath Sand.

It may be concluded that around the eastern shores of the southern and central parts of the North Sea peat was frequently formed in the coastal plains during the earlier part of the Middle Miocene. In the second half of the Middle Miocene a major transgression took place in all three of the above-mentioned areas (Neurath Sand, Reinbek, Hodde Formation). Since this transgression,

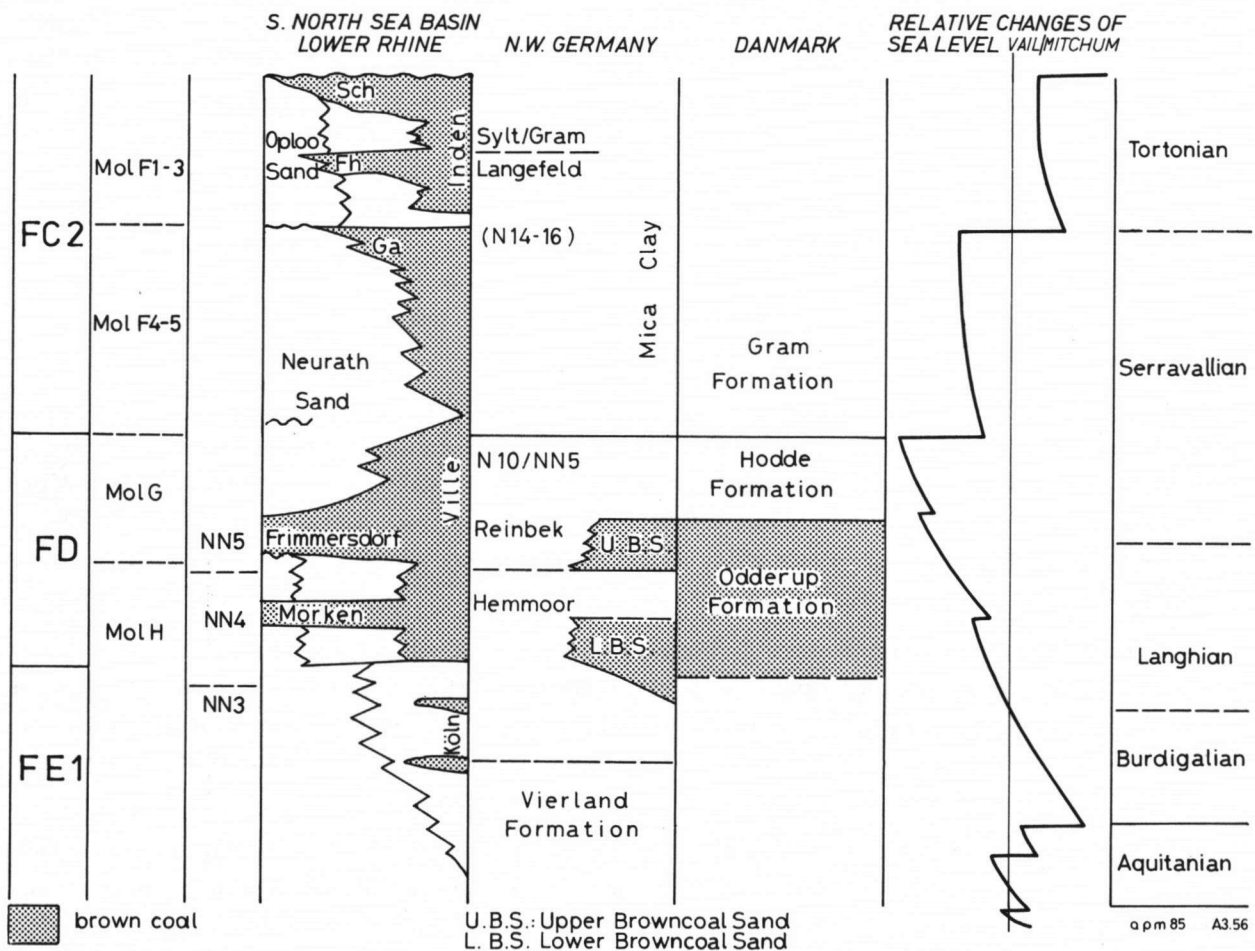


Fig. 13. Areas with brown-coal beds overlain by marine Miocene deposits around the eastern shores of the North Sea, in relation to Vail et al.'s (1977) sea-level curve.

which can be dated within nannoplankton zone NN 5, coincides with the sea-level peak in the well-known curve by Vail et al. (1977), it may be concluded that the transgression which gave rise to the Neurath Sand was related to the strong eustatic rise of the sea-level in the Middle Miocene (Serravallian). The ensuing general decline of the sea-level in the curve by Vail et al. corresponds to the general regressive trend that has prevailed since the Middle Miocene in The Netherlands. However, there is no evidence indicating that details of that part of the curve by Vail et al. are reflected in the North Sea sequence.

After the Middle Miocene transgression, brown-coal formation came to an end in the coastal areas of Denmark, NW Germany, and The Netherlands. It continued only in the centre of the Lower Rhine Embayment, and this gave rise there to the exceptionally thick Main Seam. In the other areas only relatively thin coal deposits are present.

THE PALAEOCLIMATIC FACTOR

Finally, the sixth factor of importance for an understanding of the accumulations of the Miocene coal will be discussed, namely the climate. Pollen diagrams may provide data in this respect, because pollen analysis made it possible to detect climatic fluctuations during the Pleistocene in considerable detail. The study of Neogene deposits raises some technical problems, however, a few of which will be discussed here. One of these problems is that, particularly for the earlier parts of the Neogene, it becomes increasingly difficult to identify the fossil pollen grains and spores with Recent taxa. Such problems arise as early as the Pliocene, but are much more serious for Miocene deposits. In a few cases the botanical identity of several frequently occurring pollen types remains completely unknown, in other cases a reasonable hypothesis is possible. This is not the place to discuss the situation in detail, but the general conclusion is that in the Miocene, and particularly in the Middle Miocene, evergreen trees must have been a predominant constituent of the upland forest and probably included many representatives of the oak family (Fagaceae).

It is to be expected that some of these problems will be solved by further research on Recent pollen morphology. This is exemplified by the recent identification of a well-known and highly characteristic pollen type, called *Tricolporites edmundi* (Potonié), with the genus *Mastixia* of the Cornaceae family (Herter, 1985). This is interesting, because *Mastixia* was since a long time known by the numerous finds of fossil fruits in Miocene beds (e.g. Kirchheimer, 1957), but its pollen had not been recognized.

A second serious problem is the differentiation between the pollen originating from local swamp vegetation and pollen from drier upland vegetation. In the Pleistocene most of the swamp vegetation is either herbaceous or comprises a small number of easily identifiable swamp trees or shrubs. In the Neogene a substantial part of the swamp vegetation consisted of trees, and some of the tree genera may have occurred in both the upland and the swamp vegetations.

However, climatic changes are reflected more distinctly in the upland vegetation, which necessitates working with pollen diagrams that reflect the changes in upland vegetations. This means that the pollen of swamp vegetations must be identified as such and excluded from the basic pollen sum. The present first author prepared such diagrams several years ago for Pliocene deposits (Zagwijn, 1967), and similar techniques have also been used in the study of the Miocene brown-coals (von der Brellie & Rein, 1956). Such pollen diagrams of course cannot provide information about

small climatic fluctuations, because the palaeoecology of most of the species involved is not sufficiently known for that purpose.

Some conclusions can, however, be drawn on a broad scale. To give an idea of the method, two general pollen diagrams will be discussed (fig. 14), one concerning the Early Pliocene (Brunssum Clay at Brunssum, The Netherlands) and the other the earlier part of the Late Miocene (Schophoven Seam of the Inden Formation in Pit Hambach, Federal Republic of Germany). Only elements considered to belong to the upland vegetation have been included in this figure. Four floral elements are taken into account: evergreen broad-leaved trees, deciduous broad-leaved trees, conifers, and herbs. The diagram pertaining to the Brunssumian (Early Pliocene) shows some clear maxima of evergreen forest elements. They can be interpreted as representing warm and moist periods, more temperate periods being reflected by an increase of the broad-leaved deciduous trees and the conifers. In this section peat formation is distinctly correlated with the warmer periods. The climate must have been more temperate and cooler in the Susterian (Late Miocene) than during parts of the Brunssumian.

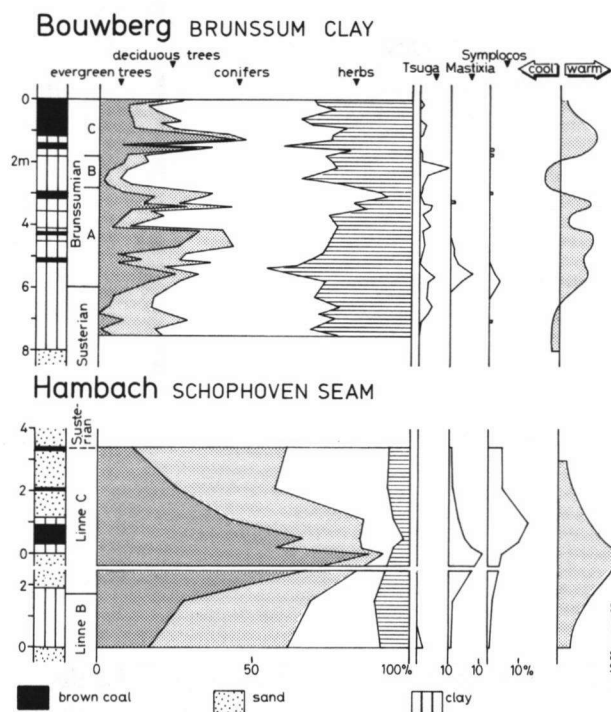


Fig. 14. Generalized pollen diagrams for two Pliocene and Upper Miocene deposits.

The diagram for the Schophoven Seam (Late Miocene), which predates the Susterian, shows distinct climatic fluctuation. At the top and the base deciduous forest elements predominate, whereas in the middle evergreen trees are unequivocally dominant, among them such subtropic genera as *Mastixia* and *Symlocos*. This pattern can be interpreted as due to a climatic change from temperate to warm and subtropic, and back to temperate again. Here, too, the main peat formation correlates with the warmest climate. Such data were used as the basis for the climatic curve in fig. 15. In the same figure the general distribution of coal and peat beds during these periods is indicated. It can be concluded from these findings that peat formation occurred especially in the warmer periods. This does

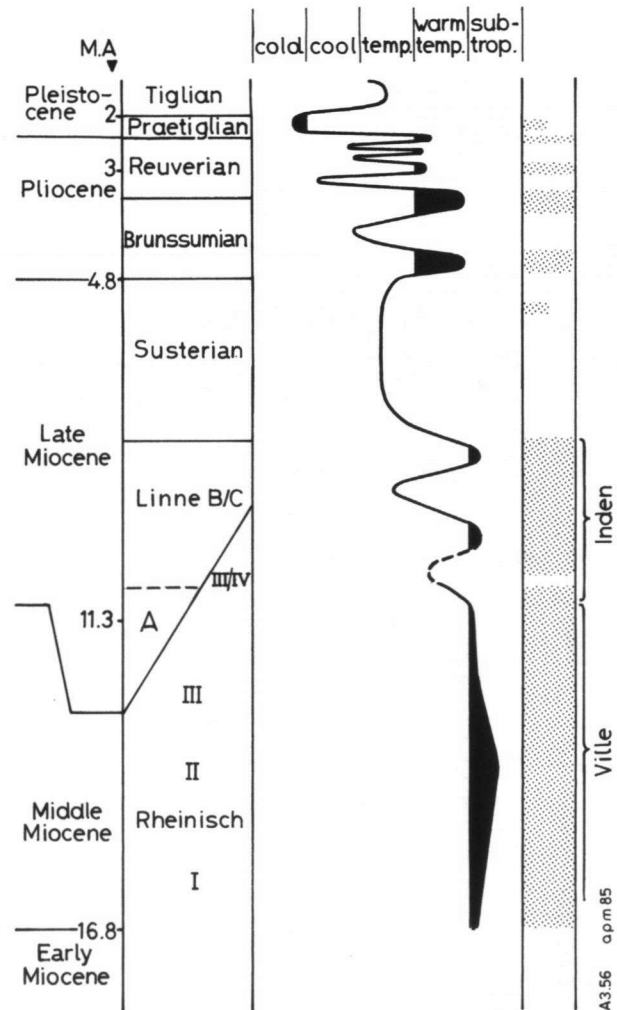


Fig. 15. Climatic development during the Neogene in relation to the vertical distribution of peat and coal in the Lower Rhine Embayment and the south-eastern part of The Netherlands.

not mean that all peat beds must date from such warmer periods; they could also develop during cooler phases, but on a smaller scale. Therefore, peat formation must have been promoted by warm and moist climatic conditions. According to the pollen-analytic data such conditions certainly prevailed during the accumulation of the Main Seam (Ville Formation) and most of that of the Upper Seam (Inden Formation). During the latter period the climate fluctuated more strongly than it had before, some temperate phases alternating with warm subtropical periods (cf. also fig. 14).

On these grounds it can be concluded that the long period with a warm moist climate that must have existed during the Middle Miocene and, according to the above data, lasted for at least about 5.5 to 6 million years, was the sixth and final condition of importance for the formation of the thick brown-coal beds of the Lower Rhine area.

CONCLUSIONS

The formation of the exceptionally thick brown-coal beds of the Lower Rhine Embayment, in particular the Main Seam which is over 100 m thick, was the result of the following factors.

1. The specific tectonic framework of the Lower Rhine Embayment and its palaeogeographic position (coastal plains, position of coastline).
2. Slow tectonic subsidence of the basin during the period of peat accumulation, few and small fault movements.
3. Strong compaction of what originally was about 300 metres of peat.
4. Formation of pure lignite due to prolonged fluvial deposition (for about 5.5 to 6 million years) beyond the center of tectonic subsidence.
5. The influence of an eustatic rise of the sea-level, which terminated peat accumulation on most of the coastal plains but not in the inner part of the Lower Rhine Embayment.
6. Prolonged warm and moist climatic conditions during the Middle Miocene.

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