Netherlands Institute of Applied Geoscience TNO - *National Geological Survey*

Explanation to map sheets VII and VIII Noordwijk-Rotterdam and Amsterdam-Gorinchem

TNO

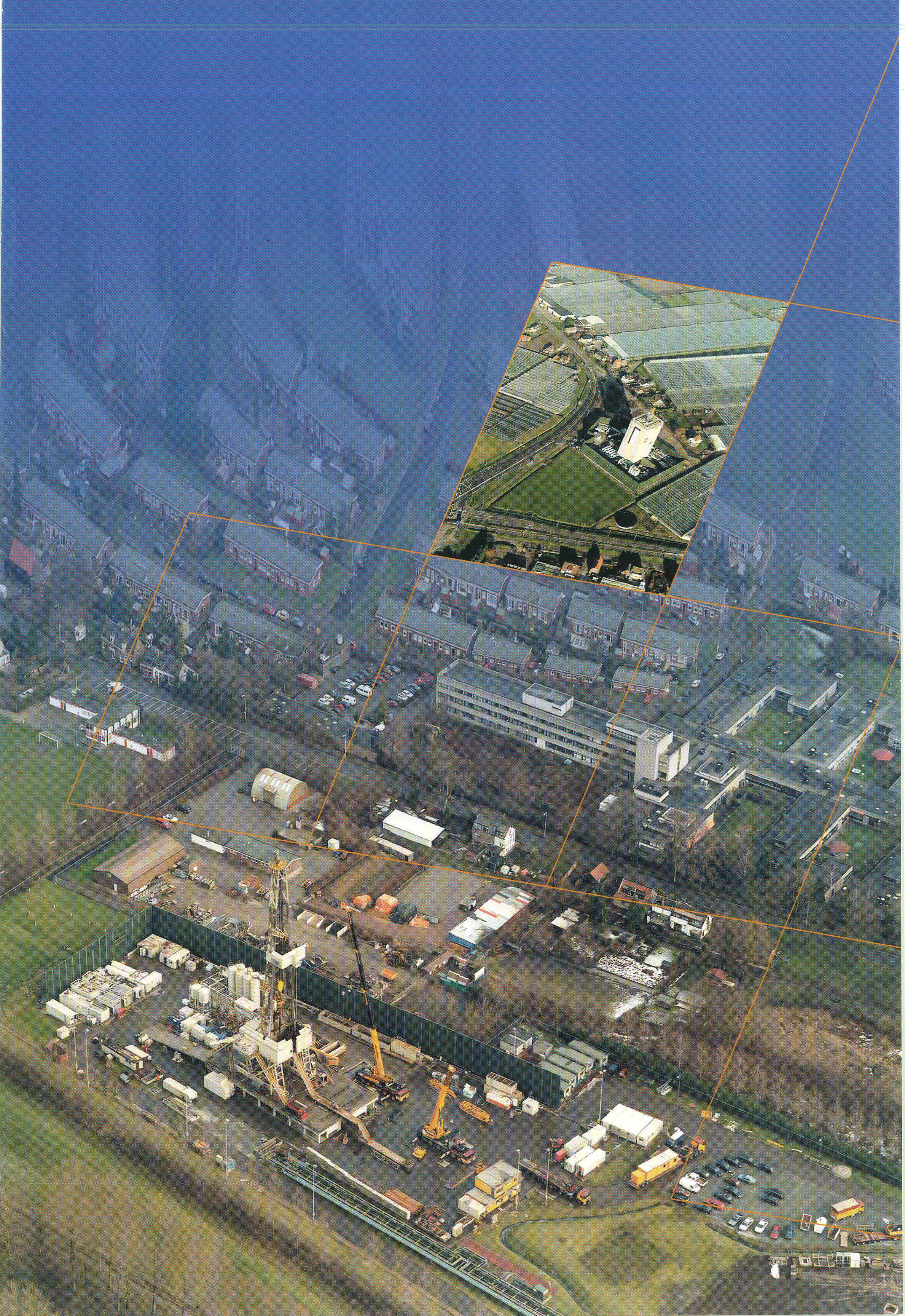
Geological Atlas of the Subsurface of the Netherlands

Explanation to map sheets VII and VIII Noordwijk-Rotterdam and Amsterdam-Gorinchem

Netherlands Institute of Applied Geoscience TNO – *National Geological Survey*, Utrecht 2002

Geological Atlas of the Subsurface of the Netherlands

Drilling rigs in the area known as "Het Westland"
Photograph courtesy Nederlandse Aardolie Maatschappij (NAM).



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Maps and sections (Map sheet VIII)

The publication of map sheet VII and VIII by the Netherlands Institute of Applied Geoscience TNO – *National Geological Survey* marks a continuation of the map sheets constituting the Geological Atlas of the Subsurface of the Netherlands. In this series, unique map sheets of the subsurface of the Netherlands are made available, presenting an overall picture of its potential exploitation. With broad-based regional-geological knowledge of the subsurface of the Netherlands and surrounding countries at its disposal, the TNO-NITG has clearly enhanced the quality of these publications, which far exceeds that of routine mapping.

Reporting of information to the general public on the deeper subsurface geology (deeper than 500 m) was limited because of the status of the data required. These data are acquired from seismic investigations and deep drilling which are nearly exclusively carried out by oil companies. Because of the considerable commercial interests involved for the oil industry these data are classified, but are made available to the TNO-NITG as delineated in the mining act.

The existing mining legislation that applies to the Netherlands Onshore area, does not permit the general release of this classified information. Agreement with industry concerning the use of these data enables the TNO-NITG to compile and publish this information, provided the data are older than 10 years. An exception is made for data from concession areas, with a restriction of 5 years. This agreement enables the TNO-NITG to bring the geological structure of the subsurface of the Netherlands to wider attention.

The Noordwijk-Rotterdam and Amsterdam-Gorinchem map sheets of the Geological Atlas of the Subsurface of the Netherlands are the eleventh and twelfth sheets to be published in the framework of the systematic mapping of the subsurface of the Netherlands, for which purpose the Netherlands has been divided into 15 map sheets published on a scale of 1:250 000 (see figure 1.1 for an overview of the area of the map sheets).

Each map sheet has its own features. The map sheets in question outline the geology of the largest part of the province of Zuid-Holland and of parts of the provinces of Noord-Holland, Utrecht, Flevoland and Gelderland. Maps and sections reveal that the present geological pattern of these provinces is dominated by two Mesozoic NW-SE-oriented basins, the West Netherlands Basin and the Central Netherlands Basin. During the Kimmerian tectonic phases, these basins experienced a period of rapid subsidence, marked by the deposition of a comparatively complete succession of Triassic, Jurassic and Early Cretaceous sediments. In the West Netherlands Basin in particular, these deposits constitute rocks with good reservoir characteristics both for oil and gas and for the Posidonia Shale Formation, the economically important oil-source rock. This has resulted in the presence of several oil and gas fields in the West Netherlands Basin, their geographic location presenting the unique situation of petroleum exploration and exploitation in the highly urbanised western part of the Netherlands.

The text broadly comprises three parts. The first part explains the research set up (Chapter 1), followed by an account of the exploration of hydrocarbons (Chapter 2) and the structural framework (Chapter 3). The second part consists of a lithostratigraphic description of the rocks (Chapters 4 - 12) and the geological history of the map sheet area (Chapter 13). The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members, which are related to the major structural elements of the map sheet area. Each chapter devotes one section to the depositional environment and the palaeogeography. In the third part (Chapter 14), special attention is given to various applied geological aspects, such as petroleum systems, thermal energy and CO_2 storage in the deeper subsurface.

The TNO-NITG anticipates that these map sheets, together with those already published or in progress, will contribute to a greater understanding of the structure and composition of the subsurface of the

Netherlands. This is important not only to companies who are active in the fields of exploration and exploitation for mineral and natural resources, but also various governmental institutions and other interested parties. The maps now published may also be viewed digitally. The TNO-NITG has developed a 3D viewer enabling the maps to be viewed in three dimensions (see: http://dinoloket.nitg.tno.nl).

As well as those people acknowledged in the credit column who are directly responsible for compiling this map sheet, many other employees of the TNO-NITG have been involved, whose efforts are all greatly appreciated. Special thanks are due to the companies which provided exploration data used in these map sheets and in particular to the Nederlandse Aardolie Maatschappij for making the various reservoir-geological data and unique historical photographs available.

Utrecht, November 2002

1 Research set up

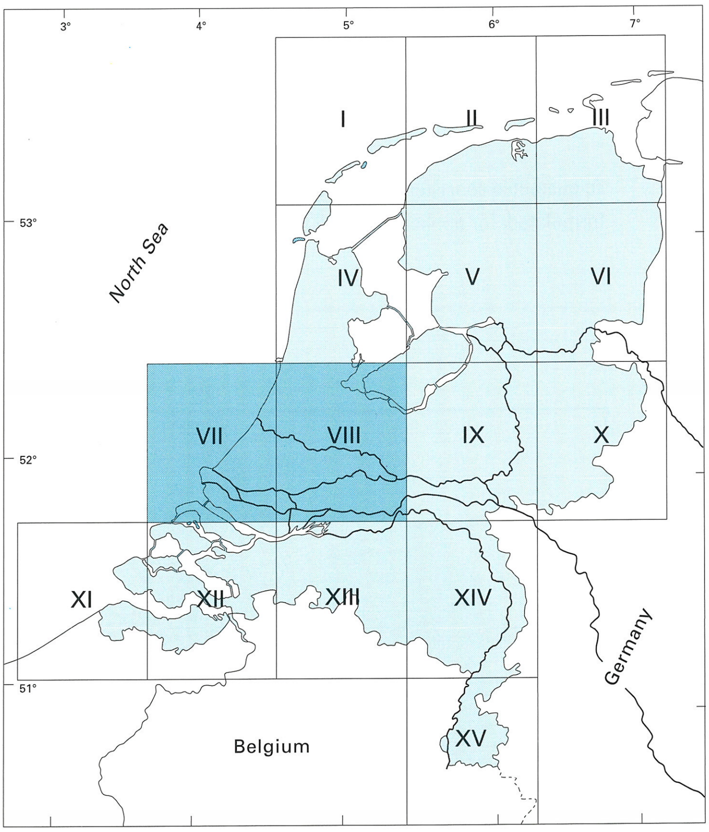
1.1 Extent of area studied

The area covered by map sheets VII (Noordwijk-Rotterdam) and VIII (Amsterdam-Gorinchem) of the Geological Atlas of the Subsurface of the Netherlands comprises the greater part of the province of Zuid-Holland and parts of the provinces of Noord-Holland, Utrecht, Flevoland and Gelderland (fig. 1.1). The area is bordered to the west by the Dutch Continental Shelf. This explanation covers two map sheets; where the term 'map sheet area' is used, the area encompassing both map sheets is intended.

1.2 Data base

The mapping of the map sheet area has made use of seismic and well data acquired by industry. For map sheet VII, predominant use of 3D seismics was made, whereas the mapping of map sheet VIII had to rely less on 3D seismics (fig. 1.2). A total of 144 boreholes were selected for the map sheets (fig. 1.3). Where a cluster of boreholes was placed, only one of the wells was used for mapping purposed.

Figure 1.1 Subdivision of the regional map sheet areas of the subsurface of the Netherlands and geographical position of map sheets VII and VIII.



I	Vlieland-Terschelling	IX	Harderwijk-Nijmegen
II	Ameland-Leeuwarden	X	Almelo-Winterswijk
III	Rottumeroog-Groningen	XI	Middelburg-Breskens
IV	Texel-Purmerend	XII	Roosendaal-Terneuzen
V	Sneek-Zwolle	XIII	Breda-Valkenswaard
VI	Veendam-Hoogeveen	XIV	Oss-Roermond
VII	Noordwijk-Rotterdam	XV	Sittard-Maastricht
VIII	Amsterdam-Gorinchem		

1.3 Geological research

The geological research focused on the lithostratigraphic succession of the rock formations present in the map sheet area (fig. 1.5) and their geological history placed in a regional-geological context. Use was made of the seismic and well-log data previously referred to. The lithostratigraphic units, which are indicated in figure 1.5, are discussed in greater detail in each chapter.

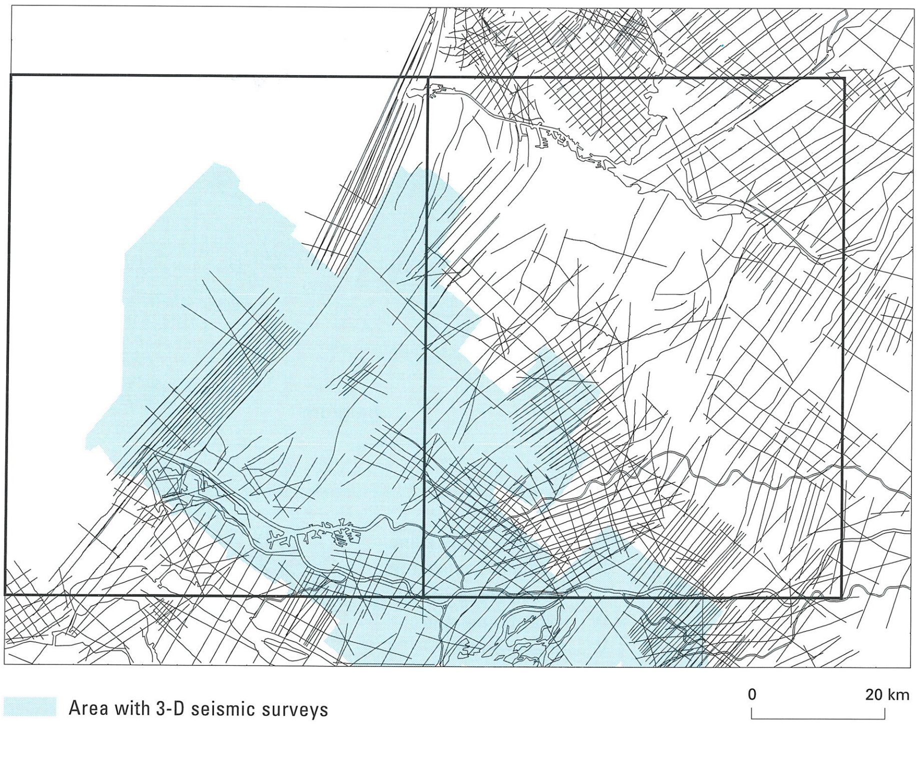
1.4 Seismic mapping

Virtually all the available seismic records were used in the mapping. The seismics used were shot between 1970 and 1995. A large part of the map sheet area was covered with 3D seismics and the remainder with 2D seismics; with the exception of the urban agglomerational areas of Haarlem, Utrecht, Hilversum and Amersfoort, where few seismic lines were shot (fig. 1.2, Appendix A). An interpretation was made of a total of over 3100 km^2 of 3D seismics and over 3000 km of 2D seismics.

The mapped reflectors form the boundaries between the lithostratigraphic units (groups and formations). Calibration of the seismic data was performed by means of acoustic logs and check-shot surveys. The time-depth conversion of the seismic data was carried out per layer (the so-called layer-cake method). For this, a linear equation between the velocity and the depth of the layer was taken (table 1.1).

To guarantee consistency between adjacent map sheets, a countrywide seismic velocity equation was formulated, for application to all the map sheets of the Geological Atlas of the Subsurface of the

Figure 1.2 Location of the seismic lines used. Appendix A contains additional information on the owner and the year of the various surveys.



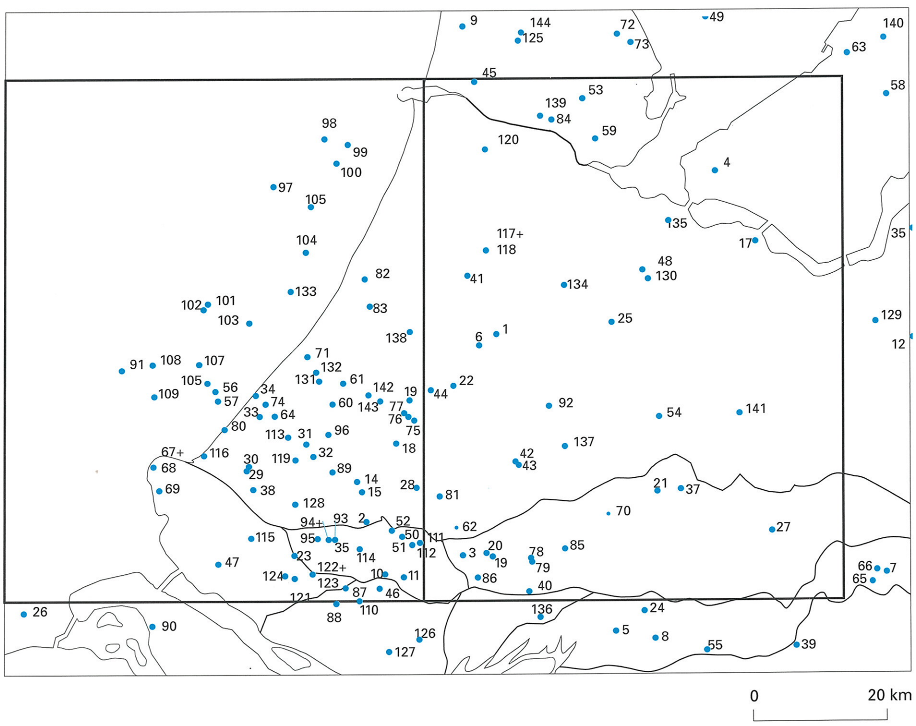
Netherlands. The parameters of this equation were determined from the acoustic data from 61 representative wells located throughout the Netherlands. Application of this velocity distribution, however, gave rise to large deviations in the depths of the base of the Rijnland, Altena and the Lower Germanic Trias Groups, particularly in the inverted areas, and consequently the equation was revised. A regional velocity distribution (TNO-NITG, 2001c) was determined from the acoustic data from over 600 wells located in the Netherlands. With respect to the map sheet area, this produced the velocity equation given in Table 1.1. As the adjacent map sheet IV was mapped using a different velocity equation, minor corrections were required for this map sheet boundary.

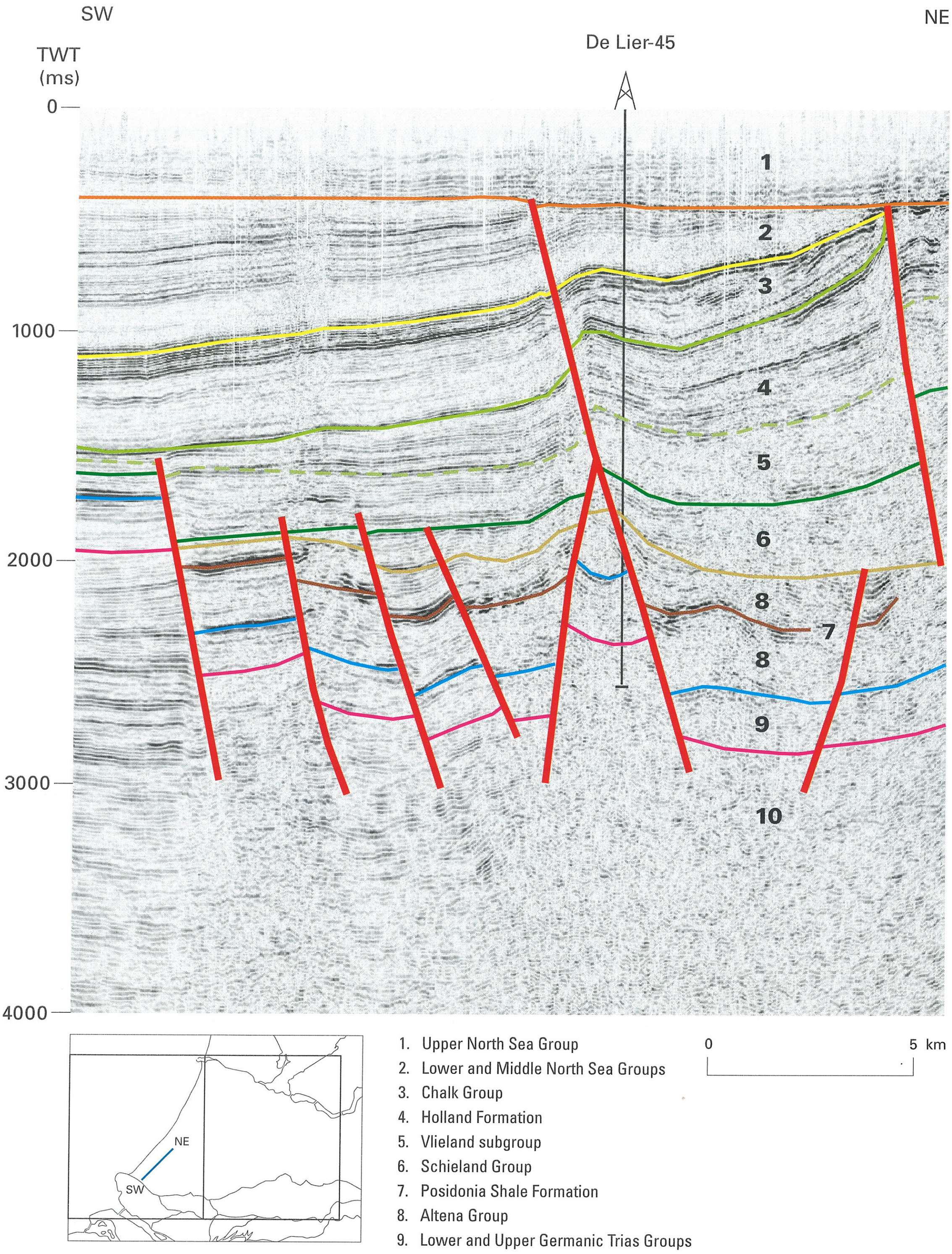
The seismically interpreted horizons are delineated by the bases of lithostratigraphic groups, namely the Upper North Sea Group, the North Sea Supergroup, the Chalk, the Rijnland, the Schieland, the Altena and the Lower and Upper Germanic Trias Groups (fig. 1.4). In addition, an interpretation has been made of the Posidonia Shale Formation, as it is generally clearly identifiable on seismic logs as a low-frequency band. This formation is also an important oil-source rock in this area.

The Upper North Sea Group is the youngest seismic unit and is characterised by typical seismo- stratigraphic phenomena such as downlaps, toplaps and onlaps, associated with a prograding sedimentary system. The Lower and Middle North Sea Groups constitute a comparatively uniform unit, with clear continuous reflectors. This unit is absent in parts of map sheet VII, where the Upper North Sea Group lies upon older, inverted Mesozoic rocks.

The base of the Chalk Group is in general difficult to identify, because no clear reflection is visible. Within the Chalk Group itself, virtually no reflections occur.

Figure 1.3 Location of the wells used for the mapping. For the numbering, reference should be made to Appendix B where the name, owner, final depth and year of the well are given.





1. Upper North Sea Group
2. Lower and Middle North Sea Groups
3. Chalk Group
4. Holland Formation
5. Vlieland subgroup
6. Schieland Group
7. Posidonia Shale Formation
8. Altena Group
9. Lower and Upper Germanic Trias Groups
10. Permian-Carboniferous

Figure 1.4 Seismic profile through the southwestern part of the West Netherlands Basin, additionally highlighting the interpreted seismic horizons.

Table 1.1 Applied velocity distribution

The velocity distribution in the map sheet area is based on $V_z = V_0 + k.z$
V_z: average velocity at depth z (m/s)
V_0: theoretical velocity at depth z = 0 (m/s)
k: specific constant (1/s)
z: depth (m)

Unit	V_0	*k*
North Sea Supergroup	1696	0.47
Chalk Group	2156	1.03
Rijnland Group	2026	0.73
Schieland Group	2770	0.53
Altena Group	2451	0.44
Lower and Upper Germanic Trias Groups	3097	0.47

In the southeastern part of the map sheet area, the base of the Rijnland Group is manifested as a clear angular unconformity. Here, the Rijnland Group comprises the Holland Formation. In map sheet VII, the base of the Rijnland Group is often not easy to trace. Sometimes there is a clear reflection, but generally this horizon is vague and indistinct. The base of the Rijnland Group contains the sand bodies of the Vlieland and the Nieuwerkerk Formations, which are each other's lateral equivalent. The lowest part of the Schieland Group is a unit with a large number of continuous reflectors. The base of the Schieland Group can sometimes be identified as an angular unconformity.

In the Altena Group, from top to bottom, three seismic units are identifiable: a unit with several reflectors frequently characterised at the base by a low-frequency band and two virtually transparent units is transected by a low-frequency band (the Posidonia Shale Formation). The base of the Altena Group is generally a prominent, continuous reflector.

The Permian-Triassic groups have been interpreted as a single unit often containing several continuous reflectors. The Zechstein and the Upper Rotliegend Groups are so thin in the map sheet area that they cannot be identified on the seismic profiles. Only in the northeastern part of the map sheet area are these groups thick enough to be seismically resolved. The thickness maps of both groups are therefore principally based on well-log data and knowledge of the regional geology. The base of the Permo-Triassic groups is usually difficult to interpret, but this horizon can sometimes be recognised as a clear angular unconformity

1.5 Biostratigraphic research

To support the geological research, use was made of a large number of biostratigraphic reports prepared within the framework of other research (RGD, 1986a,b,c,d; RGD, 1987, RGD, 1990a,b,c; RGD, 1995a,b,c,d,e; RGD, 1996a,b,c,d,e; NITG-TNO, 1999).

1.6 Petrophysical research

The petrophysical reservoir rock characteristics within the map sheet area have also been taken into account. Well-log data and core analysis results have been processed from one well (Pernis-West-1) for the calculation of porosity; these have been categorised in appendix C. Appendix D exhibits a number of test data.

1.7 Maps and sections

The results of the mapping are shown on a scale of 1:250 000 in a series of depth maps and thickness maps of the lithostratigraphic units, on subcrop maps and in three sections (Maps 1 to 19). An overview of these units is given in figure 1.4. Depth maps have been plotted of the bases of the Upper Rotliegend, the Zechstein, the Lower Germanic Trias, the Altena, the Schieland, the Rijnland and the Chalk Groups, and of the North Sea Supergroup and the Upper North Sea Group.

Virtually throughout the map sheet area, the Upper Rotliegend and Zechstein Groups are only thinly developed (0-50 m). The intervals have not been mapped separately by seismics. For the depth maps of the base of these groups, the base of the Lower Germanic Trias Group has therefore been taken, to which the combined thicknesses of the Zechstein Group and Upper Rotliegend Group have been added.

Thickness maps were made of the Zechstein, the Lower and Upper Germanic Trias, the Altena, the Schieland, the Rijnland and the Chalk Groups. The depth and thickness maps only depict wells that have fully penetrated the interval in question.

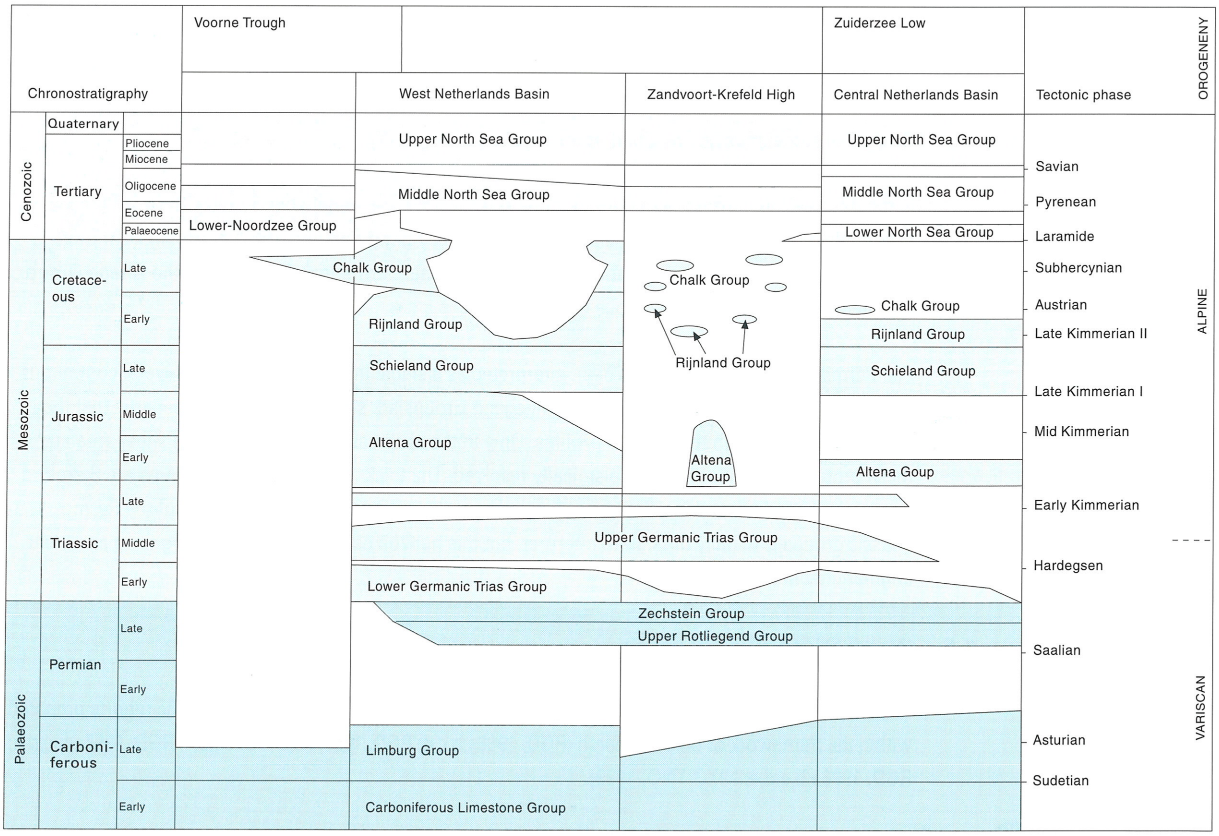


Figure 1.5 Diagram of the lithostratigraphic units and the main tectonic events for the geological development of the map sheet area.

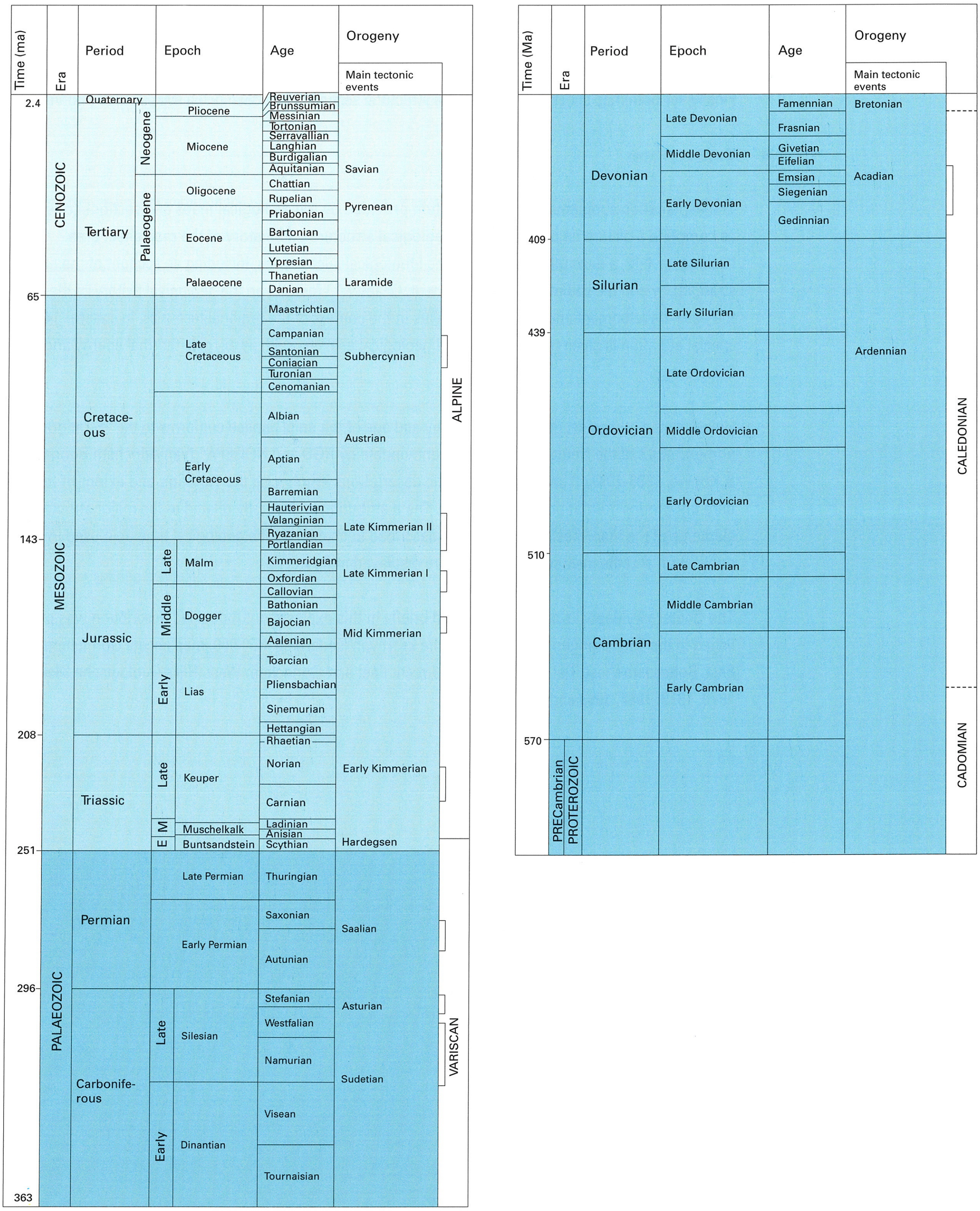


Figure 1.6 Geological timetable as used in the explanation based on Harland et al., 1990. The other chronostraticraphic timetables used in this Explanation are all based on this timetable. The tectonic phases which are referred to have been indicated in the figure.

Subcrop maps have been made of the major unconformities at the bases of the Schieland, the Rijnland Groups and of the North Sea Supergroup, providing an impression of the degree of erosion preceding the deposition of these groups.

Finally, for both map sheet VII and VIII, three structural sections have been given (Maps VII-19 and VIII-19).

1.8 Explanation

The explanation supplements the information provided by the geological maps and sections to form as complete a picture as possible of the geological structure and history of the map sheet area.
In chapters 4-12, a description is given of the lithological successions, including an account of the lithostratigraphy and the sedimentary development. Chapter 13 focuses on the geological history of the area: the basin development and the tectonic events in the context of the regional tectonics. In chapter 14, special attention is given to various applied geological aspects, such as oil, gas, thermal energy and CO_2 storage.

Unless stated otherwise, the lithostratigraphy and age of the units applied conforms to the "Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA" (Van Adrichem Boogaert & Kouwe, 1993-1997). The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members. The distribution is generally related to the major structural elements of the map sheet area, which are described in chapter 3. The geological timetable used in this publication and the main tectonic phases are displayed in figure 1.6.

The Quaternary deposits are only described briefly in this explanation. A detailed description was published in the Toelichtingen bij de Geologische kaart van Nederland 1:50 000, map sheets Gorinchem East, Rotterdam West, Tiel West and East, Utrecht East and Gorinchem West (Rijks Geologische Dienst, 1970, 1979, 1984, 1989 and 1995 resp.).

2 Exploration history

2.1 Introduction

The presence of hydrocarbons in the map sheet area was demonstrated for the first time in an exploration drilling at De Mient in The Hague in 1938. Hydrocarbon exploration was not the drilling target but the purpose was to demonstrate drilling techniques at an exhibition on petroleum exploration in the former Dutch East Indies (fig. 2.1). The N.V. Bataafsche Petroleum Maatschappij (the predecessor of the present-day Shell) had not only provided a complete drilling rig but, for the first time ever in the Netherlands, had set up an oilfield pump jack. The rig was a light Rotary type, permitting drilling to a depth of approximately 500 m. A secondary objective was to gain an understanding of the shallow subsurface beneath The Hague. The Shell magazine of the time ('De Bron' cited in Borghuis, 1988), printed the following extract referring to the proposed drilling: 'As there is no oil below The Hague, there is no reason to suppose that the drilling bit will ever come across an oil horizon. The subsurface below The Hague has never been explored to great depth, but the geological structure is so well documented that the likelihood of encountering an oil horizon may be ruled out.' Great was the amazement when one Saturday afternoon, at a depth of 464 m, traces of oil were found in the cores taken. At that moment, there were no experts available able to provide an explanation of this strike. In the end, they managed to get through to one of the 'bosses' who set off for the drilling site with all due speed. The official core report refers to 'black traces of high viscous asphalt with light-brown impregnations in drill cuttings.' The find proved to be of no commercial importance, and consequently the well was plugged and the drilling rig plus equipment left on display for a while longer.

The fact that traces of oil had been found in De Mient well instigated further exploration of the West Netherlands Basin and culminated in the first gravimetric survey in this part of the Netherlands. This was followed by an extensive seismic survey, which was carried out after the war (1947). These exploration activities revealed a number of structures that might potentially contain hydrocarbons. During the war years, a few exploration boreholes had already been drilled, one of which (Delft-1, 1944) provided a second indication of the presence of oil in the Lower Cretaceous sandstones of this area.

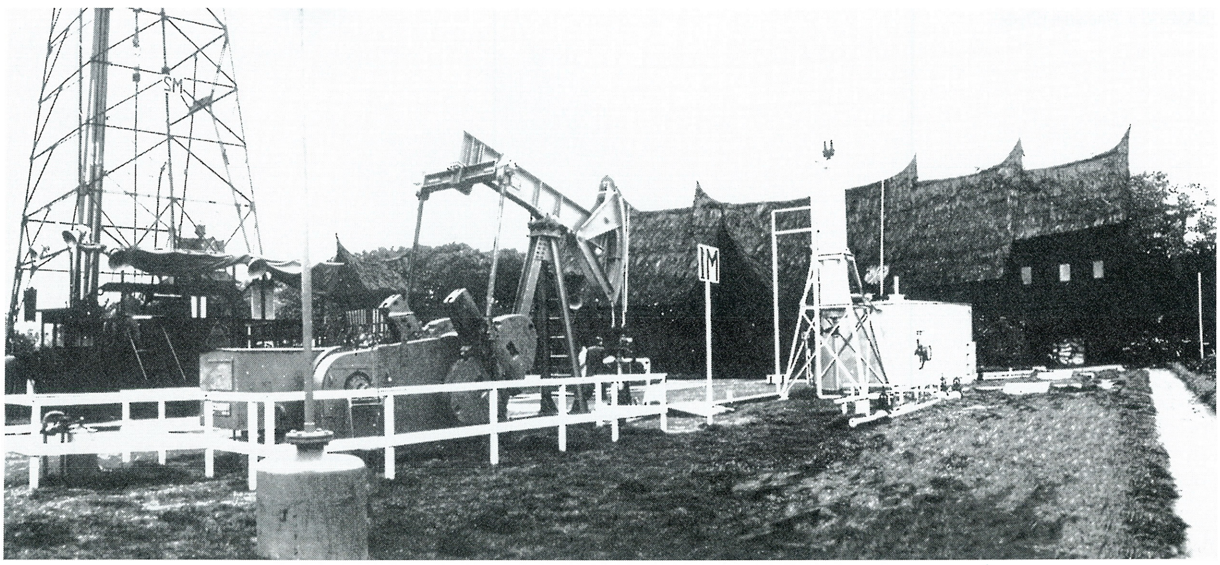


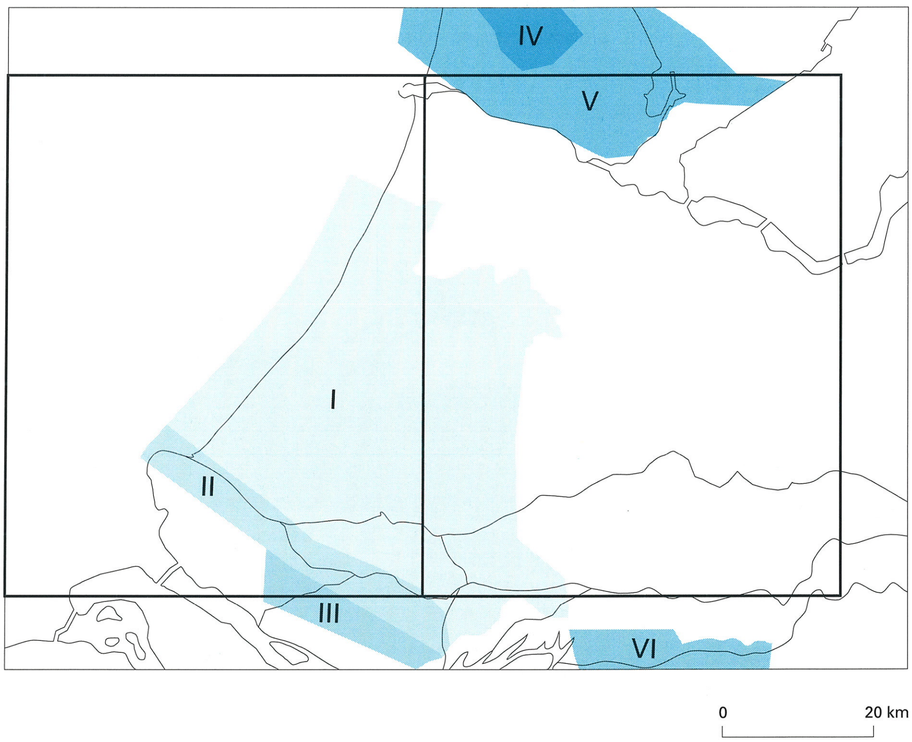
Figure 2.1 Historical photograph of operating drillsite at De Mient, The Hague in 1938 (after Borghuis, 1988).

Following the discovery of several Upper Jurassic and Lower Cretaceous oil and gas fields in the fifties and sixties, the NAM successfully focused its exploration activities on the deeper Triassic reservoir rocks (the Main Buntsandstein Subgroup and the Röt Fringe Sandstone Member). These horizons currently form the principal exploration objectives, containing predominantly gas (and a little oil). The Upper Jurassic to Lower Cretaceous sandstone reservoirs of the Schieland and Rijnland Groups not only usually contain oil, but also significant quantities of gas. Secondary reservoir objectives are also to be found in the Zechstein Fringe Sandstone members, the Middle Werkendam Member, the Brabant Formation, the Chalk Group and the Basal Dongen Sand Member (De Jager et al, 1996; Geluk et al, 1996). Chapter 14 discusses the generation and sourcing of the hydrocarbons in this map sheet in greater detail.

2.2 Oil

Although the first exploration wells initially achieved little commercial success, they at least provided indications as to the presence of oil in the Upper Jurassic – Lower Cretaceous sediments (Delft-1; 1944, Delft-2; 1947 and Berkel-1; 1952). However, this concept eventually proved successful when, in 1953, the Rijswijk-1 well revealed the first oil field in the west of the Netherlands. This field was less than 8 km from the headquarters of Royal Dutch/Shell Group of Companies. Based on this oil find, the Rijswijk concession, 16,650 ha, was granted in 1955. This concession comprised the Rijswijk, Pijnacker, Delft and Berkel structures. Additional oil finds led to considerable enlargements in the concession in the course of time (fig. 2.2). A total of ten productive oil fields (fig. 2.3) were discovered (initial reserve approx. 68 x 10^6 m^3). The majority of these fields have since been abandoned. Only the Berkel and Rotterdam

Figure 2.2 Overview of the concession areas within the map sheet area. I = Rijswijk (NAM), II = Botlek (NAM), III = Beijerland (NAM), IV = Bergen (BP), V = Middelie (NAM), VI = Waalwijk (Clyde).



fields are still under exploitation. These fields are not very large, but their position in the highly industrialised western part of the Netherlands was an important economic argument in favour of proceeding to production.

Exploration activities in this area targeted at the deeper potential reservoir rocks of the Triassic led to the discovery of oil in these horizons in the eighties (for example in the Pernis West-1 and Ottoland-1 wells). The oil occurrences in the Triassic are found in tilted fault blocks formed during the Late Jurassic rifting followed by further modification during the Late Cretaceous – Middle-Tertiary inversion.

A future challenge in the Rijswijk Concession is the possible production of the approximately 90 x 10^6 m^3 oil that has proven to be in the poor reservoir rocks of the De Lier and Holland Greensand Members (Lower Cretaceous). New developments in drilling technology may well contribute to the exploitation of this oil (Racero-Baena & Drake, 1996).

2.3 Gas

The first wells to encounter occurrences of oil in the Delfland and the Vlieland Subgroups also revealed the presence of gas in this section. Here, the gas occurs in the form of a cap to the oil-bearing horizons. The majority of this gas was generated by the Posidonia Shale, but the Pernis and De Lier gas fields are also thought likely to contain gas from Westphalian source rocks (De Jager et al., 1996). The estimated initial reserves in this play are approximately 5 x 10^9 m^3.

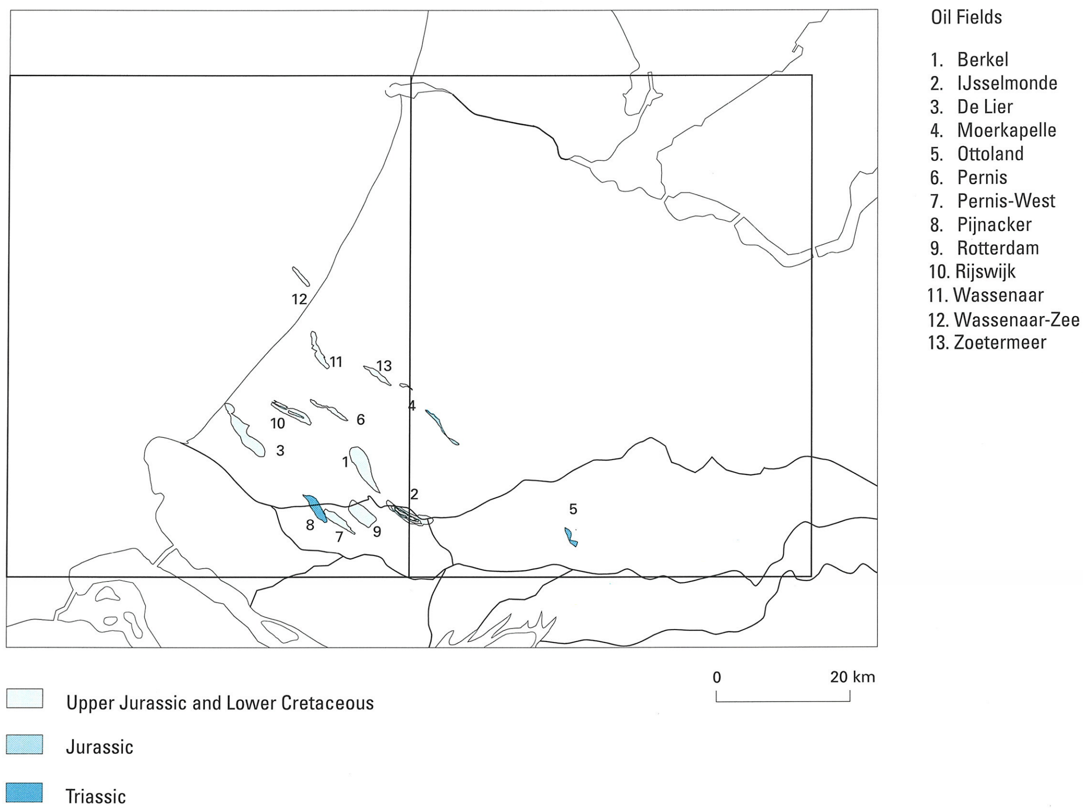
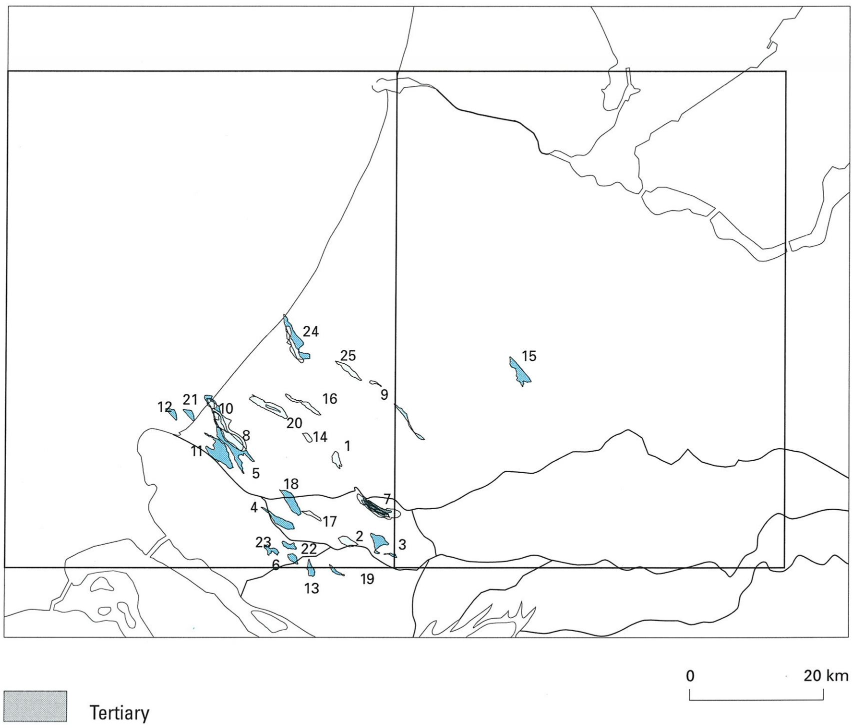


Figure 2.3 Overview of the gas fields areas within the map sheet area.

Exploration in the area to the south and east of the Rijswijk concession in the eighties resulted in a gas find at Botlek and subsequent gas finds in the Barendrecht-Ziedewij-1, Spijkenisse-Oost-1, Papekop-1 and Andel-6 wells. In 1991, the Botlek concession was granted (fig. 2.4), followed in 1996 by the Beijerland concession.

The Triassic structures contain predominantly gas, whether or not associated with oil (De Jager et al., 1996). In some cases, these reservoirs occur below the oil fields, as for example in Wassenaar, but the Pernis-West and Ottoland gas fields to the southwest of the Wassenaar field have no overlying oil field (fig. 2.3). The coal-bearing strata of the Westphalien is the principal source rock of the gas, but recent modelling studies (see chapter 14) suggest that part of the gas occurrences derive from a Namurian source rock. With its initial reserves of 65 x 10^9 m^3, the Triassic gas play is the major exploration objective in the West Netherlands Basin.



Gas fields

1. Berkel
2. Barendrecht
3. Barendrecht-Ziedewij
4. Botlek
5. Gaag
6. Hekelingen
7. IJsselmonde
8. De Lier
9. Moerkapelle
10. Monster
11. Maasdijk
12. Noorderdam
13. Oud-Beijerland-Zuid
15. Papekop
16. Pijnacker
17. Pernis
18. Pernis-West
19. Reedijk
20. Rijswijk
21. 's-Gravenzande
22. Spijkenisse-Oost
23. Spijkenisse-West
24. Wassenaar
25. Zoetermeer

Tertiary

Upper Jurassic and Lower Cretaceous

Jurassic

Triassic

Figure 2.4 Overview of the oil fields areas within the map sheet area.

3 Structural framework

In this chapter, the structural elements differentiated in the map sheet area (fig. 3.1) are illustrated in the order of sequence of their formation. The structural history is largely determined by the Variscan and Alpine orogenies, but a significant number of the structural elements present were, however, formed during the Caledonian Orogeny.

The **Brabant Massif** is a Caledonian structural element in the southwest of the Netherlands and the northwest of Belgium, comprising folded deposits of Cambro-Silurian age. On the top of this regional high, the Chalk Group rests immediately upon Early Palaeozoic deposits. The Brabant Massif was a moderate high during the Devonian and Carboniferous, with little significance in terms of sediment supply (Bless et al., 1980).

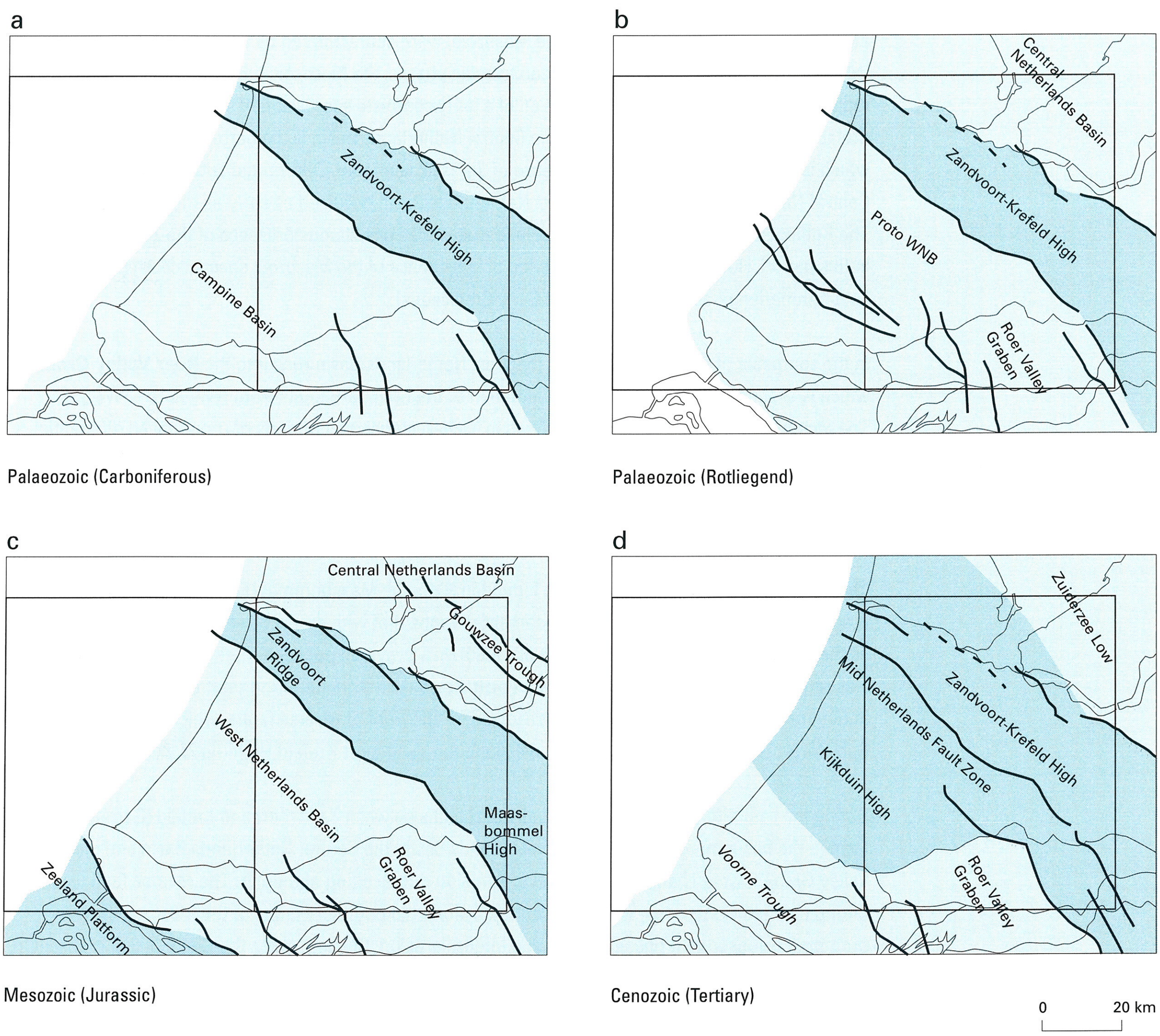


Figure 3.1 Overview of the development of structural elements in the map sheet area.

To the north of the Brabant Massif is the **Campine Basin**. Owing to the considerable burial depth, little is known about structural structures of the Early Carboniferous and earlier. The Campine Basin was probably formed during the Middle Devonian as a result of Early Variscan tectonics (Bless et al., 1980). The present form of the basin is presumed to have originated already during the Late Carboniferous and Early Permian owing to uplift of the flanks.

The northern boundary of the Campine Basis is defined by the **Zandvoort-Krefeld High**, a series of horst structures (Bless et al., 1980), which continued to be a major structural zone until during the Tertiary. To the north of the high was a precursor of the Central Netherlands Basin, flanked on its northern side by the Texel-IJsselmeer High.

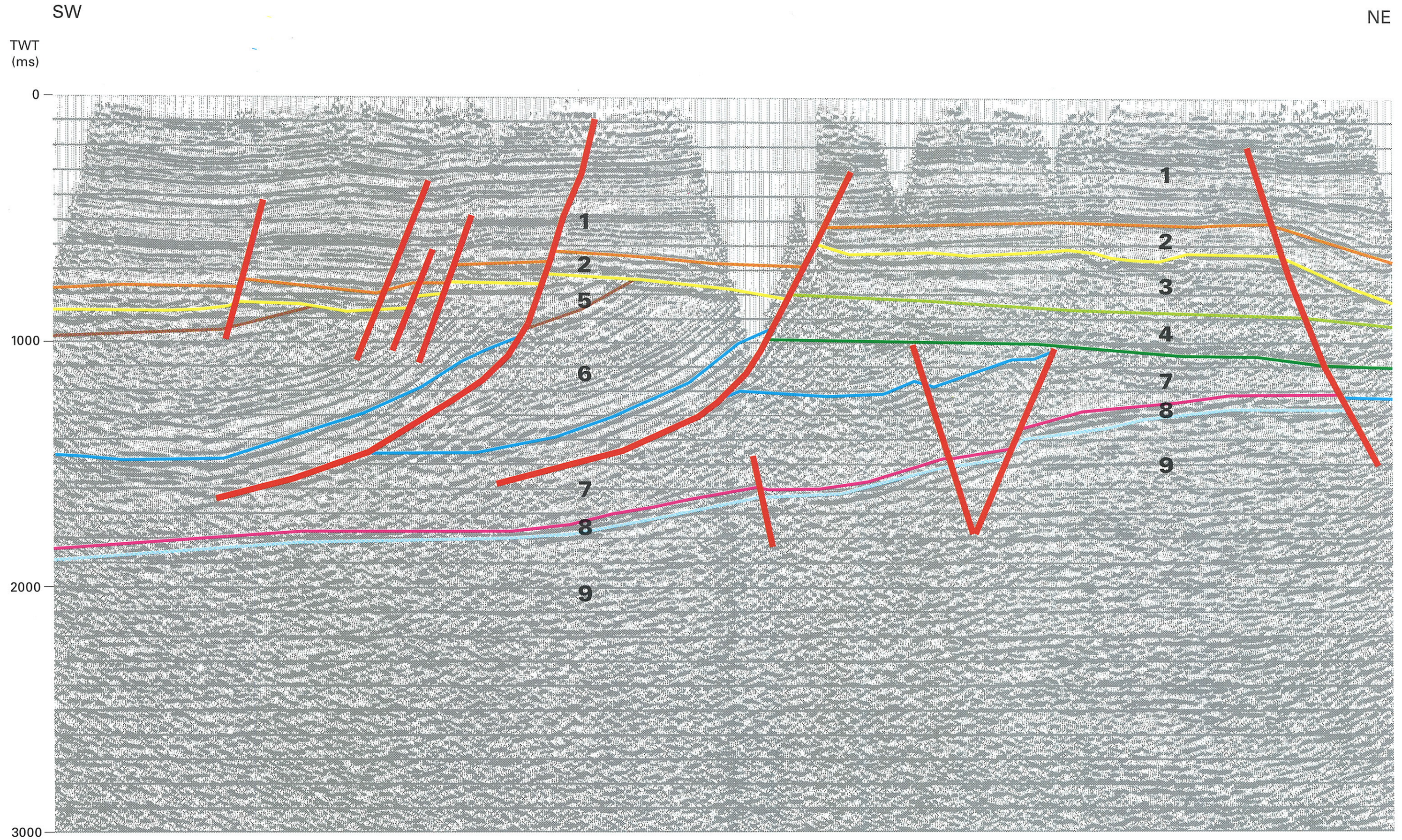
During the Mesozoic, the map sheet area was characterised by two NW-SE oriented basins: the **West Netherlands Basin** and the **Central Netherlands Basin**. These basins were separated by the **Zandvoort Ridge** and the **Maasbommel High**. Both highs lie on the same trend as the Palaeozoic Zandvoort-Krefeld High and, during the Mesozoic, were characterised by differential movements (NITG-TNO, 2001a). During the Kimmerian tectonic phases, the Mesozoic basins underwent a period of rapid subsidence, including the deposition of a fairly complete succession of Triassic, Jurassic and Early Cretaceous sediments. To the west of the Central Netherlands Basin is the narrow **Gouwzee Trough**, which is characterised by a thick sequence of Jurassic sediment. Differential subsidence of both the Central Netherlands Basin and the West Netherlands Basin occurred as early as the Late Permian. The Rotliegend sedimentation pattern demonstrates the conspicuous presence of the Zandvoort Ridge in this period. However, the principal period of subsidence of the Mesozoic basins occurred during the Late Kimmerian phase (Late Jurassic to Early Cretaceous).

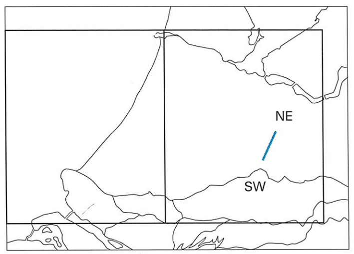
In the southeast of the map sheet area, the West Netherlands Basin runs into the **Roer Valley Graben**, which is associated with a change in orientation of the boundary faults from NW-SE to NNW-SSE. The tectonic history of the Roer Valley Graben is characterised by periods of pronounced differential subsidence during the Triassic, the Jurassic and from the Oligocene on. Uplift of the Mesozoic succession in the graben occurred during the Sub-Hercynian inversion phase in the Late Cretaceous, resulting locally in erosion as far down as the Triassic.

The Zandvoort Ridge, together with the IJmuiden High, the Maasbommel High, the Peel Block, the Venlo Block and the Krefeld High, forms a lineament of highs that with respect to the Palaeozoic is known as the Zandvoort-Krefeld High (Bless et al., 1980). In a previous publication, this lineament of highs was referred to as the **Mid Netherlands Fault Zone** (Van Adrichem Boogaart & Kouwe, 1993-1997). In the present publication, this name is reserved for the front of reverse faults, which was a result of the Sub-Hercynian inversion (Late Cretaceous) along the Zandvoort-Krefeld High (fig. 3.2).

During the Late Kimmerian phases, the individual highs between Zandvoort and Krefeld (Germany), which formed the basin margins of the West Netherlands Basin, the Central Netherlands Basin and the Roer Valley Graben, were characterised by severe erosion due to tilting and uplift. The reverse fault tectonics during the Late Cretaceous, which concentrated along the boundary faults of the Mesozoic basins, prompted a subsequent phase of uplift and intense erosion. Consequently, the Chalk Group is absent in the Central Netherlands Basin and for the most part in the West Netherlands Basin. During the inversion, certain parts of the former basin margins were characterised by pronounced subsidence, resulting in a thick sequence of the Chalk Group on the Zandvoort Ridge, Maasbommel High and the Voorne Trough.

The transition from the West Netherlands Basin to the Brabant Massif takes place via the Zeeland Platform, where the Chalk Group is covered unconformably by the Carboniferous. Owing to Late Kimmerian





1. Upper North Sea Group
2. Lower and Middle North Sea Groups
3. Chalk Group
4. Rijnland Group
5. Posidonia Shale Formation
6. Altena Group
7. Lower and Upper Germanic Trias Groups
8. Zechstein Group
9. Permian-Carboniferous

Figure 3.2 Seismic profile through the southern margin of the Zandvoort-Krefeld High, which is characterised here by reverse faulting and overthrusting by the Mesozoic succession as a consequence of tectonic inversion during the Late Cretaceous. This series of thrust faults is known as the Mid Netherlands fault zone (fig. 3.1). Here, overthrusting has produced a repetition of part of the Mesozoic succession.

uplift, the basin margin of the West Netherlands Basin is characterised by the Chalk Group unconformably overlying the Permian or the Triassic. During the Late Cretaceous inversion, subsidence of the former basin margin occurred, as a result of which a comparatively thick Chalk succession is present.

Up to the Late Oligocene, the Cenozoic was dominated by inversion tectonics induced by Alpine compression. During the Laramide, Pyrenean and Savian compressional phases, inversion of the basin structure occurred and parts of the Mesozoic and Tertiary sedimentary successions were removed by erosion. During the Tertiary, three basins were active: the Roer Valley Graben, the Zuiderzee Low and the Voorne Trough. With the exception of the Roer Valley Graben, which was also active in the Palaeozoic and the Mesozoic, these constitute newly formed subsidence centres.

From the Late Oligocene on, the **Roer Valley Graben** continued to be a major area of subsidence, characterised by a thick Tertiary accumulation. Subsidence of this graben took place along the Peelrand Fault and the Rijen Fault. Recently, seismic activity has been observed along these and associated faults (TNO-NITG, 2001a).

The **Zuiderzee Low** is situated in the northern and central part of the Netherlands. The southernmost part of this basin is in the northeast of the map sheet area, from where the basin extends in a northwesterly direction. From the Miocene on, this basin underwent a non fault-related regional subsidence. From the centre of the structure, situated north of the Texel-IJsselmeer High, a gradual thinning of the sediment succession occurred.

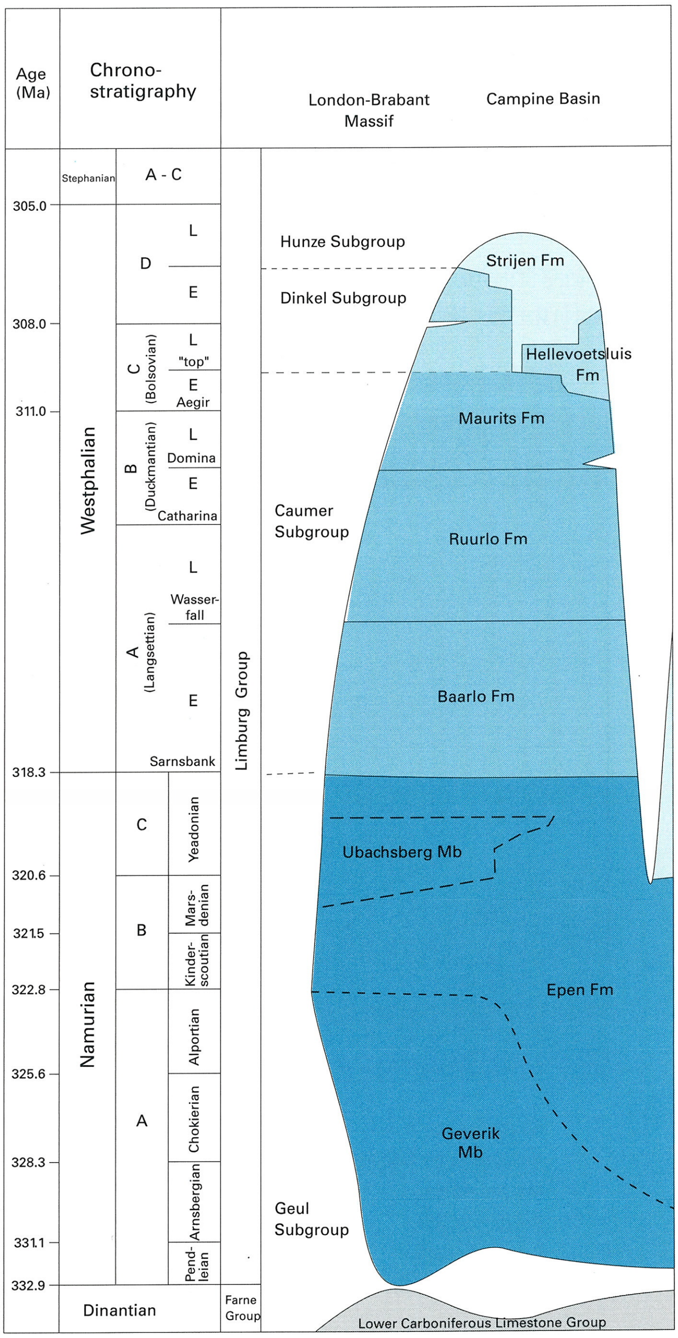
The **Kijkduin High** is the most intensively inverted part of the West Netherlands Basin. Pliocene deposits on the Kijkduin High rest immediately upon Mesozoic sediments. In the early Tertiary, as a consequence of uplift, an area of subsidence along the southern margin of the Kijkduin High developed contemporaneously, the **Voorne Trough**. This trough was active until after the Pyrenean inversion phase in the early Oligocene. The northern margin of the Kijkduin High is characterised by the even more elevated Zandvoort Ridge. This high is also the southern boundary of the Zuiderzee Low.

4 Limburg Group

4.1 Stratigraphy

The Limburg Group is the oldest unit to have been penetrated in the map sheet area and represents the Silesian (Upper Carboniferous). The group is composed of an alternation of predominantly grey to black claystones, siltstones and sandstones, which are also red coloured in the youngest part with, especially in the Westphalian B / C, a large number of intercalated coal seams. The group is subdivided into four

Figure 4.1 Stratigraphic overview of the Limburg Group with the principal Westphalian marine horizons.



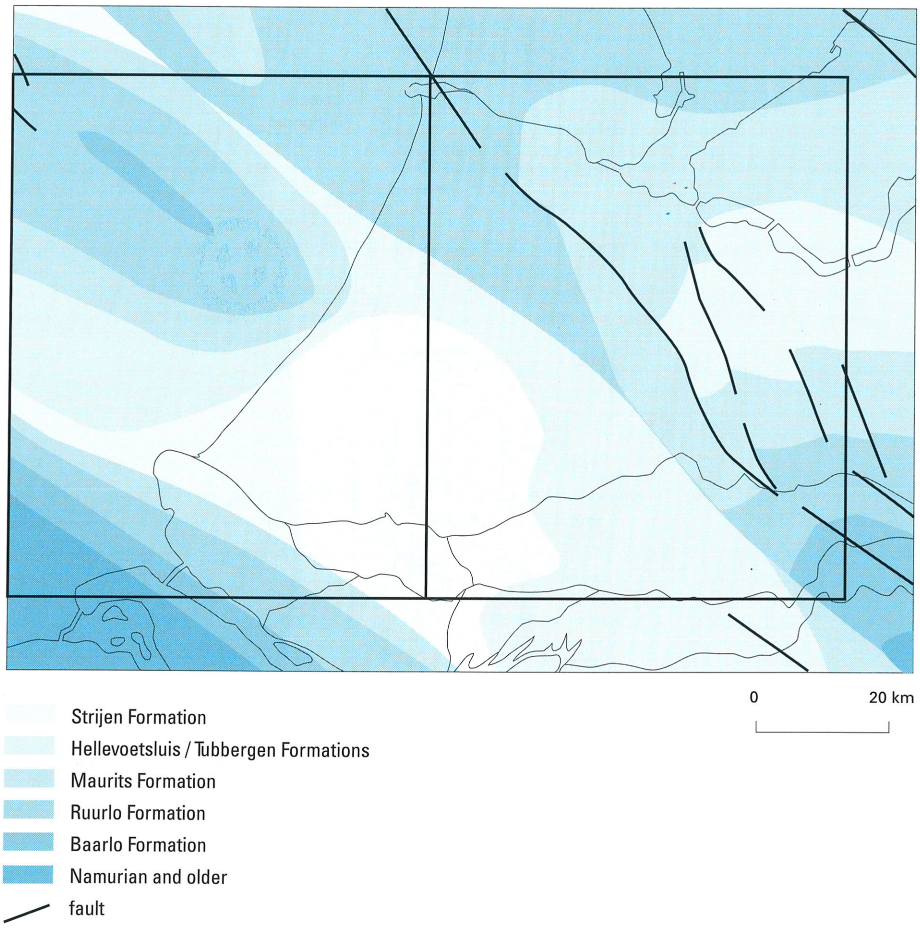
subgroups (fig 4.1). Each represents a particular phase of the Late Carboniferous regressive mega-sequence. The basal part, the Geul Subgroup, is characterised by several fossil-bearing marine bands in a succession predominantly comprising claystone. The characteristic lithologies of the Caumer Subgroup are dark coloured claystone beds and coal seams. The Dinkel Subgroup consists largely of sandstone. The Hunze Subgroup is composed mainly of red coloured claystones; coals are scarce.

The Limburg Group rests upon the Carboniferous Limestone Group separated by a hiatus and virtually throughout the map sheet area is overlain unconformably by the Upper Rotliegend Group (Maps VII-1/VIII-1), with the exception of the Zeeland Platform, where the group is unconformably overlain by deposits of the Chalk Group.

The deposits of the Limburg Group are found throughout the map sheet area. The total thickness of this group is not known, but is thought to exceed 5 km in the West Netherlands Basin. On the Zandvoort Ridge and the Zeeland Platform, the youngest part of the group is absent owing to non-deposition and erosion during the Late Carboniferous and Early Permian (fig. 4.2).

The top of the Limburg Group is on the northern flank of the Brabant Massif at a depth of less than 2000 m and in the West Netherlands Basin at depths in excess of 4000 m.

Figure 4.2 Subcrop geological map of the top of the Limburg Group.



4.1.1 Geul Subgroup

The Geul Subgroup exhibits predominantly dark coloured claystone. Coal seams do not occur in this subgroup. The subgroup comprises the Epen Formation.

4.1.1.1 Epen Formation

The Epen Formation, of Namurian age, is present throughout the map sheet area. Owing to its great depth, the formation has only been penetrated immediately to the southwest of the map sheet area by the North Sea S2-2 wells (405 m).

The Epen Formation consists predominantly of dark coloured claystone and siltstone, with a small percentage of sandstone. The formation is characterised by stacked successions of coarsening-upward sequences with a thickness of 50 to 100 m. The base of these sequences is characterised by marine fossils. Sandstone sequences 10-15 m thick are present at the top of the sequences. The base of the formation is the *Geverik Member*, a possible oil or gas-source rock (see chapter 14). However, this sequence within the map sheet area has not been penetrated. At the top of the Epen Formation is the *Ubachsberg Member*, massive medium-coarse sandstone, comprising a stacking of 10-25 m thick units.

4.1.2 Caumer Subgroup

The Caumer Subgroup is a succession of dark coloured claystones with intercalated sandstones and coal seams. The Caumer Subgroup comprises three formations, the Baarlo, the Ruurlo and the Maurits, which all occur throughout the map sheet area.

In the central part of the map sheet area, the Dinkel Subgroup rests conformably upon the Caumer Subgroup. On the Zandvoort Ridge, the Upper Rotliegend rests upon the Caumer Subgroup, while on the Zeeland Platform, the overlying unit is the Chalk Group. The Caumer Subgroup has not been fully penetrated anywhere in the map sheet area; in de Rijsbergen-1 well outside the map sheet area, the subgroup reaches a thickness of over 1200 m (TNO-NITG, 2001a).

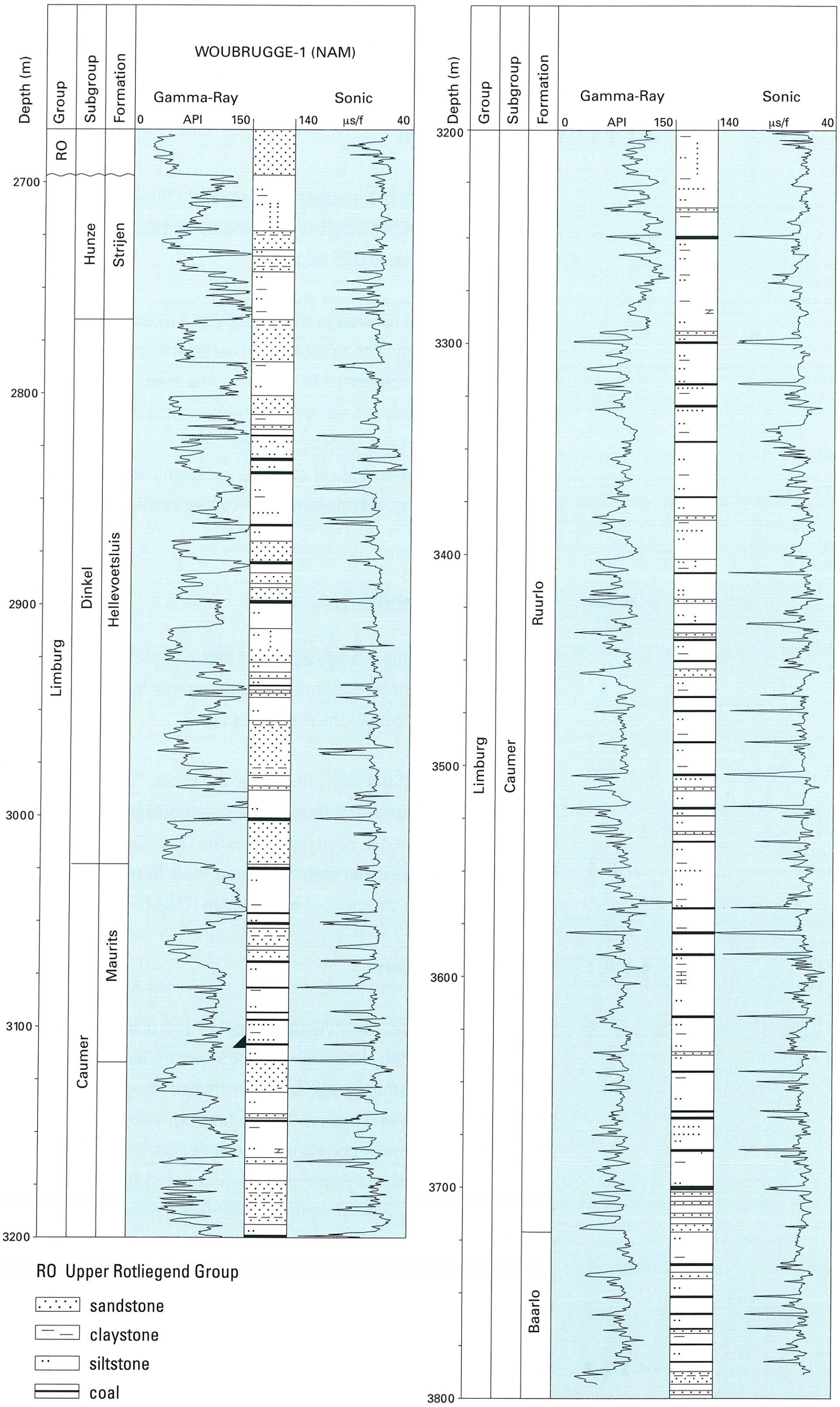
4.1.2.1 Baarlo Formation

The Baarlo Formation, Early Westphalian A in age, is composed of a large number of coarsening-upward sequences (fig. 4.3) varying in thickness from a few tens to several hundreds of metres. The basal dark claystones pass via siltstones into fine-grained to medium-coarse sandstones. Various basal claystones contain open-marine to brackish-water fossils (goniatites, *Lingula*). The large-scale sequences are regionally correlatable; however, the individual sandstone bodies have limited lateral continuity. In general, the Baarlo Formation contains fewer than four coal seams per 100 m. The coal seams are generally a few dm thick and achieve a maximum thickness of 2 m and are restricted to the topmost part of the sequences. The formation occurs throughout the map sheet area, but has only been penetrated in the Woubrugge-1 well (fig. 4.3 & 4.4). The sandstones of the Baarlo Formation reach a thickness of 30 m and occur predominantly at the top of coarsening-upward sequences.

4.1.2.2 Ruurlo Formation

The Ruurlo Formation in the map sheet area, of Late Westphalian A to Early Westphalian B age, is approximately 600 m thick and rests conformably upon the Baarlo Formation. The formation has been

Figure 4.3 Stratigraphic division and log pattern of the Limburg Group in the Woubrugge-1 well.



penetrated on the Zandvoort Ridge, the Maasbommel High and the Zeeland Platform and the formation comprises a succession of dark-grey or black silty claystones with a variable number of coal seams (fig. 4.3), and grey or light-yellow fine-grained argillaceous or silty sandstones (up to 5 m thick). The formation is characterised by a pattern of stacked fluvial sandstones, averaging approximately 50 m in thickness and displaying coarsening as well as fining-upward sequences. The sandstones developed in small channels and are also found as thin beds with good lateral continuity. Coal seams, up to 2 m thick, are common, though varying considerably in frequency laterally.

4.1.2.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Early Westphalian C age, mainly comprises light-grey claystones with abundant coal seams. In addition, a few thin layers of fine to coarse-grained sandstone are found, which may reach a thickness of 10-15 m. The formation is differentiated from the underlying formation by its fine-grained character and greater number of coal seams.

The formation is unconformably overlain by the Hunze or the Dinkel Subgroup or by the Upper Rotliegend or the Chalk Group. The Maurits Formation is found in the majority of the area, but is absent on the Zandvoort Ridge and the Maasbommel High, where it has been removed by erosion.

The transition from the Ruurlo Formation to the Maurits Formation is characterised by an increase in the clay percentage and coal content. The top of the formation is determined by the first occurrence of the thick fluvial sands of the Dinkel Subgroup.

4.1.3 Dinkel Subgroup

The Dinkel Subgroup in the map sheet area, Early Westphalian C to Early Westphalian D in age, is represented by the Hellevoetsluis Formation.

4.1.3.1 Hellevoetsluis Formation

The Hellevoetsluis Formation, of Early or Late Westphalian C age, reaching Early Westphalian D along the margins of the Campine Basin, is composed largely of sandstone and overlies the Maurits Formation, separated by a hiatus or a minor angular unconformity. The formation is found in the West Netherlands Basin and the adjacent part of the Roer Valley Graben. The formation is overlain conformably by the Strijen Formation or unconformably by the Upper Rotliegend Group.

The formation comprises an alternation of predominantly greyish-white sandstone beds and silty or sandy claystones with the occasional coal seam. The sandstones are fine to coarse-grained and occur as sheet deposits of sandstone and channel fills, with a thickness of 1 to 15 m. Locally, they are stacked, with abundant mudstone intercalations, which reach a maximum thickness of 30 m. The claystone intervals are predominantly greenish-grey or beige, usually with purple to reddish-brown horizons in the topmost parts. Coal seams are found infrequently, and are associated with 5-to-70 m-thick, grey clay sequences.

4.1.4 Hunze Subgroup

The Hunze Subgroup, Late Westphalian C up to Westphalian D in age, is represented by the Strijen Formation.

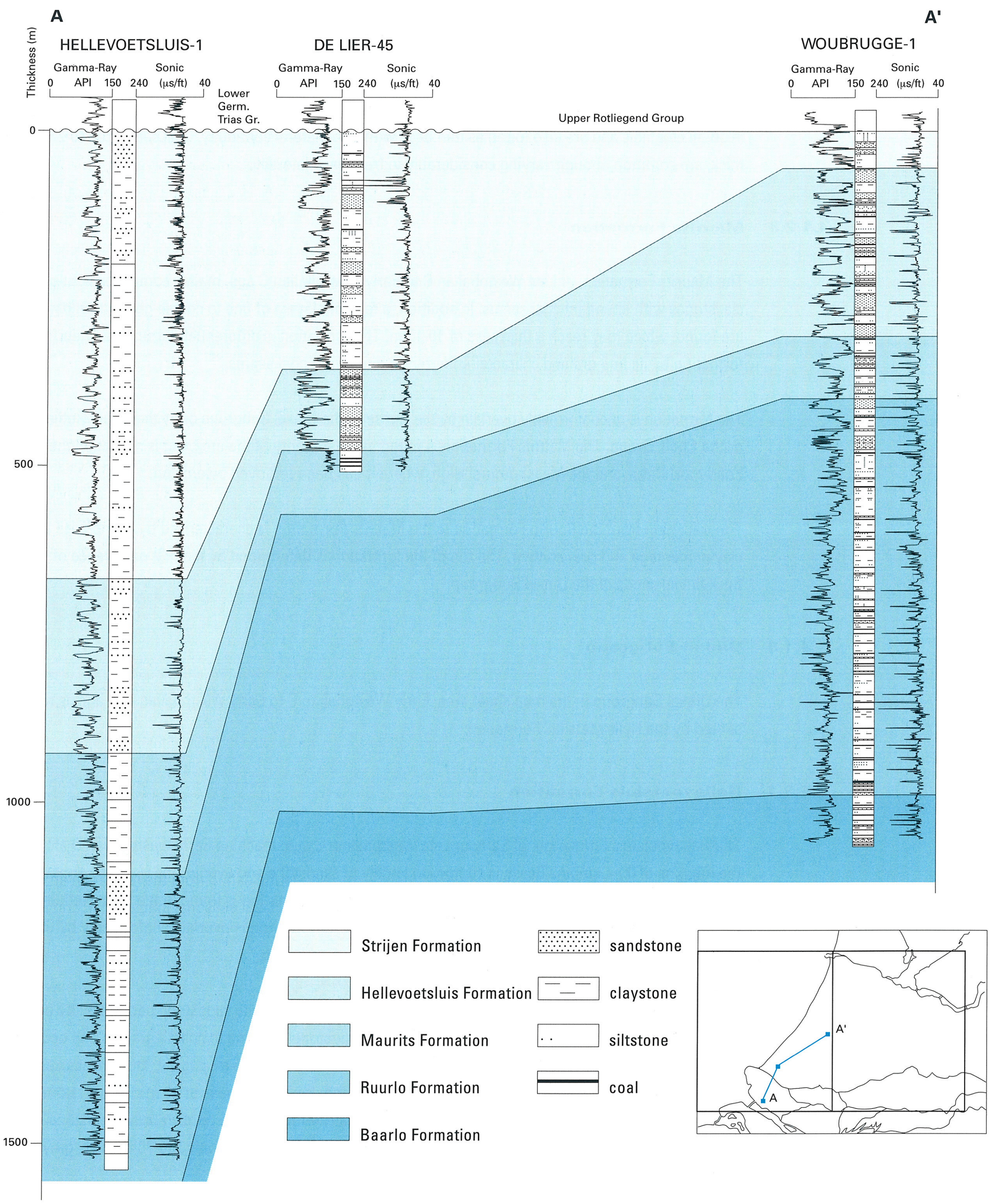


Figure 4.4 Stratigraphic section A-A' of the Limburg Group between the Hellevoetsluis-1, De Lier-45 and Woubrugge-1 wells. The reference level is the base of the Upper Rotliegend Group.

4.1.4.1 Strijen Formation

The Strijen Formation, of Late Westphalian C to Westphalian D age, is found in the West Netherlands Basin. This formation consists of a succession of reddish-brown and occasionally beige or greenish-grey, silty to very fine-sandy claystones. The succession of claystones contains 2-to-20-m-thick sandstones with fair lateral continuity. Organic rich constituents are regularly found in the claystones, particularly in the bottommost part. However, real coal seams are very rare. The base of the formation is formed by a claystone sequence over 50 m thick. The Strijen Formation rests conformably upon the massive sandstones of the Hellevoetsluis Formation. The formation is unconformably overlain by the Upper Rotliegend Group. The formation reaches a maximum thickness of 200 m in the north of the map sheet area.

4.2 Sedimentary development and palaeogeography

The deposits of the Limburg Group reflect a marine, paralic and terrestrial sedimentation in an east-west oriented foreland basin. The sedimentary succession displays a large-scale regressive sequence from deep-water deltaic facies in the Namurian to fluvial facies in the Late Westphalian. The basal Geul Subgroup consists of marine, deltaic and to a lesser extent lacustrine sediments. The middle part of the succession, the Caumer Subgroup, is characterised by lacustrine deposits and the frequent occurrence of coal seams (Van Amerom & Pagnier, 1990). The coarse-grained Hellevoetsluis Formation of the Dinkel Subgroup was deposited by braided river systems, which extended from the south and east over the basin (Thorez & Bless, 1977; Wouters & Vandenberghe, 1994).

Within the formations, scarcely any large-scale sedimentary trends occurred, which indicates that the rate of sedimentation kept pace with subsidence. However, on a small scale, the sediments display a cyclical pattern of frequent and often abrupt alternations of clay, sand and coal. Sedimentation mainly took place in a deltaic coastal plain around average sea level. As it is highly likely that pronounced sea-level fluctuations occurred during the Late Carboniferous as a result of the growing and melting of the ice caps on the Antarctic Gondwana (Bless & Winkler Prins, 1972; Veevers & Powell, 1987; Heckel, 1986; Ziegler, 1990), the often cyclical alternation of sand, clay and coal is explained by the repeated flooding and emergence of the deltaic coastal plain. The abundant coal seams are the consequence of the humid, tropical climate and deposition around sea level. The gradual transition to red clays in the Westphalian D indicates that the climate slowly became drier (Ziegler, 1990; Pagnier & Van Tongeren, 1996; Van de Laar & Van der Zwan, 1996). Sediments, flora and fauna dating from the Namurian and the Westphalian A to C, indicate a tropical, humid climate without any clear seasonal influences. During the Late Westphalian C and D as well as the Stephanian, the climate was drier (Hedeman et al., 1984; Van de Laar & Van der Zwan, 1996). The red colour of the sediments, the calcareous soils and sparse vegetation reflect a more seasonal, tropical semi-arid climate (Pagnier & Van Tongeren, 1996).

5 Upper Rotliegend Group

5.1 Stratigraphy

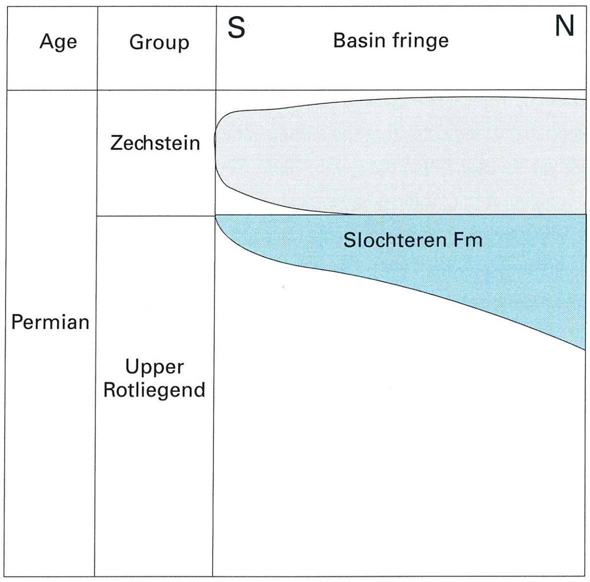
The Upper Rotliegend Group, of Late Permian age (Van Adrichem Boogaert & Kouwe, 1993-1997; Geluk, 1999a), is, in the map sheet area, entirely composed of sandstones of the Slochteren Formation.

The Upper Rotliegend Group rests unconformably upon the Limburg Group (fig. 5.1) and, separated by a hiatus, is overlain conformably by the Zechstein Group (Map VII/VIII-3). The thickness varies considerably: both in the Central Netherlands Basin and in the West Netherlands Basin, relatively thick sequences of the Upper Rotliegend Group were deposited (75-150 m). In the area in between, a thinner sequence is presumed to be present (fig. 5.2). From the West Netherlands Basin towards the south, the Rotliegend sequence rapidly becomes thinner; in the extreme south of the map sheet area, the group is completely absent. The difference in thickness is largely due to onlap against the Zeeland Platform.

5.1.1 Slochteren Formation

The Slochteren Formation consists of red and grey sandstones and possibly conglomerates. The facies development in the area is insufficiently documented owing to the absence of core material. On the basis of dip-meter logs, the sandstones, for example in the Almere-1 well, have been shown to be characterised by abundant occurrences of high-angle, aeolian cross-bedded deposits (fig. 5.3).

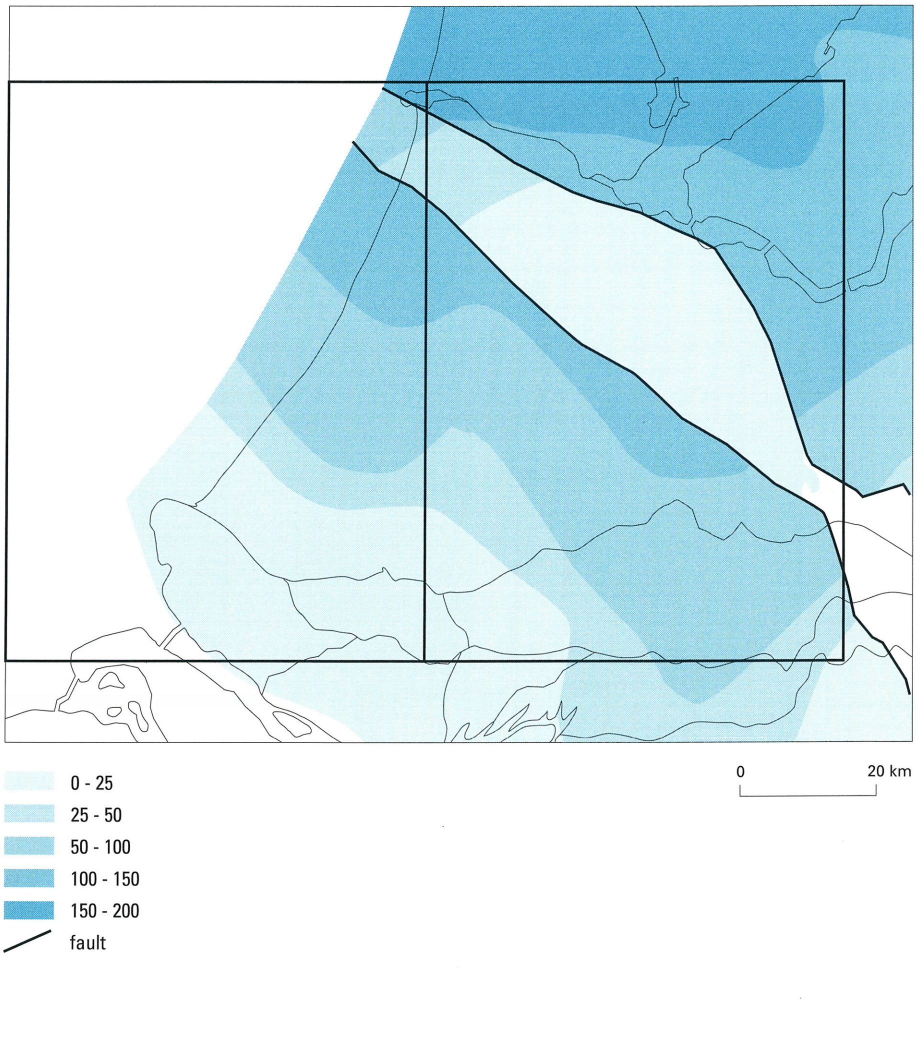
Figure 5.1 Stratigraphic overview of the Upper Rotliegend Group.



5.2 Sedimentary development and palaeogeography

The coarse-clastic material of the Slochteren Formation originates from the southern Brabant Massif and the Variscan hinterland. The basin structure was determined by the reactivation of old NW-SE lineaments (Ziegler, 1990; Verdier, 1996). The thickness pattern within the map sheet is presumed to be associated with a NW-SE oriented fault system, which broadly corresponds to the Mesozoic West Netherlands Basin and the Roer Valley Graben. The Zandvoort Ridge is likely to have already been active in the Rotliegend, because only a few metres of Rotliegend sandstone are presumed to be present on this high (Geluk et al., 1996) conformably overlain by Zechstein sediment. This is probably the consequence of syn-sedimentary tectonics, but thinning as a consequence of faulting is among the possible

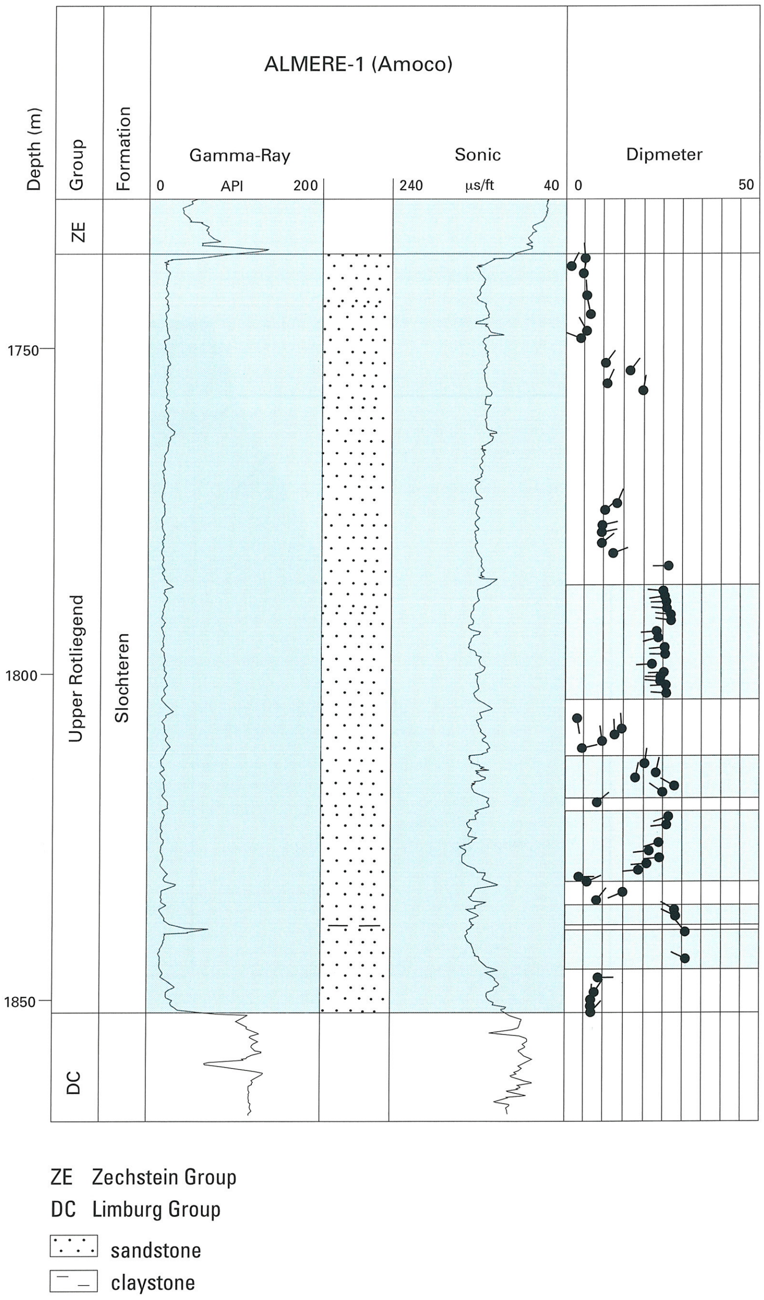
Figure 5.2 Thickness map (m) of the Upper Rotliegend Group in the map sheet area.



explanations (Geluk et al., 1996). Towards the northern Central Netherlands Basin, the thickness increases drastically (fig. 5.4).

A large proportion of the sediment along the southern margin of the Central Netherlands Basin was transported by aeolian processes (fig. 5.3).

Figure 5.3 Stratigraphic division and log pattern of the Upper Rotliegend Group in the Almere-1 well. Dipmeter data suggest that part of the succession comprises high-angle, aeolian cross-bedded deposits.



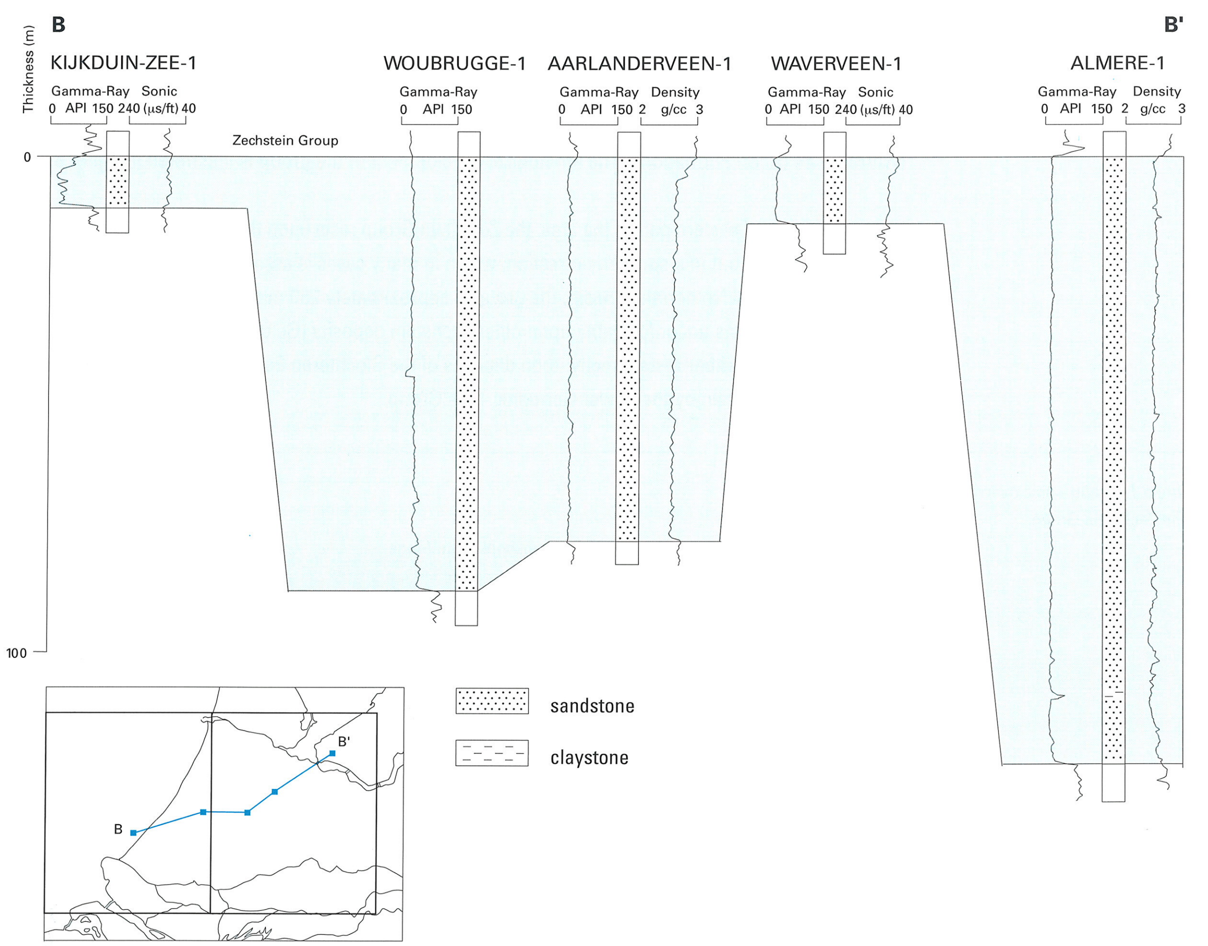


Figure 5.4 Stratigraphic section B-B' of the Slochteren Formation between the Kijkduin-Zee-1, Woubrugge-1. Aarlanderveen-1, Waverveen-1 and Almere-1 wells. The reference level is the base of the Zechstein Group.

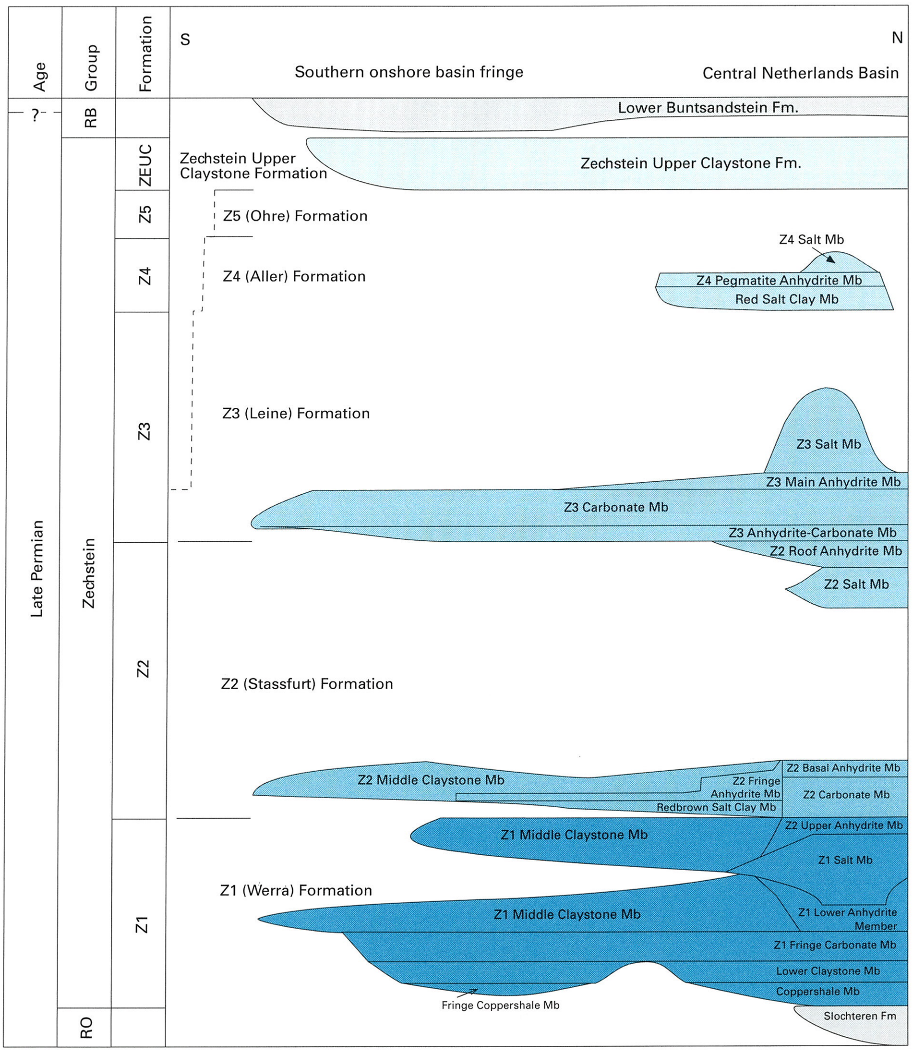
6 Zechstein Group

6.1 Stratigraphy

The Zechstein Group, of Late Permian age, is composed of the equivalents of four evaporite cycles and consists of clastic deposits, carbonates and evaporites (fig. 6.1). Evaporites are only present in the extreme northeast of the mapping area. (fig. 6.2). The group is subdivided into four formations: the Z1 (Werra) to Z4 (Aller) Formations. The lithological development of the group is illustrated in figure 6.3.

In the northern and eastern part of the area, the Zechstein Group rests upon the Upper Rotliegend Group. The group pinches out in a southerly direction, which in many cases is associated with synsedimentary faults. In the Central Netherlands Basin, the group is approximately 250 m thick. The thin Zechstein Upper Claystone rests unconformably upon older Zechstein deposits (Geluk, 1999a; TNO-NITG, 2001a); in the south, the member rests directly upon deposits of the Slochteren Formation. The Zechstein Group is conformably overlain by the Lower Germanic Trias Group.

Figure 6.1 Stratigraphic overview of the Zechstein Group.



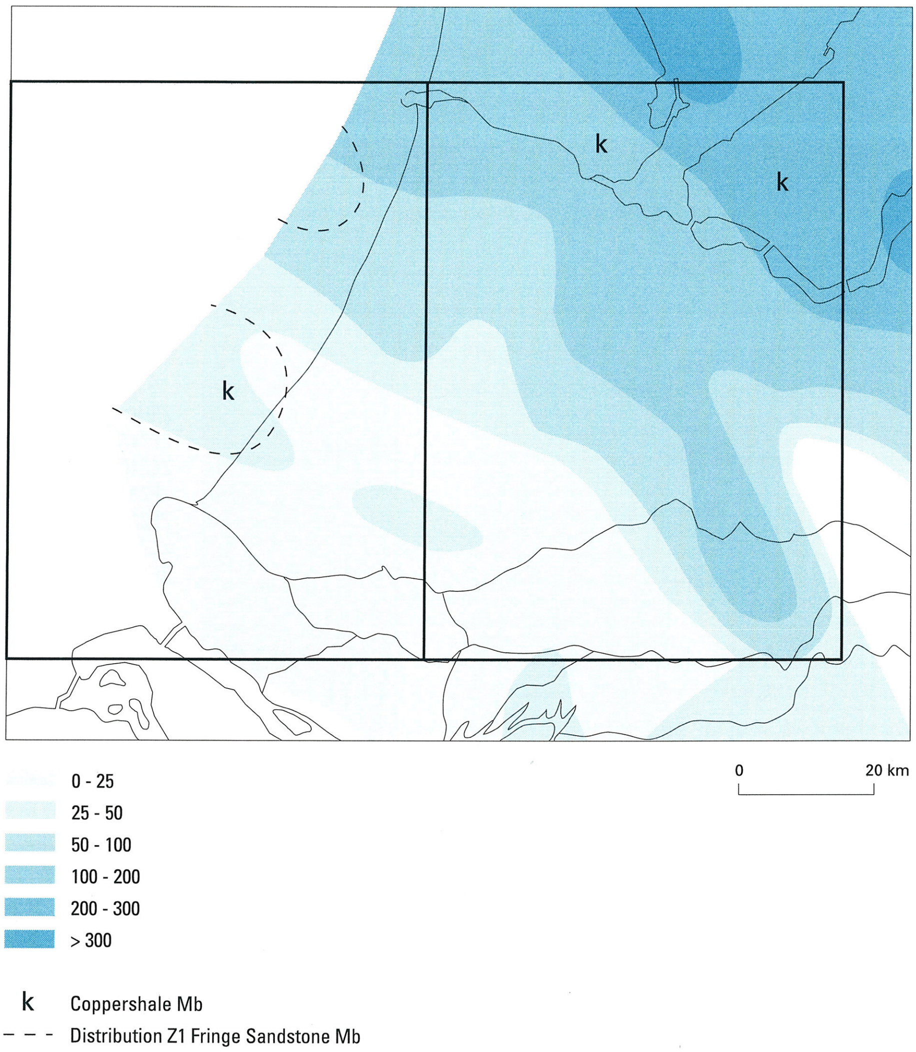
RB Lower Germanic Trias Group
RO Upper Rotliegend Group

6.1.1 Z1 (Werra) Formation

The Z1 (Werra) Formation consists of a number of members, some of which are each other's lateral equivalent. These are the Fringe Coppershale, the Z1 Lower Claystone, the Z1 Fringe Carbonate, the Z1 Middle Claystone, the Z1 Lower Anhydrite, the Z1 Salt and the Z1 Upper Anhydrite Members. The Z1 Middle Claystone Member occurs below, above and lateral to the Z1 Lower Anhydrite Member. The Z1 Fringe Sandstone Member is only present in the offshore area (fig. 6.2). The total thickness of the Z1 sequence is 120 m in the north of the map sheet area; in the other parts, it is a few tens of metres thick.

The *Coppershale Member* is a fine-laminated brown, grey bituminous claystone up to approximately 1 m thick. The succession rests conformably upon the Slochteren Formation and occurs in the north of the map sheet area and in a part of the southwestern offshore area (fig. 6.2).

Figure 6.2 Thickness map (m) of the Zechstein Group in the map sheet area.



The *Fringe Coppershale Member* is a grey massive claystone. The thickness is less than 3 m. The member was deposited conformably upon the Slochteren Formation and occurs in the south of the map sheet area and in a fault-bounded part of the southwestern offshore area (fig. 6.2).

The *Z1 Lower Claystone Member* is a grey to brown claystone sequence that upwardly gradually grades into marl. Locally, the unit is anhydritically or dolomitically developed. The member rests conformably

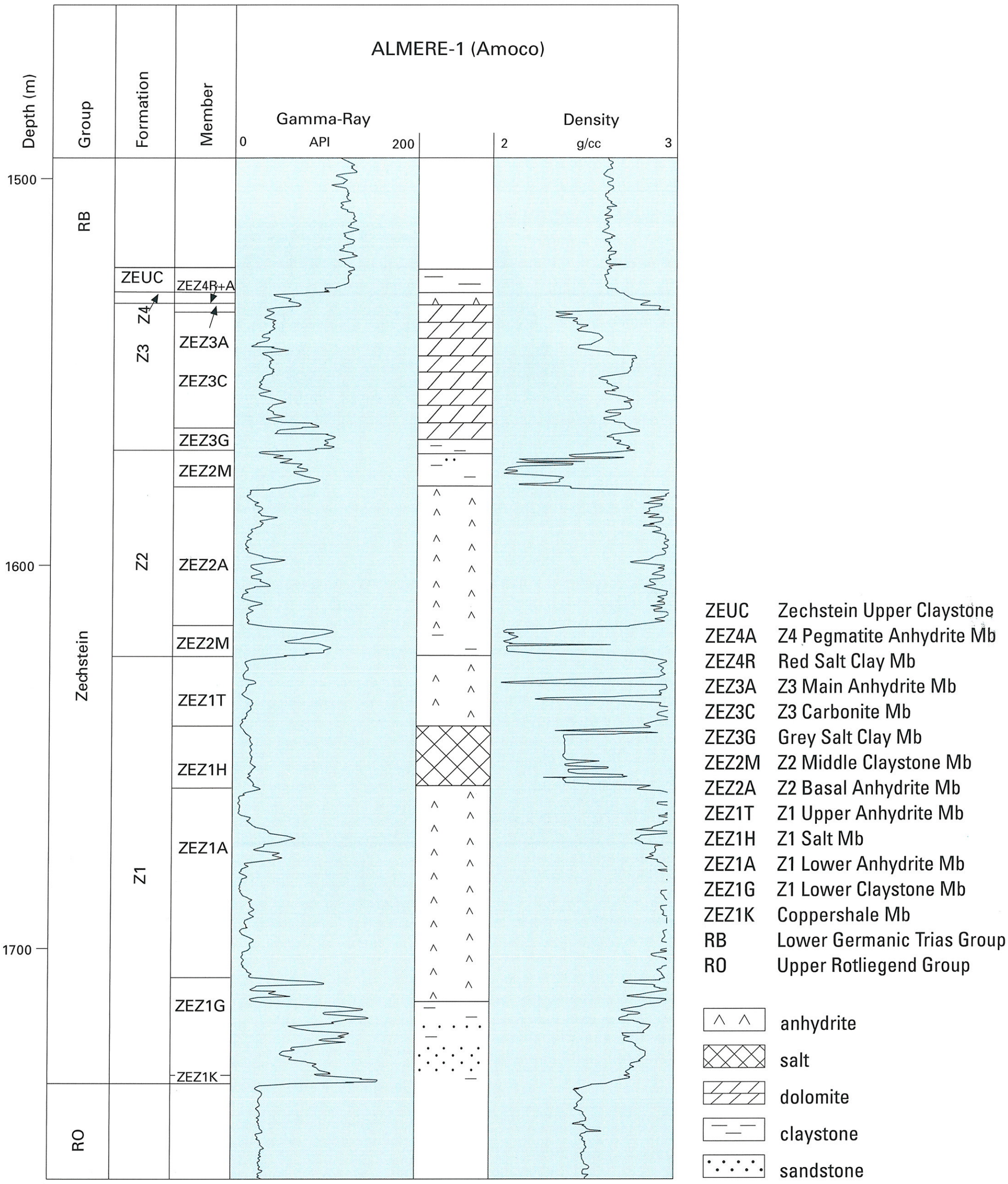


Figure 6.3 Stratigraphic division and log pattern of the Zechstein Group in the Almere-1 well.

upon the Fringe Coppershale Member or, via a hiatus, upon the Slochteren Formation. The unit reaches its greatest thickness in the north of the map sheet area (20 m).

The *Z1 Fringe Carbonate Member* is a grey to brown coloured limestone or dolomite. In the Everdingen-1 well, where the unit has been fully cored, the limestone contains oolitic sequences. Locally, a few claystone layers occur. The thickness increases from the west to approximately 35 m in Blaricum-01-S1 well. Slightly to the north, in Almere-1 well (fig. 6.4), the carbonate has been replaced by anhydrite.

The *Z1 Middle Claystone Member*, up to 15 m thick, consists of a red to grey coloured laminated claystone containing numerous anhydrite concretions and dessication cracks, and thin sand beds and sand lenses also occur. The areal extent of the unit corresponds to that of the Z1 Fringe Carbonate Member. Towards the north, this member grades into the Z1 Anhydrite. The Z1 Middle Claystone Member occurs below, above and laterally to the Z1 Lower Anhydrite Member.

The Z1 evaporite succession is only found in the extreme north of the map sheet area (fig. 6.4). The *Z1 Lower Anhydrite Member* is up to 55 m thick in the north. The *Z1 Salt Member* within the map sheet area has the same areal extent as the underlying anhydrite. In the Central Netherlands Basin, the member reaches a thickness of 100 m. The Z1 Salt Member (halite) is conformably overlain by the *Z1 Upper Anhydrite Member.*

The *Z1 Fringe Sandstone Member* is a fine-grained to medium-coarse sandstone with intercalations of grey to red claystone. The sandstone sequence only occurs in the west of the mapping area, predominantly in the offshore area.

6.1.2 Z2 (Stassfurt) Formation

The Z2 (Stassfurt) Formation is composed of the Z2 Middle Claystone Member, the Z2 Fringe Anhydrite Member and the Z2 Salt Member. The thickness in the south and middle of the map sheet area is limited; in the northeast, the formation is 50 m thick.

The *Z2 Middle Claystone* consists of a red to grey coloured, laminated claystone, containing anhydrite concretions as well as desiccation cracks. Anhydrite occurs mainly in the basal part of the member. This unit reaches its greatest thickness, approximately 30 m, along the southern margin of the Central Netherlands Basin. In the Almere-1 well, the Z2 (Stassfurt) Formation consists mainly of anhydrite and the *Z2 Middle Claystone Member* is only 10 m thick.

The *Z2 Fringe Anhydrite Member* is found in the northeastern part of the map sheet area, where its maximum thickness is approximately 35 m. The southern boundary of the occurrences of anhydrite is fault-related (fig. 6.2).

The *Z2 Salt Member* absent to a large extent; only in the extreme northeast does a thin (25 m) layer of halite occur. This unit becomes thicker in the Central Netherlands Basin (Rijks Geologische Dienst, 1993a).

6.1.3 Z3 (Leine) Formation

The Z3 (Leine) Formation is subdivided into the Grey Salt Clay, Z3 Carbonate, Z3 Fringe Sandstone and Z3 Salt Members. The formation is only developed in the northern part of the map sheet area; the sequence is up to approximately 50 m thick, but achieves a thickness of approximately 100 m in the Central Netherlands Basin.

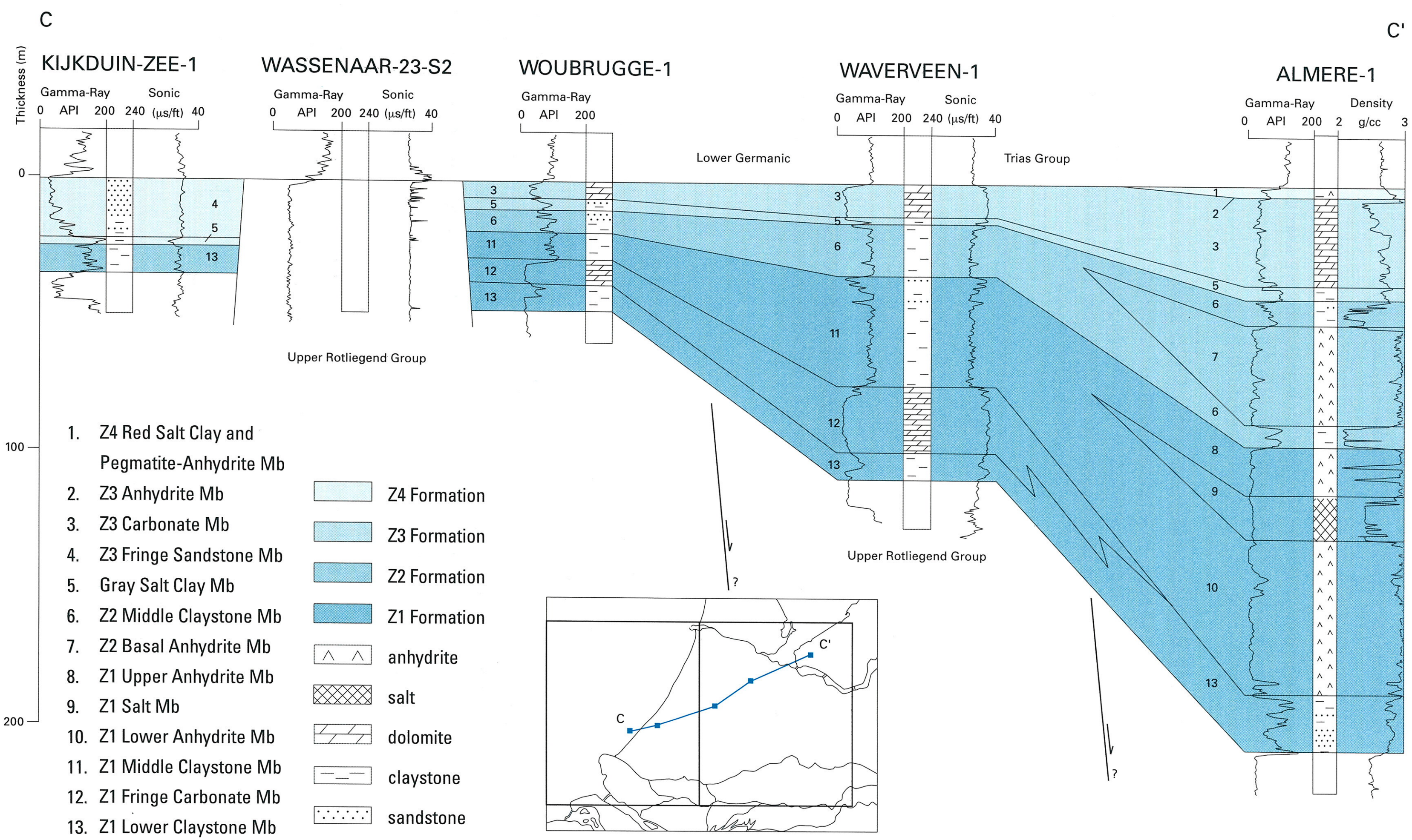


Figure 6.4 Stratigraphic section C-C' between the Kijkduin-Zee-1, Wassenaar-23-S2, Woubrugge-1, Waverveen-1 and Almere-1 wells. The reference level is the base of the Lower Germanic Trias Group.

The *Grey Salt Clay Member* is a dolomitic claystone, 1 to 8 m thick. It has the same areal extent as the Z3 Formation; the thickness increases towards the northeast.

The *Z3 Carbonate Member* (Platy Dolomite) is a light-brown limestone with a maximum thickness of over 30 m in the northeast. In the northern part of the map sheet area, this unit is partially composed of dolomite.

The *Z3 Fringe Sandstone Member* is present in the west of the map sheet area, mainly offshore. The member consists of a light coloured, fine-grained sandstone.

The *Z3 Main Anhydrite Member* occurs as a 10-m-thick sequence in the northeast of the map sheet area. The Z3 Salt is not present in the map sheet area but occurs elsewhere locally in the central Netherlands Basin (Rijks Geologisch Dienst, 1993a; 1993b).

6.1.4 Z4 (Aller) Formation

The Z4 (Aller) Formation has only been observed in the extreme northeast of the area, where it is only 2 m thick. The thin succession comprises the *Red Salt Clay* and the *Z4 Pegmatite Anhydrite* Members.

6.1.5 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone is a claystone with thin sand intercalations whose thickness is between a few metres and to approximately 15 m. The layer rests unconformably upon older Zechstein sediments or the Upper Rotliegend Group (Geluk, 1999a; TNO-NITG, 2001a).

6.2 Sedimentary development and palaeogeography

The transgression that heralded the beginning of the Zechstein period resulted in deposition of the organic-rich Coppershale in the extreme north of the area and locally in the southwestern offshore area (fig. 6.2) under euxinic conditions. In the southern shallower part of the map sheet area, the Fringe Coppershale was deposited under oxidising conditions. Sea-level rise resulted in an enlargement of the sedimentation area and under open-marine conditions, carbononates, marls and clays of the Z1 Fringe Carbonate Member were deposited. In the Central Netherlands Basin sea-level lowering resulted in deposition of the Z1 Anhydrite succeeded by rock salt. In the offshore area, to the west of the map sheet area, sands were deposited by fluvial systems (Z1 Fringe Sandstone Member). The remainder of the area was occupied by a mud flat.

During the deposition of the Z2 (Stassfurt) Formation, no major changes occurred in the palaeogeography of the area. The greater part of the area was still occupied by a mud plain. Only in the Central Netherlands Basin did the contemporaneous deposition of anhydrite and halite occur.

The transgression of the Z3 (Leine) Formation is presumed to have covered the entire map sheet area. Under shallow-marine conditions, carbonates were deposited; in the offshore area, the sand deposits were restricted to the fringes of the basin (Geluk et al., 1996). Following a drop in sea level, anhydrite and rock salt were deposited in the Central Netherlands Basin.

7 Lower and Upper Germanic Trias Groups

7.1 General

The Triassic deposits, of latest Late Permian to Norian age, consist predominantly of red and green coloured clastics and grey coloured carbonates, marls and evaporites. The Triassic is subdivided into the Lower and Upper Germanic Trias Groups (fig. 7.1). The deposits are found in large areas of the map sheet area (Maps VII/VIII-4, 5).

7.2 Lower Germanic Trias Group

7.2.1 Stratigraphy

Within this group, four formations can be distinguished, the Lower Buntsandstein, the Volpriehausen, the Detfurth and the Hardegsen Formations. (fig. 7.2). The Lower Buntsandstein Formation exhibits a predominantly fine-grained composition. The other formations are composed predominantly of sandstone, with intercalations of claystone and siltstone. The Volpriehausen, Detfurth and Hardegsen form, in combination, the Main Buntsandstein Subgroup. The bases of the Volpriehausen and the Detfurth Formations are unconformities that represent non-deposition or slight erosion. In the West Netherlands Basin, the successions are more complete (Ziegler, 1990; Geluk & Röhling, 1997).

The Lower Germanic Trias Group, of Late Permian to Scythian age (Kozur, 1999), rests conformably on the Zechstein Group, and is unconformably overlain by the Upper Germanic Trias (fig. 7.3), the Schieland or the Rijnland Group, or by the North Sea Supergroup (Maps VII/VIII-16, 17 & 18).

7.2.2 Lower Buntsandstein Formation

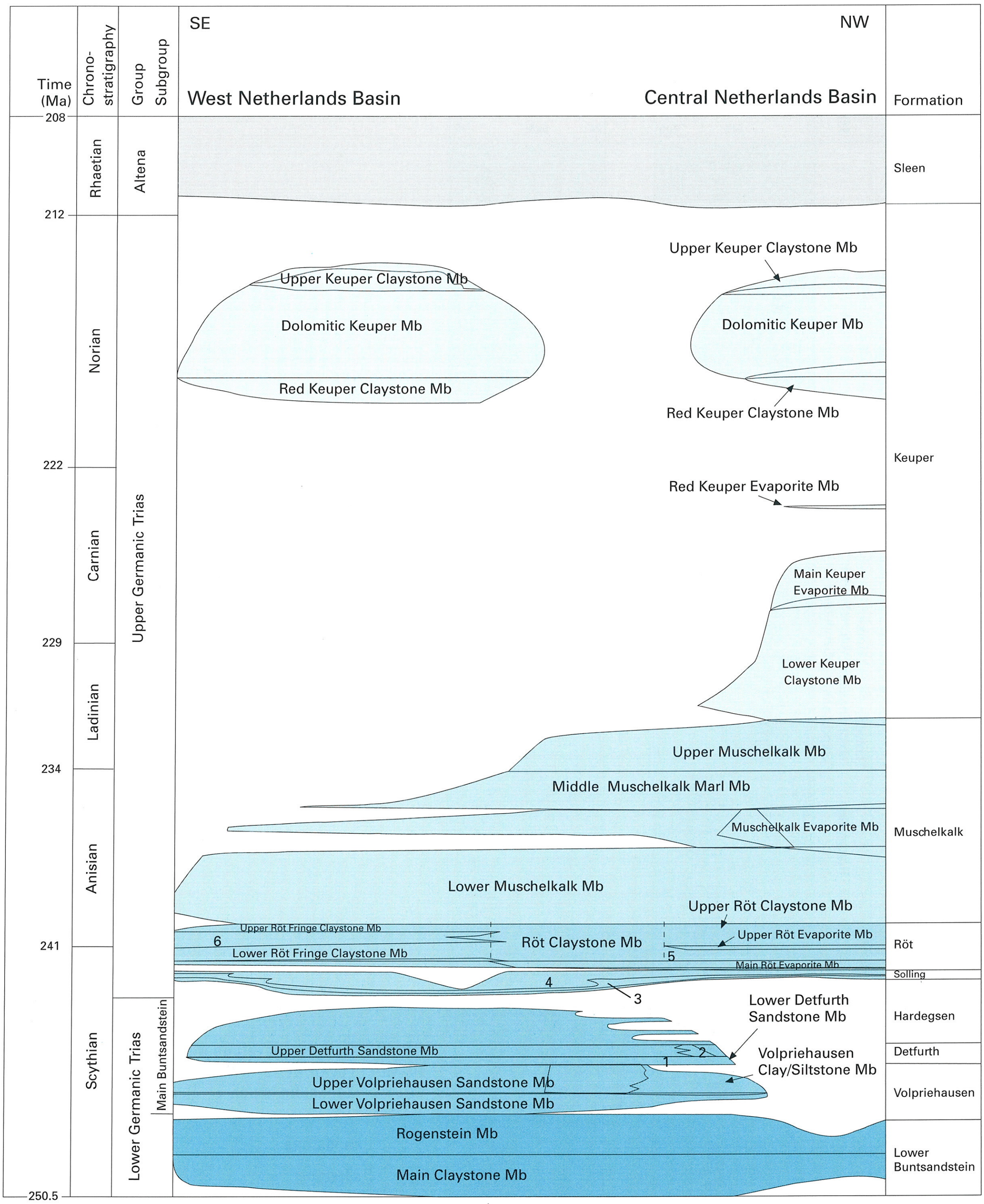
This formation is composed of the Main Claystone and the Rogenstein Members. The formation is sharply overlain by the Main Buntsandstein Subgroup. In the north of the map sheet area, the Schieland or the Rijnland Group or the North Sea Supergroup rests unconformably upon the Lower Buntsandstein Formation. In a northerly direction, the thickness of the formation increases from under 150 m to over 300 m (fig. 7.4). West of the Maasbommel High, the formation reaches a thickness of 350 metres.

The *Main Claystone Member* is composed of a cyclical succession of 20 to 35-m-thick, fining-upwards clay-siltstone sequences, with sands at the base. These sequences are highly uniformly developed in large parts of the Northwest European Basin (Ziegler, 1990; Geluk & Röhling, 1997). In the north of the map sheet area, a thickness of 140 m is reached.

The *Rogenstein Member* consists of red and green coloured fine-sandy, fine-laminated claystones and siltstones. The member also contains five characteristic oolite beds, which form horizons with good regional correlation potential (Ziegler, 1990; Geluk & Röhling, 1997). In the south of the area, frequent sandstone layers are intercalated in the member. In the northerly map sheet area, the sequence is over a hundred metres thick.

7.2.3 Main Buntsandstein Subgroup

This subgroup occurs in the Central and West Netherlands Basin. In the West Netherlands Basin, the subgroup is over 200 m thick (fig. 7.5). In a northerly direction, the thickness decreases sharply owing to truncation below the Solling unconformity. Within the subgroup, three formations can be distinguished, the Volpriehausen, the Detfurth and the Hardegsen Formations. The subdivision is based on on log



1 Lower Detfurth Sandstone Mb
2 Detfurth Claystone Mb
3 Basal Solling Sandstone Mb
4 Solling Claystone Mb
5 Intermediate Röt Claystone Mb
6 Röt Fringe Sandstone Mb

Figure 7.1 Stratigraphic overview of the Lower and Upper Germanic Trias Groups.

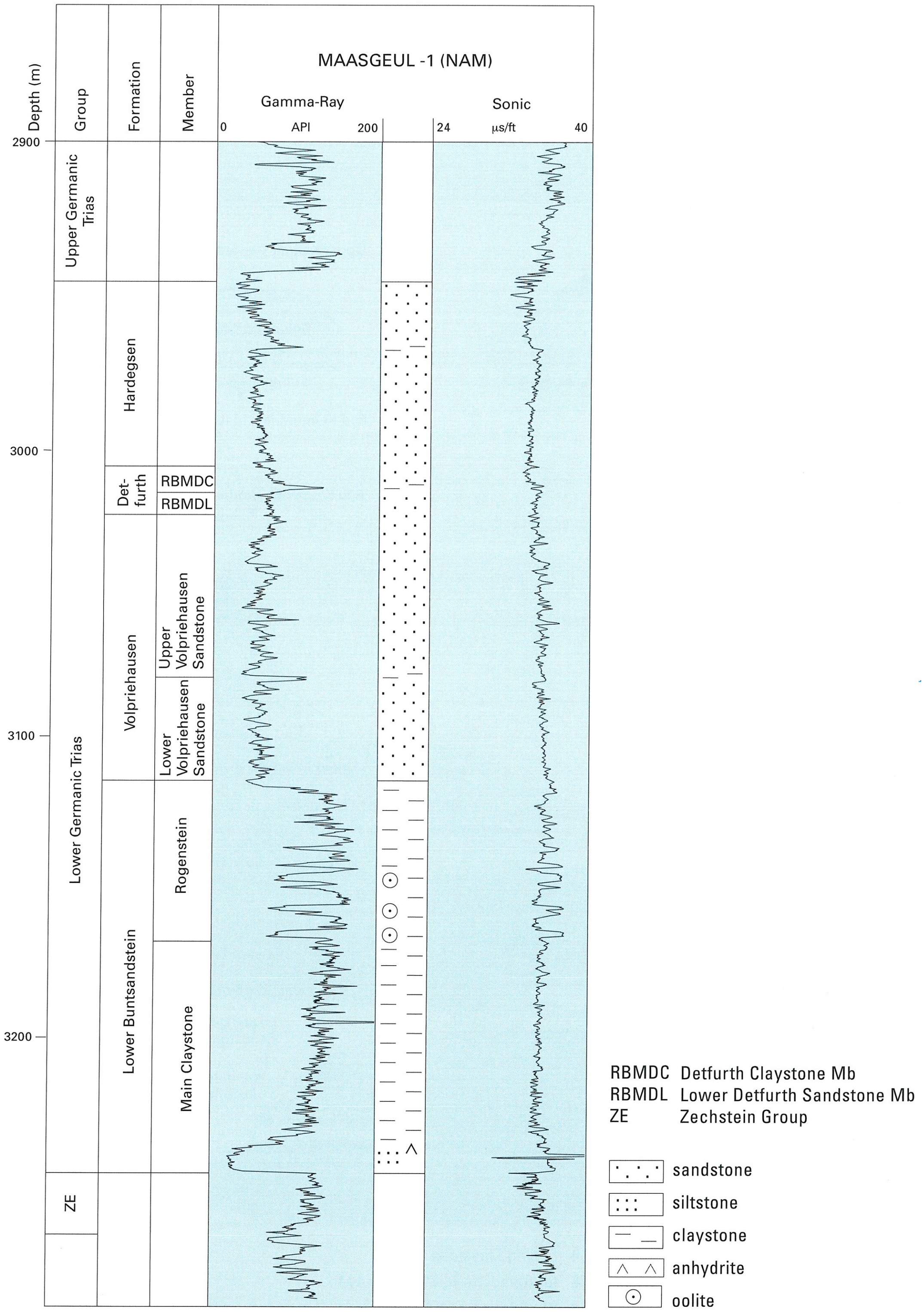


Figure 7.2 Stratigraphic division and log pattern of the Lower Germanic Trias Group in the Maasgeul-1 well.

character. The Main Buntsandstein Subgroup rests sharply on the Lower Buntsandstein Formation which, particularly in the east of the map sheet area, marks a minor unconformity, and is unconformably overlain by the Upper Germanic Trias Group.

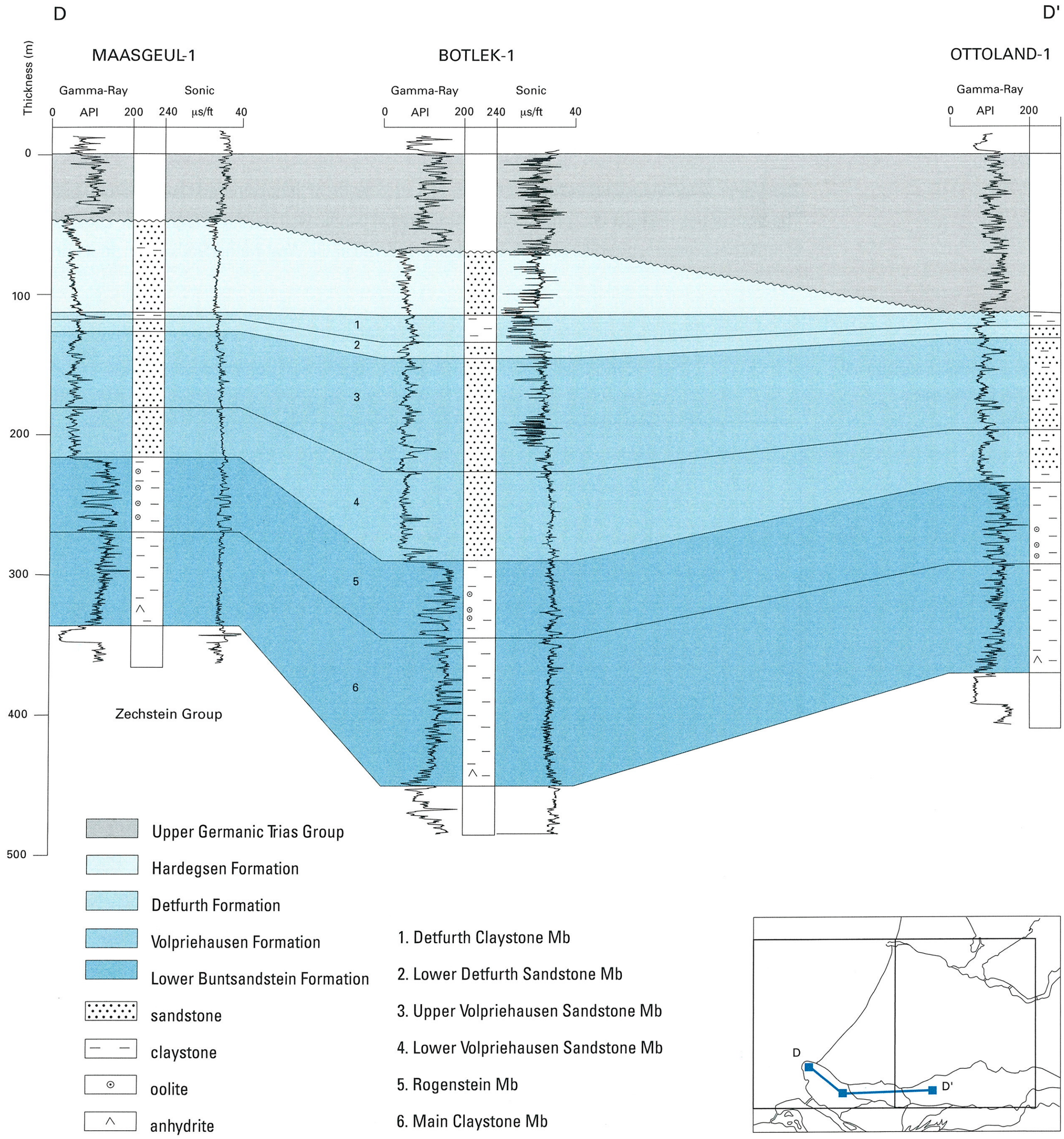


Figure 7.3 Stratigraphic section D-D' of the Lower Germanic Trias Group and the Upper Germanic Trias Group between the Maasgeul-1, Botlek-1 and Ottoland-1 wells. The reference level is the base of the Muschelkalk Formation.

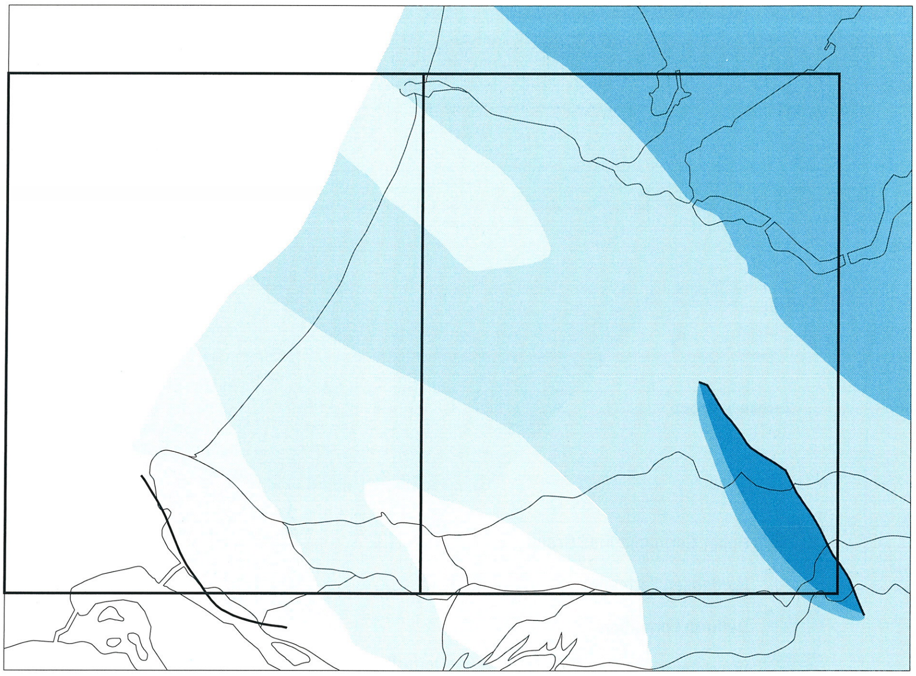
7.2.3.1 Volpriehausen Formation

The Volpriehausen Formation is subdivided into the Lower and Upper Volpriehausen Sandstone and the Volpriehausen Claystone-Siltstone Members. The formation rests conformably to unconformably upon the Lower Buntsandstein Formation (Geluk & Röhling, 1997), and is overlain by the Detfurth or the Solling Formation. The formation reaches its greatest thickness, over 130 m, in the West Netherlands Basin.

The *Lower Volpriehausen Sandstone Member* rests sharply on the underlying Rogenstein Member, and comprises a sandstone unit displaying a blocky pattern on the gamma-ray logs. The member is approximately 35 m thick in the West Netherlands Basin, but in a northerly direction, decreases to under 10 m on the Netherlands Swell.

The *Upper Volpriehausen Sandstone Member* is a succession of light coloured sand-siltstone beds. The base of this member comprises a thin, laminated siltstone, well traceable regionally. The most complete succession, over 100 m thick, has been preserved in the West Netherlands Basin. In a northerly

Figure 7.4 Thickness map (m) of the Lower Buntsandstein Formation.



0 20 km

< 150
150 - 200
200 - 250
250 - 300
> 300
fault

direction, the proportion of claystone and siltstone layers rapidly increases, and the formation passes into the Volpriehausen Clay-Siltstone Member.

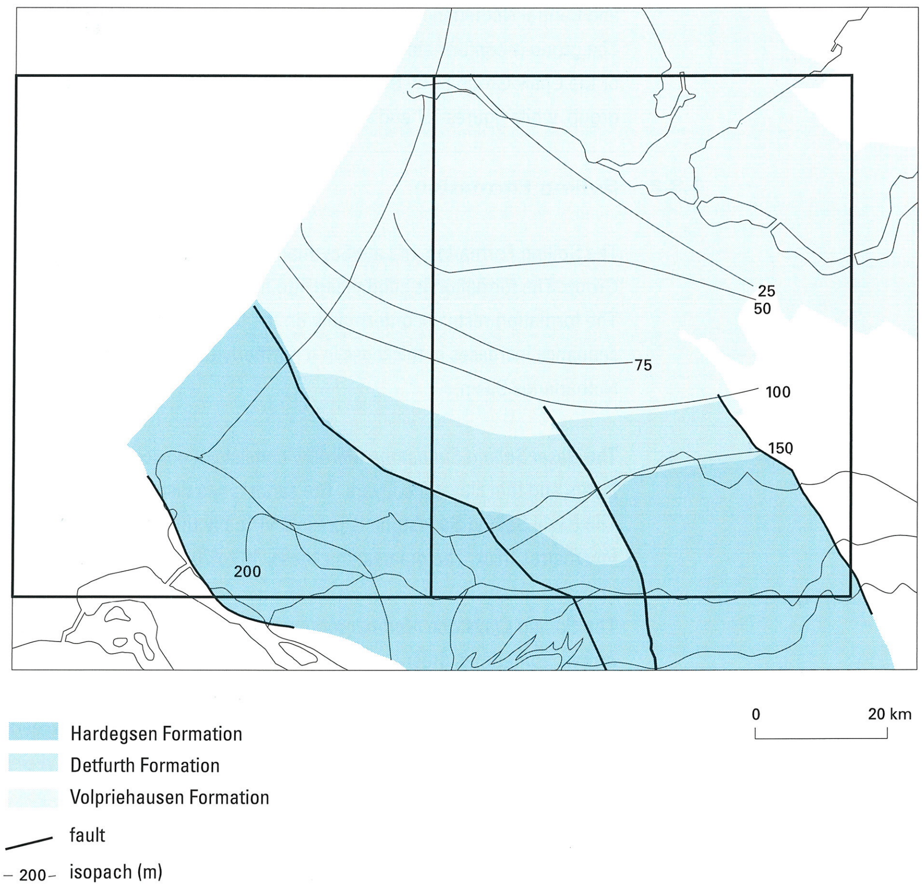
The *Volpriehausen Clay-Siltstone Member* is found in the central and northern part of the map sheet area. The member comprises a succession of upward-fining alternations of thin sandstone and clay/siltstone. In a southerly direction, the proportion of sandstone in the formation increases and the member grades laterally into the Upper Volpriehausen Sandstone.

7.2.3.2 Detfurth Formation

The Detfurth Formation is subdivided into the Lower and Upper Detfurth Sandstone and the Detfurth Claystone Members. The Detfurth Formation rests sharply upon the Volpriehausen Formation, and is overlain conformably by the Hardegsen Formation. The formation, which, in the map sheet area only occurs in the West Netherlands Basin, reaches a thickness of over 30 m.

The *Lower Detfurth Sandstone Member* consists of medium-fine to coarse-grained sandstone. The thickness of the sandstone increases in a southwesterly direction from approximately 5 to over 20 m.

Figure 7.5 Thickness map (m) of the Main Buntsandstein Subgroup and subcrop map of the base of the Solling.



The *Upper Detfurth Sandstone Member* is composed of two sandstone intervals, separated by claystone. The thickness is relatively constant, and ranges from 20 to 30 m. In a northwesterly direction, this sandstone passes into the Detfurth Claystone.

The *Detfurth Claystone Member* is the distal equivalent of the two Detfurth Sandstone members. The member is a claystone succession which occurs exclusively on the southern border of the map sheet area, where the thickness is 10 to 25 m. In the northern part of the map sheet area, the member is absent owing to erosion.

7.2.3.3 Hardegsen Formation

The Hardegsen Formation consists of a grey to pink medium-coarse sandstone. The formation has only been preserved in the West Netherlands Basin. The thickness of the formation is determined by the extent of the pre-Solling erosion and is up to 50 m in West Netherlands Basin.

7.3 Upper Germanic Trias Group

7.3.1 Stratigraphy

The Upper Germanic Trias Group, of Late Scythian to Norian age, is composed of four formations, namely the Solling, the Röt, the Muschelkalk and the Keuper Formations. The group is mainly found in the West and Central Netherlands Basins and rests unconformably upon the Lower Germanic Trias Group (fig. 7.1). The group is conformably overlain by the Altena Group or unconformably by the Schieland, the Rijnland or the Chalk Group or by the North Sea Supergroup. Figure 7.6 depicts the thickness development of the group, while figures 7.7 and 7.8 provide information on the lithostratigraphic composition.

7.3.2 Solling Formation

The Solling Formation, of Late Scythian age, occurs within the areal extent of the Upper Germanic Trias Group. The formation is subdivided into the Basal Solling Sandstone and the Solling Claystone Members. The formation rests unconformably on the Main Buntsandstein Subgroup. In the map sheet area, this sequence increases in thickness in a northerly direction from under 10 to over 35 m in the Central Netherlands Basin.

The *Basal Solling Sandstone Member* consists of a succession of one or more fine-grained sandstone layers and thin claystone layers. The sandstones display an blocky appearance on the gamma-ray log. The Basal Solling Sandstone is present virtually throughout the map sheet area. The sandstone is only a few metres thick. The greatest thickness, 10 to 20 m, occurs in the adjacent offshore Q5 and Q8 blocks.

The *Solling Claystone Member* represents the largest part of the formation and consists of reddish-brown, sometimes green-mottled claystone. The lower parts of the member contain grey layers, which are characterised by a high gamma-ray log reading. In the claystone, anhydrite concretions occur. In the Central Netherlands Basin, the thickness of this sequence may exceed 35 m; in the West Netherlands Basin, normally less than 10 m.

7.3.3 Röt Formation

The Röt Formation, of Early Anisian age, is subdivided into the Main Röt Evaporite, the Röt Fringe Sandstone and the Röt Claystone Members The sandstone is only found on the southern margin of the

West Netherlands Basin and the Roer Valley Graben. Where the sandstone sequence is present, a distinction is made between the Lower and Upper Röt Fringe Claystone Members. The deposition of evaporite, took place in particular in the Central Netherlands Basin.

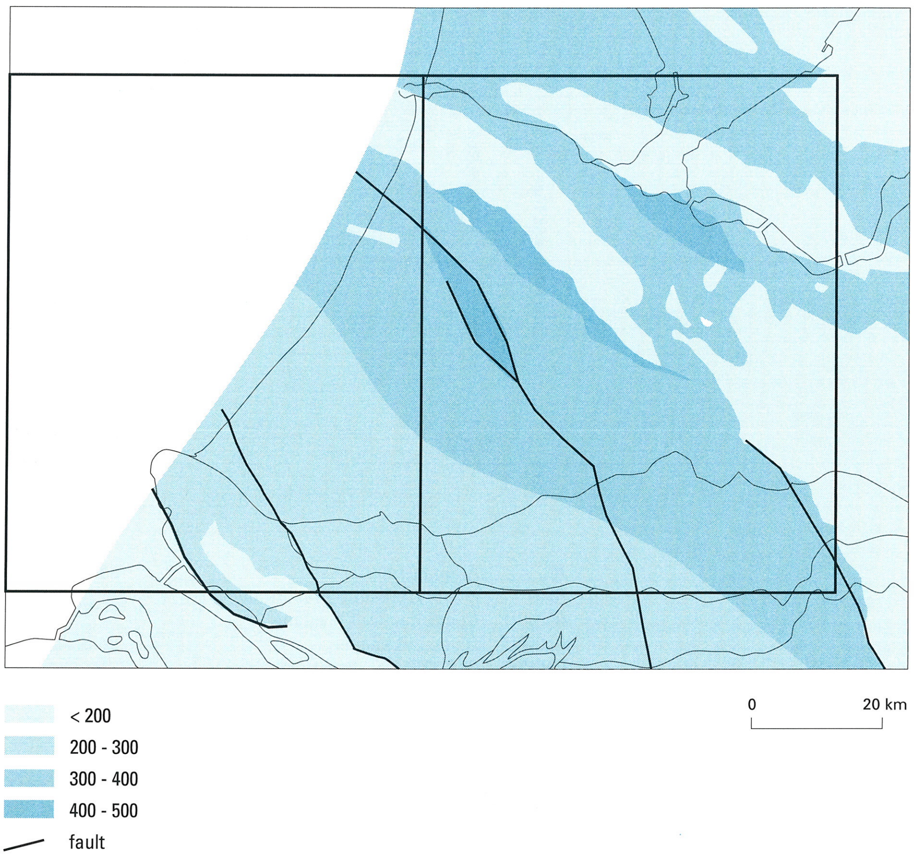
The Röt Formation occurs within the entire areal extent of the Upper Germanic Trias Group. The greatest thickness, over 150 m, is reached in the Central Netherlands Basin. The thickness decreases in a southwesterly direction to under 50 m on the margin of the West Netherlands Basin (fig. 7.8).

The *Main Röt Evaporite Member* occurs in the northern part of the West Netherlands Basin and in the Central Netherlands Basin. Rock salt is found in the Central Netherlands Basin. Further towards the south, the member comprises a thin anhydrite bed. The Main-Röt Evaporite Member achieves a thickness of up to approximately 20 m. The evaporite is overlain conformably by the (Lower) Röt Claystone.

The *Lower Röt Fringe Claystone Member* occurs throughout the areal extent of the Röt Fringe Sandstone. The unit comprises a reddish-brown, silty claystone. On the southern border of the areal extent, the member is over 20 m thick.

The *Röt Fringe Sandstone Member* comprises an alternation of grey, arkosic sandstone and reddish brown claystone beds. The sequence occurs parallel to the southern boundary faults of the West

Figure 7.6 Thickness map (m) of the Upper Germanic Trias Group.



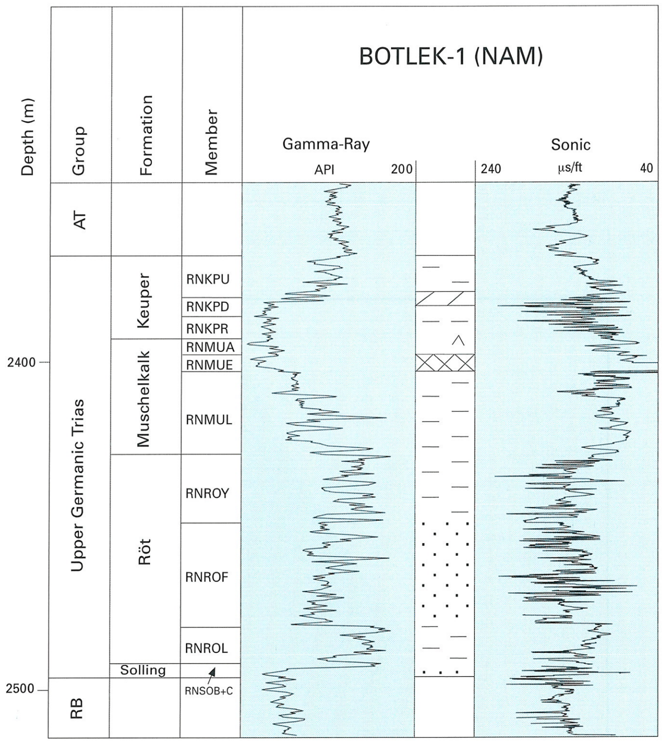
Netherlands Basin and the Roer Valley Graben and the unit pinches out in a northerly direction (Geluk et al., 1996; TNO-NITG, 2001a). In the southeast, the member reaches a thickness of approximately 30 metres.

The *Upper Röt Fringe Claystone* comprises a silty, occasionally sandy claystone. The member contains a few thin dolomite layers. The thickness of the unit is a few tens of metres.

7.3.4 Muschelkalk Formation

The Muschelkalk Formation in the map sheet area, deposited in the Late Anisian to Ladinian period, is, unconformably or separated by a small hiatus, overlain by the Keuper Formation. The formation is subdivided into the Lower Muschelkalk, the Muschelkalk Evaporite, the Middle Muschelkalk Marl and the

Figure 7.7 Stratigraphic division and log pattern of the Upper Germanic Trias Group in the Botlek-1 well.



AT	Altena Group
RB	Lower Germanic Trias Group
RNKPU	Upper Keuper Claystone
RNKPD	Dolomitic Keuper
RNKPR	Rode Keuper Claystone
RNMUA	Middle Muschelkalk Marl
RNMUE	Muschelkalk Evaporite
RNMUL	Lower Muschelkalk
RNROY	Upper Röt Fringe Claystone
RNROF	Röt Fringe Sandstone
RNROL	Lower Röt Fringe Claystone
RNSOC	Solling Claystone
RNSOB	Basal Solling Sandstone

sandstone
claystone
dolomite
anhydrite
salt

Upper Muschelkalk Members. The formation occurs in the West and Central Netherlands Basins. The formation reaches a maximum thickness of over 200 m in the Central Netherlands Basin. In a few places, the thickness was drastically reduced by erosion during the Early Kimmerian phase (Carnian); on the Zandvoort High, only the bottommost member has been preserved.

The *Lower Muschelkalk Member* is composed of an alternation of greyish-white limestone/dolomite beds and grey marls, with the proportion of dolomite beds decreasing towards the top. On the southern margin of the West Netherlands Basin, the sequence comprises a single massive limestone bed, a few tens of metres thick. In the West Netherlands Basin, the member achieves its greatest thickness, over 70 m, in the vicinity of the Mid Netherlands Fault Zone.

The *Muschelkalk Evaporite Member* consists of a 5-to-15 m-thick anhydrite in the greatest part of the map sheet area. An exception to this is a narrow zone in the vicinity of the Mid Netherlands Fault Zone, where rock salt also occurs. Here, the sequence reaches its greatest thickness, over 130 m.

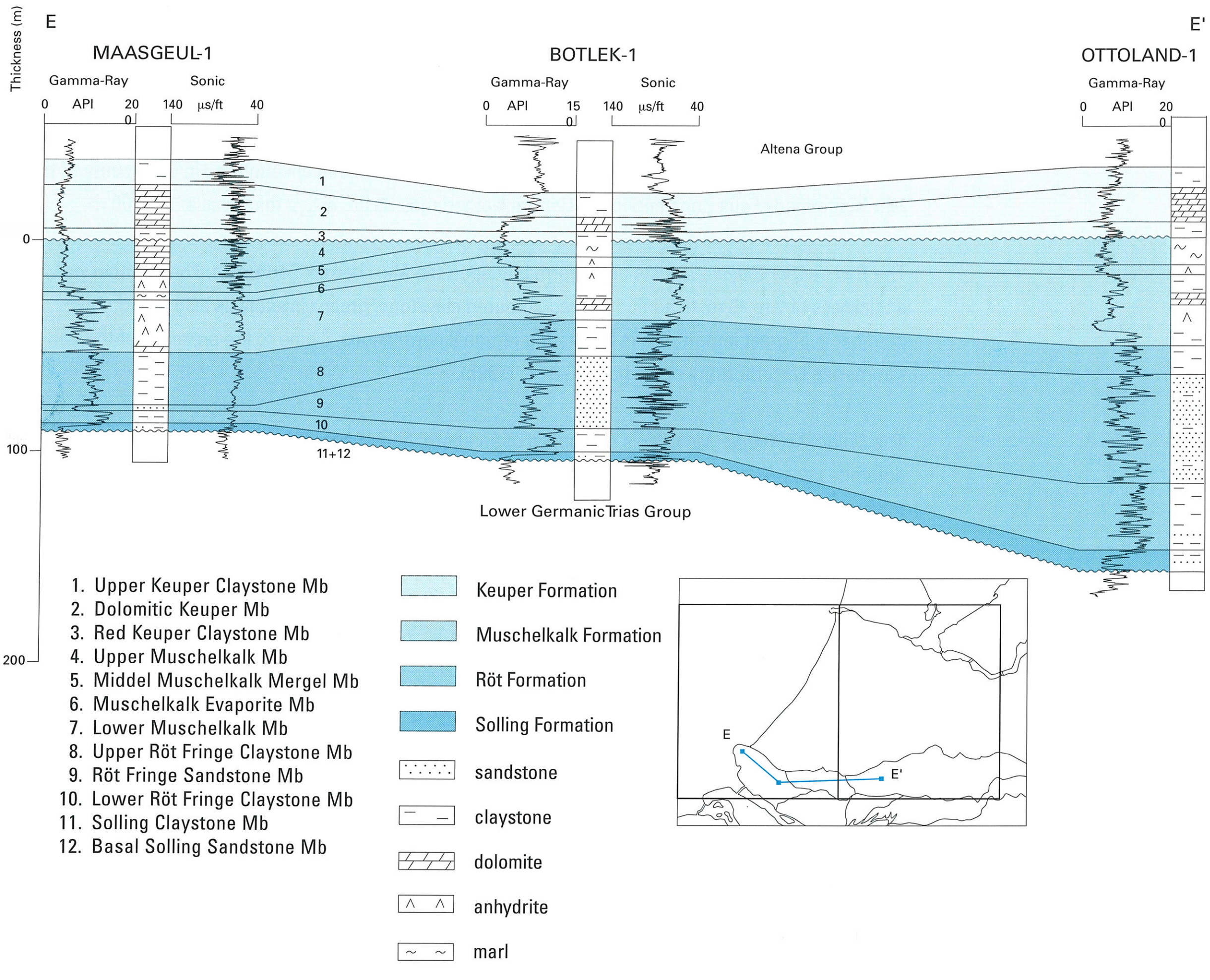


Figure 7.8 Stratigraphic section E-E' of the Upper Germanic Trias Group and the Solling Formation between the Maasgeul-1, Botlek-1 and Ottoland-1 wells. The reference level is the base of the Keuper Formation.

The evaporite is overlain by the 20 to 30 m-thick *Middle Muschelkalk Marl Member*, consisting of light-grey, sometimes greenish to brownish-grey marls and claystone with a few anhydrite beds at the base. This sequence displays a characteristic, upward increasing, gamma ray reading. The thickness is 15 to 20 m.

The topmost calcareous unit, the *Upper Muschelkalk Member*, is composed of an alternation of grey and greenish-grey dolomite, limestone and marl layers. The proportion of dolomite beds decreases upward. The base is formed by a massive dolomite bed, the so-called *Trochitenkalk*. In the West Netherlands Basin, the member is only locally complete; in the vicinity of the Mid Netherlands Fault Zone the thickness is 50 m. Elsewhere, the thickness was drastically reduced by the Early Kimmerian erosion.

7.3.5 Keuper Formation

The Keuper Formation consists predominantly of claystone and dolomite layers. Throughout the area the formation is subdivided into the Lower Keuper Claystone, the Red Keuper Claystone, the Dolomitic Keuper and the Upper Keuper Claystone Members, of Late Ladinian to Norian age. At the base of the Red Keuper Claystone is the Early Kimmerian unconformity. In the West Netherlands Basin, the formation achieves a thickness of 30 to 50 m and a thickness of 80 to 100 m in the Central Netherlands Basin.

The *Lower Keuper Claystone Member* consists of greenish-grey and reddish-brown, dolomitic claystones with anhydrite in small beds and concretions. The unit has only been encountered in the vicinity of the Mid Netherlands Fault Zone and in the Central Netherlands Basin, with a thickness of over 50 m.

The *Red Keuper Claystone* rests unconformably upon the Muschelkalk Formation. The member has a thickness of 2 to 15 m. In addition to red-coloured claystone, green claystone is also found. This member is of great importance in facilitating regional correlations, owing to the presence of the Early Kimmerian Unconformity at the base (Geluk, 1999b).

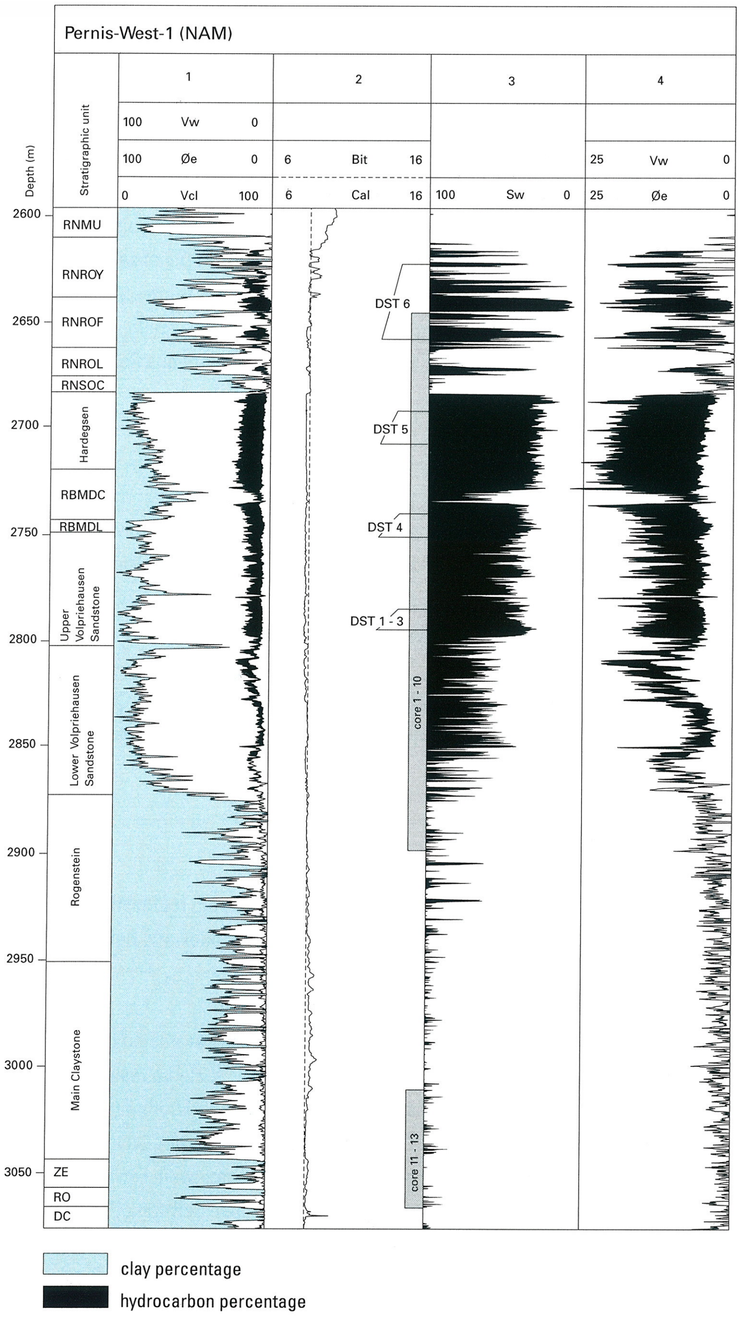
The *Dolomitic Keuper Member* is composed of an alternation of claystone with several anhydrite and dolomite beds. The member is characterised by a conspicuously light colour. The thickness decreases towards the southwest. The maximum thickness is 50 m in the West Netherlands Basin. In the Central Netherlands Basin, the thickness decreases in an easterly direction.

The *Upper Keuper Claystone Member* varies in thickness from a few metres to a maximum of 20 m in the West Netherlands Basin. The member mainly comprises grey silty claystones and marls.

7.4 Sedimentary development and palaeogeography

The transition from Zechstein to Triassic was characterised by an increase in the supply of clastic material, which was due to an increase in regional rift activity in the hinterland (Ziegler, 1990). The red clay sequences with intercalations of oolite beds of the Lower Buntsandstein were deposited in a shallow, frequently dry playa lake in the centre of the basin (Ziegler, 1990).

An increase in the clastic supply, probably due to a more humid climate (Ziegler, 1990), resulted in the deposition of the sandy Main Buntsandstein Subgroup. This sandy unit was deposited by a fluvial system regularly prograding towards the basin. The sandy material that originated in the Southern Variscan massifs, was transported to the basin by braided channel systems via the Trier and Roer Valley Grabens (Wuster, 1968). In the transition to the basin lake, the sand was deposited in fluvial fan systems, which



ZE Zechstein Group
RO Upper Rotliegend Group
DC Limburg Group
RNMU Muschelkalk Fm
RNROY Upper Röt Fringe Claystone Mb
RNROF Röt Fringe Sandstone Mb
RNROL Lower Röt Fringe Claystone Mb
RNSOC Solling Claystone Mb
RBMDC Detfurth Claystone Mb
RBMDL Lower Detfurth Sandstone Mb

Figure 7.9 Petrophysical evaluation of the sandstones of the Lower and Upper Germanic Groups in the Pernis-West-1 well. Column 1: clay content V_{cl}, effective porosity Φ_e and pore volume water V_w, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained by the use of a *shaly sand model* (density log/neutron log), in which the calculated log porosity was corrected for the clay and the hydrocarbons present. Column 2: drill hole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the cored interval is given. Column 3: water saturation S_w in percentages. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Φ_e (left curve) and the volume of water in the pores V_w (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the true depths.

protruded into a shallow ephemeral playa lake. The regular advances and retreats of this arid fluvial system are presumed to have been induced by climate fluctuations.

Following the erosion during the Solling event, the large-scale sand influx from the south ceased. The thin sandstone of the Solling Formation, which immediately overlies the erosion surface, is interpreted as a transgressive sandstone of redistributed erosional material (TNO-NITG, 2001a). The superimposed Solling Claystone and Röt Claystone were once again formed in a shallow lake. The deposition partly took place under marine conditions. The alluvial Röt Fringe Sandstone is present in a belt along the southern margin of the West Netherlands Basin. Here, fault activity initiated the supply of sand from the Brabant Massif to the centre of the West Netherlands Basin. This fluvial system is interpreted as a braided fluvial system that fanned out distally at the margin of the playa lake (Geluk, 1999b). The very dry nature of the climate is confirmed by the presence of salts in the Central Netherlands Basin (Main Röt Evaporite).

The Muschelkalk succession comprises sediments, which were predominantly deposited in shallow-marine waters, near the tidal zone. Deposition of anhydrite and rock salt (Muschelkalk Evaporite Member) indicates that the connection with the ocean was temporarily interrupted. Rock salt was only deposited in the vicinity of the Mid Netherlands Fault Zone. During deposition of the Upper Muschelkalk Member, an open-marine setting prevailed. A presumably eustatic sea-level fall favoured the resumption of fine-clastic and evaporite sedimentation during the Keuper (Ziegler, 1990).

The Lower Keuper Claystone, Red Keuper Claystone, Dolomitic Keuper and Upper Keuper Claystone Members were deposited under continental to marginal marine and evaporitic conditions, presumably in a coastal sabkha setting.

7.5 Petrophysical evaluation

Commercially interesting occurrences of liquid and gaseous hydrocarbons are well represented in the map sheet area and have been exploited for a considerable time. The Rijswijk,Botlek and Beijerland concessions are within the map sheet area (see chapter 2).

The Triassic deposits of one well in the map sheet area have been petrophysically evaluated (appendix C). Borehole Pernis-West-1 was selected, because it is of a relatively recent date (1987), the reservoir has been extensively tested and cored, the Pernis-West field is currently productive and both oil and gas have been encountered. In the well, the sandstones of the Lower Germanic Trias Group have been found to be gas-bearing (appendix D). Core analysis data are available from the selected well. Fig. 7.9 is an illustration of a log evaluation of the reservoir sequence of the Lower and Upper Germanic Trias Group in the Pernis-West-1 well.

8 Altena Group

8.1 Stratigraphy

The Altena Group, of Rhaetian to Oxfordian age, consists predominantly of dark coloured claystone with, in the upper part, intercalations of sandstone, limestone and marl as well. The group is subdivided into five formations (fig. 8.1), which all occur within the map sheet area: the Sleen, the Aalburg, the Posidonia Shale, the Werkendam and the Brabant Formations (see figures 8.2 and 8.3 for the areal

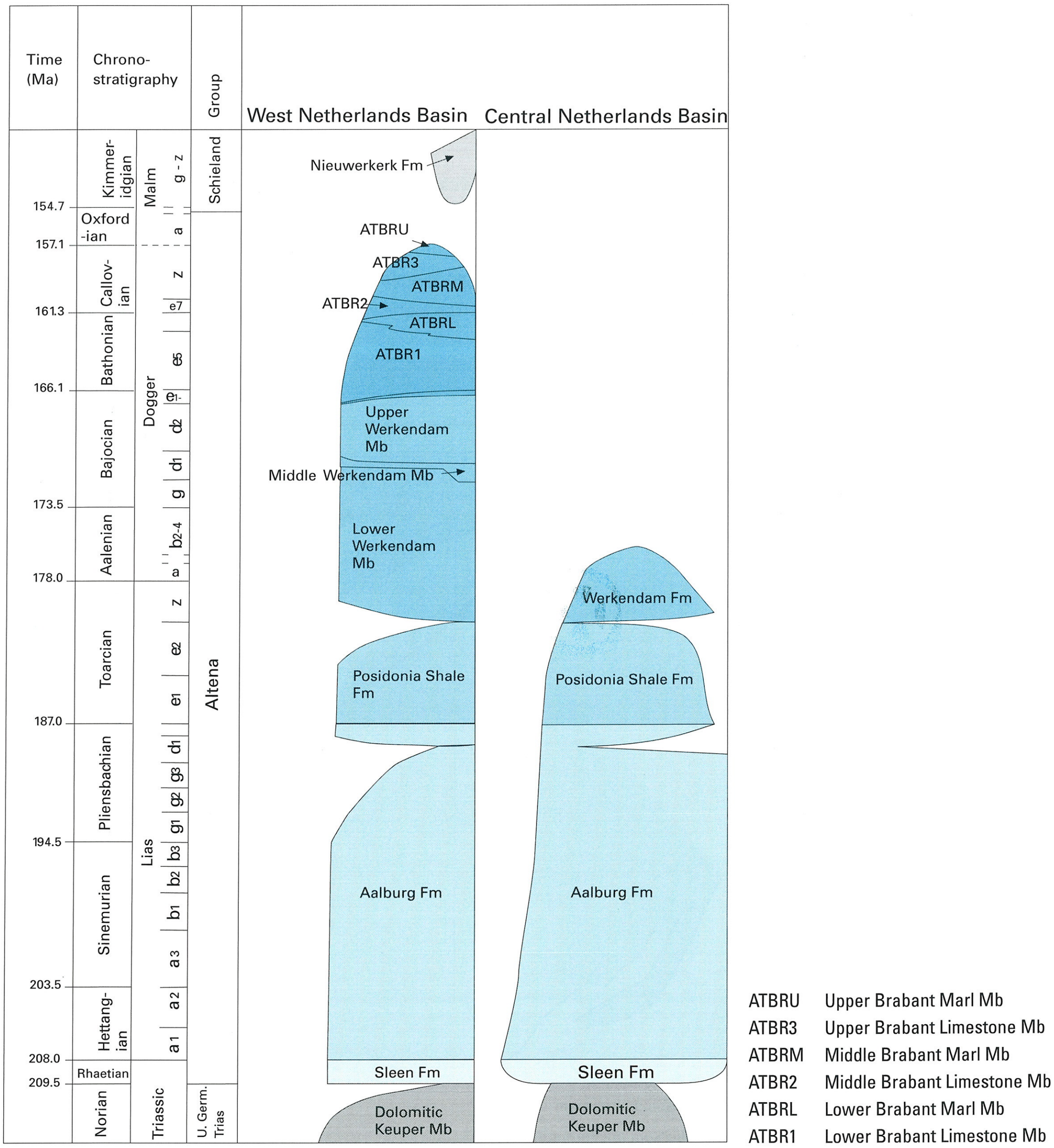


Figure 8.1 Stratigraphic overview of the Altena Group with the lithostratigraphic units occurring in the map sheet area.

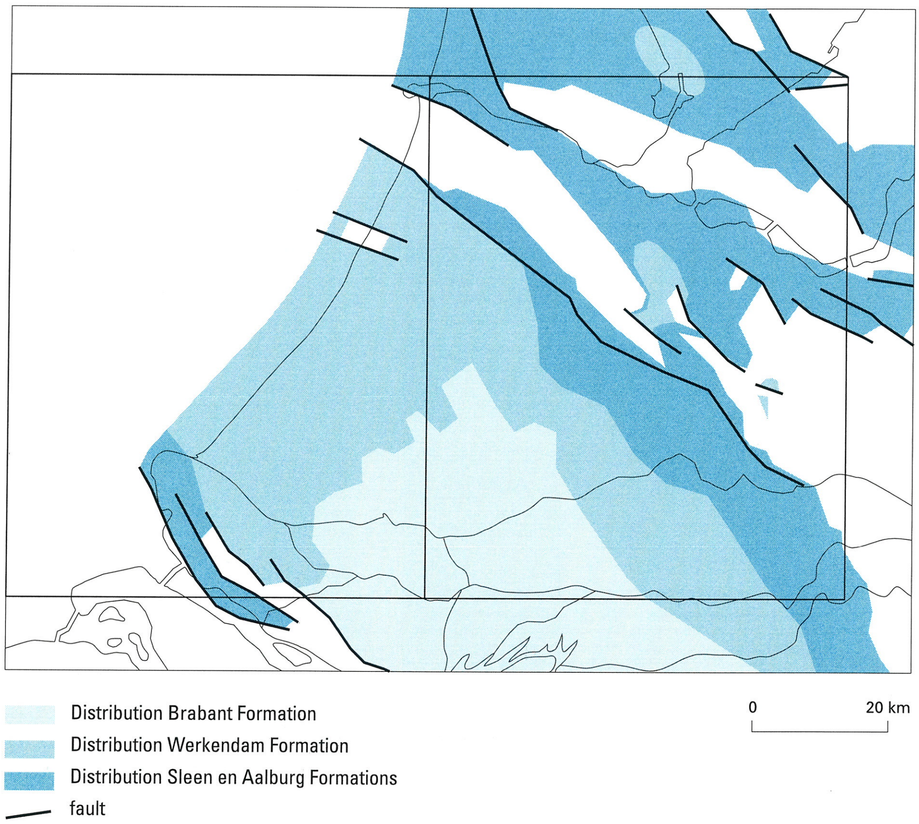
extent of these formations). The stratigraphically most complete succession of the group occurs in the southeastern part of the West Netherlands Basin. This succession is illustrated by the Werkendam-2 well (fig. 8.4).

Within the map sheet area, the Altena Group rests on the Upper Germanic Trias Group, separated by a minor hiatus (fig. 8.5). The deposits occur in the West Netherlands and the Central Netherlands Basins (Maps VII/VIII-6). Erosion and synsedimentary subsidence resulted in pronounced changes in thicknesses, few metres to nearly 1200 m in the southeastern part of the West Netherlands Basin (Maps VII/VIII-7). The depth of the base of the group ranges at 1000 to 3400 m (Maps VII/VIII-6). The deposits are covered unconformably by the Schieland, the Rijnland or the Chalk Group, or by the North Sea Supergroup.

8.1.1 Sleen Formation

The Sleen Formation, of Rhaetian age, occurs within the entire areal extent of the Altena Group. The formation rests, separated by a hiatus, on the Upper Germanic Trias Group (fig. 8.5) and is conformably overlain by the Aalburg Formation. The deposits comprise dark grey to black, sometimes bituminous claystone and shale, with abundant pyrite, fossil and plant remains in patches. The formation is subdivided into two parts by a thin sandstone unit. The topmost part of the formation may be reddish brown in colour. The formation is 20 to 45 m thick.

Figure 8.2 Subcrop geological map of the top of the Altena Group.



8.1.2 Aalburg Formation

The Aalburg Formation, of Hettangian to Pliensbachian age, is also found throughout the areal extent of the Altena Group. The formation rests conformably on the Sleen Formation and is conformably overlain by the Posidonia Shale Formation or unconformably by the Schieland, the Rijnland or the Chalk Group or by the North Sea Supergroup. Lithologically, the formation has a monotonous character and comprises greenish-grey to black, sometimes calcareous claystone with thin limestone beds. In addition, a few organic-rich claystone beds are found in the bottommost part of the formation (Herngreen & De Boer, 1974). There are abundant occurrences of ammonites, belemnites and molluscs. Pyrite, iron oolites and siderite nodules are also frequently present. The thickness of the Aalburg Formation displays pronounced differences as a result of synsedimentary faulting and is a maximum of 600-650 m.

8.1.3 Posidonia Shale Formation

The Posidonia Shale Formation, of Toarcian age, consists of a dark organic-rich shale with a few limestone beds. The formation is clearly distinguishable by its characteristic peak on gamma-ray logs. The formation is also clearly identifiable on seismic logs as a result of the strong reflection caused by the low acoustic velocity of the bitumen present in the shale. Owing to the presence of the bitumen, the shale is an important oil-source rock in the Netherlands. The formation rests conformably on the Aalburg Formation and is overlain, likewise conformably, by the Werkendam Formation. The occurrence

Figure 8.3 Extent of the de Posidonia Shale Formation in the map sheet area and the adjacent offshore area.

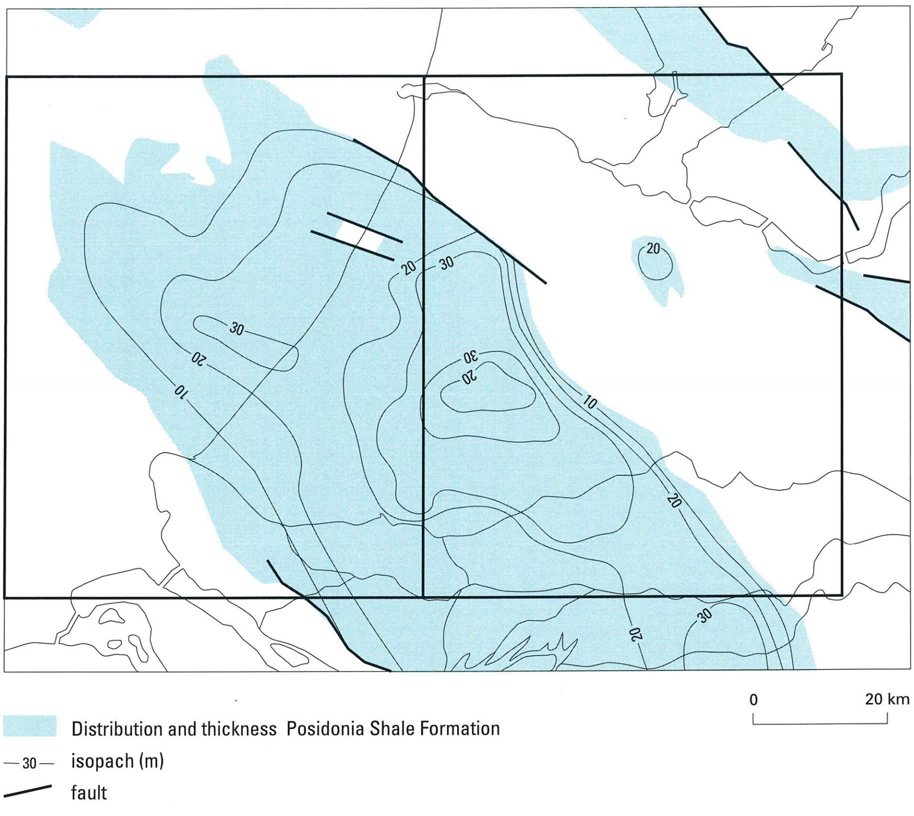
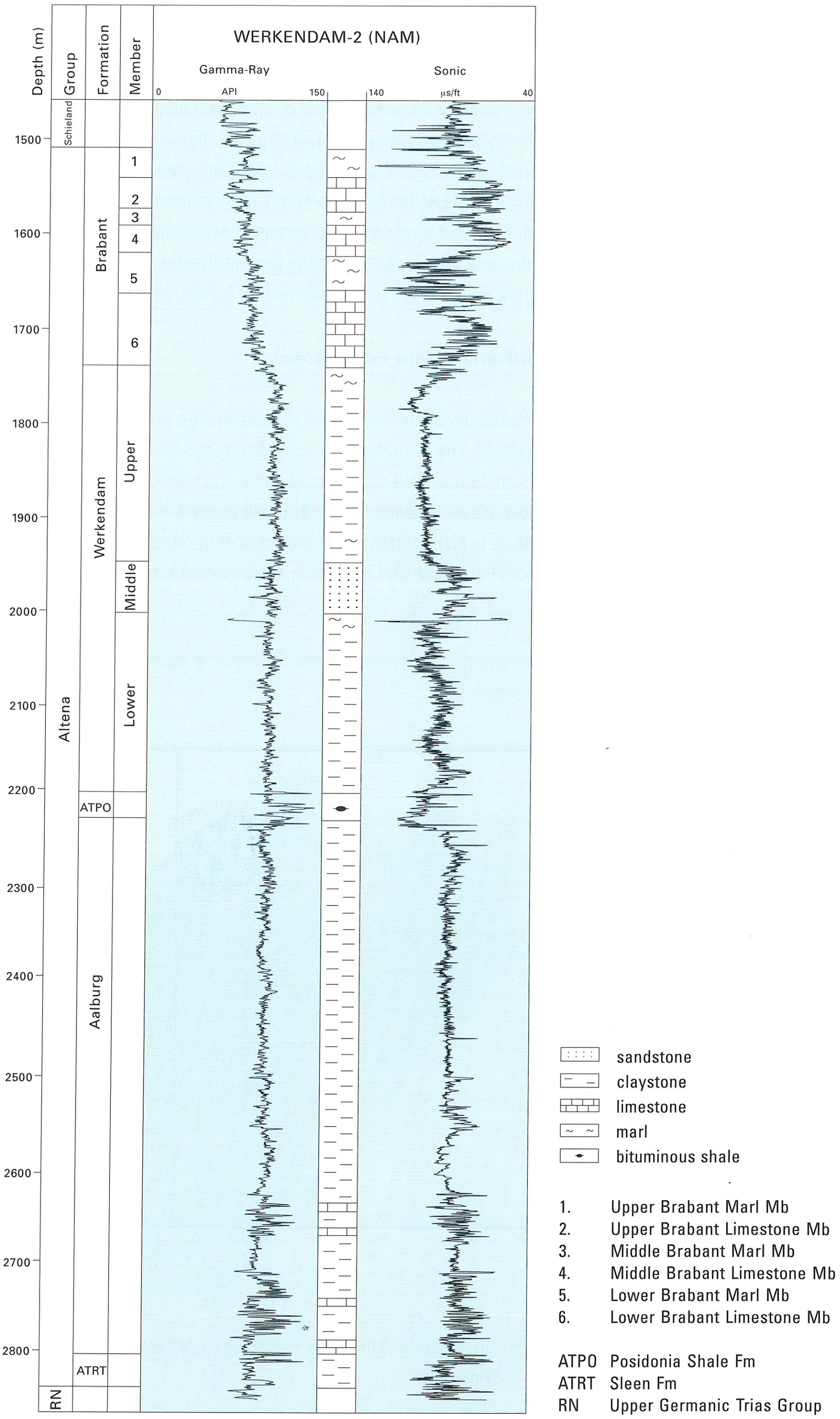


Figure 8.4 Stratigraphic division and log pattern of the Altena Group in the Werkendam-2 well.



of the formation in the map sheet area is restricted to the northern part of the Roer Valley Graben and the West and Central Netherlands Basins (fig. 8.3). The formation is 30 to 55 m thick.

8.1.4 Werkendam Formation

The Werkendam Formation, of Late Toarcian up to Early Bathonian age, consists of grey, marly claystone with, in the middle of the section, a sandy interval with limestone beds and siltstone intercalations. The formation within the map sheet area is only present in the northern part of the Roer Valley Graben, the West Netherlands Basin and locally in the Gouwzee Trough (Central Netherlands Basin) (fig. 8.2, 13.3). The Werkendam Formation rests conformably upon the Posidonia Shale Formation and is overlain conformably by the Brabant Formation or unconformably by the Schieland Group or the Chalk Group and locally by the North Sea Supergroup. There are pronounced differences in thickness as a result of erosion, but a maximum thickness of approximately 500 m is achieved. Towards the northwest, the thickness decreases. The formation is subdivided into three members. (fig. 8.1).

The *Lower Werkendam Member*, of Late Toarcian to Middle Bajocian age, consists of grey, occasionally silty claystone, often with characteristic siderite concretions and/or iron oolites. Locally, a few bituminous intercalations occur at the base. The thickness is variable and may exceed 250 m.

The *Middle Werkendam Member*, of Middle Bajocian age, comprises sandstones with limestone beds and siltstone intercalations, and has manifestly lower sonic values compared with the underlying and overlying members (fig. 8.5). The thickness varies from 20 to over 100 m. The basal part of the member is generally characterised by a sandstone succession.

The *Upper Werkendam Member*, of Middle Bajocian to latest Bajocian or earliest Bathonian, consists of a homogeneous section of grey, somewhat marly, claystones. The thickness may exceed 200 m.

8.1.5 Brabant Formation

The Brabant Formation displays an alternation of sandy claystone and marly, sandy, fossil-rich, occasionally oolitic limestones. The sandy part of the formation has sometimes previously been compared to the "Cornbrash", a coeval equivalent and lithologically comparable deposition in England (Haanstra, 1963; Heybroek, 1974, Herngreen & De Boer, 1978). The formation rests conformably upon the Werkendam Formation. The present-day areal extent has been strongly determined by erosion (fig. 8.2). The formation is unconformably overlain by the Schieland, the Rijnland or the Chalk Group or by the North Sea Supergroup. Where the formation is complete, the maximum thickness is slightly over 350 m. On a basis of the carbonate/sand ratio, the formation can be subdivided, in stratigraphic order, into seven members.

The *Lower Brabant Limestone Member*, Early Bathonian (possibly also Late Bajocian) in age, consists of an alternation of marls and limestones, in which the number of limestone beds upwardly increases. The thickness ranges from 30 to 110 m. The transition from the Upper Werkendam to the Lower Brabant Limestone is gradual, via a marl succession with thin limestone beds to a limestone sequence.

The *Lower Brabant Marl Member*, of Late Bathonian age, comprises sandy marl deposits with ferruginous sediments at the top. Locally, thin, sandy limestone beds may be intercalated. The member is 10-80 m thick.

The *Middle Brabant Limestone Member*, of Early Callovian age, is a unit of very sandy, fossil-rich limestones with an intercalation of sandy marls. The thickness of this member ranges from 10 to 40 m.

The *Middle Brabant Marl Member,* of Early to Late Callovian age, consists of sandy marls that are ferruginous at the base. The member is 10-30 m thick. Where the thickness is slight, the differentiation between the upper and underlying limestones is impeded. The unit has only been penetrated in the transition area between the Roer Valley Graben and the West Netherlands Basin.

The *Upper Brabant Limestone Member,* of Late Callovian age, consists of very sandy limestone. The thickness ranges from 10 to 40 m. The base of this unit is thought likely to contain a hiatus (RGD, 1996c).

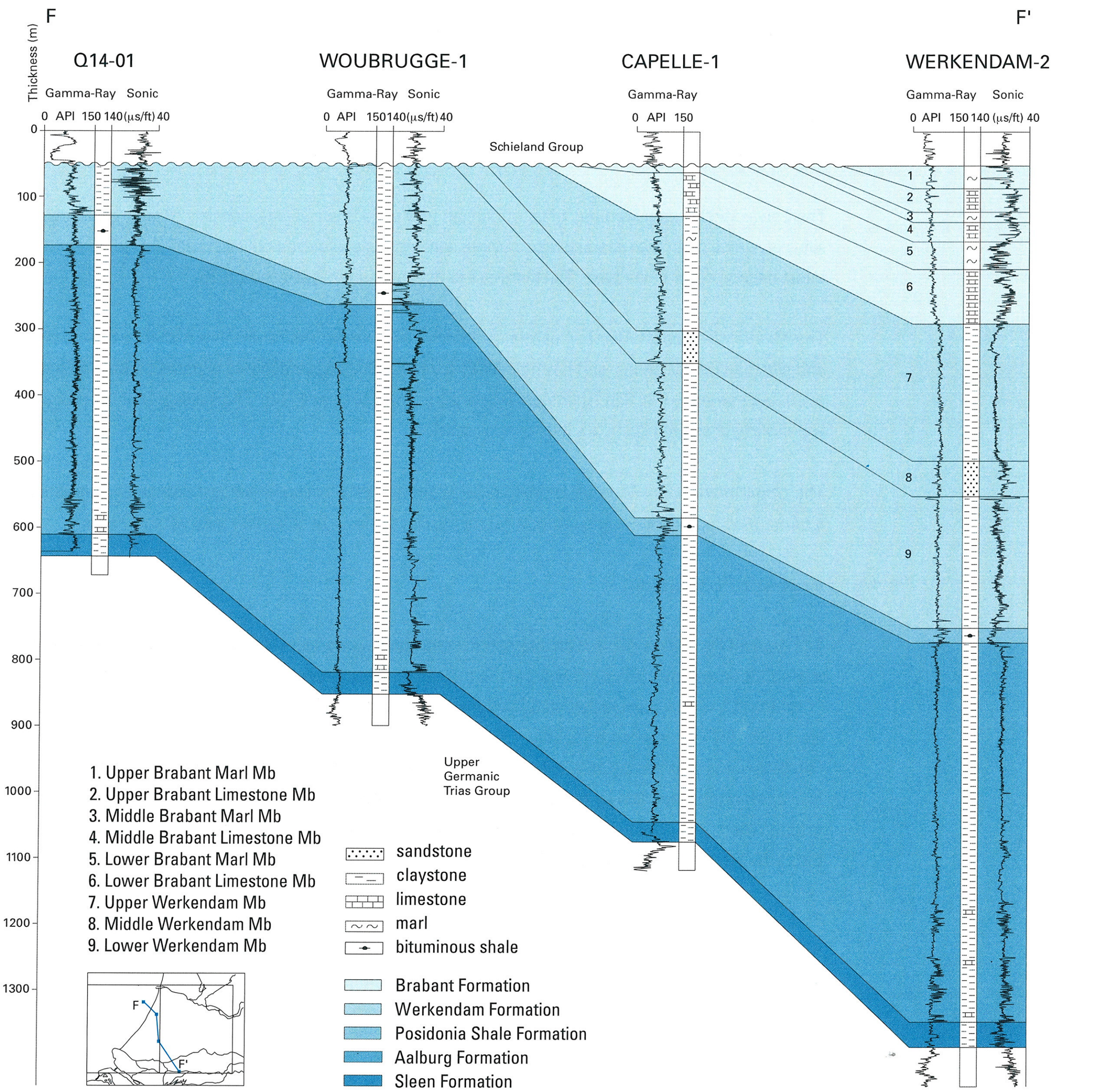


Figure 8.5 Stratigraphic section F-F' of the Altena Group between the Q14-01, Woubrugge-1, Capelle-1 and Werkendam-2 wells corresponding to the longitudinal axis of the West Netherlands Basin. The reference level is the base of the Schieland Group.

The *Upper Brabant Marl Member*, of Late Callovian to Oxfordian age, is a unit of extremely sandy marls with sandstone layers at the base. The sand content upwardly decreases. The maximum thickness is 30 m.

The *Oisterwijk Limestone Member*, of Late Callovian to Oxfordian age, only occurs in the extreme southeast of the West Netherlands Basin and the northern part of the Roer Valley Graben. The member, consisting of massive oolitic limestone beds, has only been encountered in the Lekkerkerk-1 well, where the thickness is 13 m.

8.2 Sedimentary development and palaeogeography

After a long period of continental or shallow-marine depositional conditions, a transgression during the Late Triassic (Rhaetian) favoured an open-marine depositional area, which extended over a large part of North Western Europe. This marks the beginning of the deposition of the Altena Group. The conspicuous uniformity of the deposits over a wide area indicates that the sedimentation took place in a single large basin. The homogeneous, fine-grained composition of the Altena Group indicates that the presence on the highs is not primary, but the consequence of subsequent erosion predominantly related to the Late Kimmerian uplift. Owing to the inversion phases, the group underwent additional erosion during the Late Cretaceous and/or Early Tertiary.

The sedimentation of the Altena Group in the map sheet area commenced with the transgressive deposition of the Sleen Formation. The fairly constant thickness of the formation is indicative of a steadily subsiding area. A brief regressive period at the end of the deposition of this formation gave the top of the Sleen Formation more of a lagoonal character. This was superseded by a sea-level rise and deposition of the open-marine sediments of the Aalburg Formation. This deposition occurred primarily below the wave base, with the thin organic-rich layers pointing to the occurrence of periodical, anoxic conditions in the basin. Thickness variation within the formation reflects differential subsidence in the area.

The Posidonia Shale Formation is a pelagic deposition with a bituminous character deposited under anoxic conditions likely to have been induced by a stagnating deep-water circulation which was possibly due to the combination of a deep basin with an intensively faulted basin floor and the closure of the connection with the oceanic domain, facilitating the anoxic conditions.

The open-marine conditions resumed during the deposition of the Werkendam Formation and the Brabant Formation. Both formations were deposited in shallow, open-marine conditions, during which several sea-level fluctuations were responsible for facies changes in a coastal area. The fossil content of the Brabant Formation occasional indicates the presence of brackish-water conditions (RGD, 1995c,e; 1996e).

9 Schieland Group

9.1 Stratigraphy

The Schieland Group, Kimmeridgian up to Barremian in age, is represented by the Delfland Subgroup, which in the map sheet area consists predominantly of an alternation of dark to variegated claystones and sandstones with lignite beds The subgroup is represented by the Nieuwerkerk Formation in the West Netherlands Basin and in the Central Netherlands Basin by the Zurich Formation (fig. 9.1).

The depth of the base of the Schieland Group in the map sheet area is between 600 and 2500 m (Maps VII/VIII-8). The thickness is a maximum of 1600 m (Maps VII/VIII-9) and has been determined by synsedimentary fault movements. The Schieland Group rests conformably or, separated by a slight hiatus or unconformably upon the Altena Group and is conformably overlain by the Rijnland Group or

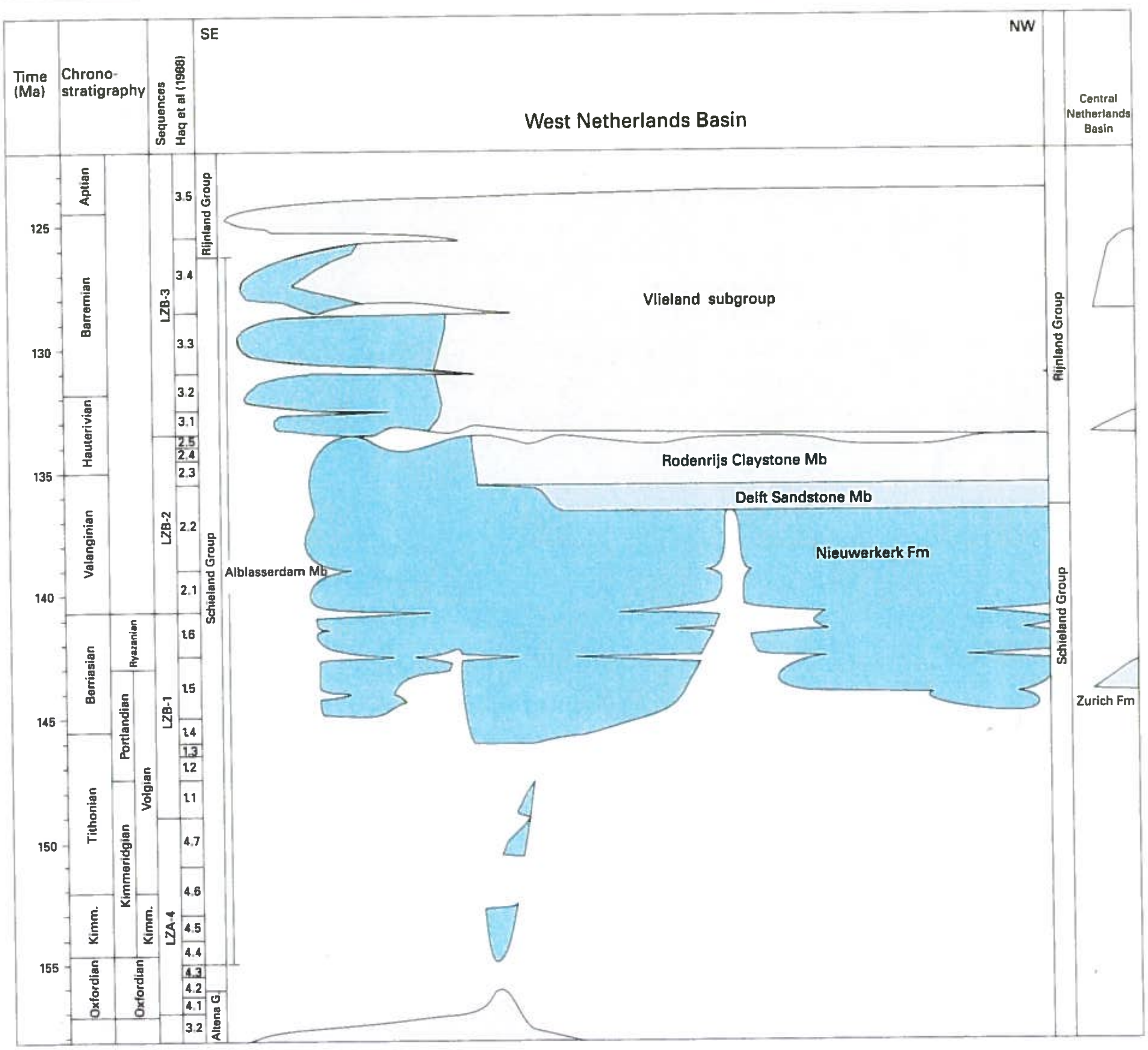


Figure 9.1 Stratigraphic overview of the Schieland Group with the lithostratigraphic units occurring in the area (after Van Adrichem Boogaert & Kouwe, 1993-1997).

unconformably by the Chalk Group or by the North Sea Supergroup. The group is partly the (coeval) equivalent of the Rijnland Group.

9.1.1 Nieuwerkerk Formation

The Nieuwerkerk Formation is subdivided into the Alblasserdam, the Delft Sandstone and the Rodenrijs Claystone Members (figs. 9.2 & 9.3). The age of the formation is predominantly Portlandian and Ryazanian; locally, however, older deposits (Kimmeridgian) also occur, while on the southwestern margin of the West Netherlands Basin, the youngest deposits are of Valanginian or even Barremian age. Fig. 9.4 displays the composition and the thickness development of the formation in the west of the map sheet area.

The *Alblasserdam Member* comprises a succession of grey, red and mottled claystones and siltstones, with intercalations (up to few metres) of fine-grained to middle-coarse sandstone and thick-layered coarse-grained sandstone. The claystones and siltstones contain coal seams. The sandstones occur as blanket sand deposits and channel sand bodies. The red coloured sediments are restricted to the bottommost part of the member, while the grey coloured, organic-rich sediments predominate in the topmost part. The total thickness of the member varies considerably, ranging from a few metres to over 1500 m. This great variation in thickness is the result of the synsedimentary tectonics and as intensified by

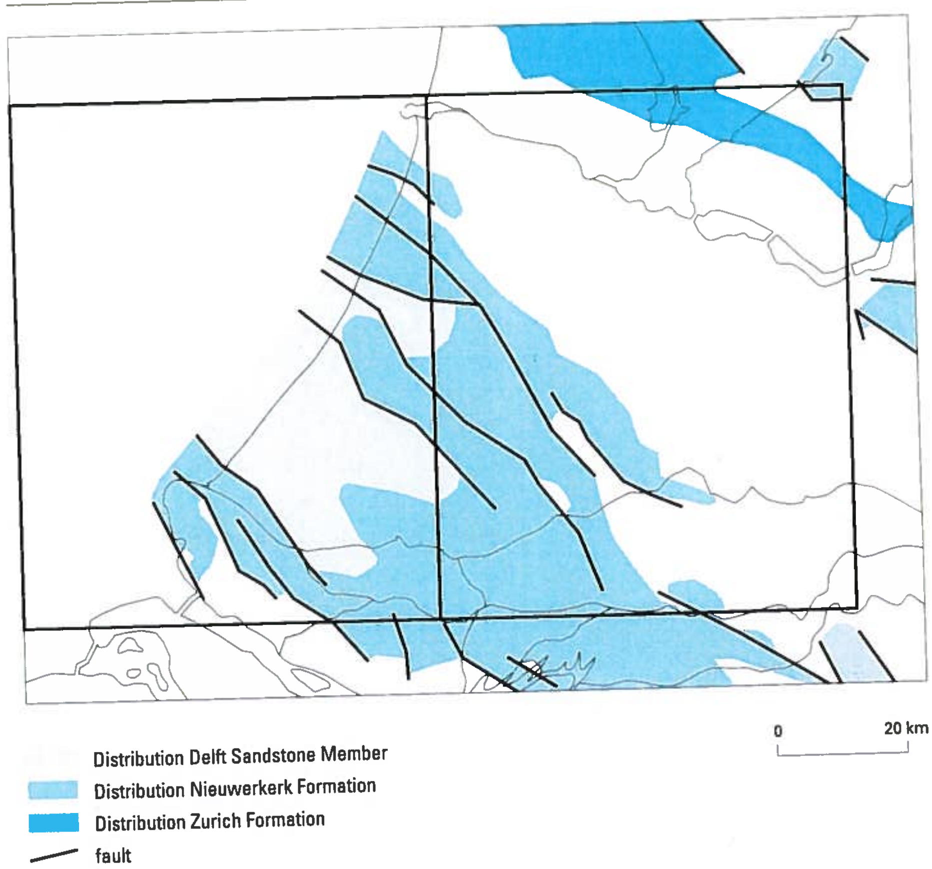
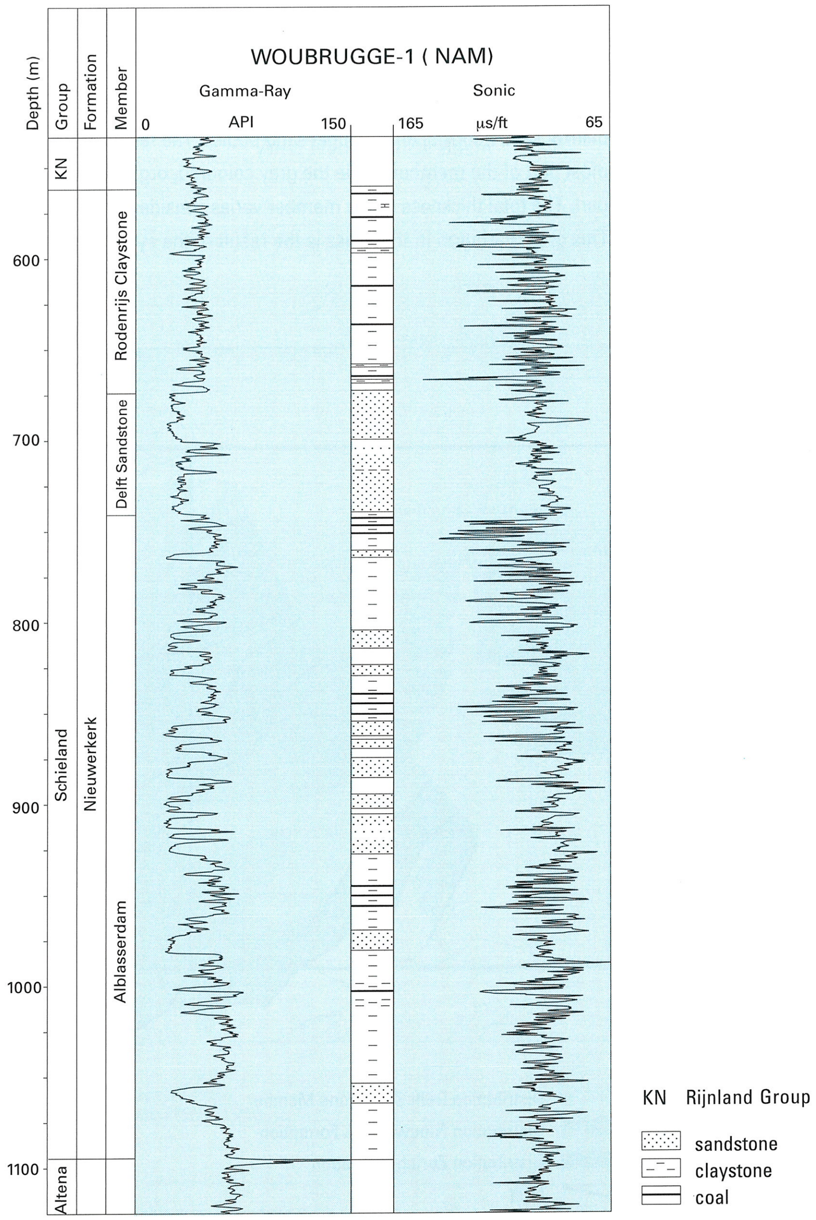


Figure 9.2 Extent of the Schieland Group including the extent of the Delft Sandstone Member.

erosion induced by the subsequent inversion. The sandstones generally display slight lateral continuity. The sand/shale ratio in the Roer Valley Graben and the West Netherlands Basin was demonstrated by Den Hartog Jager (1996) to diminish from the southeast to the northwest. The same trend can be observed in the direction of the adjacent horst blocks.

The *Delft Sandstone Member*, of Valanginian age, is a light-grey, massive, fining-upwards sandstone succession. The sandstone, varying in thickness from 30 to 75 m, contains a certain amount of lignitic material. The unit rests conformably upon the Alblasserdam Member. In a northwesterly direction, the Delft Sandstone in the offshore area passes into the basal part of the Rijswijk Sandstone.

Figure 9.3 Stratigraphic division and log pattern of the Schieland Group in the Woubrugge-1 well.



The *Rodenrijs Claystone Member*, of Valanginian to Hauterivian age, is a grey to dark-grey succession of coal-bearing claystone and coal seams. Locally, shell beds occur. The member has a thickness ranging from 40 to over 100 m.

9.1.2 Zurich Formation

The Zurich Formation, of Late Portlandian to Ryazanian age (NITG-TNO, 1999), comprises fine-grained deposits of multicoloured or grey sandy to silty claystone with thin intercalated sandstone and limestone beds and coal seams. The claystone sequence also contains pyrite, siderite, thin beds of sandstone and limestone and coal seams. Sparse data have enabled a distinction to be made between a calcareous

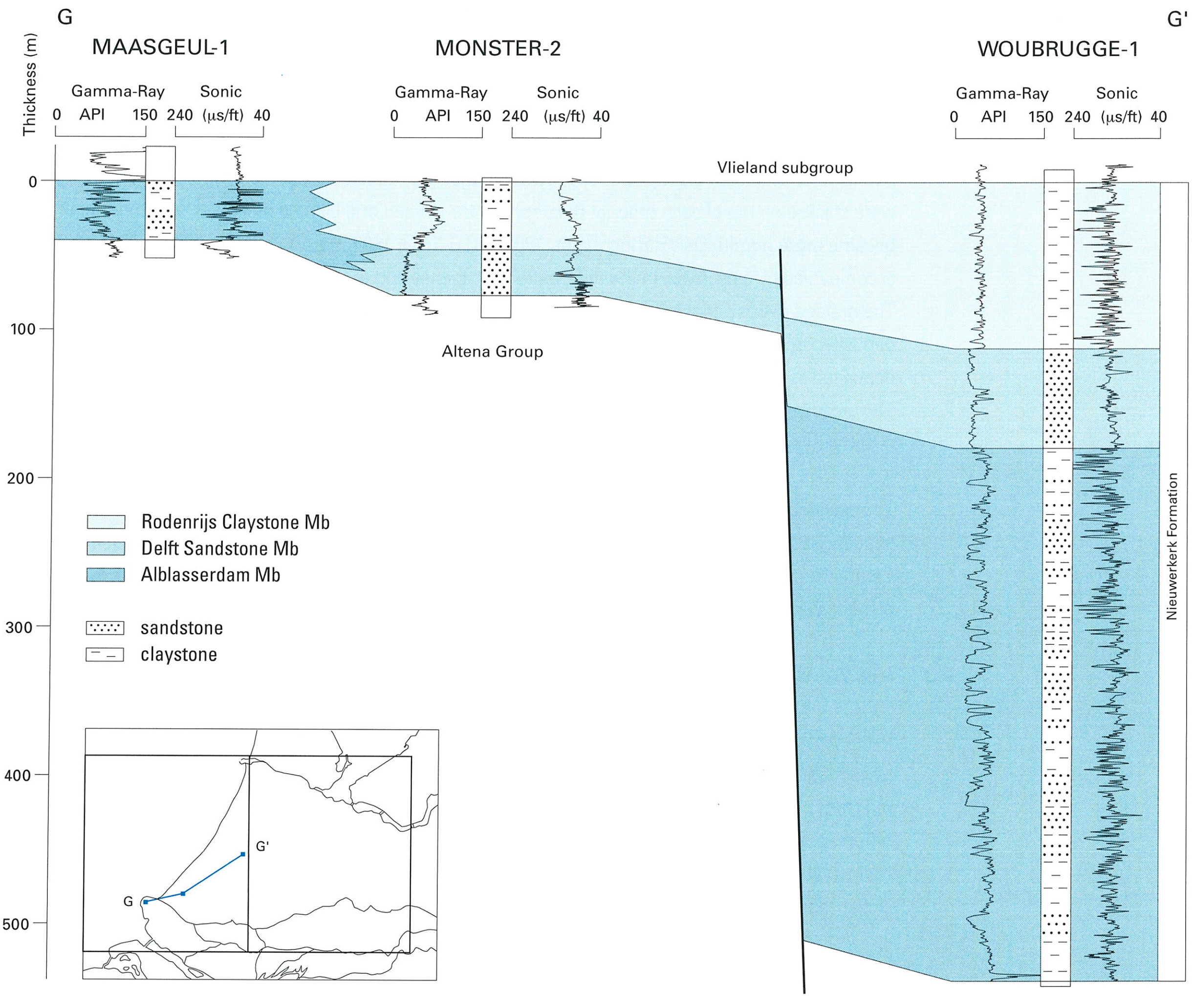


Figure 9.4 Stratigraphic section G-G′ of the Schieland Group between the Maasgeul-1, Monster-2 and Woubrugge-1 wells from the basin margin to the centre of the West Netherlands Basin. Reference level is the base of the Vlieland subgroup. This section illustrates the enlargement of the sedimentation area during the deposition of the formation. The oldest parts of the formation were deposited in fault-confined grabens.

base, covered by a claystone and a sandy uppermost succession (Van Adrichem Boogaert & Kouwe, 1993-1997). The topmost, sandy succession has the greatest areal extent in the western part of the Central Netherlands Basin. This part of the succession is characterised by a coarsening-upward sequence. The formation only occurs in the Central Netherlands Basin (Rijks Geologische Dienst, 1993a). The formation is up to 450 m thick in the northeast of the map sheet area.

9.1.3 Volcanic rocks

In the Heinenoord-1 well, picrite has been encountered at a level of 2106 to 2151 m in the Nieuwerkerk Formation. The rocks are light grey-green, occasionally yellow. Picrite is an ultrabasic rock, constituting over 90% FeMg-minerals, the remainder constituent being feldspars. No data on the rocks are available.

9.2 Sedimentary development and palaeogeography

The sediments of the Nieuwerkerk Formation were deposited during the late Jurassic in the highly differentiating subsiding West Netherlands Basin (Den Hartog Jager, 1996). The bottommost ("red bed") section represents a depositional system of braided rivers, which flowed via the longitudinal axis of the subsiding grabens. This was accompanied by rapid sedimentation of channel sandstones. These sand bodies were of limited areal extent and, owing to the rapid subsidence at the centre of the rift basins, were stacked on top of each other at the depo centre. A semi-arid climate prevailed, which gradually became more humid (Den Hartog Jager, 1996; NITG-TNO, 1999, Herngreen et al., 2000). This was accompanied by a decrease in the differential subsidence and gradual, regional subsidence occurred. The braided river system made way for a pattern of meandering rivers flowing in flat valleys. Sand was deposited in channels, while sand, in the form of crevasse splays, as well as clays and lignite, were also deposited in flood plains. In a northwesterly direction, the fluvial systems protruded into a shallow sea. The areas of provenance of the sands in the West Netherlands Basin are the Brabant Massif and possibly also the Rhenish Massif.

The claystone sequence in the Zurich Formation is a brackish-water deposit, while the overlying sand sequence was deposited partly in freshwater (RGD, 1986d). The area of provenance of the sands in the Central Netherlands Basin is thought to be the Texel IJsselmeer High (Rijkers & Geluk, 1996), and partly also the Zandvoort Ridge to the south of this basin.

9.3 Petrophysical data

In the West Netherlands Basin, oil was exploited from the sandstones of the Nieuwerkerk Formation in the IJsselmonde/Ridderkerk oil field. These fields have now been abandoned. Oil production was also carried out from this formation of the Moerkapelle, Zoetermeer, Wassenaar and Pijnacker fields. Considerable differences in permeability (< 100 tot 3000 mD) and cementation are typical of the sediments of the Nieuwerkerk Formation. The porosity displays values of under 10 increasing to 27% (Racero-Baena & Drake, 1996). Appendix E gives some reservoir calculations from the IJsselmonde-55 well.

10 Rijnland Group

10.1 Stratigraphy

The Rijnland Group in the map sheet area, Valangian to Albian in age, comprises glauconite-bearing sandstones, siltstones, claystones and marls. The group is subdivided into the Vlieland Sandstone, the Vlieland Claystone and the Holland Formations. The two first-mentioned formations together form the informal Vlieland subgroup.

The Rijnland Group is present in the majority of the area. In the southwest, on the Zeeland Platform, the group was not deposited. The bottommost part of the Rijnland Group is the (coeval) equivalent of the topmost part of the Schieland Group (fig. 10.1). The depth of the group ranges from 500 to 2300 m (Maps VII/VIII-10). The group reaches a maximum thickness of over 1400 m in the West Netherlands Basin (Maps VII/VIII-11).

During deposition of the group, the sedimentation area extended from the basins across the surrounding highs, with the result that, in this direction, the base of the group is formed by progressively younger sediments. The group is overlain conformably by the Chalk Group, or unconformably by the North Sea Supergroup and itself rests conformably or with a small hiatus upon the Schieland Group, or unconformably on the Altena Group.

10.1.1 Vlieland subgroup

The Vlieland subgroup is present in a large part of the map sheet area (fig. 10.2). The subgroup is overlain conformably or with a small hiatus by the Holland Formation, or unconformably by the Chalk Group or the North Sea Supergroup.

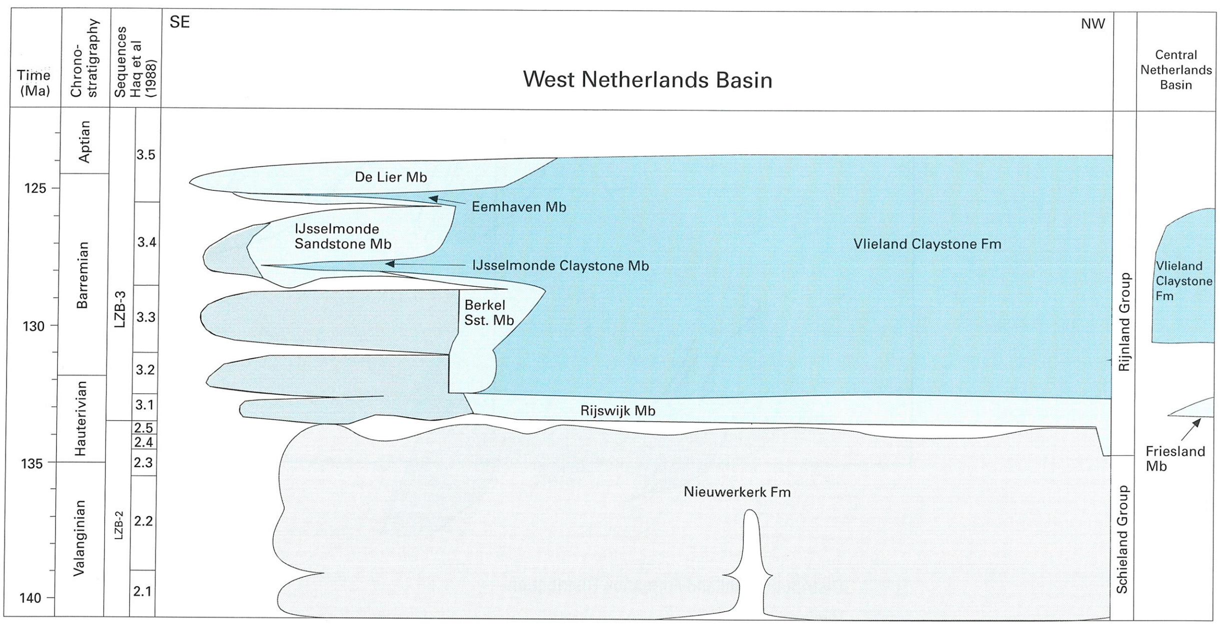


Figure 10.1 Stratigraphic overview of the Vlieland subgroup with the lithostratigraphic units occurring in the map sheet area.

The subgroup achieves its greatest thickness in the West and Central Netherlands Basins. On the highs around these basins, the subgroup has been reduced in thickness and displays several hiatuses (Rijks Geologische Dienst, 1993a,b). The thickness of the subgroup to the south of the West Netherlands Basin, decreases primarily in the transition zone towards the Roer Valley Graben; furthermore, the base of the subgroup on the Zeeland Platform becomes increasingly younger towards the south. The absence of the subgroup in the northeastern part of the West Netherlands Basin is the result of basin inversion and erosion during the Late Cretaceous and Early Tertiary.

Within the subgroup, of Valanginian to Barremian age, the Vlieland Sandstone Formation and the Vlieland Claystone Formations can be distinguished. These formations are each other's lateral equivalent.

10.1.1.1 Vlieland Sandstone Formation

The Vlieland Sandstone Formation in the West Netherlands Basin is composed of a number of sand bodies, which, in a northeasterly direction, laterally pass into the Vlieland Claystone Formation. These are, from bottom to top, the Rijswijk, the Berkel Sand-Claystone, the Berkel Sandstone, the IJsselmonde Sandstone and the De Lier Member. The members referred to are only encountered on the southwestern margin of the West Netherlands Basin, with the exception of the Rijswijk Member, which occurs throughout the West Netherlands Basin at the base of the Rijnland Group (fig. 10.3a-d). In the adjacent

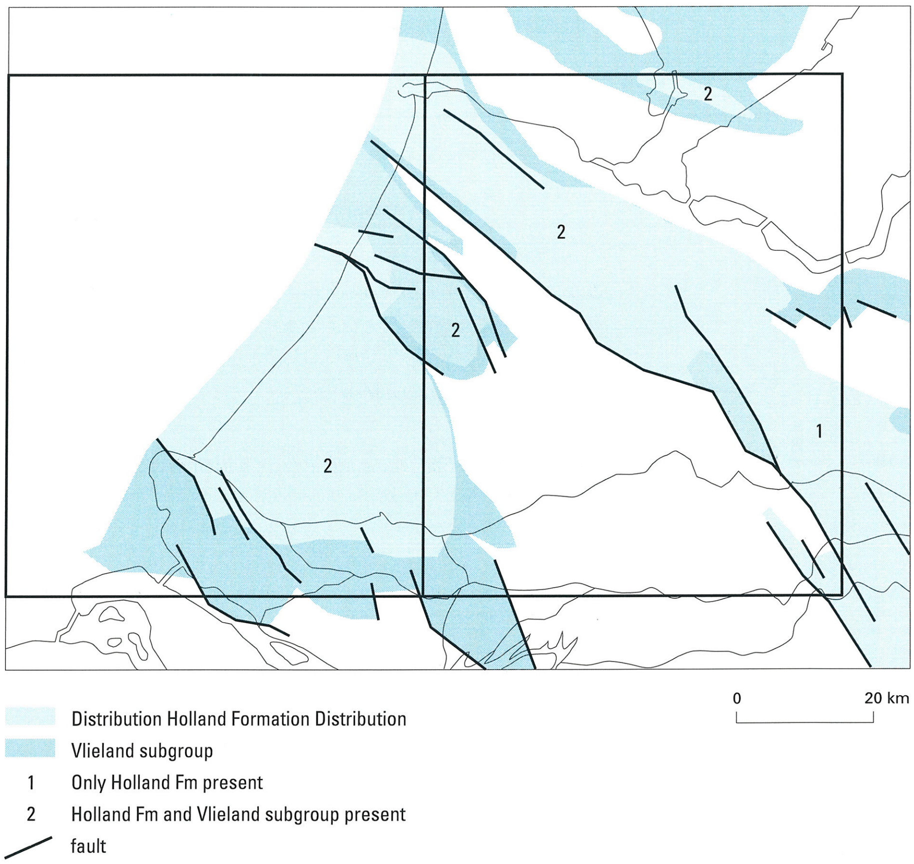


Figure 10.2 Extent of the Vlieland subgroup and the Holland Formation.

offshore area, this particular sandstone is termed the Rijn Member (Van Adrichem Boogaert & Kouwe, 1993-1997). In the Central Netherlands Basin, there are only local occurrences of a sandstone at the base of the Rijnland Group, the Friesland Member.

In the Central Netherlands Basin, the sandy successions of the Nieuwerkerk Formation and the Vlieland Sandstone Formation cannot be clearly differentiated from each other. The log characteristics of both units are virtually identical; a clear distinction is only possible on the basis of biostratigraphic research (see Herngreen et al., 1980).

The *Rijswijk Member*, Late Hauterivian age in age, is the basal sandstone succession in the formation. The member comprises a grey, fine to medium-coarse sandstone. Locally, the member may contain a quantity of conglomerate. Lignite and siderite frequently occur in the sandstone. Near the base, occasional lignitic claystone beds occur. The member is 40 to 140 m thick.

The Rijswijk Member occurs in a large part of the West-Netherlands Basin (fig. 10.3a); in a northwesterly direction, the sandstone passes into the Rijn Member and; in a southerly and easterly direction, into the uppermost part of the Nieuwerkerk Formation.

The *Berkel Sandstone Member*, of Late Hauterivian to Barremian age, is a light-grey, fine to coarse-grained sandstone. At some places, the unit is conglomeratic. Locally, the sandstone is glauconitic or lignitic. In the topmost part of the sandstone, calcite-cemented beds occur. There are also local occurrences of shell beds. In cores, high angle and low angle cross stratification bedding is visible, as is abundant parallel bedding. The thickness of the sandstone exceeds 100 m; in the vicinity of Berkel, thicknesses even in excess of 200 m are found, in the vicinity of faults (fig.10.3b). In a northwesterly direction, the unit passes into the Berkel Sand-Claystone, and subsequently into the Vlieland Claystone. Sand bodies of the Berkel Sandstone can be identified far into the West Netherlands Basin, as far as blocks Q11 and Q13.

The *Berkel Sand-Claystone Member*, also of Late Hauterivian to Barremian age, is an alternation of fine-grained, argillaceous sandstone and brownish grey, silty to sandy claystone. Locally, siderite concretions occur. In the bottommost part of the member, the claystones predominate. The unit is over 130 m thick. The occurrence of the unit is restricted to a narrow strip along the southern margin of the West Netherlands Basin; this sequence laterally forms the transition zone between the Vlieland Claystone Formation and the Berkel Sandstone Member.

The *IJsselmonde Sandstone Member*, of Barremian age, is a light-grey, massive sandstone. In general, this sandstone is fine to medium-coarse grained; locally, however, conglomeratic thick sandstone also occurs. Calcite sedimentation occurs, particularly in the uppermost part of the sandstone. Characteristic is the presence of a 5-to-10-m-thick intercalation of lignitic claystone (fig.10.1). The occurrence of the sandstone is restricted to a narrow zone parallel to the margin of the West Netherlands Basin, to the south of Rotterdam (fig.10.3c). The maximum thickness is approximately 200 m.

The *De Lier Member*, Late Barremian to Early Aptian in age, is an alternation of thinly-bedded, fine to very fine-grained argillaceous sandstone. Glauconite, siderite and lignite frequently occur, as well as shell fragments. Bioturbation is also frequently present, as a result of which the original sedimentary structures have largely disappeared. The member displays dm-scale coarsening upwards cycles. The sequence is a maximum of 70 m thick. The member occurs in a zone along the southwestern margin of the West Netherlands Basin (fig. 10.3d).

The *Friesland Member*, of Hauterivian age (RGD, 1990b), only occurs locally in the Central Netherlands Basin and is restricted to the north of the map sheet area (fig. 10.3a). The thickness varies considerably, from 10 to over 70 m. The sandstone is in general fine-grained, but locally, coarse sandstone also occurs. Glauconite occurs frequently. The sandstone upwardly grades into siltstone and claystone. These silty and argillaceous intervals are laminated and rich in organic material. Brown coloured sandstone beds cemented with siderite and calcite also occur, intercalated within the graded intervals (RGD, 1986a & 1990b).

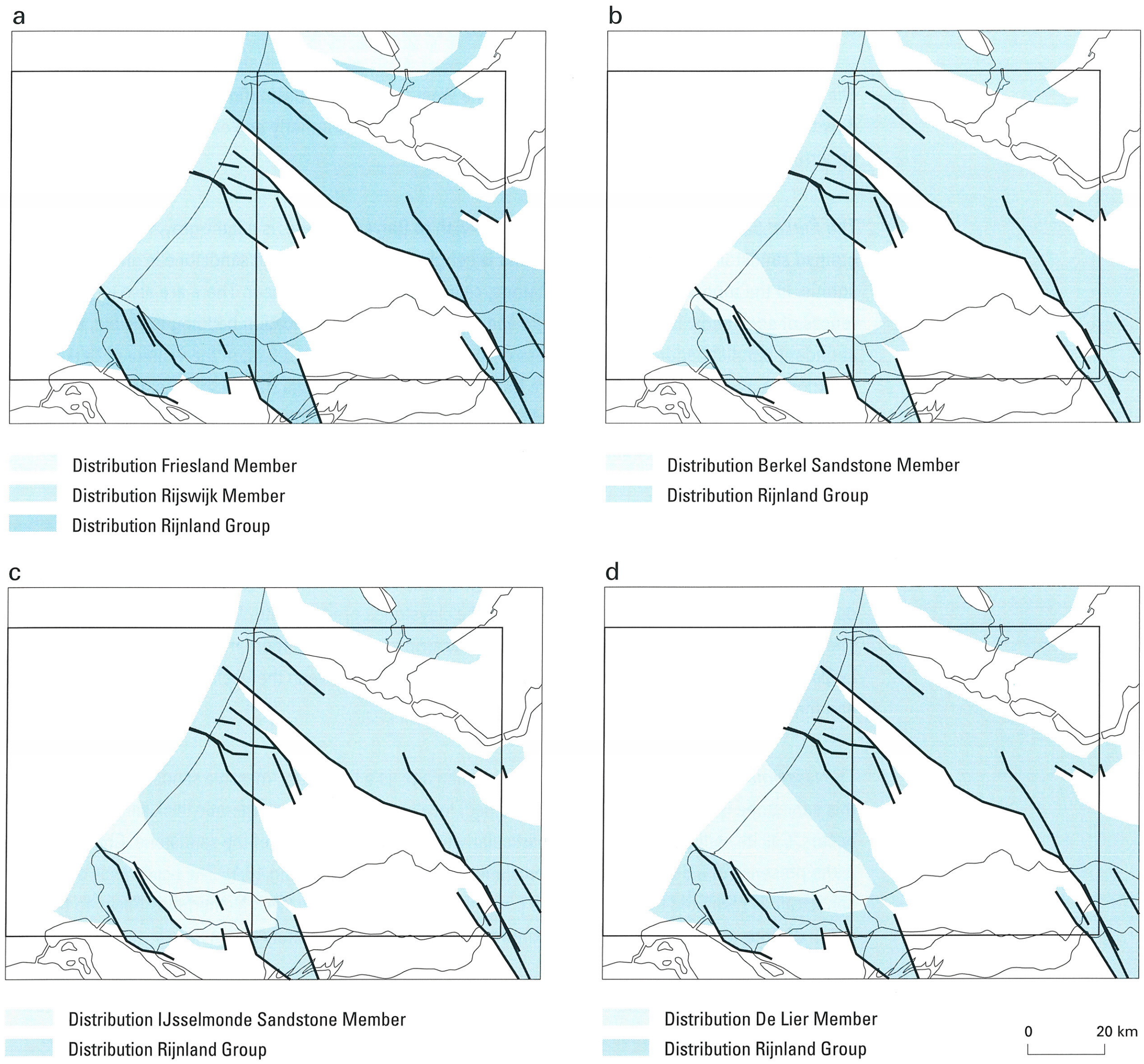


Figure 103a-d a. Extent of the Friesland and Rijswijk Members; b. extent of the Berkel Sandstone Member; c. extent of the IJsselmonde Sandstone Member; d. extent of the De Lier Member.

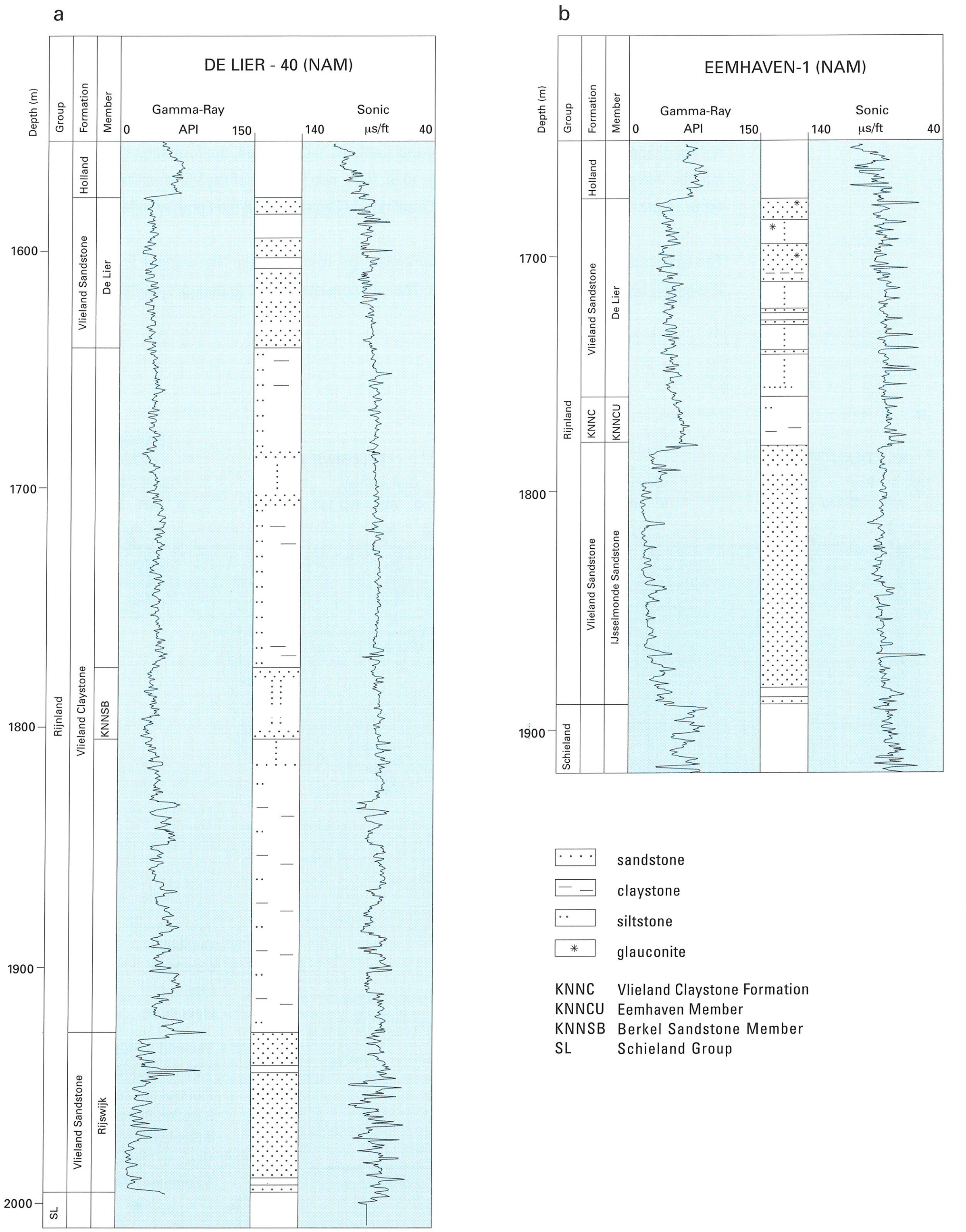


Figure 10.4a-b Stratigraphic division and log pattern of the Vlieland subgroup in the De Lier-40 well (a) and the Eemhaven-1 well (b).

10.1.1.2 Vlieland Claystone Formation

The Vlieland Claystone Formation, of Late Hauterivian to Barremian age, comprises dark-brown to dark-grey, silty claystone. The unit is marly at the top. Well data reveal that in the basins the thickness increases to 400-450 m, while on the Zandvoort Ridge, the thickness is no more than a few tens of metres, owing to erosion or to non deposition. In the basins, the formation is a monotonous succession not subdivided into members. Near the former southern basin margin, the formation changes laterally into the Vlieland Sandstone Formation (fig. 10.5). Here, two tongues of the Vlieland Claystone Formation occur, intercalated in the sandstones: the IJsselmonde Claystone and the Eemhaven Member.

The *IJsselmonde Claystone Member*, of Barremian age, rests upon the Nieuwerkerk Formation and is overlain by the IJsselmonde Sandstone. The unit consists of light to dark-grey, silty to fine-sandy

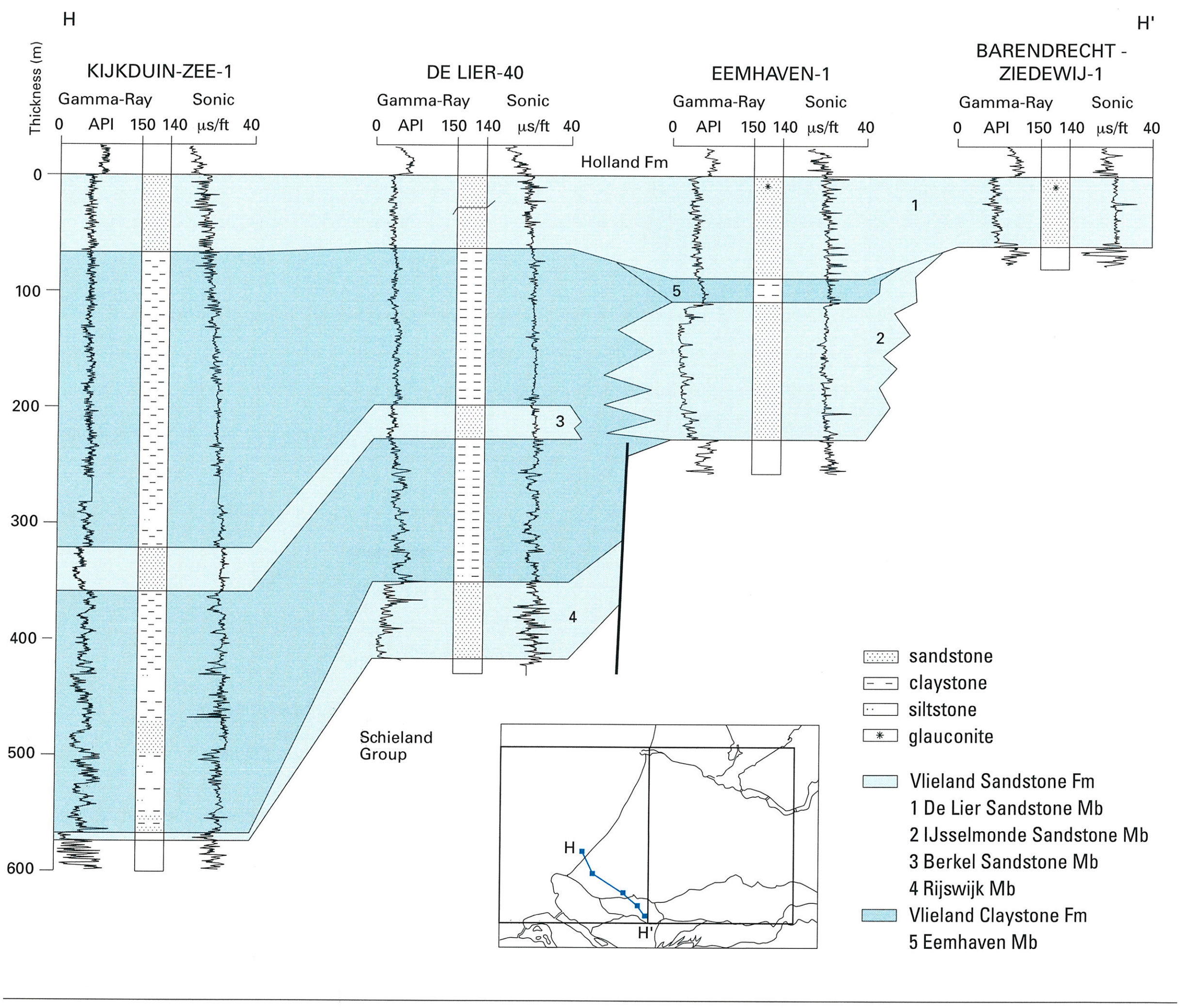
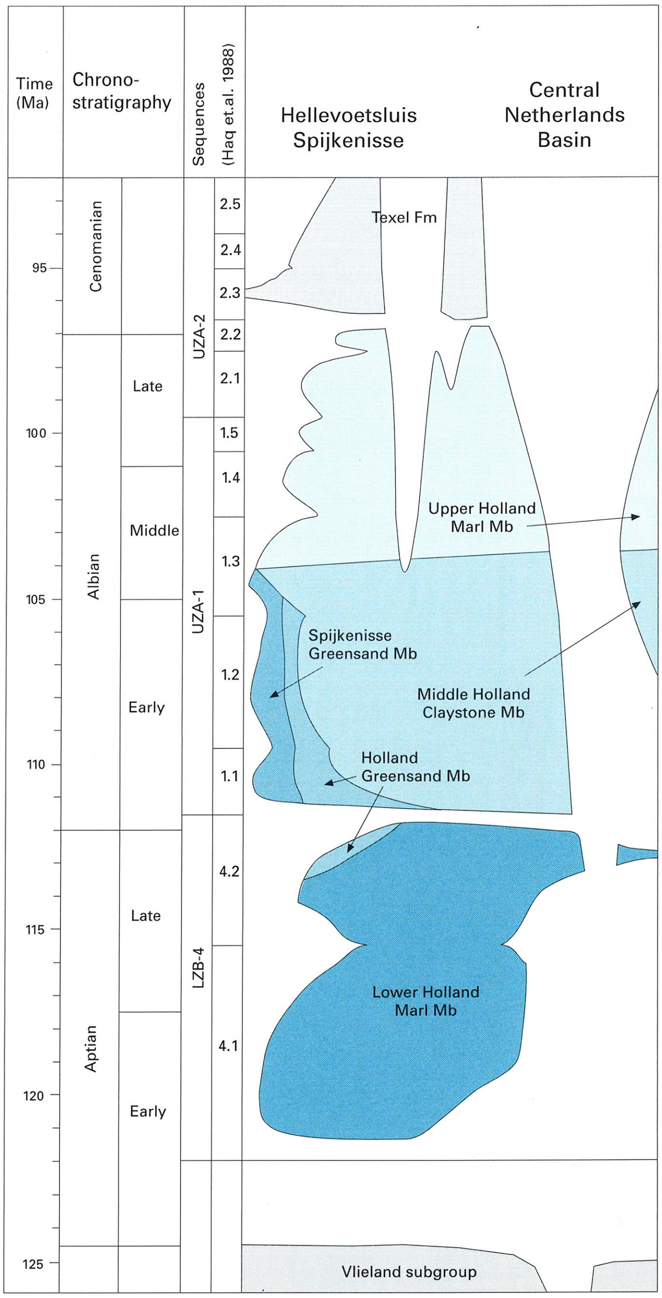


Figure 10.5 Stratigraphic section H-H' of the Vlieland subgroup between the Kijkduin-Zee-1, De Lier-40, Eemhaven-1 and Barendrecht-Ziedewij-1 wells along the axis of the West Netherlands Basin. The reference level is the base of the Holland Formation.

claystone, and may contain a few argillaceous sandstone beds. The member only occurs within the areal extent of the IJsselmonde Sandstone Member, on the southwestern margin of the West Netherlands Basin and achieves a thickness of approximately 45 m.

The *Eemhaven Member*, of Late Barremian age, is a thin claystone intercalation between the IJsselmonde Sandstone and the De Lier Member. The member occurs in the same area as the IJsselmonde Sandstone. The thickness is a maximum of approximately 20 m.

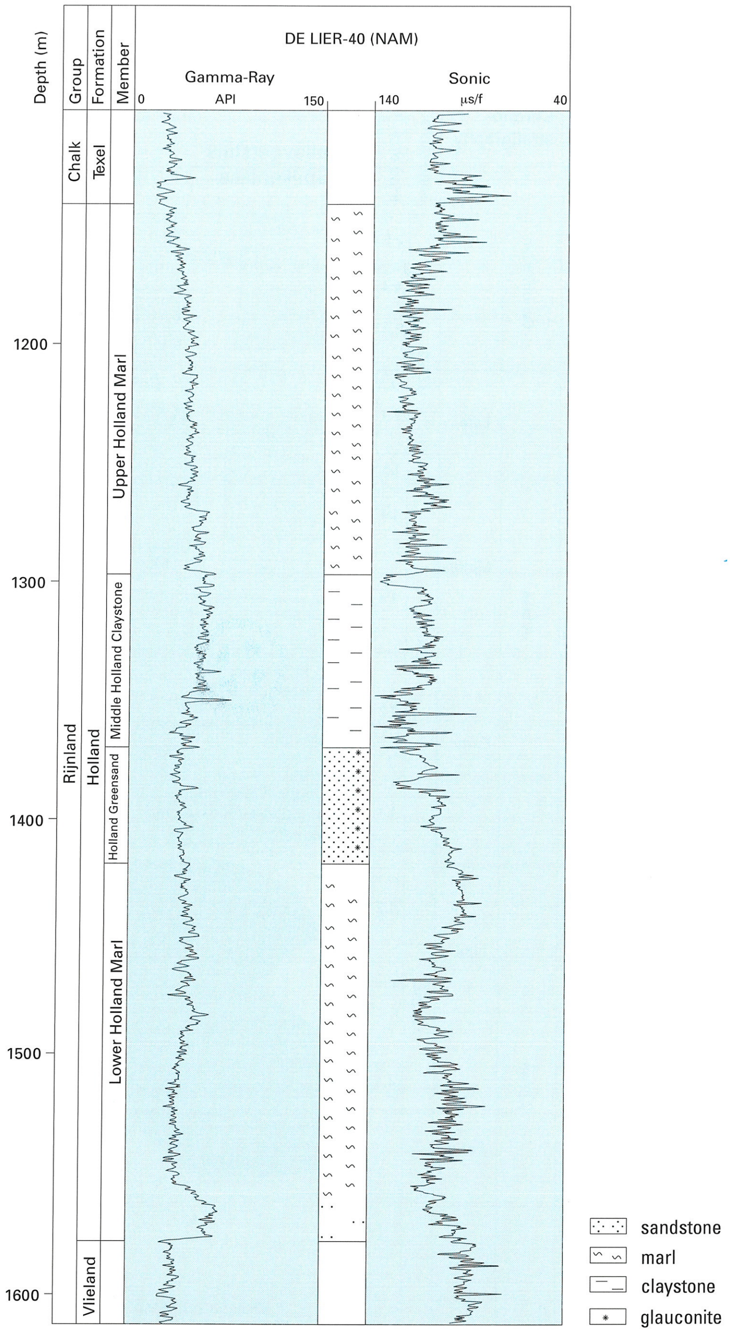
Figure 10.6 Stratigraphic overview of the Holland Formation with the lithostratigraphic units occurring in the map sheet area.



10.1.2 Holland Formation

The Holland Formation consists predominantly of grey and reddish-brown marl and claystone deposited during the Aptian to possibly Early Cenomanian. The formation is subdivided into the Lower Holland Marl, the Spijkenisse Greensand, the Holland Greensand, the Middle Holland Claystone and the Upper Holland Marl Members (fig. 10.6, 10.7 & 10.8). The Holland Formation rests conformably upon the

Figure 10.7 Stratigraphic division and log pattern of the Holland Formation in the De Lier-40 well.



Vlieland subgroup and is conformably overlain by the Chalk Formation or unconformably by the North Sea Supergroup (fig. 10.8).On the Maasbommel High, the formation rests unconformably upon the Upper Germanic Trias Group. The formation occurs in a major part of the map sheet area (fig. 10.2) and reaches its greatest thickness, over 500 m, in the West Netherlands Basin.

The *Lower Holland Marl Member*, of Aptian age (RGD, 1990a), is composed of a grey, sometimes red, brown or yellowish coloured marly claystone. The member attains a thickness of over 60 m in the Central Netherlands Basin, while thicknesses of up to 250 m in the West Netherlands Basin occur.

The *Holland Greensand Member*, of Late Aptian to Early Albian age, comprises an alternation of dark, silty and sandy clay and glauconitic sands (greensands) with carbonate beds. The unit rests upon the Lower Holland Marl and is overlain by the Middle Holland Claystone. The unit is over 200 m thick.

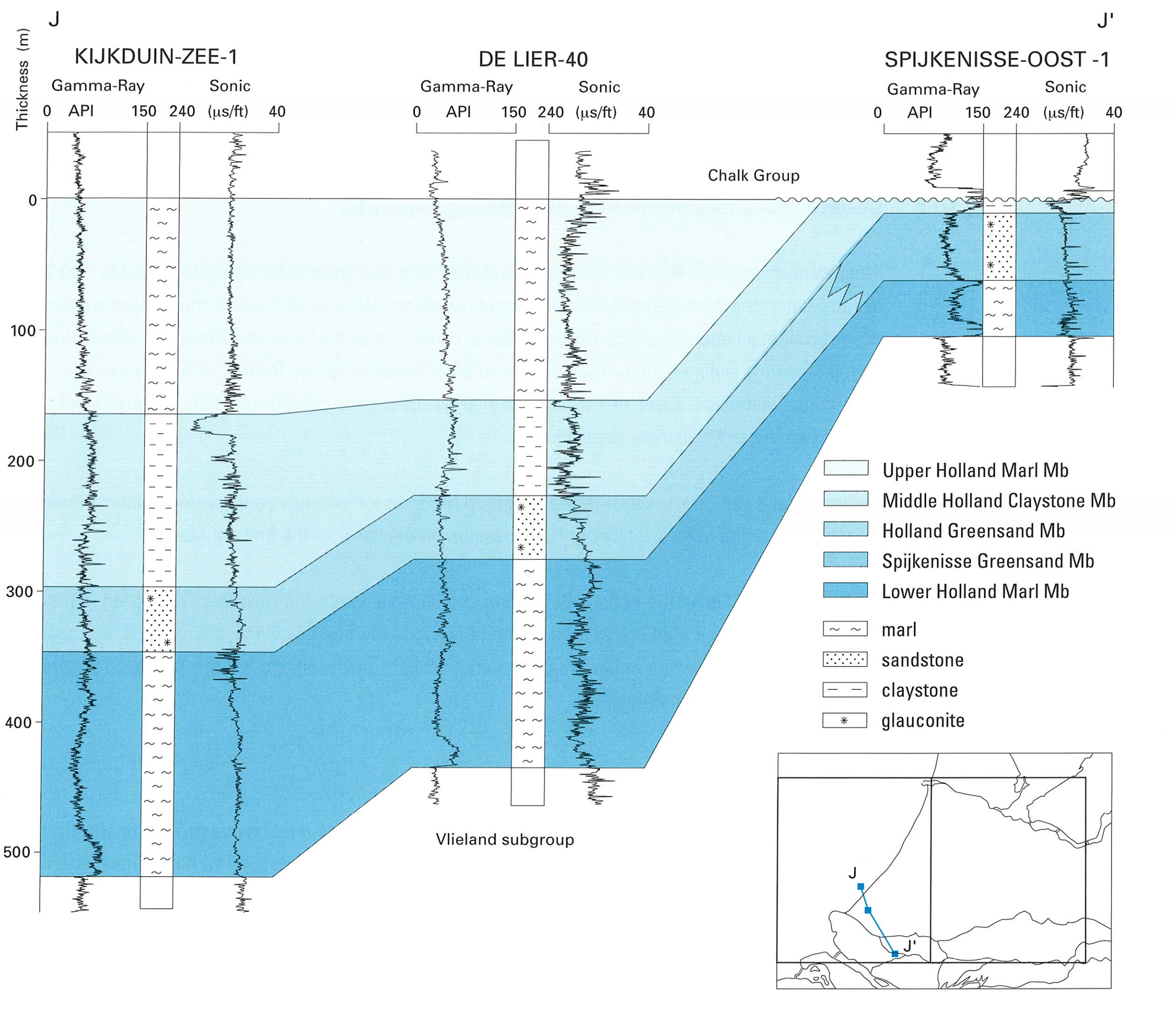


Figure 10.8 Stratigraphic section J-J' of the Holland Formation between the Kijkduin-Zee-1, De Lier-40, and Spijkenisse-Oost-1 wells from the centre of the West Netherlands Basin to the basin margin. The reference level is the base of the Chalk Group.

The *Spijkenisse Greensand Member*, of Early to Middle Albian age,, is a local deposition on the south-western margin of the West Netherlands Basin and is the proximal equivalent of the Holland Greensand. The member comprises coarse-grained glauconitic sandstone and has only been encountered in a few wells and measures 50 to 90 m.

The *Middle Holland Claystone Member* comprises a grey, marly clay. The clay content is higher than that of the underlying and overlying members. In the Central Netherlands Basin, the member rests upon the Lower Holland Marl Member without any demonstrable hiatus (RGD, 1990a). The unit achieves a thickness of approximately 80 m in the Central Netherlands Basin, and over 100 metres in the West Netherlands Basin. Biostratigraphic research and log correlations have revealed that the bottommost part of the member is of Late Aptian age (RGD, 1990a), contrary to the generally accepted age of Early to Middle Albian.

The *Upper Holland Marl Member*, of Middle Albian to presumably earliest Cenomanian age, comprises a light-grey and locally variegated marly and silty claystone.The uppermost part is often lighter-coloured. Characteristic of the sequence is the decrease in clay content from the base to the top. The member rests upon the Middle Holland Claystone and is unconformably overlain by the Chalk Group or by the North Sea Supergroup. The member is a maximum of 200 m thick in the Central Netherlands Basin and over 200 m thick in the West Netherlands Basin.

10.2 Sedimentary development and palaeogeography

When deposition of the Rijnland group commenced, the palaeogeography was determined by two areas of subsidence: the West Netherlands Basin and the Central Netherlands Basin. A major transgression, which brought an end to the lacustrine and fluvial conditions of the Schieland Group, heralded a long period of marine sedimentation. The deposits of the Vlieland subgroup formed in this manner are only represented in the map sheet area by shallow-marine sediments in the form of transgressive sands, coastal barriers and nearshore deposits.

On the Zeeland Platform, the base of the subgroup becomes increasingly younger in a southerly direction, reflecting the onlap of the Cretaceous transgression on the flanks of the Brabant Massif.

During the deposition of the Holland Formation, argillaceous marls and clays were deposited in the basins (Lower Holland Marl and Middle Holland Claystone Member), while on the margins, in a shallow-marine setting, glauconitic sands were deposited (Holland Greensand and, slightly further to the west, the Spijkenisse GreensandMember).

10.3 Petrophysical data

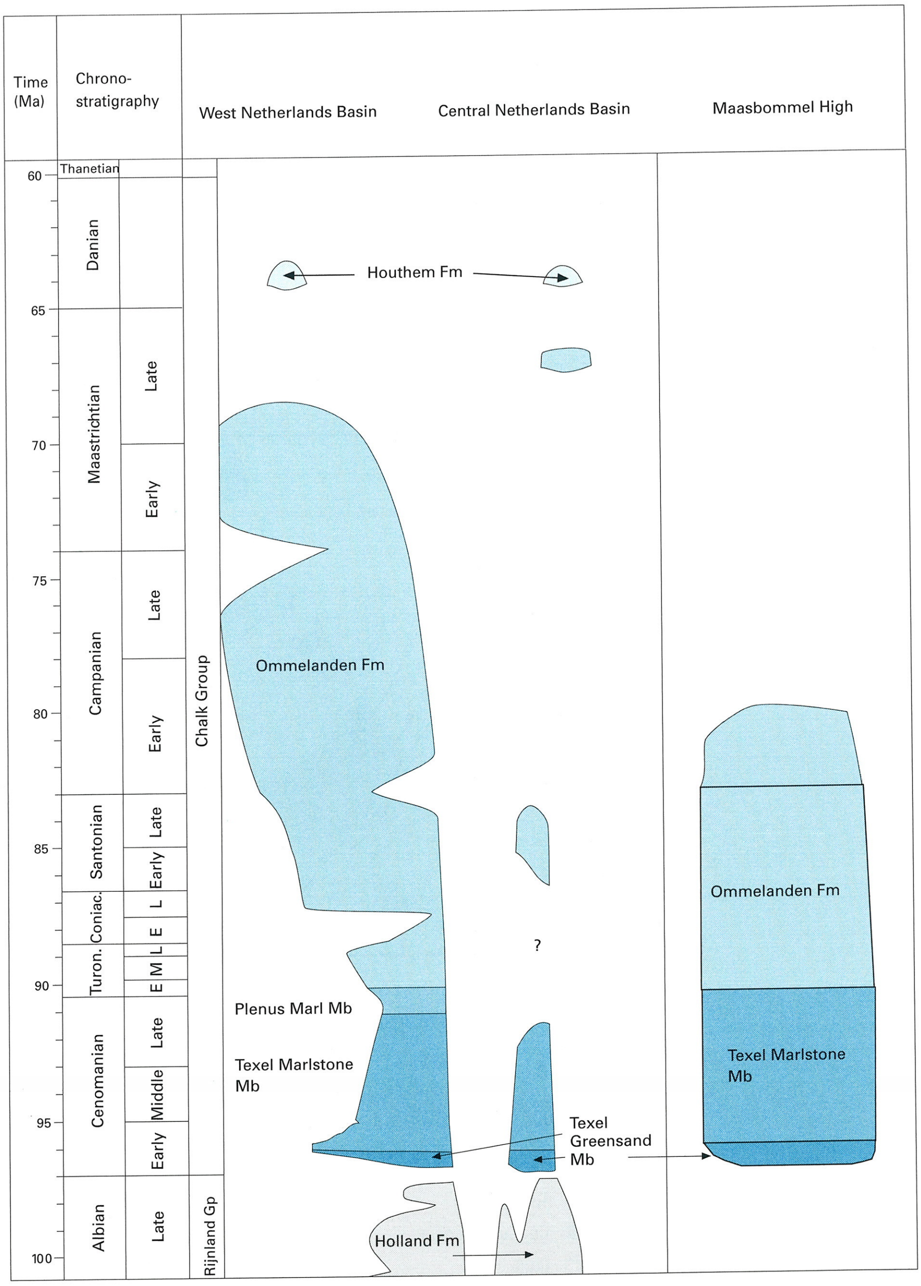
Various sandstones in the Vlieland Sandstone Formation form good reservoirs for hydrocarbons (Racero-Baena & Drake, 1994). The Rijswijk Member comprises a marine sand with the gross reservoir thickness of up to 140 m. The n/gr ratio is 60-85%, with a porosity of 15-28% and a permeability that may reach 4000 mD. The IJsselmonde Sandstone and Berkel Sandstone Members were deposited as coastal barriers in a prograding system and have a net sand thickness of up to 120 m, with a porosity of 20-30% and a permeability that may range from 400->3000 mD. The De Lier Member and the Holland Greensand Member of the Holland Formation have a gross reservoir thickness that may reach 100 m. The n/gr ratio is low, the porosity is 16-28% with a low permeability of 10-400 mD. Both members are considered less good reservoirs, as for example in the case of the Rotterdam and Berkel fields. Appendix E gives some reservoir calculations from the Berkel-4 and the IJsselmonde-55 wells.

11 Chalk Group

11.1 Stratigraphy

The Chalk Group consists predominantly of light coloured, hard, fine-grained bioclastic limestone and marly limestone. Intercalations of marls, calcareous claystones and, at the base, glauconitic greensands are also found. There are numerous chert concretions, which occur in isolation as well as in layers. The Chalk Group is subdivided into the Ommelanden and the Texel Formations (fig. 11.1).

Figure 11.1 Stratigraphic overview of the Chalk Group.

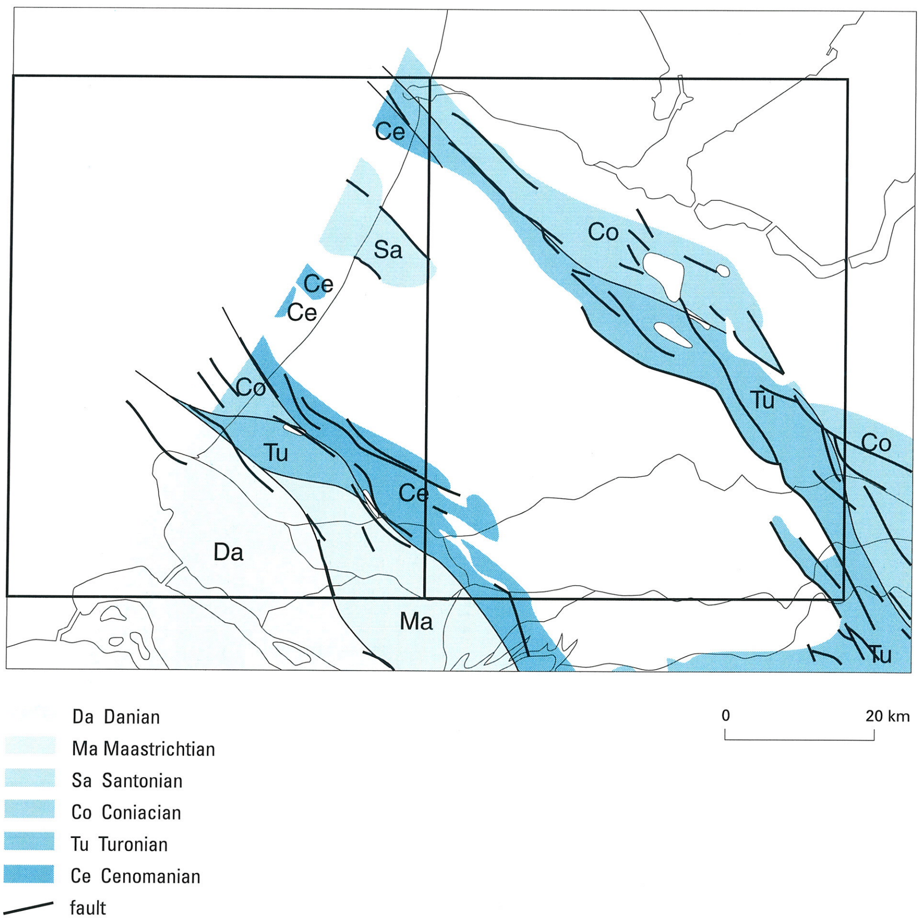


The Chalk Group is to a great extent absent in the map sheet area owing to inversion tectonics and subsequent erosion. In the major part of map sheet VIII and in the northern part of map sheet VII, the Chalk Group has been removed by erosion (fig. 11.2). In the West Netherlands Basins and on the Zandvoort Ridge, the group rests upon the Holland Formation separated by a minor unconformity. In the major part of the map sheet area, the Landen Clay Member (Lower North Sea Group) rests unconformably on the Chalk Group. At the southern margin of the West Netherlands Basin, the Breda Formation (Upper North Sea Group) rests immediately, unconformably upon the Chalk Group. In the north, on the Zandvoort Ridge, the Rupel Formation (Middle North Sea Group) rests unconformably on the Chalk Group.

In the southwestern part of the West Netherlands Basin, the base of the Chalk Group is at a maximum depth of 2 km. Towards the northeast of the map sheet area, the depth of the base gradually decreases to less than 500 m. Towards the north, the group is completely absent (Maps VII/VIII-12). In the vicinity of the Zandvoort Ridge, the Chalk Group is also present.

The preserved thickness of the Chalk group, of Cenomanian up to Danian age (fig. 11.1), has largely been determined by the inversion movements of the Sub-Hercynian and Laramide phases. In the

Figure 11.2 Extent of the Chalk Group.



strongly inverted northern part of the West Netherlands Basin and in the Central Netherlands Basin, the group has been removed by erosion entirely. In the southern part of the West Netherlands Basin, the thickness of the Chalk Group gradually increases to over 900 m. On the Zandvoort Ridge, the maximum thickness of the group is approximately 700 m (Maps VII/VIII-13). In the extreme southwest of the map sheet area the thickness is approximately 1200 m.

11.1.1 Texel Formation

The Texel Formation is found virtually throughout the entire areal extent of the Chalk Group. In the basins, the transition of the Holland Formation into the Texel Formation is very gradual and therefore the boundary is difficult to depict. Within the Texel Formation, the Texel Greensand, the Texel Marlstone and the Plenus Marl Members can be distinguished. The Texel Formation displays onlap in the direction of the Brabant Massif, and consequently has an increasingly younger base. In the West Netherlands Basin, the formation achieves a thickness of 100 m and pinches out towards the south. Further to the north, at the level of the Zandvoort Ridge, the thickness of the Texel Formation increases to over 200 m. The Texel Formation is Cenomanian to possibly earliest Turonian in age. In the basins, the base of the diachronous Texel Formation may well be of Late Albian age.

The base of the formation is formed by the *Texel Greensand Member.* This comprises glauconitic sands and is only encountered in the vicinity of the Rijen Fault and on the southern margin of the West Netherlands Basin. The thickness ranges from a few metres in the south to 40 m.

The *Texel Marlstone Member*, consists of an alternation of white marl sequences with a few limestone beds. The thickness of the sequence varies considerably, from a few metres in the south to over two hundred metres near the Zandvoort Ridge.

The *Plenus Marl Member*, latest Cenomanian to possibly earliest Turonian in age, consists of a calcareous, dark coloured laminated claystone, clearly distinguishable by high gamma-ray values. The sequence is generally a mere 1 to 2 m thick.

11.1.2 Ommelanden Formation

The Ommelanden Formation is found virtually throughout the entire areal extent of the Chalk Group formation comprises white, fine-grained limestone, which is locally argillaceous or marly. Abundant layers of chert concretions occur. The rocks predominantly comprise pelagic biogenetic remains.
The formation is not subdivided into members; but log correlations supported by datings enabled the various Cretaceous stages to be identified (fig. 11.3) and correlated (fig. 11.4).

The formation consists, at the base, of massive limestone of Turonian age, succeeded by more marly sequences of Santonian and Coniacian age. These, in turn, are overlain by a calcareous succession of the Campanian, which is marly to slightly sandy and which grades upward into massive limestone containing abundant chert nodules. Chalk of Maastrichtian age is found at the top of the Ommelanden Formation.

On the margins of the inverted basins, the topmost part of the Ommelanden Formation rests unconformably upon older deposits; for instance, this is the case near IJsselmonde (Maastrichtian Chalk on the Holland Formation). In the southwest, the formation is conformably overlain by the Houthem Formation, but further to the northeast, this formation has been removed by erosion owing to uplift and the Ommelanden Formation is unconformably overlain by the Landen Formation.

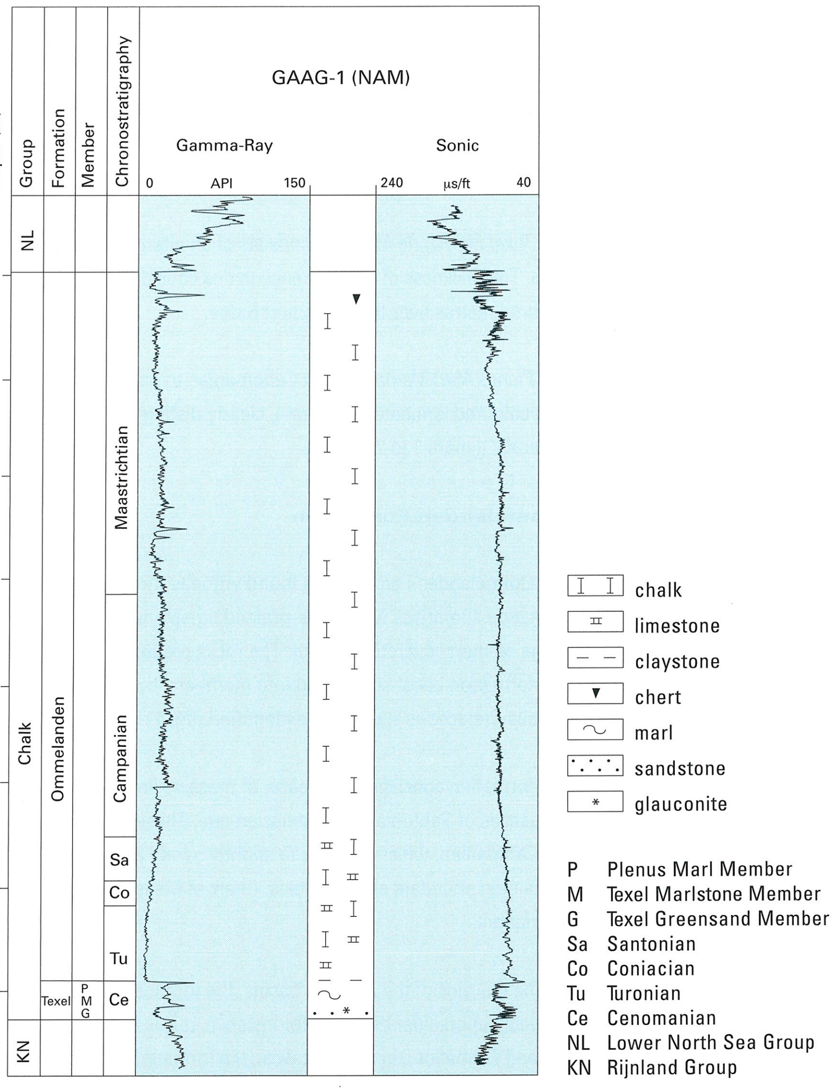
11.1.3 Houthem Formation

This formation, of Danian age, comprises soft, light-grey to light-yellow, fine to coarse-grained chalk. The formation is differentiated lithologically from the underlying Maastrichtian by the abundant argillaceous intervals, a clear example being immediately at the base of the interval. The formation contains calcite concretions, hardgrounds and fossil hash layers. The bottommost part of the formation is characterised by the occurrence of glauconite. The formation is found in the southwestern part of the map sheet area. The formation is approximately 75 m thick.

11.2 Sedimentary development and palaeogeography

The earliest Cretaceous was marked by a global sea-level rise, with a maximum highstand during the Late Cenomanian (Haq et al. 1987; Ziegler, 1990). A highstand prevailed until the end of the Cretaceous.

Figure 11.3 Stratigraphic division and log pattern of the Chalk Group in the Gaag-1 well.



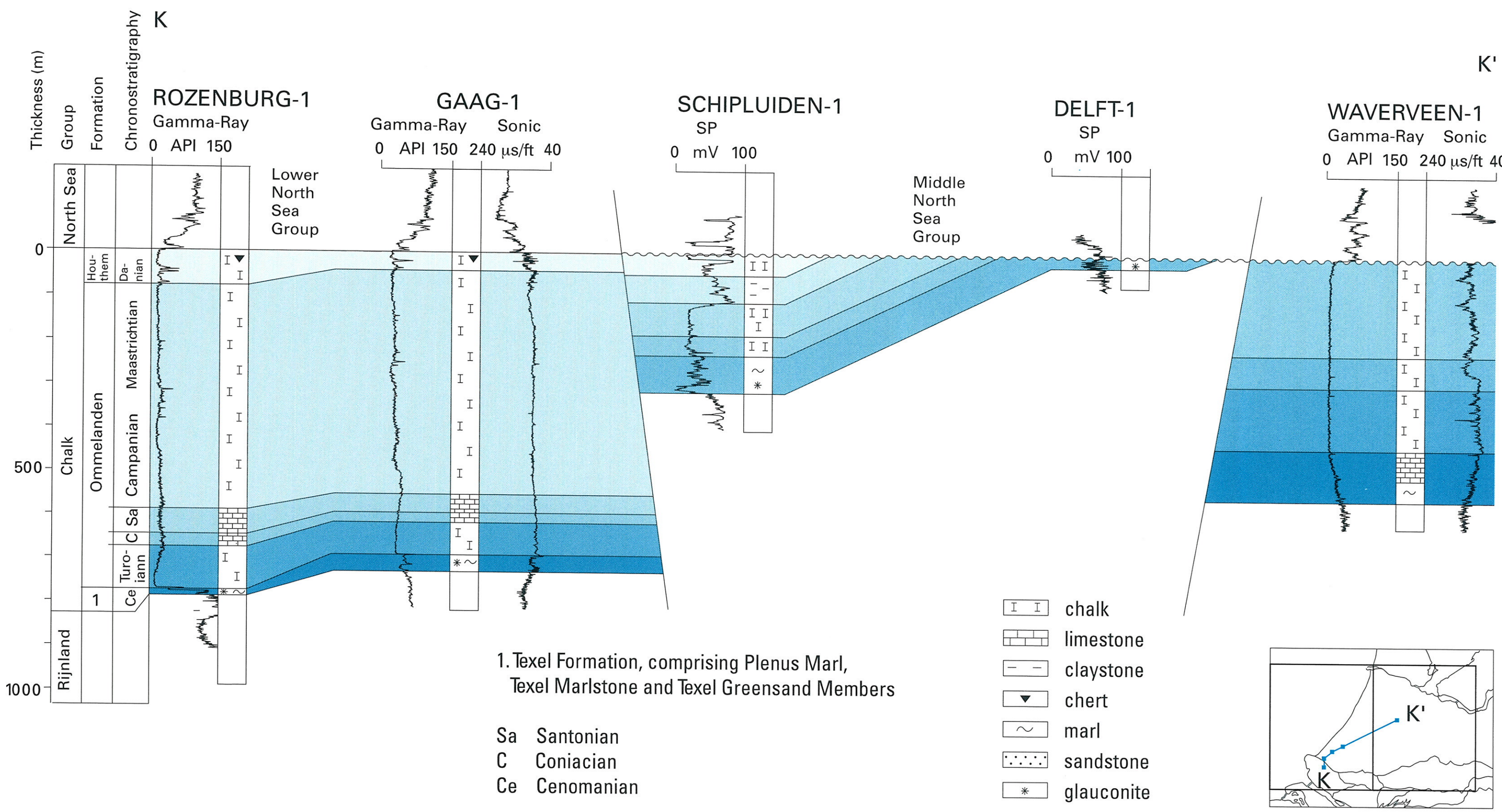


Figure 11.4 Stratigraphic section K-K' of the Chalk Group between the Rozenburg-1, Gaag-1, Schipluiden-1, Delft-1 and Waverveen-1 wells. The reference level is the base of the North Sea Supergroup.

This sea-level rise resulted in a transgressive succession at the base of the Chalk Group. Along the basin margin, greensands of the Texel Formation were deposited by a gradual southward coastal migration; these glauconite-rich sands were covered by the sediments of the Texel Marlstone Member. The high glauconite concentration in the sands of the Texel Greensand indicates a low sedimentation rate and considerable biogenic activity, thus confirming the transgressive character of the Texel Greensand succession.

During the highstand of the Late Cenomanian, the Plenus Marl was deposited basin-wide. The organic-rich character of this argillaceous marl points to anoxic conditions near the sea floor. This anoxic period has been identified globally (Schlanger et al., 1987).

During the Turonian, a succession of pure limestone was deposited. The low percentage of clays is attributed to the highstand, which caused flooding of the clastic source areas , which subsequently played no further role in sediment supply. In the succession of the Late Turonian and overlying stages, the clay percentage again gradually increases. The increase in the clastic supply was caused by uplift of former basins during the Sub-Hercynian inversion phase in the Santonian and Early Campanian. In the map sheet area, the West and Central Netherlands Basins was inverted. The horsts, on the other hand, displayed subsidence. Uplift activated the supply of sediment from the former basins to the adjacent new basins and a part of the Cenomanian-Campanian interval was removed by erosion.

12 North Sea Supergroup

12.1 Stratigraphy

The North Sea Supergroup is subdivided into the Lower, the Middle and the Upper North Sea Groups (fig. 12.1) and is composed almost entirely of sands and clays (fig. 12.2). The three groups are separated from each other by unconformities. The North Sea Supergroup rests conformably or unconformably upon the Chalk Group, or unconformably upon older lithostratigraphic units, such as the Rijnland, the Schieland, the Altena and the Upper Germanic Trias Groups. The sedimentation was to a large extent influenced by a combination of regional tectonics and eustatic sea-level changes. In the map sheet area, marine conditions were predominant during deposition of the group (Letsch & Sissingh, 1983).

The North Sea Supergroup is present throughout the map sheet area. The thickness ranges from a maximum of 1200 m in the Voorne Trough to nearly 400 m on the Kijkduin High in the vicinity of Delft (Maps VII-14 and VIII-14). In the Voorne Trough, all three groups are present (fig. 12.3); on the Kijkduin High, the Cenozoic section is composed almost entirely of the Upper North Sea Group. The Quaternary deposits are discussed in the "Toelichtingen bij de Geologische kaart van Nederland 1:50.000" (Rijks Geologische Dienst, 1970, 1979, 1984, 1989 and 1995).

12.1.1 Lower North Sea Group

The Lower North Sea Group, deposited during the Late Palaeocene and the Eocene, is composed of the Landen and Dongen Formations and is found in the Voorne Trough and in the Zuiderzee Low. Both formations were initially deposited throughout the map sheet area but (fig. 12.3) owing to erosion, following the uplift during the Pyrenean tectonic phase (Late Eocene to Early Oligocene), these formations are absent in the most inverted sectors of the map sheet area. The deposits rest conformably and unconformably on the Chalk Group or unconformably on the Rijnland, the Schieland, the Altena and the Upper Germanic Trias Groups and are unconformably overlain by the Middle or Upper North Sea Group. The thickness of the group is a maximum of 700 m in the Voorne Trough. In the north, the thickness is a little over 200 m.

12.1.1.1 Landen Formation

The Landen Formation, of Late Palaeocene age, comprises the Heers, the Landen Clay and the Gelinden Members. In the Zuiderzee Low, the Swalmen Member has been encountered below the base of the Heers Member in a few wells.

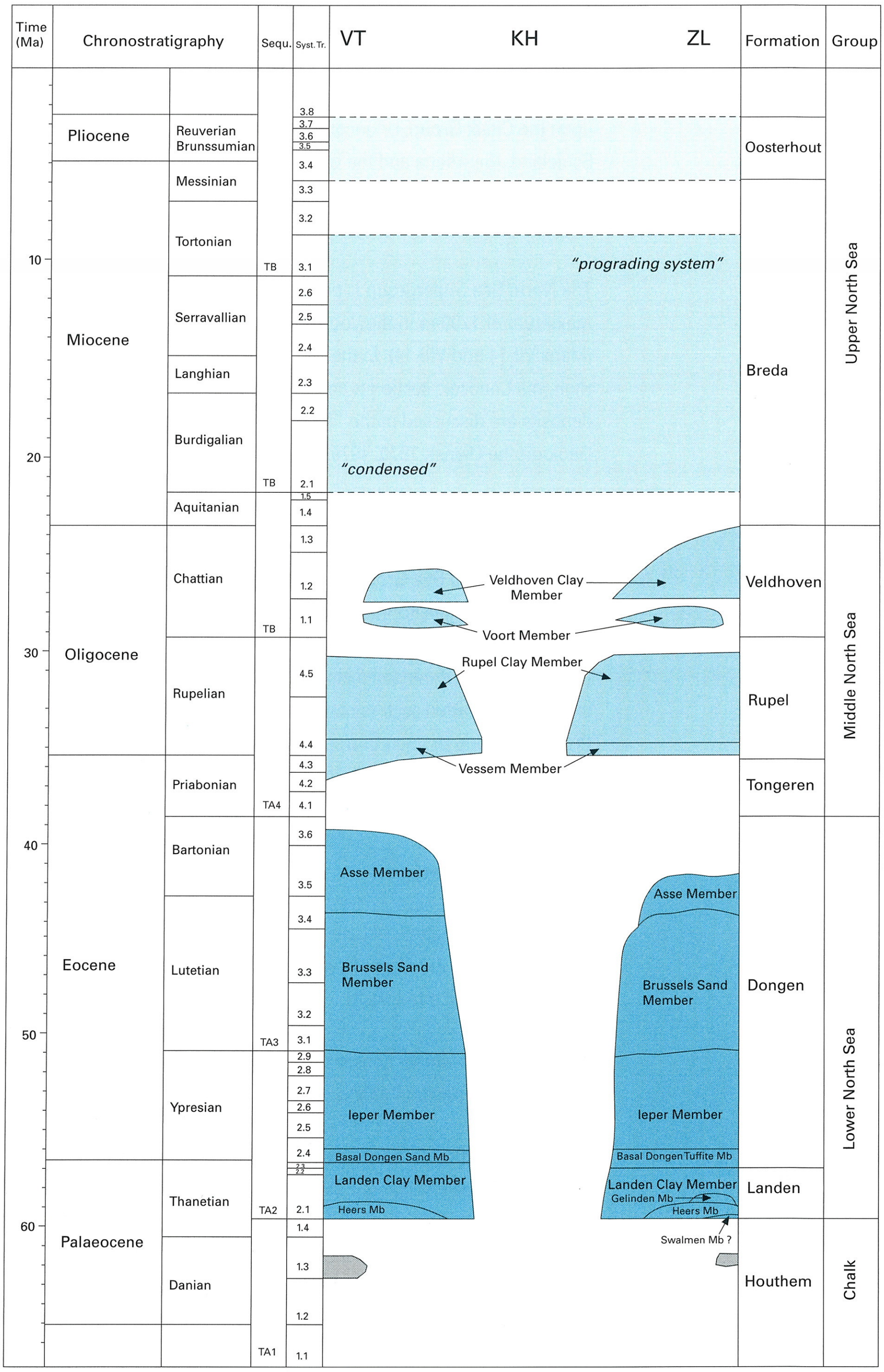
The *Swalmen Member* consists of a sandy and argillaceous sequence containing a few small brown coal seams. This deposition only occurs in the Zuiderzee Low. Here, the maximum thickness is 10 m.

The *Heers Member* is a very fine-grained greenish-grey glauconite-rich sand, locally cemented into sandstone by calcite cement. In a northwesterly direction, the unit passes laterally into the Landen Clay. The thickness is a maximum of approximately 15 m in the southeast of the Voorne Trough and is 36 m in the northeast of the map sheet area.

The *Gelinden Member* comprises greyish-white to yellowish-brown, argillaceous marls with yellow concretions. The base generally consists of dark green, marly clay. The thickness varies from 5 to 25 m in the Zuiderzee Low; in the vicinity of the Maasbommel High, thicknesses of a few metres have been encountered.

The *Landen Clay Member* is a dark-grey, pyrite-bearing and glauconitic clay sequence. The thickness ranges from 45 to 70 m but quickly pinches out towards the Kijkduin High owing to erosion. In the north of the map sheet area, the thickness is a mere 10 to 30 m.

Figure 12.1 Stratigraphic overview of the North Sea Supergroup showing the lithostratigraphic units occurring in the map sheet area.



VT Voorne Trough
KH Kijkduin High
ZL Zuiderzee Low

12.1.1.2 Dongen Formation

The Dongen Formation, of Eocene age, is composed of the Basal Dongen Sand, the Basal Dongen Tuffite, the Ieper, the Brussels Sand and the Asse Members. The formation is only found in the Voorne Trough and adjacent area and in the Zuiderzee Low. As a result of erosion, the formation is absent or drastically reduced in thickness in the interlying area.

The *Basal Dongen Sand Member*, of Early Eocene age, consists of fine-grained, brown humus, sometimes glauconitic sand. The occurrence is restricted to the Voorne Trough and the area around the Maasbommel High. The thickness is generally restricted to 10 to 15 m.

The *Basal Dongen Tuffite Member* is an alternation of brown clay with small tephra layers. The succession is clearly identifiable on well logs by its low natural radioactivity and a high acoustic velocity. The unit is found in the northeastern part of the map sheet at a thickness of 10 to 20 m.

The *Ieper Member*, of Early Eocene age, consists of brownish-grey and reddish-brown clay at the base and sandy clay at the top and may, locally, contain pyrite, shells, coalified plant remains and benthic foraminifera. The clays contain sandy and silty horizons. The topmost part of the unit is characterised by the presence of greenish-grey, glauconitic and marly sand intercalations. The member reaches a thickness of over 300 m in the Voorne Trough.

The *Brussels Sand Member* consists of fine-grained, glauconitic sands with, particularly at the top, many thin limestone and sandstone beds. In the Voorne Trough, the unit is over 300 m thick, while in the Zuiderzee Low, the sand achieves a thickness of a mere 30 m. The primary thickness of the member decreases towards the former West Netherlands Basin.

The *Asse Member* is a highly plastic and greenish-grey to bluish-grey calcareous clay. The member is found locally in the Voorne Trough at thicknesses up to 100 metres and in the Zuiderzee Low, reaches a thickness of 25 m.

12.1.2 Middle North Sea Group

In the map sheet area, the Middle North Sea Group, of Oligocene age, comprises the Rupel and Veldhoven Formations. With the exception of a small area in the vicinity of Delft, the group is found throughout the map sheet area. The greatest thickness, approximately 250 m, occurs in the Voorne Trough.
The Middle North Sea Group rests upon the Lower North Sea Group separated by a minor unconformity or unconformably upon older deposits such as the Chalk, the Rijnland, the Schieland and the Upper Germanic Trias Groups and is covered, also unconformably, by the Upper North Sea Group. The thickness of the group on the Kijkduin High is exceptionally reduced, as a result of minimal deposition as well as erosion.

12.1.2.1 Rupel Formation

The Rupel Formation, of Priabonian up to Rupelian age, occurs throughout the map sheet area and reaches thicknesses of approximately 250 m. The formation is composed of the Vessem and Rupel Clay Members.

The *Vessem Member* comprises very fine, greenish-grey glauconite-bearing sands with a few argillaceous intercalations. The thickness is the greatest in the Voorne Trough, where values in excess of 100 m are attained. Towards the flanks of the Trough, the thickness rapidly decreases to less than 10 m on the Kijkduin High. In the Zuiderzee Low, the member is over 30 m thick.

The *Rupel Clay Member* consists of a sequence of brown to greyish-brown stiff clay, characterised by pyrite and septarian nodules. In the Voorne Trough, the Rupel Clay reaches a thickness of 140 m; towards the flanks, this unit also rapidly decreases. On the Kijkduin High, the observed thickness of 15 to 50 m has been strongly determined by erosion. The unit is found virtually throughout the map sheet area.

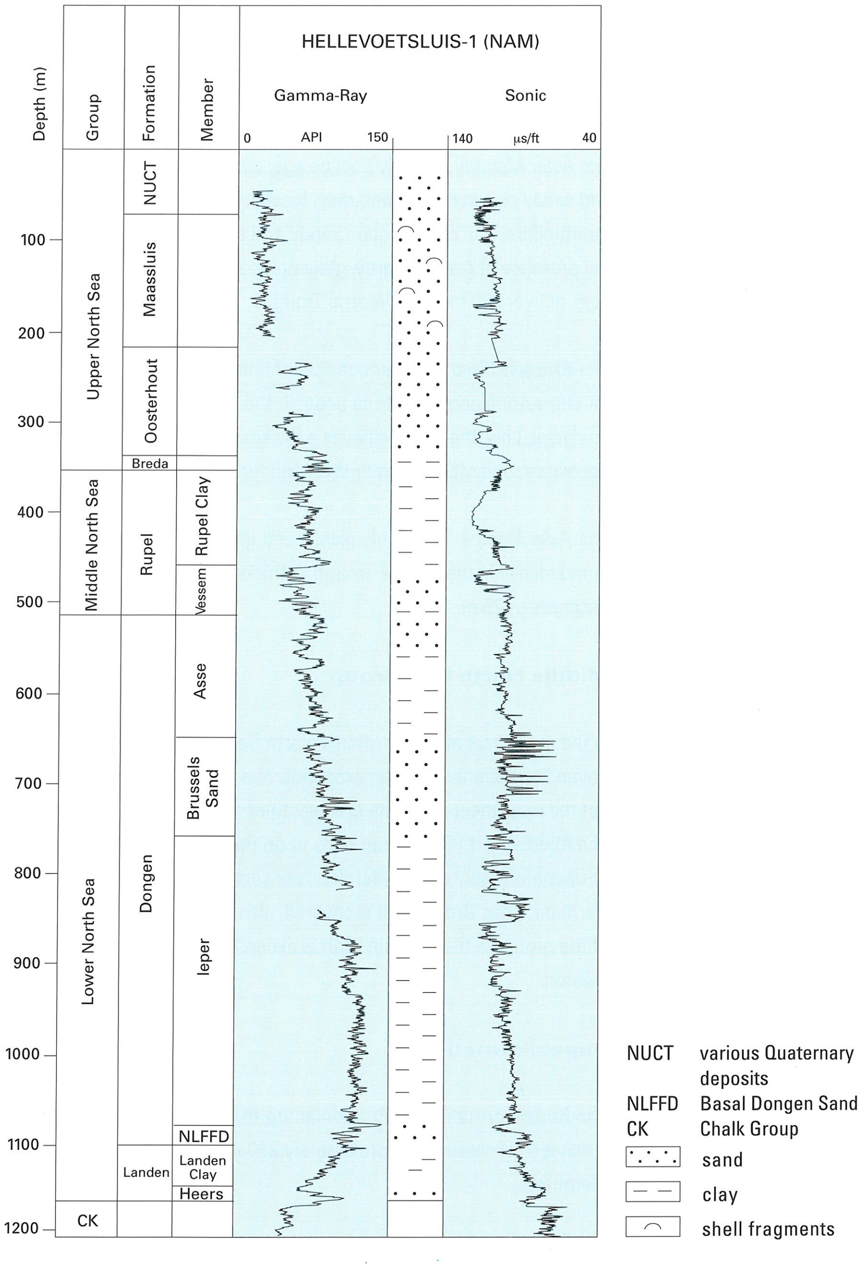


Figure 12.2 Stratigraphic division and log pattern of the North Sea Supergroup in the Hellevoetsluis-1 well.

12.1.2.2 Veldhoven Formation

The Veldhoven Formation, of Chattian age, like the Rupel Formation consists of a sandy base overlain by a clay sequence, the Voort and Veldhoven Clay Members. The thickness is a maximum of 30 to 40 m in the map sheet area.

The *Voort Member*, comprising a succession of coarsening-upward sandy units, achieves a thickness of a few metres in the map sheet area to over 100 m to the east of the map sheet area. In the areas where this unit is several metres thick, the log characteristics are those of a fining-upward transgressive sand.

The *Veldhoven Clay Member* achieves its greatest thickness of over 100 m in the northeast of the map sheet area. Within the map sheet area, the unit is 10 to 40 m thick. This member is composed of silty clays and, at the top, sandy clays.

12.1.3 Upper North Sea Group

In the map sheet area, the Upper North Sea Group, of Miocene to Quaternary age, comprises the Breda and Oosterhout Formations and Quaternary deposits. The group rests disconformably upon the Middle North Sea Group or unconformably upon older deposits of the Chalk and Rijnland Groups. The group reaches its maximum thickness, over 1000 m, in the Zuiderzee Low (Map VIII-15).

12.1.3.1 Breda Formation

The deposits of the Breda Formation in the Voorne Trough are characterised by an argillaceous section with a maximum thickness of 10 to 20 m. In the Zuiderzee Low, thicknesses of 500 m and over are found (fig. 12.5). The lithological composition displays similarities with the deposits in the Roer Valley Graben. The basal, argillaceous part of the formation comprises two to three coarsening-upward intervals and is approximately 150 m thick. The overlying sandy part comprises a bipartition, each unit displaying a prograding character; the bottommost unit is 200 m and the topmost, approximately 150 m thick. The Breda Formation has a Miocene age (RGD, 1983; TNO-NITG, 2001a).

12.1.3.2 Oosterhout Formation

The Oosterhout Formation, of Pliocene age, is a predominantly sandy, glauconite-rich formation. In the eastern part of the map sheet area, the unit achieves a thickness of 150 m. In the western part, the formation consists of prograding sands, which achieved considerable thicknesses, in excess of 250 m in the later Pliocene.

12.1.3.3 Maassluis Formation

The Maassluis Formation, of Pleistocene age, is found throughout the map sheet area. The thickness ranges from a few tens of metres in the east to 250 m in the west. The formation consists of fine to coarse-grained sands with shell fragments, and the occasional local intercalation of sandy clay layers and clay lenticles.

12.2 Sedimentary development and palaeogeography

During deposition of the North Sea Supergroup, the map sheet area was situated near the southern margin of the North Sea Basin. The depositional pattern was largely controlled by tectonic surface

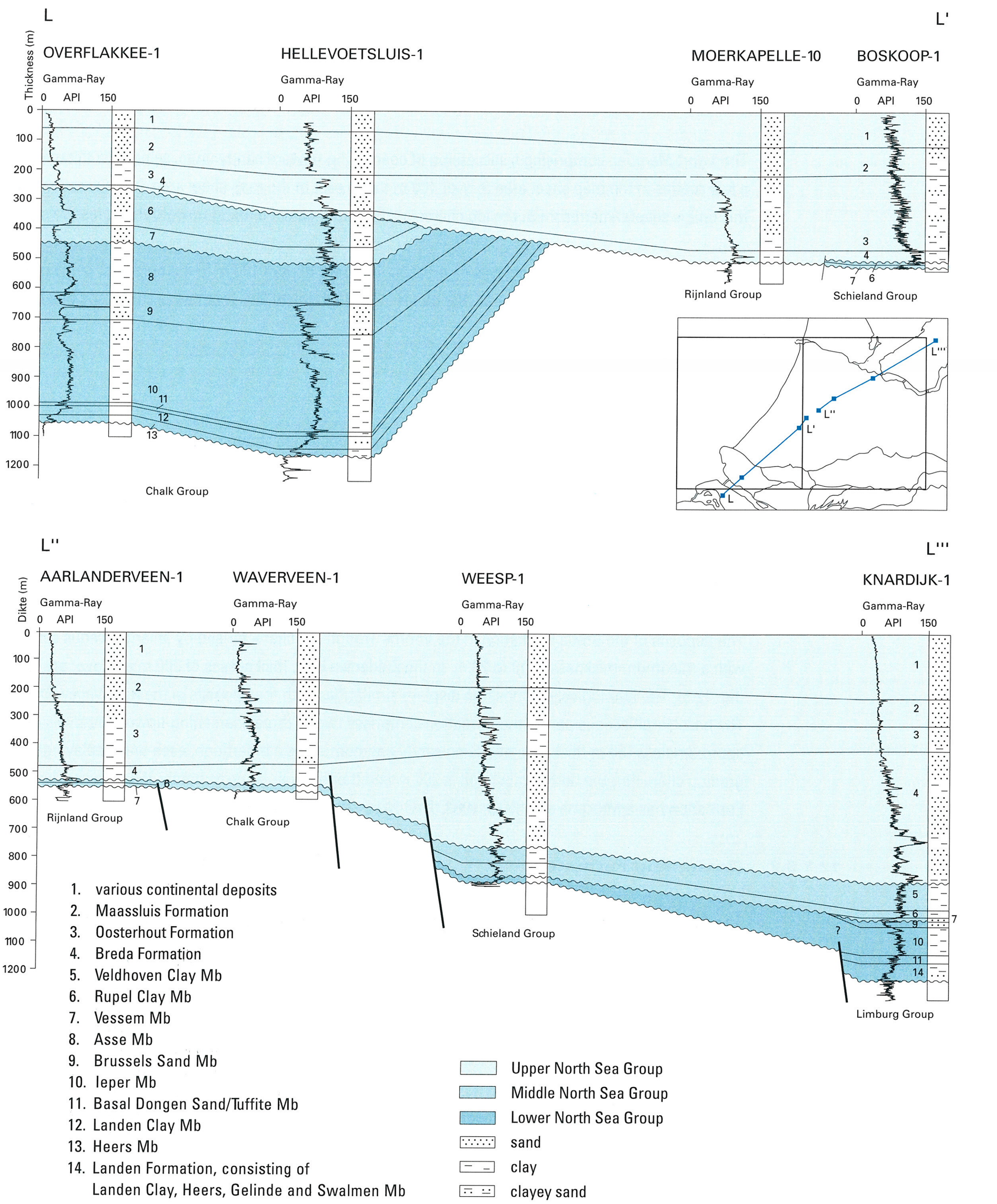


Figure 12.3 Stratigraphic sections L-L' and L''-L''' of the North Sea Supergroup between the Overflakkee-1, Hellevoetsluis-1, Moerkapelle-10, Boskoop-1, Aarlanderveen-1, Waverveen-1, Weesp-1 and Knardijk-1 wells. These sections clearly illustrate the differential tectonic movements and consequent erosion. On section L''-L''', the thickening of the Breda Formation in the Zuiderzee Low (Knardijk-1 well) can be clearly traced, while the Oosterhout Formation displays a thickening in the area to the southwest of the Zandvoort-Krefeld High.

movements and eustatic sea-level fluctuations. Of particular importance were the tectonic movements of the Roer Valley Graben, to the southeast of the map sheet area, the former West Netherlands Basin, and the movements of the Zandvoort-Krefeld High.

Following the Laramide phase, a period commenced during which predominantly clastic sediments were deposited in marine conditions. The first transgression subsequent to the Laramide phase resulted in the deposition of the sediments of the Landen Formation during the Late Palaeocene. Subsequently, the persevering transgression facilitated deposition of the marine sands, clays and marls of the Dongen Formation. At the end of the Eocene, during the Pyrenean tectonic phase, subsequent erosion occurred, accounting for the absence of the Eocene and the Palaeocene deposits in large parts of the map sheet area. However, in the Voorne Trough and the Zuiderzee Low, these deposits have been preserved from erosion.

The deposits of the Rupel Formation reflect the resumption of sedimentation in the map sheet area in the Early Oligocene. The conditions were initially shallow-marine and later open-marine. There are no indications of differential subsidence of the area and the uniform character of the Rupel Clay suggests deposition in a vast marine basin. During the Late Oligocene, deposition of the Veldhoven Formation took place in a shallow-marine environment in an area extending on from the Roer Valley Graben. In the Late Oligocene, the Voorne Trough was no longer an area of subsidence and deposition is presumed not to have occurred here.

During the Oligocene-Miocene transition, regional uplift resumed during the Savian phase. This, together with a lowstand, culminated in regional erosion during the Early Miocene, truncating the Late Oligocene sediments over a vast area. In the area of the Voorne Trough, sediments of the Breda Formation are found, indicating minimal sedimentation; the Zuiderzee Low was characterised by a prograding system that was part of a vast protruding coastal system in North Western Europe that persevered into the Pliocene in the map sheet area and into the Pleistocene in the northern offshore area (Bijlsma, 1981; Zagwijn, 1989).

During the Late Pliocene, in the western part of the map sheet area, thick sequences of sediment of the Oosterhout Formation were deposited in a prograding system. During the Miocene and the Pliocene, the sea withdrew from the east and southeast of the map sheet area. In the Quaternary, during the deposition of the Maassluis Formation, marine conditions still prevailed in the map sheet area, but owing to intensified uplift of the hinterland, the subsequent Quaternary deposits were predominantly continental.

13 Geological history

13.1 Introduction

This chapter describes the geological history of the map sheet area, from the Cambro-Silurian to the Quaternary. Data on the pre-Carboniferous in the map sheet area are non-existent. For this period, the description is based entirely upon publications on the surrounding areas. For details of the Quaternary of the map sheet area, reference should be made to the publication by Zagwijn (1989), the "Toelichtingen bij de geologische kaart van Nederland 1:50.000", map sheets "Gorinchem Oost, Rotterdam West, Tiel West en Oost, Utrecht Oost en Gorinchem West "(Rijks Geologische Dienst, 1970, 1979, 1984, 1989 and 1995 resp.).

The geological history of each subsequent period is illustrated by the different tectonic phases that were active in the map sheet area and environment (fig. 1.5). The Late Carboniferous to earliest Permian period was characterised by the Variscan Orogeny, related to the forming of the Variscan Mountains to the south and east of the map sheet area. During these tectonic phases, the broad outlines of the structural framework were formed. The Late Triassic to earliest Cretaceous was marked by the Kimmerian tectonic phases; these extensional phases were associated with the disintegration of Pangaea and were responsible for the formation of major structural units in the Mesozoic, such as the West Netherlands Basin and the Central Netherlands Basin. The Sub-Hercynian phase during the Late Cretaceous and Tertiary displayed a compressive stress field, causing a brief change (inversion) in the direction of movement of the major fault systems and structural elements. The tectonic phases during the Tertiary (Laramide, Pyrenean and Savian phases) are related to stages in the opening of the Atlantic Ocean and to the Alpine Orogeny. The tectonic phases, together with the climate changes and associated sea level fluctuations (Haq et al., 1987), were the determining factors in the geological development of the area.

The geographic position of the map sheet area in a regional context is illustrated in figure 13.1. The principal structural elements discussed in this chapter are outlined in figure 3.1. The NE-SW sections (fig. 13.5 and fig. 13.6) provide a clear view of the structural development of the area.

13.2 Basin development, sedimentation and tectonics

13.2.1 Carboniferous

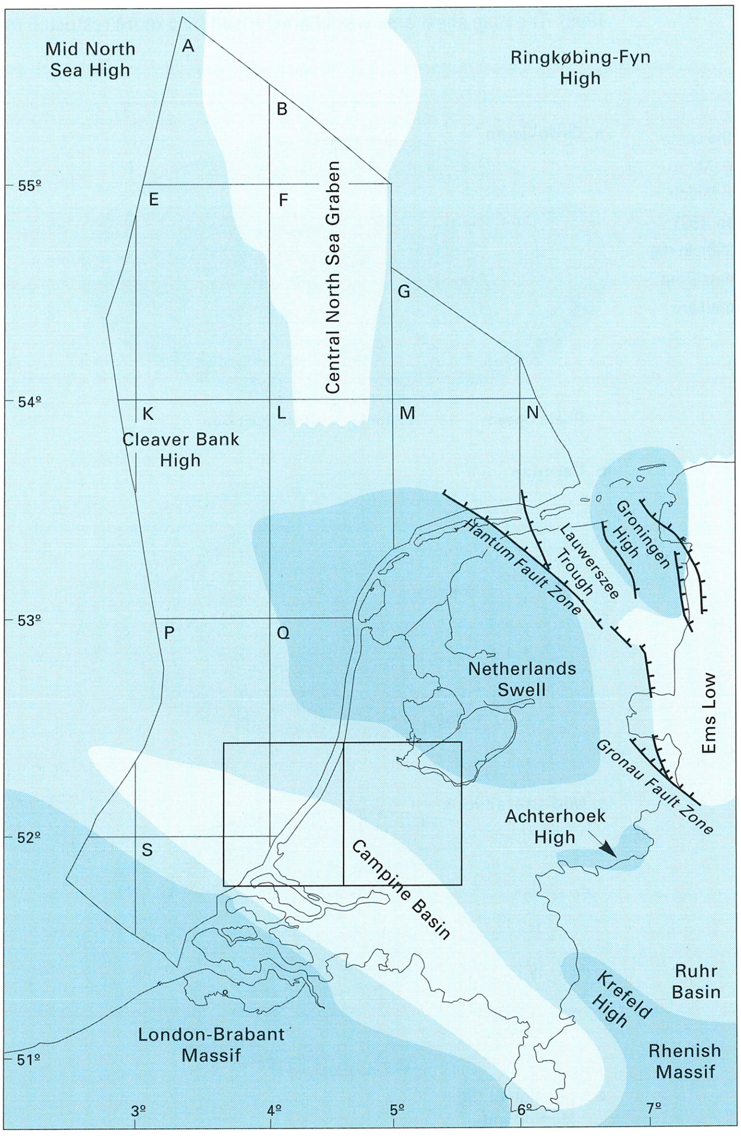
The Late Viséan was marked by the collision of Gondwana and Laurussia, responsible for the development of the Supercontinent Pangaea (fig. 13.2), induced a change from extension to a compression in the foreland basin (Sudetic phase). The basin to the north of the Variscan thrust front became a foreland basin and was characterised by rapid subsidence. During the Namurian and Westphalian, large quantities of clastic material were transported from the south, gradually filling up the deep foreland basin. The Namurian is characterised by deep-water deltas, the Westphalian by coal-bearing, shallow delta deposits. The strongly cyclical nature of these deposits is attributed to highly frequent, regular eustatic sea-level fluctuations (Leeder, 1988).

Halfway through the Westphalian, the culmination of the Variscan Orogeny occurred and the most northerly position of the thrust front was reached. The Westphalian C and D consequently display a very sandy development. The depositional pattern was dominated by fluvial systems under increasingly drier conditions. From the Westphalian C on, the deposits in the foreland were folded and local areas were uplifted (for example the Netherlands Swell), initiating intra-Westphalian erosion. In the map sheet area, however, the sedimentation persisted into the late Westphalian D. During the Stephanian, a regional system of transverse movements developed in response to the dextral movement of Laurussia in relation to Gondwana. The faults within this system have a NW-SE orientation and are thought to be reactivated Caledonian lineaments. This fault system was reactivated several times during the course of geological history, making a major impact on the subsequent basin development in the map sheet area. In the Stephanian and Early Permian periods, the deposits in the foreland became uplifted and were folded in wide anticlines; in the foreland, parts of the Westphalian were affected by contemporaneous erosion.

13.2.2 Permian

After a long period of non-deposition and erosion during the Permian, sedimentation did not resume until the Late Permian. Owing to thermal subsidence and transtensional movements along the Late Variscan transverse movement system, the Southern Permian Basin formed to the north of the Variscan

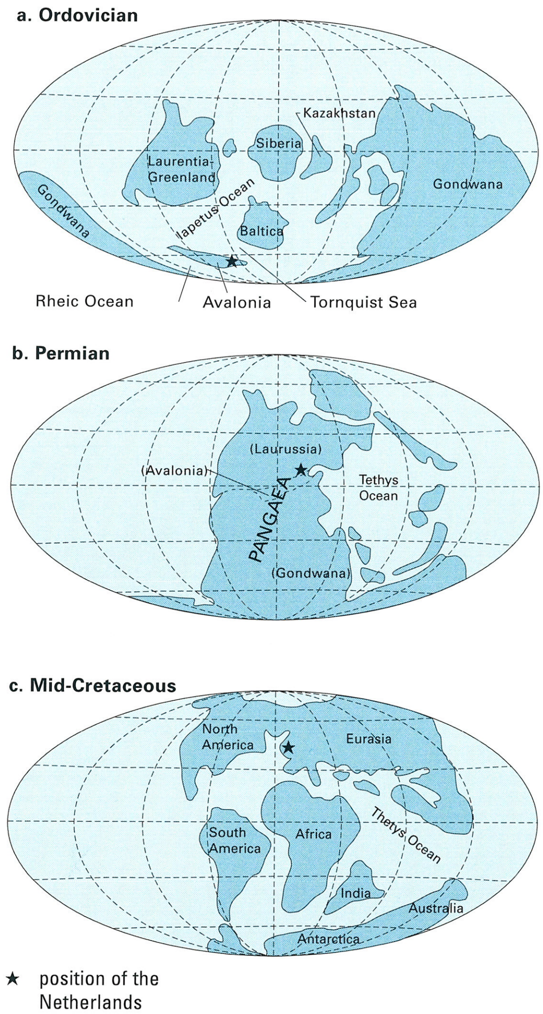
Figure 13.1 Overview map of the principal structural elements in the Netherlands during the Late Carboniferous. The position of the map sheet area is outlined.



mountain chain (Ziegler, 1990). This basin gradually extended from Germany and Poland towards the west. In the map sheet area, owing to the position on the southern margin of the Southern Permian Basin, only a thin Rotliegend succession was deposited. Towards the north, its thickness within the map sheet area increases on a large scale. Thickness differences on a smaller scale suggest that a NW-SE oriented graben was present in the map sheet area, through which sand was transported towards the northwest by aeolian and fluvial systems.

At the end of the Saxonian, a catastrophic transgression preluded the Zechstein depositional system (Glennie, 1998). The high sea level brought an end to the clastic sedimentation dominating the Rotliegend system. In the Southern Permian Basin, a succession of five to six carbonate-evaporite cycles were formed (Taylor, 1998). Only the Z1, Z2 and Z3 cycles are fully developed in the map sheet area. In the south of the Central Netherlands Basin, a thin Z4 succession has also been identified. The regular alternation of marine carbonates, anhydrite and halite is explained by sea-level fluctuations and a contemporaneous, episodical connection with and separation from the marine domain (Tucker, 1991; Taylor, 1998). The map sheet area was characterised by a more restricted marine influence. The Zechstein

Figure 13.2 Position of the continents and oceans during the Ordovician, Permian and Middle Cretaceous (after Scotese, 1991; Scotese & McKerrow, 1990). In the middle figure, the elements from which Pangaea was formed are given in brackets.

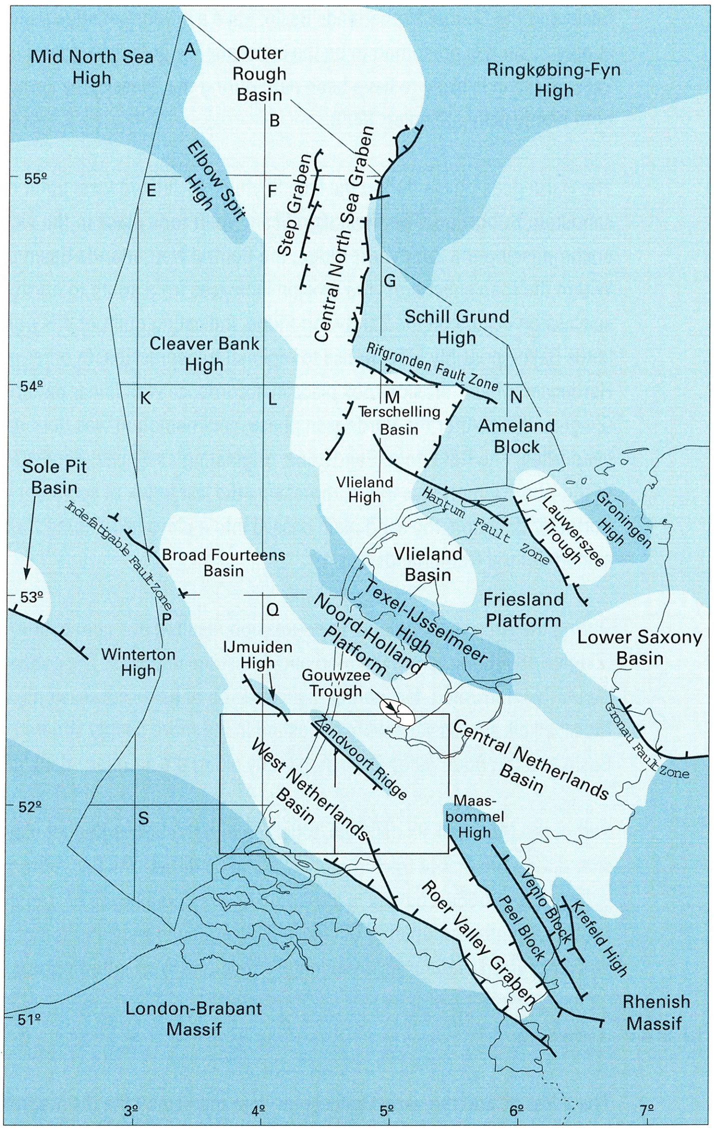


succession in the map sheet area, which is dominated by sabkha clays in the onshore and fluvial sands in the offshore area, was less affected by marine processes owing to the marginal position on the extreme southern margin of the Southern Permian Basin. In the Central Netherlands Basin, a thick anhydrite-halite succession was deposited.

13.2.3 Triassic

The thermal subsidence continued during the Triassic. The most pronounced subsidence during the Early Triassic period occurred in the West Netherlands Basin and the Roer Valley Graben. Via these interconnected basins, a large quantity of sediment was transported from the southeasterly Variscan massifs via the Trier Basin (Wuster, 1968); some of this reached the central part of the Southern Permian Basin. The Brabant Massif also periodically supplied sediment (Ziegler, 1990). During the Early Triassic,

Figure 13.3 Overview of the principal structural elements in the Netherlands during the Late Jurassic to Early Cretaceous. The position of the map sheet area has been outlined.



the Zandvoort Ridge was characterised by subsidence which lagged behind that of the surrounding area. In the Central Netherlands Basin, to the north of the ridge, the more pronounced subsidence resulted in a thicker sediment succession.

The Lower Buntsandstein Formation was deposited under predominantly lacustrine conditions; the fluvial system extended as far as the Roer Valley Graben (TNO-NITG, 2001a). Both the West Netherlands Basin and the Central Netherlands Basin were part of an extensive central basin, which was dominated by the deposition of argillaceous material. The regional character of this basin can be inferred from the occurrence of regionally correlatable oolite intercalations (Geluk & Röhling, 1997). The sediment was transported via a large-scale braided fluvial system which, in varying degrees, prograded in a north-westerly direction over the course of time. Owing to the dry climate, this fluvial system was active only periodically. The centre of the basin contained a playa lake that was dominated alternately by lacustrine, fluvial and aeolian sedimentation processes, probably the result of climatological changes. The deposits of the Main Buntsandstein Subgroup, in the Roer Valley Graben as well as in the West Netherlands Basin and the Central Netherlands Basin, have a predominantly sandy, fluvial character. The large-scale supply of sand is presumed to be the consequence of fault tectonics in the hinterland, of which the Roer Valley Graben is likely to have been part: during the Triassic, the Tethys and the Arctic rift systems were both highly active (Ziegler, 1990).

The Hardegsen phase during the Late Scythian facilitated local uplift of and erosion of the Main Buntsandstein Subgroup. The most significant uplift took place in the vicinity of the Netherlands Swell, encompassing the Zandvoort Ridge, the Central Netherlands Basin and the Texel-IJsselmeer High. Within the map sheet area, the erosion increases from south to north; the thinnest Main Buntsandstein succession occurs on the Zandvoort Ridge, indicating uplift of this northern flank of the West Netherlands Basin, possibly in response to regional transpression. In other parts of Western Europe, during the Hardegsen phase, erosion took place in accordance with linear patterns, which points to transpression (Ziegler, 1990). After the Hardegsen phase, sedimentation was dominated by clays, carbonates and evaporites. The Röt Fringe Sandstone, originating as alluvial deposits along the southern basin fringe of the West Netherlands Basin, represents the last influx of sediment with a southern provenance. In a northerly direction, the sand plain passed into a playa lake. Halite was deposited in the more deeply seated Central Netherlands Basin.

During the Anisian, a regional transgression resulted in a connection, via the east, with the Tethys ocean (Ziegler, 1990), triggering the marl and limestone deposits. The connection with the marine domain was regularly interrupted, facilitating the formation of halite successions. Within the map sheet area, these Muschelkalk successions were deposited in the more deeply situated parts of the West Netherlands Basin and the Roer Valley Graben, namely along the southern flank of the Zandvoort-Krefeld High.

Part of the Muschelkalk deposits, together with the Lower Keuper clays and evaporites, underwent erosion during the first of the Kimmerian tectonic phases. The Early Kimmerian unconformity was observed in large parts of Europe and is attributed to a regional phase of transpressional tectonics, during which basin margins were uplifted (Ziegler, 1990). Following resumption of basin subsidence, sedimentation again occurred under arid, continental conditions in an intramontane sabkha plain.

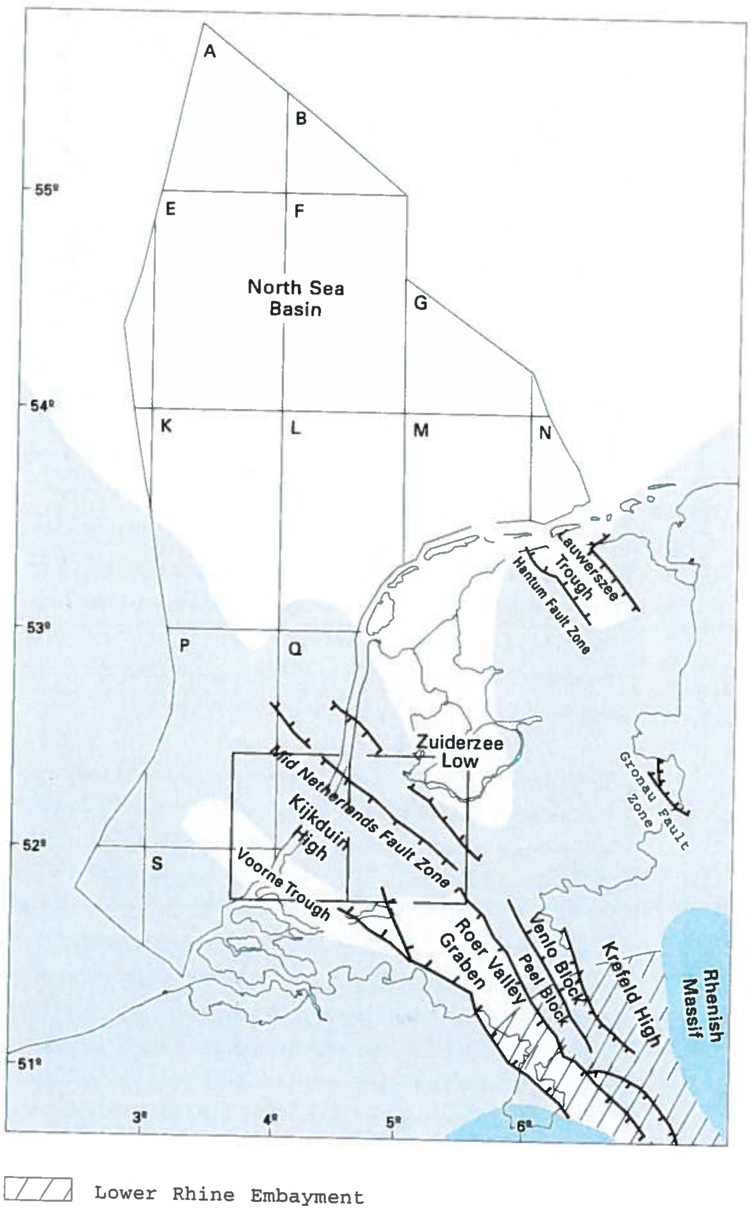
13.2.4 Jurassic

The Jurassic and the early Cretaceous were marked by the disintegration of Pangaea. The evolution of the North Atlantic/Arctic and the Biscay rift system had a great effect on the rift and subsidence history of the West Netherlands Basin and the Central Netherlands Basin (fig. 13.3). The Central Graben of the

North Sea rift system, which had been active since the Permian, underwent a major rift phase during the Jurassic. During the early Jurassic, the Central Graben became a connection with the northern marine domain while, from the Callovian on, a southwards extension resulted in a connection between the northern and the Southern Atlantic systems (Ziegler, 1990).

From the late Triassic Rhaetian, the West Netherlands Basin and the Central Netherlands Basin were connected to the Central Atlantic Basin (Ziegler, 1990), resulting in regional marly and argillaceous marine sedimentation. In shallow parts, thin, carbonate-rich successions were deposited, containing

Figure 13.4 Overview of the principal structural elements in the Netherlands during the Cenozoic. The position of the map sheet area has been outlined.



iron oolites in places. Intercalated sandstones, sandy and oolite-rich carbonates reflect periods of low stand and uplift of the hinterland.

The Early Toarcian is characterised by the deposition of the bituminous Posidonia Shale Formation, the most important oil-source rock in the map sheet area (Bodenhausen & Ott, 1981; De Jager et al., 1996) and the adjacent southern North Sea (Cornford, 1990; Oele et al., 1981). The formation of this highly organic-rich clay was the result of stagnating deep-water circulation, presumably relating to the influx of cold Arctic water from the north and warm, salt water from the southern Tethys (Ziegler, 1990). In the Late Toarcian, normal open marine conditions were restored.

In the Late Aalenian, the Mid Kimmerian uplift of the Central North Sea Dome (Whiteman et al., 1975; Ziegler, 1990) commenced in the central North Sea. This uplift was caused by volcanic and thermal activity in response to a rifting-related drastically thinned continental crust (Whiteman et al., 1975; Underhill & Partington, 1993). In the central North Sea, this initiated profound erosion (Mid Kimmerian unconformity); although the complete Mesozoic succession was removed in the centre of the uplift, this erosional phase had little effect in the map sheet area.

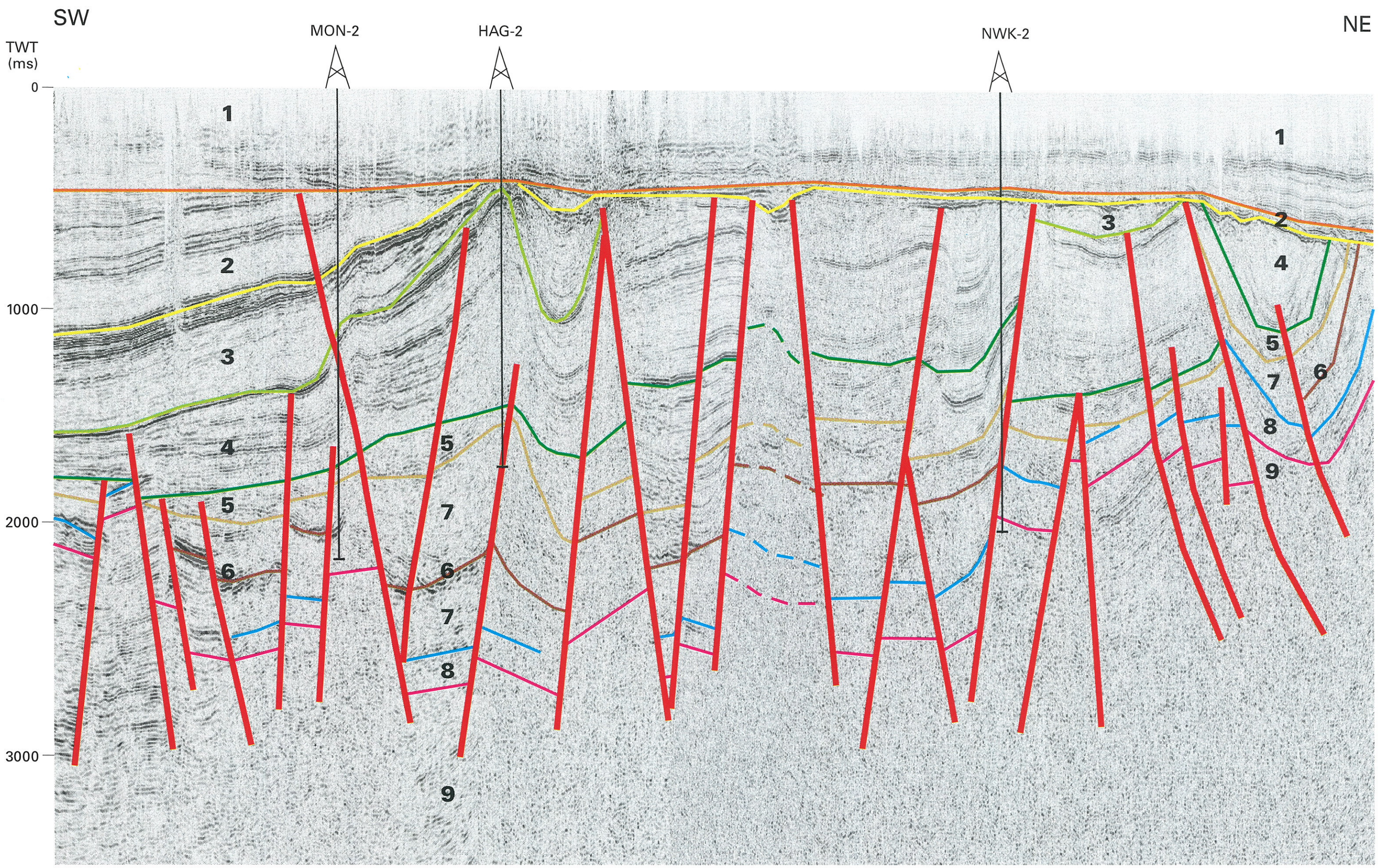
During the late Jurassic, the Late Kimmerian rift phase took place, after which spreading tectonics came to an end. This occured during two pulses: Late Kimmerian I and II, in the subsidence Late Jurassic and the earliest Cretaceous respectively (Rijks Geologische Dienst, 1991). The Late Kimmerian phase was accompanied by mafic volcanic activity (Dixon et al., 1981). During the Late Jurassic, the basin margins were uplifted, causing erosion of part of the Jurassic of the Middle Brabant Formation, while in the more deeply situated central part of the basin, fluvial and paralic deposition occurred (Nieuwerkerk Formation). The Portlandian was marked by a decline in differential subsidence in favour of a more regional subsidence.

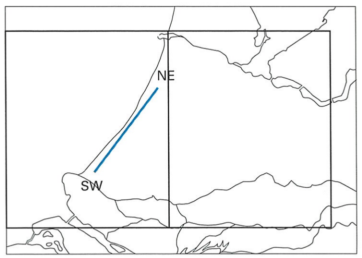
13.2.5 Cretaceous

After the first rift phase during the Late Jurassic, renewed Late Kimmerian rift activity in the Early Cretaceous resulted in uplift of the Northwest European basin margins and highs, including the Brabant Massif (Vercoutere & van den Haute, 1993). This uplift resulted in erosion of Jurassic sediments in particular in the southwest of the map sheet area. The southern areas, which were subjected to the greatest uplift, underwent truncation of the Lower Triassic.

The Cretaceous was characterised by a sea-level rise initiated by the opening of the southern Atlantic Ocean and the Indian Ocean (Pitman, 1978; Donovan & Jones, 1979; Ziegler, 1990). The sea reached a highstand during the Campanian, followed by a slight lowering; during the Maastrichtian and the Palaeocene, the sea level remained relatively high (Hays & Pitman, 1973; Vail et al., 1977; Ziegler, 1990).

In the Ryazanian, sedimentation resumed in the map sheet area. In the West Netherlands Basin, this resulted in deposition of the Schieland Group, an interval of fluvial and deltaic sands and clays up to 1500 metres thick. Towards the western deeper parts of the West Netherlands Basin, this fluvio-deltaic system passed gradually into a marine coastal system. A regional sea level rise (Haq et al., 1987) in combination with a subsiding, cooling crust in the Late Kimmerian post-rift phase initiated a large-scale transgression. The coastal sands and clays of the Rijnland Group increasingly invaded the West Netherlands Basin until, halfway through the Barremian, the marine system extended over the margins of this basin as well as the Central Netherlands Basin. The Aptian was characterised by the Austrian tectonic phase, favouring prograding greensands on the flank of both basins (Van Adrichem Boogaert & Kouwe, 1993-1997). The end of the Albian preluded a period of tectonic rest (Ziegler, 1990). As the highs





1. Upper North Sea Group
2. Lower and Middle North Sea Groups
3. Chalk Group
4. Rijnland Group
5. Schieland Group
6. Posidonia Shale Formation
7. Altena Group
8. Lower and Upper Germanic Trias Groups
9. Permian-Carboniferous

0 10 km

Figure 13.5 Seismic section through the central part of the West Netherlands Basin and the Voorne Trough.

became flooded during the transgression, the coarse-clastic sedimentation was interrupted over a long period.

The Aptian and Albian marls and clays of the Holland Formation were deposited in a widely extending, shallow-marine basin, which encompassed the entire southern and central North Sea (Ziegler, 1990). On the southern margin of the West Netherlands Basin, coastal sands were deposited as late as the Early Albian.

The Late Cretaceous was characterised by a long period of highstand. A rapid rise during the Late Albian and the Cenomanian induced flooding of the clastic source areas and deposition of the Chalk Group commenced. During this rise, greensands were deposited on the southern margin of the West Netherlands Basin. The deposition of these glauconite-rich sands reflects the southward migration of the coastal system towards the Brabant Massif.

As the sea level rise persisted during the Cenomanian, these marginal coastal systems also gradually became flooded. The end of the Cenomanian was characterised by a temporary highstand, which triggered an anoxic period worldwide (Schlanger et al., 1987). The consequence of this was basin-wide deposition of the organic-rich Plenus Marl. In the Turonian, a long period of pelagic deep-water deposition commenced, resulting in an alternation of marls and pure chalks.

At the end of the Coniacian a period of regional compression commenced induced by the collision of the European and the African plates and the active spreading along the Atlantic and Arctic mid-oceanic ridges (Ziegler, 1990; Coward, 1991). In Western Europe, this resulted in the N-S compression of the so-called Sub-Hercynian phase. The transition from regional extension to compression (inversion) resulted in uplift of Mesozoic successions in the West Netherlands Basin and the Central Netherlands Basin. During this inversion, the subsidence of the platform areas and of the former basin margins continued steadily, as a result of which the inverted basins acted as sediment source for the adjacent subsidence areas. The marginal areas are characterised by the deposition of sandy limestones. At a greater distance from the inversion areas, relatively deep-water chalk sedimentation occurred.

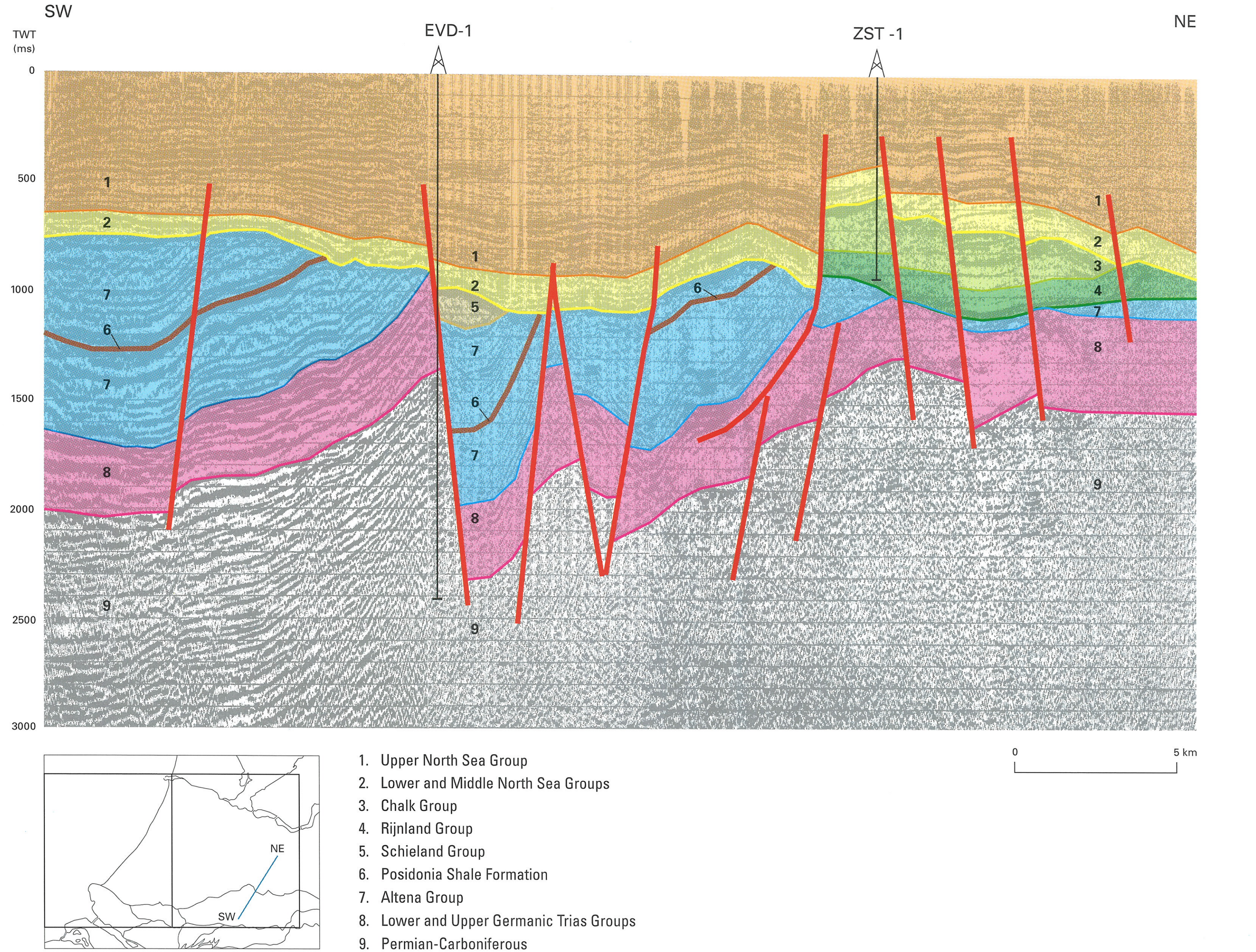
The Sub-Hercynian inversion persisted during the Santonian and the Campanian and induced partial erosion of the Chalk succession. Following a gradual diminishing and termination of the uplift during the Campanian, the resulting relief levelled off and the inverted areas were gradually flooded by the sea. During the Late Maastrichtian, the entire West European Basin once again became submerged and basin-wide chalk sedimentation resumed. This sedimentation pattern continued into the Danian.

13.2.6 Cenozoic

The Cenozoic was a period of alternating shallow and deeper marine sedimentation governed by Alpine tectonic activity. Three phases of uplift (Laramide, Pyrenean and Savian) resulted in regional differences in sedimentation rates, non-deposition and erosion.

During the Laramide phase, the West Netherlands Basin was uplifted and the Upper Cretaceous succession of the Chalk Group was removed by erosion. The thus formed Kijkduin High was bounded to the north as well as to the south by newly developed basins, the Zuiderzee Low and the Voorne Trough respectively (fig. 13.4). The Voorne Trough ceased to exist after the Pyrenean phase (Van Adrichem Boogaert & Kouwe, 1993-1997); the Zuiderzee Low remained an area of subsidence up to the Quaternary.

After the Laramide tectonic phase at the beginning of the Late Palaeocene, deposition of a transgressive marine succession occurred in the map sheet area. An alternation of sands, clays and brown-coal layers



1. Upper North Sea Group
2. Lower and Middle North Sea Groups
3. Chalk Group
4. Rijnland Group
5. Schieland Group
6. Posidonia Shale Formation
7. Altena Group
8. Lower and Upper Germanic Trias Groups
9. Permian-Carboniferous

Figure 13.6 Seismic section through the northern prolongation of the Roer Valley Graben in the southeastern part of the map sheet area. The cross-section illustrates the folding and uplift of Mesozoic successions as a consequence of inversion during the Late Cretaceous.

at the base of the Landen Formation indicates a nearshore environment. During the Eocene, a gradual deepening led to the deposition of marine coastal sands and clays. At the end of the Eocene, a thick marine clay succession was deposited (Asse Member) in comparatively deep-water conditions.

A new period of uplift at the time of the Late Eocene Pyrenean phase initiated erosion of the Early Tertiary succession in the map sheet area. Only in the Voorne Trough and the Zuiderzee Low have deposits of Palaeocene and Eocene age been preserved. When subsidence resumed in the Early Oligocene, the mapping area was occupied by a vast, shallow sea, which facilitated the deposition of a marine succession with a highly uniform areal extent (Rupel Formation). In the former West Netherlands Basin, the Veldhoven Formation was subsequently deposited in shallow-marine conditions.

The Savian tectonic phase, which triggered a final inversion pulse during the transition from Oligocene to Miocene, may have caused a regional change in the Tertiary drainage and sedimentation pattern. The uplift in the central part of the Kijkduin High induced erosion of the Late Oligocene sediments. After this phase of uplift, the only part of the mapping area to undergo sedimentation was the Voorne Trough. The most of the sediment supplied was, however, deposited by a prograding coastal system in the Zuiderzee Low. The change in sedimentation pattern may also be attributed to a sea-level fall (Letsch & Sissingh, 1983).

A phase of uplift during the Pliocene resulted in renewed supply of sediment and coastal progradation along the southern edge of the map sheet area (the Voorne Trough). In combination with intensified uplift of the hinterland, this finally resulted in warping of the mapping area during the Late Quaternary.

14. Applied geology

14.1. Introduction

Since the discovery of oil below The Hague in 1938 (see chapter 2), the subsurface in the map sheet area has increasingly been the subject of hydrocarbon extraction. Oil and gas exploitation is conducted both on land and in the adjacent offshore area. Oil is relatively scarce in the Netherlands, but a considerable proportion of the Dutch oil reserves have accumulated in the subsurface of this map sheet area.

The subsurface has not only been the target of surveys into the prospect of potential fossil energy but this has recently extended into surveys into the scope for alternative applications. One such instance is investigation of potential geothermal conditions (thermal energy utilisation) and waste storage by a number of institutions (Novem, 2001; NITG-TNO, 2001b). Possible applications in the field of geothermal energy include the production of warm groundwater or the exploitation of energy by circulation of surface water through deeper, warm parts of the subsurface. Exhausted oil or gas fields might in the future provide suitable conditions for the storage of waste, for example greenhouse carbon dioxide (CO_2). The various options for utilisation of the shallow and deeper subsurface, both now and in the future, are discussed below.

14.2 Hydrocarbons

14.2.1 Introduction

The West Netherlands Basin, a major hydrocarbon basin in the Netherlands, lies mainly within the areal extent of the map sheet area. Since the first oil indications were demonstrated in 1938, several oil and gas fields have been discovered (see chapter 2).

Gas is mainly exploited from the Main Buntsandstein and Röt (Triassic) sandstone reservoirs; oil occurs predominantly in Lower Cretaceous sandstone (see chapter 2). The Triassic reservoirs are found in tilted fault blocks with overlying and lateral sealing layers of Upper Triassic evaporite, clay and dolomite (Geluk et al., 1996; Spain & Conrad, 1997) and Lower and Middle Jurassic shale (De Jager et al., 1996). The hydrocarbons in Lower Cretaceous reservoirs, predominantly oil, are trapped in anticlinal structures that were formed during the Late Cretaceous to Early Tertiary structural inversion. Folding took place during the uplift of fault blocks along inverted steep faults.

14.2.2 Petroleum systems in the West Netherlands Basin

An understanding of the history of hydrocarbon occurrences can be gained by evaluating the petroleum systems in the West Netherlands Basin. Every petroleum system comprises a source rock, a migration route, a reservoir and sealing rocks above the reservoir. All these elements are of essential importance in the formation and preservation of hydrocarbons through geological time. Timing is also crucial: all the elements must already have been in place at the moment that expulsion of the hydrocarbons from the source rock took place.

Reconstruction of the burial history of rocks at various well locations enables the period of deepest burial to be determined. This period is generally contemporaneous to hydrocarbon generation and expulsion. The West Netherlands Basin was characterised by gradual subsidence, alternated by brief periods of uplift. The inversion phases at the end of the Cretaceous were of particular importance for the petroleum system in the West Netherlands Basin. The Cretaceous inversion was the most intensive in the centre of the basin (fig. 14.1), resulting in the erosion of the Chalk Group. The deepest burial of the sediments was reached in the centre prior to the Late-Cretaceous inversion; the subsidence during the Tertiary was considerably less than the uplift. The principal phase of hydrocarbon generation and expansion in the centre of the basin therefore occurred at the end of the Cretaceous, prior to the time of formation of the structural reservoirs. Towards the basin margins, the intensity of the inversion phase diminishes, as is evidenced by the increasingly more complete preservation of the Chalk Group. The sediments there did not achieve the deepest burial until during the Tertiary. Consequently, the principal phase of generation and expulsion took place on the basin margins during the Tertiary, where the structural reservoirs had already been formed.

Three different plays have been identified in the West Netherlands Basin, the Lower Cretaceous oil and gas play, the Triassic gas play and the Triassic oil play (fig. 14.2). In order to account for the presence of hydrocarbons in the basin, a model has been used relating the time spans of generation and migration to the tectonic evolution of the basin. For details of the procedure involved, reference should be made to Van Balen et al. (2000). The results have been calibrated using present-day temperatures (obtained from various sources) and vitrinite reflections (NITG-TNO, 1998) from reference wells.

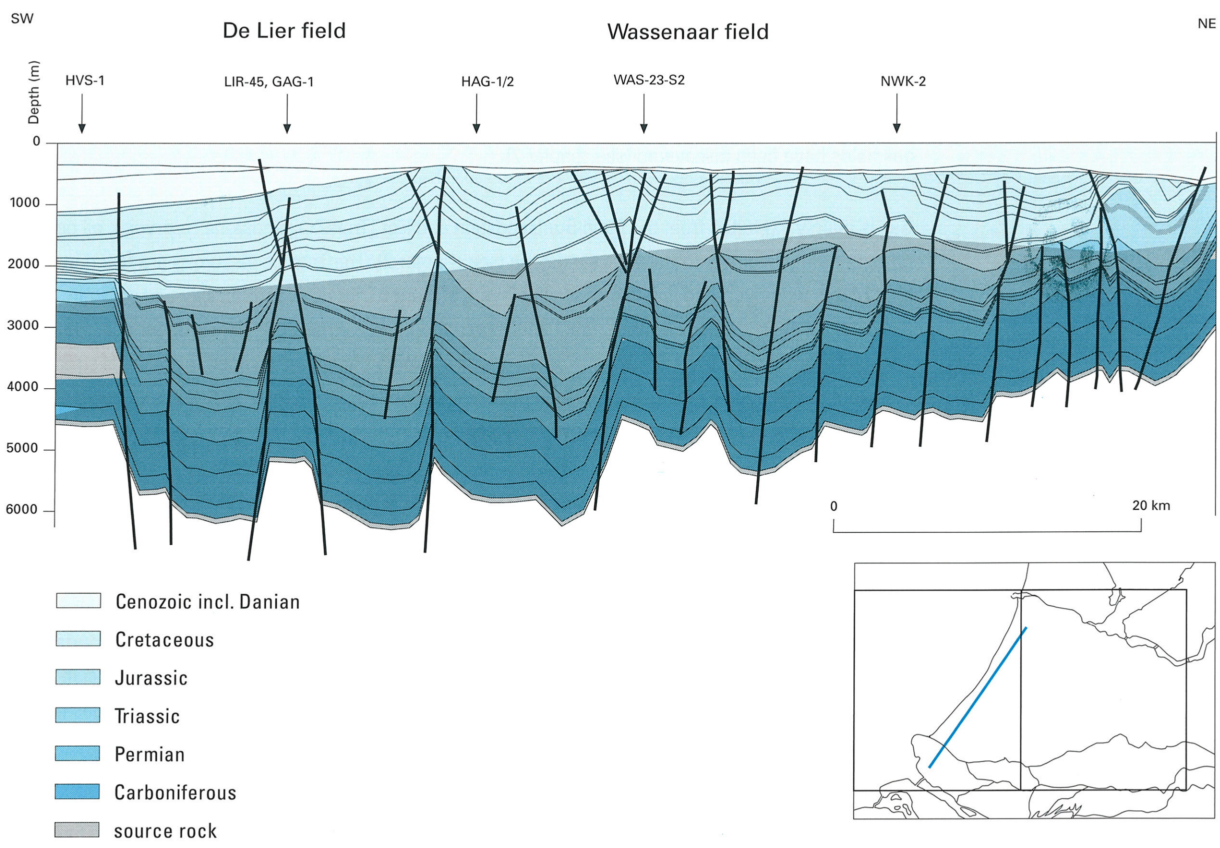


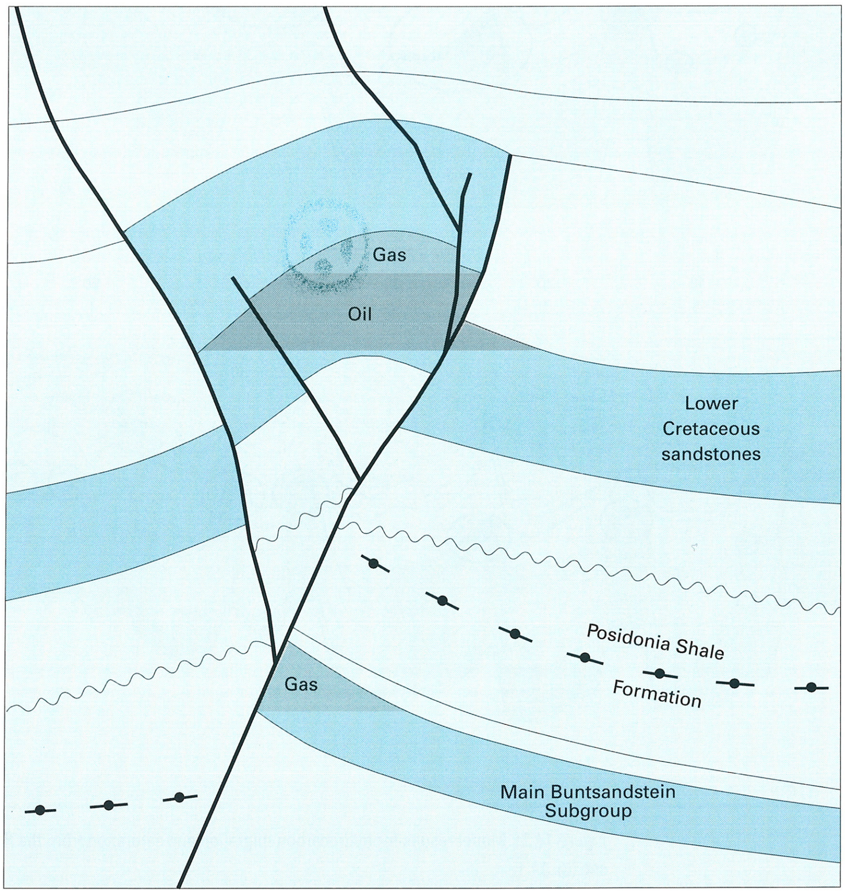
Figure 14.1 SE-NE section of the West Netherlands Basin.

14.2.3 The Lower Cretaceous oil and gas plays

The Posidonia Shale Formation is the major oil-source rock in the West Netherlands Basin and is 10 to 35 m thick. The amount of (marine) organic material ranges from 5 to 10%. The combination of various organic-geochemical indicators from samples of this oil-source rock demonstrates that this unit is at present immature or else lies only just within the oil window at many well locations. However, the analysed samples mostly originate from structural highs. Between these highs, the Posidonia Shale Formation does indeed lie within the oil window and, locally, within the gas window (NITG-TNO, 1998). The presence of associated gas in the Lower Cretaceous reservoirs, generated from the Posidonia Shale Formation (De Jager et al., 1996), confirms that parts of the formation are located within the gas window. Migration to the Lower Cretaceous reservoirs occurred via the sandstones of the Brabant Formation as well as via open faults.

The deposits of the Aalburg Formation lie conformably below the Posidonia Shale Formation, at a thickness ranging from 140 to 740 m. The level of organic material of this formation ranges from 1 to 3%. In view of the substantial thickness of the deposits and the type of organic material (partly marine), this formation also holds considerable generation potential for petroleum. It is therefore probable that the

Figure 14.2 Schematic diagram of oil and gas plays in the West Netherlands Basin (after De Jager et al., 1996).



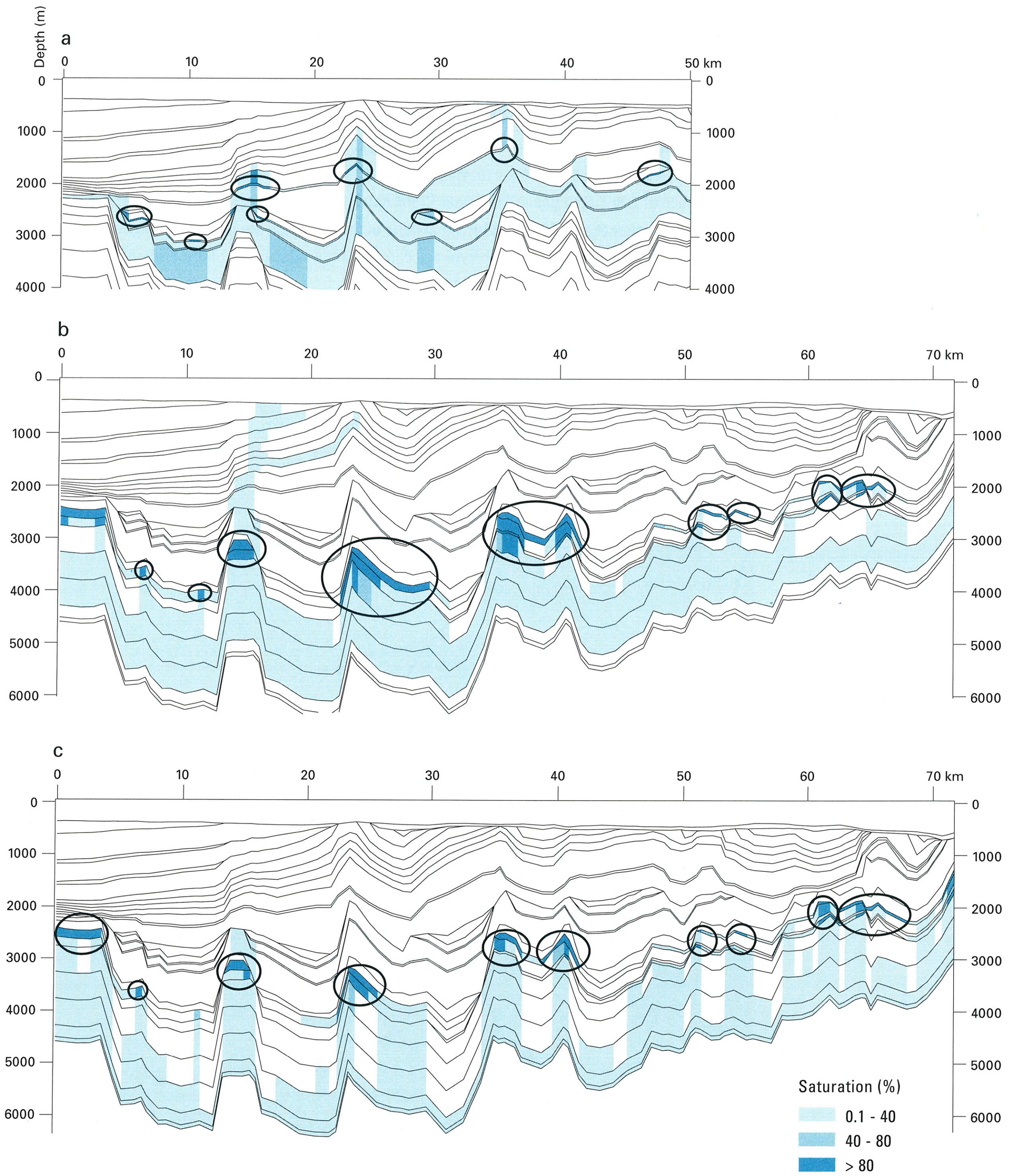


Figure 14.3a Model results for hydrocarbon migration and saturation from the Posidonia Shale Formation. For location, see fig. 14.1.

Figure 14.3b Model results for gas migration and saturation from Westphalian coal seams. For location, see fig. 14.1.

Figure 14.3c Model results for hydrocarbon migration and saturation from the Lower Namurian source rock. For location, see fig. 14.1.

Aalburg Formation made a contribution to the oil occurrences in the Lower Cretaceous reservoirs (De Jager et al., 1996; NITG-TNO, 1998). At the base of the Aalburg Formation, a number of bituminous clay layers occur (De Jager et al., 1996). These marine clay layers have been encountered in the Werkendam-2 well (Van Adrichem Boogaert & Kouwe, 1993-1997); oil shales have also been encountered in the eastern part of the Netherlands, in the Aalburg Formation (Herngreen & de Boer, 1974). Owing to the corresponding geochemical signatures of the Posidonia Shale Formation and the Aalburg Formation, it is difficult to differentiate the various contributions of these formations to the geochemical signatures of the oil from the Lower Cretaceous reservoirs (NITG-TNO, 1998).

The 2D modelling of the history from a north-south profile through the basin assumes a Type II source rock at the base of the Lower Jurassic sediments. Figure 14.3a displays the modelled current oil saturation in the various geological units. The results indicate that generation of hydrocarbons from Lower Jurassic source rocks commenced during the Late Jurassic – Early Cretaceous rift phase (approximately 130 Ma) and that the velocity of generation increased from south to north owing to more rapid burial (fig. 14.4a). At the centre of the basin, locally (for example at the well location of Wassenaar-23-S2, the deepest burial was reached during the Late Cretaceous, prior to the inversion that put an end to hydrocarbon generation from the Late Cretaceous on. At other places in the basin (for example at well location De Lier-45), the greatest burial depth was reached during the Oligocene. In the south of the basin, the sediments of the Lower Jurassic are at present encountered at the point of optimum burial, and generation is currently taking place. According to the model, the anticlinal structures of the Lower Cretaceous filled up (fig. 14.4a) immediately following the Sub-Hercynian inversion (80 Ma).

14.2.4 The Triassic gas play

The most important gas-source rock in the West Netherlands Basin comprises the coal seams of the Limburg Group. Below the entire basin, a thick succession of sediments of Westphalian age is present; within these, the Westphalian A and B, in particular, are coal bearing. The average coal content of the total sequence is approximately 5.5% (Dusar et al., 1998). The total organic level of this coal is at least 70%. The coalification at the top of the deposits of the Carboniferous increases from south to north (NITG-TNO, 1998). In the south (Hellevoetsluis-1 well), the top of the coal-bearing sequence is within the oil window, while the top of the Carboniferous in the north of the basin (Oostzaan-1 well) is within or below the gas window. These differences were caused by differences in burial depth. Stratigraphic differences at the top of the Carboniferous, caused by folding and erosion during the Late Carboniferous, are not significant as the principal stage of coalification occurred subsequent to the Carboniferous. Migration to the Triassic reservoirs took place via the sandstones of the Upper Carboniferous and the Upper Rotliegend Group as well as via open faults.

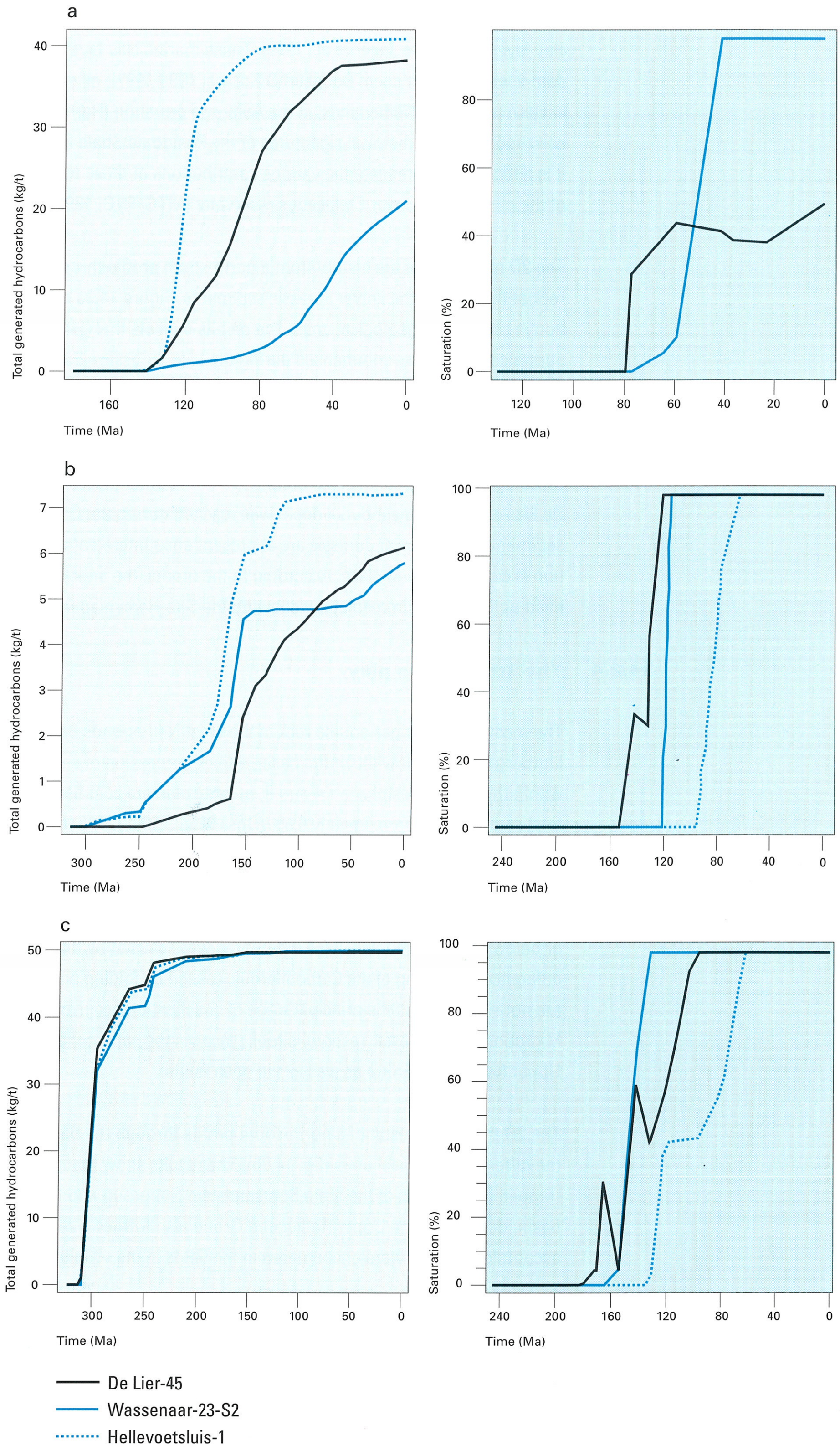
The 2D-modelling result of a north-south profile through the basin shows the present gas saturation in the different geological units (fig. 14.3b). The results show that the gas was generated from the coal trapped in the sands of the Main Buntsandstein Subgroup and the Röt Formation. In the north of the basin, deposits of the Upper Rotliegend Group also formed a reservoir. The model results reproduce the accumulations that were encountered in the fields in the vicinity of De Lier (Gaag) and Wassenaar.

According to the model, generation of hydrocarbons commenced in the Triassic (240 Ma) and subsequently increased during the Middle Jurassic (160 Ma). From the Middle Jurassic on (150 Ma), there was a clear distinction between the generation in the centre and the north of the basin, as a consequence of the differences in burial history (fig. 14.4b), which also influenced the time span of reservoir filling. In the centre of the basin, the reservoirs were filled during the Middle Late Jurassic (150-118 Ma), but in the south of the basin, this did not occur until the Cretaceous (fig. 14.4b). The local burial history in the

Figure 14.4a Hydrocarbon generation (on the left) and accumulation (on the right) in a number of locations in fig. 14.3a.

Figure 14.4b Hydrocarbon generation (on the left) and accumulation (on the right) in a number of locations in fig. 14.3b.

Figure 14.4c Hydrocarbon generation (on the left) and accumulation (on the right) in a number of locations in fig 14.3c.



basin was strongly related to the local effects of the Late Jurassic – Early Cretaceous rift phase and the end-Cretaceous inversion phase.

A second potential source of part of the gas occurrences in the Triassic reservoirs is a layer rich in organic material at the base of the Epen Formation, the Geverik member (Lokhorst, 1998). Despite the fact that this member has never been penetrated in the West Netherlands Basin, the presence of this unit may be considered likely in view of the palaeogeographic situation during the Early Namurian (Cameron & Ziegler, 1997). Further corroborative evidence is the presence of a Type II source rock in wells to the south (Langenaeker, 1998) and to the east (Van Balen et al., 2000) of the West Netherlands Basin. Indications from the isotope ratios and from the distribution of the gas in the West Netherlands Basin also point to the Geverik Member contributing to the gas accumulations in the basin (Lokhorst, 1998; Van Balen et al., 2000).

In view of the expected depth of the Geverik Member in the West Netherlands Basin, the deposition is presumed to have a high coal rank. Generation of hydrocarbons, in the first instance oil, is presumed to have occurred during the Carboniferous, thus reducing the likelihood of preservation. A proportion of the hydrocarbons will have escaped at an early stage owing to seepage via faults. However, if it is assumed that a proportion of the generated hydrocarbons also migrated via the overlying sedimentary sequence, then the proposition of a contribution to the gas reservoir may be regarded as likely. Owing to the long migration route through the poorly permeable strata of the Upper Carboniferous at a relatively high temperature and pressure over a long period of time, the generated oil is able to be converted to gas during migration via a process of secondary cracking. Modelling of this latter scenario reveals that this gas did not reach the Lower Triassic reservoir until the Late Jurassic (fig. 14.4c), roughly at the same time as the gas from the Westphalian coal (Van Balen et al., 2000). According to the model, the secondary gas generated from the Geverik Member accumulated in the same structures as the gas generated from the Westphalian coal (fig. 14.3c).

14.2.5 The Triassic oil play

Oil as well as gas have been encountered in sandstone reservoirs of the Main Buntsandstein Subgroup at various locations in the West Netherlands Basin (De Jager et al., 1996). The provenance of this oil is dependent on the structural geology of the reservoir (De Jager et al., 1996). Structural reservoirs at a higher level than the Posidonia Shale Formation, such as the Pernis-West and the Gaag field, are presumed to be largely filled with oil originating from this formation (De Jager et al., 1996). With regard to the current geometry, it is not possible for structural reservoirs below the level of the Posidonia Shale Formation, such as the Papekop and the Ottoland field, to have been filled with oil generated from this formation (De Jager et al., 1996). There are a number of possible explanations for the source of these oil accumulations.

In the first place, the oil generated may originate from the bituminous marine clays at the base of the Aalburg Formation (De Jager et al., 1996). According to the present geometry, these layers lie at a deeper level than the reservoirs and oil may have migrated from these layers to the reservoirs even after the inversion. The suggestion that the oil could have originated from source rocks of Westphalian age, as postulated by De Jager et al. (1996), would appear less likely considering the marine signature of the oils, which shows no similarities with the terrestrial signature of the Westphalian deposits (NITG-TNO, 1998). Another possibility is that the oil was indeed generated from the Posidonia Shale Formation, but prior to inversion. Unlike the current configuration, the formation at the end of the Cretaceous could have been at a deeper level than the reservoir. It is, however, not likely that this oil survived the inversion, with the accompanying changes to the geometry. A final alternative for the provenance of the oil is in the marine source rock of the Geverik Member, as discussed with reference to the Triassic gas play. In this case, the oil would have to have been preserved over a long period instead of having been cracked during migration, as was propounded in the case of the Triassic gas play (Van Balen et al., 2000). Migration from the flanks of the basin would also be a possibility, whereby the oil would have been generated at a later stage as a result of slower burial.

14.3 Thermal energy

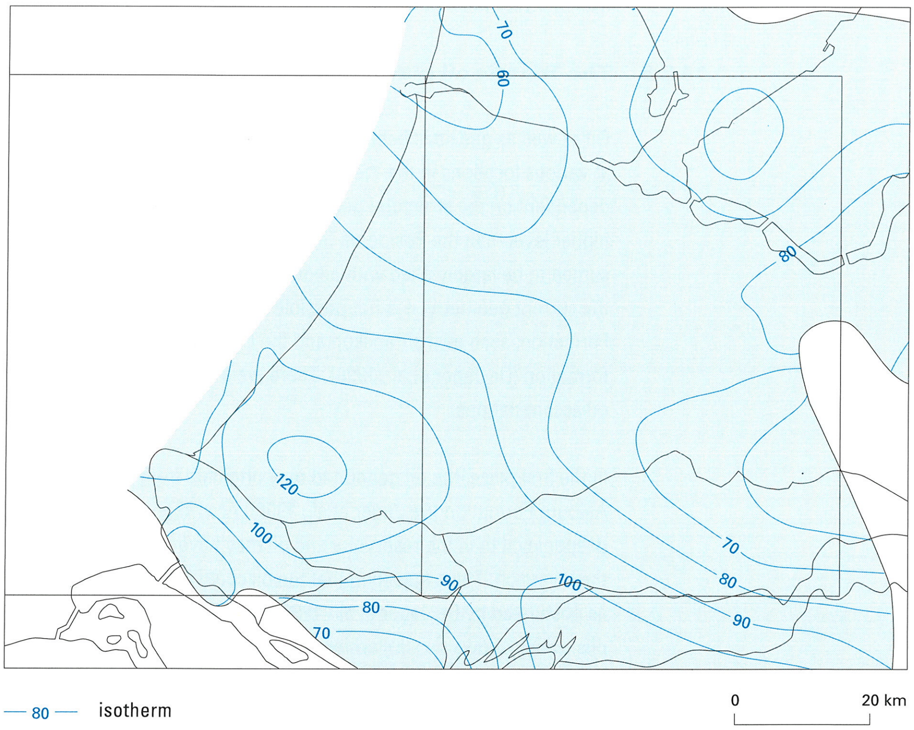
14.3.1 Introduction

Thermal energy is a sustainable energy that can be obtained without producing CO_2 emissions. Thermal energy can be used to provide space heating, for example in greenhouse complexes and for district heating. Some years ago, a survey was conducted in order to investigate the potential of the western part of the map sheet area for geothermal applications (TNO-NITG, 2001b).

14.3.2 Aquifers

The aquifers in the southern province of Zuid-Holland providing appropriate conditions for thermal energy exploitation are located in sections of the Triassic (Main Buntsandstein Subgroup) and the Lower Cretaceous (the Rijswijk Sandstone beds, the Berkel Sandstone and IJsselmonde Sandstone Members). The most suitable areas are those with a temperature exceeding 40 °C (fig. 14.5) and a heat content of at least 20×10^9 J/m^2 for Triassic aquifers and at least 10×10^9 J/m^2 for Lower Cretaceous aquifers (NITG-TNO, 1997). The latter have better permeability. In the southern part of the province of Zuid-Holland,

Figure 14.5 Temperature at the top of the Triassic Sandstone in the map sheet area.



aquifers meeting these criteria occupy an area of approximately 500 km^2 (Triassic aquifers) and approximately 250 km^2 (Lower Cretaceous aquifers); the Lower Cretaceous aquifers satisfying these conditions completely overlap the suitable Triassic aquifers (RGD, 1984). The sediments of the Upper Rotliegend Group (Permian) pinch out in southern Zuid-Holland and, insofar as still present, have a minimal heat content.

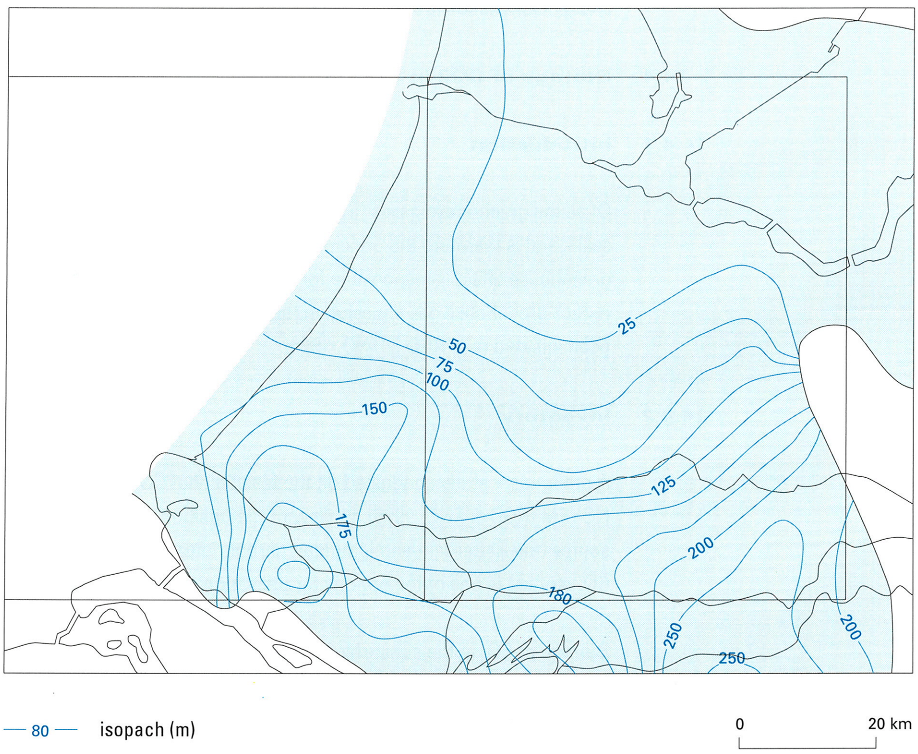
Volpriehausen Sandstone Member (Triassic)

The top of the Main Buntsandstein Subgroup in Zuid-Holland is at a depth ranging from 1000 to 4500 m. The temperature at the top of the Volpriehausen Sandstone Member in the map sheet area is above 70° C (fig. 14.5). The total thickness of the Main Buntsandstein Subgroup ranges from 25 m 225 m, and the net sand thickness from 0 to 200 m (fig. 14.6); towards the centre of the basin, the clay content increases and the net sand thickness decreases. In Spijkenisse, the sandstone succession is still 47 m thick but in Woubrugge (the northern part of Zuid-Holland), the thickness has decreased to around 10 m. The sandstone sequences contain many thin claystone and siltstone beds, which may be sandy or silty. Calculated porosity values range mainly from 8% in the north to 18% in the south (TNO-NITG, 2001).

Vlieland Sandstone Formation (Lower Cretaceous)

The Lower Cretaceous formations in the southern part of Zuid-Holland (RGD, 1983; Den Hartog Jager, 1996; Racero-Baena & Drake, 1996; De Jager et al., 1996) were deposited as an alternation of sandstone and claystone along the southern margin of the West Netherlands Basin. The thickness of the IJsselmonde Sandstone Member ranges from 70 to 300 m. Locally, porosity values have been measured of between 20 and 30% and permeability values of between 0.5 and 1 D (Racero-Baena & Drake, 1996). The Berkel Sandstone Member in the map sheet area is 40 to 100 m thick and lies at a depth of 1 to 2 km.

Figure 14.6 Thickness of the Volpriehausen Sandstone Member in the map sheet area.



Measured porosity and permeability values have a range of 20-30% and 0.5-3 D respectively (Racero-Baena & Drake, 1996). The Rijswijk Sandstone Member is up to 70 m thick; measured porosity and permeability values range from 15 to 28% and 0.5 to 4 D (Racero-Baena & Drake, 1996).

14.3.3 Depth and temperature

The top of the Main Buntsandstein Subgroup within the map sheet area is at a depth ranging from 1000 to 4500 m. Over a wide area, the depth increases from the NNE to the SSW. In the southwestern fringe zone, in the vicinity of the edge of the areal extent of the Main Buntsandstein Subgroup, this subgroup is found at a shallow depth. The contour lines of the top of the Nieuwerkerk Formation (Upper Jurassic) display a similar picture: a decrease in depth in a northeasterly direction. The maximum depth difference in this direction is approximately 1750 m. With regard to the Vlieland Sandstone Formation, which was deposited immediately on top of the Nieuwerkerk Formation, the same tilted position may be assumed. The depth of the top of the Nieuwerkerk Formation (which is the base of the Vlieland Sandstone Formation) ranges from 1250 to 2500 m. The temperature of the formation water in the map sheet area ranges from 80° C at a depth of 2000 m to 95° C at a depth of 2500 m and 110° C at a depth of 3000 m (RGD, 1984).

14.3.4 Effects and hazards

Interference in the subsurface may occur if thermal energy exploitation is sited too close to a structural oil or gas field or near gas or CO_2 storage. Thermal energy exploitation could then have a negative effect on the pressure distribution in the oil or gas field or in the storage location. There are no particular hazards attached to thermal energy exploitation. If there is any likelihood of oil or gas being penetrated, the same safety procedures should be observed at the well as are required for an oil or a gas well. Thermal energy exploitation is sustainable and environmentally friendly.

14.4 Storage of CO2 in the subsurface

14.4.1 Introduction

Of all the greenhouse gases (CO_2, CH_4 and CFCs, etc), carbon dioxide (CO_2) is emitted on the largest scale, and is therefore the principal cause of the greenhouse effect. It is generally assumed that the greenhouse effect is responsible for the recent sharp global rise in average temperatures. In order to reduce greenhouse gas emission in the short term, a number of research and feasibility studies have been initiated (e.g. RGD & TNO, 1996).

14.4.2 Inventory

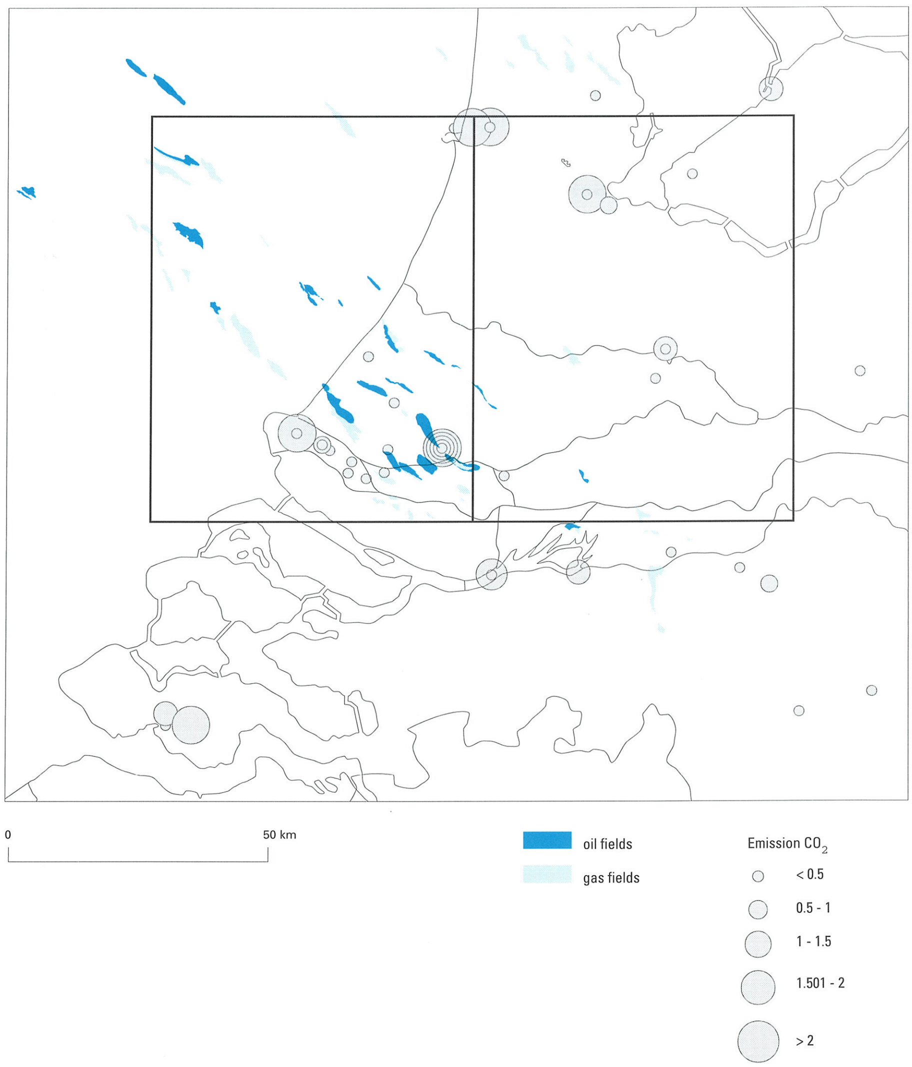
A preliminary study conducted on the feasibility of CO_2 storage in the subsurface was commissioned by NOVEM (RGD & TNO, 1996). In view of the position of two of the three largest clusters of Dutch CO_2 source (the Rotterdam and IJmuiden harbour areas) in and on the edge of the map sheet area (fig. 14.7), CO_2 storage is one of the options for utilisation of the subsurface in the future.

Storage of CO_2 in the subsurface in the map sheet area could be performed in a number of ways: in exhausted gas fields, in productive and exhausted oil fields or in deep aquifers (water-bearing porous strata). Research has revealed (RGD & TNO, 1996) that aquifers offer sufficient capacity for storage of the CO_2 production of the large IJmond power stations. However, all these aquifers are situated in the north of the map sheet area.

Within the map sheet area, the storage capacity in aquifers as well as oil and gas fields is limited (RGD & TNO, 1996). The total maximum aquifer storage capacity is estimated at 200 MT (Megaton) CO_2. Exactly how much of this is suitable is uncertain, because a substantial part of the total capacity is in small individual structures. The lithological units which might potentially be used for aquifer storage of CO_2 are the Slochteren Formation (140 MT) and the Main Buntsandstein Subgroup (60 MT). The low estimates in the case of the Triassic and Cretaceous structures are due to the fact that a large proportion of the closed structures are in fact oil-bearing (RGD & TNO, 1996). Although the Slochteren Formation is promising in terms of water-bearing volume, there are doubts as to the impermeability of the overlying strata (RGD & TNO, 1996). The Zechstein salt, which forms a good sealing layer in other parts of the country, is, in the map sheet area, either very thin or else completely absent.

In the map sheet area, only three gas fields satisfy the technical conditions for safe and realistic storage. These are gas fields in the Triassic sands. Other fields are situated too close to the surface (above 800 m)

Figure 14.7 CO_2 sources and exhausted hydrocarbon fields in the map sheet area and surroundings.



or have too limited a storage capacity (less than 10 MT CO_2). The total capacity provided by gas fields, after depletion, is estimated at 50 MT CO_2; none of the oil fields present meet the necessary criteria (RGD & TNO, 1996). Oil fields with a lower storage capacity might well be suitable for storage if CO_2 is used in productive fields to enhance production (EOR: 'enhanced oil recovery').

Because the sealing layers of gas fields have already demonstrated their reliability, they form a suitable option for long-term, safe storage. However, it is likely that large, exhausted gas fields may be used for temporary storage of natural gas, which makes the potential for CO_2 storage uncertain. If half the total estimated storage capacity ultimately proves usable, then approximately the entire CO_2 production of a single 700 MW power station could be accommodated during its 25-year life.

14.4.3 Execution and feasibility

The process of CO_2 storage in the subsurface can be divided into the following stages: (1) capture and separation of the CO_2 emissions, (2) compression of the gas to supercritical phase, (3) transportation via a pipeline system, (4) injection into the subsurface and (5) monitoring of the subsurface situation. Each of the different stages has its own difficulties and/or financial aspects. At present, the capture of CO_2 is an expensive, energy-consuming process (RGD & TNO, 1996). Transportation from the source to the storage plant surface site will require a pipeline system capable of withstanding high pressure (120 bar). The principal costs in storing the CO_2 are incurred by the drilling of the injection wells.

14.4.4 Safety

In the storage of CO_2 in the subsurface, a number of important safety aspects are of importance. Potentially hazardous situations may arise where incorrectly stored CO_2 escapes into the atmosphere or if drinking water becomes polluted. There are also earthquake hazards as a result of changes in pressure in the subsurface. A preliminary survey of the Dutch situation has shown that in the event of leakage, there would be a delay of a possible 5,000 years before CO_2 at a depth of 2 km could reach the surface. Earthquake hazards are low (RGD & TNO, 1996). To guarantee safety, thorough research will be required, in general as well as location-specific. Furthermore, exhaustive monitoring studies will need to be carried out into the subsurface and surface situations, both during and subsequent to the injection.

Appendices

Overview of seismic data used

Survey	Year	Owner	2D/3D
7040*	1970	NAM	2D
7110*	1971	NAM	2D
7141*	1971	NAM	2D
7142*	1971	NAM	2D
72Y-*	1972	AMC	2D
ANE73*	1973	AMC	2D
7410*	1974	NAM	2D
7420*	1974	NAM	2D
7490*	1974	NAM	2D
7591*	1975	NAM	2D
7610*	1976	NAM	2D
7710*	1977	NAM	2D
7820*	1978	NAM	2D
7940*	1979	NAM	2D
ZY79-*	1979	ELF	2D
HL80-*	1980	ELF	2D
8120*	1981	NAM	2D
ANE81-3*	1981	AMC	2D
BW81-*	1981	ELF	2D
8220*	1982	NAM	2D
BW82-*	1982	ELF	2D
8361*	1983	NAM	2D
BW83-*	1983	ELF	2D
8422*	1984	NAM	2D
8432*	1984	NAM	2D
8462*	1984	NAM	2D
MZ84-*	1984	MOB	2D
8521*	1985	NAM	2D
85F5*	1985	NAM	2D
85H5*	1985	NAM	2D
HA85-*	1985	ELF	2D
MZ85-*	1985	MOB	2D
AM86-*	1986	ELF	2D
MZ86-*	1986	MOB	2D
8719*	1987	NAM	2D
8721*	1987	NAM	2D
8723*	1987	NAM	2D
8726*	1987	NAM	2D
AM87-*	1987	ELF	2D
MZ87-*	1987	MOB	2D
MZ88-*	1988	MOB	2D
8921*	1989	NAM	2D
Q11	1990	WIN	3D
Rotterdam	1985	NAM	3D
Pijnacker	1985-1986	NAM	3D
Biesbosch	1986	NAM	3D

Survey	*Year*	*Owner*	*2D/3D*
Oud-Beijerland	1987	NAM	3D
Haastrecht	1988	NAM	3D
Uitwijk	1988-1989	NAM	3D
Dordrecht	1988-1990	NAM	3D
Gouda	1989	NAM	3D
Leiden	1989-1990	NAM	3D
Monster-Land	1990-1991	NAM	3D
Den Haag	1991	NAM	3D
Mookhoek	1991	NAM	3D
Nieuwkoop	1995	NAM	3D

AMC	Amoco Netherlands Petroleum Co
ELF	Elf Petroland B.V.
MOB	Mobil Producing Netherlands Inc.
NAM	Nederlandse Aardolie Maatschappij B.V.
WIN	Wintershall Noordzee B.V.

Overview of wells used

Well nr.	Name	Code	Owner	Final depth	Year
1	Aarlanderveen-1	ARV-01	NAM	2550	1976
2	Ahoy-E55	AHO-E-55	NAM	1406	1955
3	Alblasserdam-1	ALD-01	NAM	1650	1959
4	Almere-1	ALE-01	AMC	1877	1976
5	Almkerk-1	ALM-01	NAM	2370	1970
6	Alphen-1	ALP-01	NAM	747	1948
7	Altforst-1	ALT-01	BPM	654	1944
8	Andel-6	AND-06	NAM	3136	1991
9	Bakkum-Castricum-1	BAC-01	NAM	2283	1964
10	Barendrecht-1	BRT-01	NAM	3365	1984
11	Barendrecht-Ziedewij-1	BRTZ-01	NAM	3259	1993
12	Barneveld-1	BNV-01	AMC	3066	1971
13	Benthuizen-1	BEN-01	NAM	725	1948
14	Berkel-1	BRK-01	NAM	2988	1952
15	Berkel-4	BRK-04	NAM	2050	1995
16	Berkel-7	BRK-07	NAM	2278	1980
17	Blaricum-1-S1	BLA-01-S1	PET	2059	1982
18	Bleiswijk-1	BLE-01	NAM	890	1948
19	Bleskensgraaf-1	BLG-01	NAM	1517	1951
20	Bleskensgraaf-2	BLG-02	NAM	1604	1958
21	Boeikop-1	BKP-01	NAM	1000	1949
22	Boskoop-1-S1	BSKP-01-S1	NAM	2785	1995
23	Botlek-1	BTL-01	NAM	3290	1984
24	Brakel-1	BRAK-01	NAM	2689	1992
25	Breukelen-1	BKN-01	BPM	589	1943
26	Brouwershavensegat-1	BHG-01	NAM	2907	1978
27	Buurmalsen-1	BUM-01	NAM	2195	1970
28	Capelle-1	CAP-01	NAM	3700	1985
29	De Lier-40	LIR-40	NAM	2010	1967
30	De Lier-45	LIR-45	NAM	3915	1982
31	Delft-1	DEL-01	NAM	765	1944
32	Delft-3	DEL-03	NAM	2200	1954
33	Den Haag-1	HAG-01	NAM	2128	1954
34	Den Haag-2	HAG-02	NAM	2661	1955
35	Eemhaven-1	EHV-01	NAM	2803	1966
36	Ermelo-1	ERM-01	NAM	2650	1969
37	Everdingen-1	EVD-01	NAM	2196	1965
38	Gaag-1	GAG-01	NAM	3659	1972
39	Gewande-1-S1	GWD-01-S1	NAM	2324	1991
40	Giessendam-1	GSD-01	NAM	2575	1977
41	Haarlemmermeer-1	HLM-01	NAM	1122	1951
42	Haastrecht-1	HST-01	NAM	2527	1951
43	Haastrecht-2-S1	HST-02-S1	NAM	2650	1983
44	Hazerswoude-1	HZW-01	NAM	1111	1948
45	Heemskerk-1	HEK-01	NAM	1967	1965
46	Heinenoord-1	HEI-01	NAM	2316	1991

Well nr.	*Name*	*Code*	*Owner*	*Final depth*	*Year*
47	Hellevoetsluis-1	HVS-01	NAM	3841	1969
48	Hilversum-1	HIL-01	BPM	732	1944
49	IJsselmeer-1	IJM-01	NAM	2892	1966
50	IJsselmonde-3	IJS-03	NAM	2132	1957
51	IJsselmonde-55	IJS-55	NAM	1892	1977
52	IJsselmonde-64-S2	IJS-64-S2	NAM	3655	1985
53	Ilpendam-1	ILP-01	NAM	1064	1948
54	Jutphaas-1	JUT-01	NAM	3409	1969
55	Kerkwijk-1	KWK-01	NAM	3281	1988
56	Kijkduin-Zee-1	KDZ-01	NAM	1916	1961
57	Kijkduin-Zee-2	KDZ-02	NAM	3775	1986
58	Knardijk-1	KRD-01	AMC	1524	1978
59	Landsmeer-1	LSM-01	NAM	1703	1977
60	Leidschendam-1	LED-01	NAM	1867	1956
61	Leidschendam-3	LED-03	NAM	1170	1972
62	Lekkerkerk-1	LEK-01	NAM	1965	1961
63	Lelystad-1	LEL-01	CON	2057	1970
64	Loosduinen-1	LOD-01	NAM	1518	1949
65	Maasbommel-1	MSB-01	NAM	1714	1951
66	Maasbommel-2	MSB-02	NAM	1278	1953
67	Maasgeul-1	MSG-01	NAM	4260	1989
68	Maasgeul-2	MSG-02	NAM	4218	1993
69	Maasvlakte-1	MSV-01	NAM	2685	1989
70	Meerkerk-1	MRK-01	NAM	2813	1990
71	Meyendel-1	MED-01	NAM	1726	1958
72	Middelie-101	MID-101	NAM	2626	1964
73	Middelie-201	MID-201	NAM	2913	1980
74	Mient-1	MNT-01	NAM	464	1938
75	Moerkapelle-1	MKP-01	NAM	1460	1957
76	Moerkapelle-10	MKP-10	NAM	1260	1977
77	Moerkapelle-14	MKP-14	NAM	2820	1984
78	Molenaarsgraaf-1	MOL-01	NAM	1445	1959
79	Molenaarsgraaf-2	MOL-02	NAM	3287	1986
80	Monster-2	MON-02	NAM	3030	1982
81	Nieuwerkerk-1	NKK-01	NAM	2254	1958
82	Noordwijk-2	NWK-02	NAM	2940	1983
83	Oegstgeest-1	OEG-01	NAM	1965	1959
84	Oostzaan-1	OZN-01	NAM	2767	1951
85	Ottoland-1	OTL-01	NAM	3096	1988
86	Oud-Alblas-1	OAS-01	NAM	2177	1958
87	Oud-Beijerland-1	OBL-01	NAM	2714	1985
88	Oud-Beijerland-Zuid-1	OBLZ-01	NAM	2745	1990
89	Oude Lede-1	OLE-01	NAM	1868	1959
90	Overflakkee-1	OVE-01	CHE	1800	1969
91	P18-02	P18-02	AMC	3766	1989
92	Papekop-1	PKP-01	NAM	2751	1986
93	Pernis-1	PRN-01	NAM	2980	1989

Well nr.	Name	Code	Owner	Final depth	Year
94	Pernis-West-1	PRW-01	NAM	3460	1987
95	Pernis-West-2	PRW-02	NAM	2874	1990
96	Pijnakker-13	PNA-13	NAM	2500	1977
97	Q10-01	Q10-01	NAM	2358	1962
98	Q11-01	Q11-01	NAM	2497	1969
99	Q11-02	Q11-02	WIN	1250	1982
100	Q11-03	Q11-03	WIN	3197	1992
101	Q13-01	Q13-01	NAM	2387	1962
102	Q13-02	Q13-02	AMC	2810	1978
103	Q13-04	Q13-04	NAM	3023	1985
104	Q14-01	Q14-01	BOW	2222	1984
105	Q14-02	Q14-02	CLY	3100	1991
106	Q16-01	Q16-01	PLA	2631	1970
107	Q16-02	Q16-02	BPE	3975	1978
108	Q16-04	Q16-04	BPE	3839	1985
109	Q16-05	Q16-05	NAM	2979	1985
110	Reedijk-1	RDK-01	NAM	3053	1992
111	Ridderkerk-1	RKK-01	NAM	2425	1957
112	Ridderkerk-32-S3	RKK-32-S3	NAM	3691	1990
113	Rijswijk-1	RWK-01	NAM	2575	1953
114	Rotterdam Schulpweg-1	RTD-01	NAM	3305	1984
115	Rozenburg-1	RZB-01	NAM	3244	1987
116	's-Gravenzande-1	SGZ-01	NAM	3415	1997
117	Schiphol-1	SPL-01	AMC	2232	1970
118	Schiphol-2	SPL-02	AMC	2889	1970
119	Schipluiden-1	SCL-01	CLY	1467	1949
120	Spaarnwoude-1	SPW-01	NAM	923	1949
121	Spijkenisse-1	SPK-01	NAM	3276	1960
122	Spijkenisse-Oost-1	SPKO-01	NAM	2379	1990
123	Spijkenisse-Oost-2-S1	SPKO-02-S1	NAM	3333	1993
124	Spijkenisse-West-1	SPKW-01	NAM	2910	1992
125	Starnmeer-1	STM-01	AMC	2884	1975
126	Strijen-1	STR-01	AMS	2779	1964
127	Strijen-West-1	STW-01	NAM	3101	1987
128	Vlaardingen-Noord-1	VLN-01	NAM	4109	1994
129	Voorthuizen-1	VHZ-01	NAM	1774	1950
130	Vreeland-1	VRE-01	PET	1015	1950
131	Wassenaar-1	WAS-01	NAM	1369	1956
132	Wassenaar-23-S2	WAS-23-S2	NAM	3153	1976
133	Wassenaar-Zee-1	WAZ-01	NAM	2200	1980
134	Waverveen-1	WRV-01	AMC	2458	1971
135	Weesp-1	WSP-01	AMC	2259	1970
136	Werkendam-2	WED-02	NAM	3516	1965
137	Willeskop-1	WLK-01	NAM	2666	1988
138	Woubrugge-1	WOB-01	NAM	3801	1966
139	Zaandam-1	ZAD-01	NAM	951	1948
140	Zeewolde-1	ZEW-01	CON	2000	1966

Well nr.	Name	Code	Owner	Final depth	Year
141	Zeist-1	ZST-01	BPM	1100	1948
142	Zoetermeer-1	ZOM-01	NAM	1305	1957
143	Zoetermeer-28	ZOM-28	NAM	1275	1979
144	Zuid-Schermer-1	ZSRM-01	AMC	2250	1997

AMC	Amoco Netherlands Petroleum Co.
AMS	American Overseas Petroleum Ltd.
BOW	Bow Valley Industries Ltd.
BPE	British Petroleum Exploratie Maatschappij Nederland B.V.
BPM	Bataafsche Petroleum Maatschappij
CHE	Chevron Oil Company of the Netherlands
CLY	Clyde Petroleum Exploratie B.V.
CON	Continental Netherlands Oil Company B.V.
NAM	Nederlandse Aardolie Maatschappij B.V.
PET	Elf Petroland B.V.
PLA	Placid International Oil Ltd.
WIN	Wintershall Noordzee B.V.

Reservoir calculations Lower and Upper Germanic Trias Groups

The calculations in the tables below have been carried out for the Lower and Upper Germanic Trias Groups. In the calculation, the reservoirs of the Lower Germanic Trias Group have been subdivided into a gas zone (2684-2769 m), an oil zone (2769-2804 m), a water zone containing a significant quantity of residual oil (up to 40%) (2804-2855 m) and finally a water zone containing 100% water (2855-2875 m). Cut-off values applied: clay content Vcl = 50%; effective porosity = 6%.
The 50% cut-off for the clay content is customary in industry. The 6% cut-off for the porosity derives from the crossplot of core permeability versus core porosity, where it is assumed that for permeabilities lower than 0.1 mD the producibility of the gas is zero.

Gross. Net in metres
Øem = average effective porosity (in percentages)
Vclm = average clay content (in percentages)
Swm = average water saturation (in percentages) (Hydrocarbaon saturation = 100 - Sw)

In order to be able to compare the cut-off values of oil with those of gas, the same value has been used for both reservoirs.

Lower and Upper Germanic Trias Groups

Well	*Unit*	*Reservoir*				
		Gross	*Net*	*Øem*	*Vclm*	*Swm*
PRW-1	RNRO	67.0	14.3	16.4	38.5	19
	RBM – gas zone	84.8	83.4	17.5	20.8	34
	RBM – oil zone	35.4	33.1	13.6	14.9	44
	RBM – water zone + residual hc	50.8	47.6	11.8	15.9	65
	RBM – water zone 100% water	20.5	14.1	10.7	27.4	—
	Total/Average for all units	258.5	192.5	14.8	20.4	43

Show, status and test data Lower and Upper Germanic Trias Groups

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
PRW-1	oil/gas	First oil,	DST1	3108-3117.5	G	GOR = 83	RBM
		currently			O	18.2	
		injection	DST2	3108-3117.5	G	GOR = 83	RBM
		well			O	78	
			DST3	3108-3117.5	G	GOR = 95	RBM
					O	81.3	
			DST4	3062-3072.5	G	222	RBM
			DST5	3015-3030	G	297	RBM
			DST6	2945.5-2981	G	257	RNRO

Legend appendices C, D en E

Status:

oil	= oil production

Test:

DST	= drill stem test (quantity in litres)

Interval:

Interval in metres log depth

Yield:

G	= gas
O	= oil
W	= water

Flow/GOR:

Gas, Q50, in 1000 m^3/day
Oil, in m^3/day
GOR, gas/oil ratio

Unit:

NLFFD	= Basal Dongen Sand Member
KNGLG	= Holland Greensand Member
KNNSL	= De Lier Member
KNNSY	= IJsselmonde Sandstone Member
KNNSB	= Berkel Sandstone Member
SLDN	= Nieuwerkerk Formation
RNRO	= Röt Formation
RBM	= Main Buntsandstein Subgroup

Reservoir calculations Upper Jurassic, Lower Cretaceous and Tertiary units

The calculations have been carried out by the Nederlandse Aardolie Maatschappij.

Gross, Net in metres
N/Gr = Net-Gross ratio
Ø = porosity (in percentages)
Vcl = clay content (in percentages)
Sw = water saturation (in percentages)
OWC = Oil-water contact
tvd = true vertical depth

BRK-04

De Lier Member (KNNSL) 1073-1256 m

Well	*Net*	*N/Gr*	*Vcl*	*Ø*	*Sw*
Berkel-4	5.5	0.03	17	21	43

Berkel Sandstone Member (KNNSB) 1589-1730 m

Well	*Net*	*N/Gr*	*Vcl*	*Ø*	*Sw*
Berkel-4	116.2	0.82		24	20

OWC at 1633 m (1263 m tvd)
This well has not been tested

IJS-55

Unit	*Yield*	*Interval (m ah)*	*Reservoir*			
			Gross	*Net*	*Ø*	*Vcl*
NLFFD	G	527.5-535	7.5	6.1	35	37.3
KNGLG	G	656-692	36	35.6	30	35.3
	W	692-700	8	8	27	37.7
KNNSL	G	867.5-927.5	60	14.5	19	31.1
	O	927.5-945.0	17.5	1.8	21	40.9
KNNSY	O	980.5-1050.6	70.1	39.9	25	16.8
	W	1050.6-1143.5	92.9	0	0	13.7
SLDN	O	1183-1432	249	0.01	22	72.6
	O	1432-1549	117	0.08	18	73.3

No test data are available but this well has produced oil and associated gas from the KNNSY and the SLDN for 7 years with average yields of 14 to 6 m^3/day oil and 280 to 1700 m^3/day gas.

References

Bijlsma, S. (1981) *Fluvial sedimentation from the Fennoscandian area into the north-west European basin during the Late Cenozoic.* Geol. Mijnbouw, 60, p. 337-345.

Bless, M.J.M. & Winkler-Prins, C.F. (1972) *Palaeoecology and palaeogeography of the Aegir marine band and its equivalents in north-west Europe.* 72e C.R. Congr. Int. Strat. Geol. Carbonif. (1971), Vol.1, p. 231-239.

Bless, M.J.M., Bosum, W., Bouckaert, J., Dürbaum, H.J., Kockel, F., Paproth, E., Querfurth, H. & van Rooyen, P. (1980) *Geophysikalische Untersuchungen am Ost-Rand des Brabanter Massifs in Belgien, -den Niederländen und der Bundesrepublik Deutschland.* Meded. Rijks Geol. Dienst, 32, p. 313-343.

Bodenhausen, J.W.A. & Ott, W.F. (1981) *Habitat of the Rijswijk oil province, onshore, The Netherlands.* In: L.V. Illing, & G.D. Hobson (eds) *Petroleum Geology of the Continental Shelf of NW Europe,* Inst. Petrol., London, p. 301-309.

Borghuis, G.J. (1988) *Veertig jaar NAM. De geschiedenis van de Nederlandse Aardolie Maatschappij 1947-1987.* Nederlandse Aardolie Maatschappij, Assen, 112 pp.

Cameron, N. & Ziegler, T. (1997) *Probing the lower limits of a fairway: further pre-Permian potential in the southern North Sea.* In: Ziegler, K., Turner, P. & Daines, S.R. (eds) *Petroleum Geology of the southern North Sea: future potential.* Geol. Sec. Spec. Pub. 123, London, p. 123-142.

Cornford, C. (1990) *Source rocks and hydrocarbons of the North Sea.* In: Glennie, K.W. (ed.) *Introduction to the petroleum geology of the North Sea.* JAPEC, Blackwell, Oxford, p. 294-361.

Coward, M.P. (1991) *Inversion tectonics in NW Europe.* Abstracts EUG VI, Strassbourg, p. 229.

Crittenden, S. (1987) *The 'Albian transgression' in the Southern North Sea Basin.* Journ. Petr. Geol. 10, p. 395-414.

De Jager, J., Doyle, M.A., Grantham, P.J. & Mabillard, J.E. (1996) *Hydrocarbon habitat of the West Netherlands Basin.* In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds) *Geology of Gas and Oil under the Netherlands,* Kluwer, Dordrecht, p. 191-209.

Den Hartog Jager, D.G. (1996) *Fluviomarine sequences in the Lower Cretaceous of the West Netherlands Basin: correlation and seismic expression.* In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds) *Geology of Gas and Oil under the Netherlands,* Kluwer, Dordrecht, p. 229-242.

Dixon, J.E., Fitton, J.G. & Frost, R.T.C. (1981) *The tectonic significance of Post-Carboniferous igneous activity in the North Sea Basin.* In: Illing, L.V., Hobson, G.D. (eds) *Petroleum geology of the Continental Shelf of NW Europe,* Heyden & Son, London, p. 121-137.

Donovan, D.T. & Jones, E.J.W. (1979) *Causes for wordwide changes in sea level.* Journ. Roy. Soc. London. 136, p. 187-192.

Dusar, M., Bless, M.J.M., Burger, K., Demaret, M., Hardy, M., Langenaeker, V., Lie, S.F., Paproth, E., Pierart, P., Somers, Y., Streel, M. & Wouters, L. (1998) *De steenkoolverkenningsboring Hechtel-Hoef (Boring 174 van het Kempens bekken).* Belgische Geologische Dienst Professional Paper 1998/1, 286, 88 pp.

Fertl, W.H. (1987) *Log-derived evaluation of shaly clastic reservoirs.* Journ. Petr. Techn. February 1987, p.175-194.

Geluk, M.C. (1999a) *Late Permian (Zechstein) rifting in the Netherlands - models and implications for petroleum geology.* Petroleum Geoscience, 5 (2), p. 189-199.

Geluk, M.C. (1999b) *Palaeogeographic and structural development of the Triassic in the Netherlands - new insights.* In: Bachmann, G.H. & Lerche, I. (eds) *The Epicontinental Triassic,* Zentralblatt für Geologie und Paläontology, Heft 7-8, p. 727-745.

Geluk, M.C., Plomp, A. & van Doorn, Th.H.M. (1996) *Development of the Permo-Triassic succession in the basin fringe area.* In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, H.W. (eds) *Geology of Gas and Oil under the Netherlands.* Kluwer Acad. Publ., Dordrecht, p. 57-78.

Geluk, M.C. & Röhling, H.G. (1997) *High-resolution sequence stratigraphy of the Lower Triassic 'Buntsandstein' in the Netherlands and Northwestern Germany.* Geol. Mijnbouw, 76, p. 227-246.

Glennie, K.W. (1998) *Lower Permian – Rotliegend.* In: Glennie, K.W. (ed.) *Introduction to the petroleum geology of the North Sea* (4th ed.), Blackwell Scient. Publ., Oxford, p. 137-173.

Haanstra, U. (1963) *A review of Mesozoic history of the Netherlands.* Verh. Kon. Ned. Geol. Mijnbouwk. Gen., Geol. serie, vol. 21-1, p. 35-55.

Haq, B.U., Hardenbol, J. & Vail, P.R. (1987) *Chronology of fluctuating sea levels since the Triassic.* Science, 235, p. 1156-1167.

Haq, B.U., Hardenbol, J. & Vail, P.R. (1988) *Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change.* In: Wilgus, C.K., Hastings, B.C., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A. & Van Wagoner, J.C. (eds): *Sea-level changes – An integrated approach.* Society of Economic Paleontologists and Mineralogists. Spec. Publ. 42, p. 71-108.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G. & Smith, D.E. (1990) *A geologic time scale 1989.* Cambridge Univ. Press, 263 pp.

Hays J.D. & Pitman, W.C. (1973) *Lithospheric plate motion, sea level changes and climatic and ecological consequences.* Nature, 246, p. 18-22.

Heckel, P.H. (1986) *Sea-level curve for Pennsylvanian eustatic marine transgressive-regressive depositional cycles along midcontinent outcrop belt, North America.* Geology, 14, p. 330-334.

Hedemann, H.A., Schuster, A., Stancy-Kristoff, G. & Loesch, J. (1984) *Die verbreitung der Kohlenflöze des Oberkarbons in Nordwestdeutschland und ihre stratigrafische Einstufung.* Fortschr. Geol. Rheinld. Westf., 32, p. 39-88.

Heybroek, P. (1974) *Explanation to tectonic maps of The Netherlands.* Geol. Mijnbouw, 53, p. 43-50.

Herngreen, G.F.W. & De Boer, K.F. (1974) *Palynology of Rhaetian, Liassic and Dogger strata in the eastern Netherlands.* Geol. Mijnbouw, 53, p. 343-368.

Herngreen, G.F.W. & De Boer, K.F. (1978) *Dinoflagellate zonation of Upper Dogger and lowermost Malm in the Netherlands.* Palinologia, 1, p. 283-291.

Herngreen, G.F.W., van Hoeken-Klinkenberg, P.M.J. & de Boer, K.F. (1980) *Some remarks on selected palynomorphs near the Jurassic-Cretaceous boundary in The Netherlands.* Proc. IVth Int. Palynol. Conf., II, p. 357-367.

Herngreen, G.F.W., Kerstholt, S.J. & Munsterman, D.K. (2000) *Callovian-Ryazanian ('Upper Jurassic') palynostratigraphy of the Central North Sea Graben and Vlieland Basin, the Netherlands.* Meded. Ned. Inst. Toegep. Geowet. TNO, 63, 99 pp.

Kozur, H. (1999) *The correlation of the Germanic Buntsandstein and Muschelkalk with the Tethyan scale.* In: Bachmann, G.H. & Lerche, I. (eds) *The Epicontinental Triassic,* Zentralblatt für Geologie und Paläontology 1998, Heft 7-8, p. 701-725.

Langenaeker, V. (1998) *The Campine Basin. Stratigraphy, structural geology, coalification and hydrocarbon potential for the Devonian to Jurassic.* Doctoraatsthesis, Katholieke Universiteit Leuven, Fac. Wetensch., Dept. Geografie-Geologie. Afd. Hist. Geologie, 213 pp.

Leeder, M.R. (1988) *Recent developments in Carboniferous geology: a critical review with implications for the British Isles and N.W. Europe.* Proceedings of the Geologists' Association, 99, p. 73-100.

Letsch, W.J. & Sissingh, W. (1983) *Tertiary stratigraphy of the Netherlands*. Geol. Mijnbouw, 62, p. 305-318.

Lokhorst, A. (ed.) (1998) *Northwest European Gas Atlas - composition and isotope ratios of natural gases*. Netherlands Institute of Applied Geoscience TNO – National Geological Survey, Haarlem, ISBN 90-72869-60-5.

Novem (2001) Potential *for CO_2 sequestration and enhanced Coalbed Methane production in the Netherlands*, Utrecht, 105 pp.

Oele, J.A., Hol, A.C.P.J. & Tiemens, J. (1981) *Some Rotliegend gasfields of the K and L blocks, Netherlands offshore (1968-1978) – a case history*. In: Illing, L.V. & Hobson, G.D. (eds). *Petroleum Geology of the Continental Shelf of NW Europe*, Inst of Petroleum, London, p. 289-300.

Pagnier, H.J.M. & Van Tongeren, P.C.H. (1996) *Upper Carboniferous of borehole 'De Lutte-6' and evaluation of the Tubbergen Formation in eastern and southeastern parts of the Netherlands*. Meded. Rijks Geol. Dienst, 55, p. 3-30.

Pitman, W.C. (1978) *Relationship between eustacy and stratigraphic sequences on passive margins*. Geol. Soc. Am. Bull., 89, p.1389-1403.

Racero-Baena, A. &. Drake, S.J. (1996) *Structural style and reservoir development in the West Netherlands oil province*. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds) *Geology of Gas and Oil under the Netherlands*, Kluwer, Dordrecht, p. 211-227.

Rijkers, R.H.B. & Geluk, M.C. (1996) *Sedimentary and structural history of the Texel-IJsselmeer High, the Netherlands*. In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuizen, W.H. (eds) *Geology of Gas and Oil under the Netherlands*, Kluwer, Dordrecht, p. 265-284.

Rijks Geologische Dienst (1970) *Toelichtingen bij de Geologische kaart van Nederland, 1:50.000, Blad Gorinchem Oost (38O)*, Haarlem, 139 pp.

Rijks Geologische Dienst (1979) *Toelichtingen bij de Geologische kaart van Nederland, 1:50.000, Blad Rotterdam West (37W)*, Haarlem, 137 pp.

Rijks Geologische Dienst (1984) *Toelichtingen bij de Geologische kaart van Nederland, 1:50.000, Blad Tiel West (39W) en Tiel Oost (39O)*, Haarlem, 327 pp.

Rijks Geologische Dienst (1989) *Toelichtingen bij de Geologische kaart van Nederland, 1:50.000, Blad Utrecht Oost (31O)*, Haarlem, 111 pp.

Rijks Geologische Dienst (1991) *Geological Atlas of the Subsurface of The Netherlands: Explanation to map sheet I: Vlieland-Terschelling*. Haarlem, 79 pp.

Rijks Geologische Dienst (1993a) *Geological Atlas of the Subsurface of The Netherlands: Explanation to map sheet IV: Texel-Purmerend*. Haarlem, 128 pp.

Rijks Geologische Dienst (1993b) *Geological Atlas of the Subsurface of The Netherlands: Explanation to map sheet V: Sneek-Zwolle*. Haarlem, 126 pp.

Rijks Geologische Dienst (1995) *Toelichtingen bij de Geologische kaart van Nederland, 1:50.000, Blad Gorinchem West (38W)*, Haarlem, 155 pp.

Schlanger, S.O., Arthur, M.A., Jenkins, H.C. & Scholle, P.A. (1987) *The Cenomanian-Turonian oceanic event. Stratigraphy and distribution of organic-carbon rich beds and the marine d13C excursion*. In: Brooks, J. & Fleet, A.J. (eds) *Marine petroleum source rocks*, Blackwell, Oxford, p. 371-400.

Scotese, C.R (1991) *Jurassic and Cretaceous plate tectonic reconstructions*. Palaeogeogr., Palaeoclimat., Palaeoecol., 87, p. 493-501.

Scotese, C.R. & McKerrow, W.S. (1990) *Revised world maps and introduction*. Mem. Geol. Soc. London, 12, p. 1-21.

Spain, D.R. & Conrad, C.P. (1997) *Quantitative analysis of top-seal capacity: offshore Netherlands, southern North Sea*. Geol. Mijnbouw, 76, p. 217-226.

Taylor, J.C.M. (1998) Upper *Permian-Zechstein.* In: Glennie, K.W. (ed.) *Introduction to the petroleum geology of the North Sea* (4th ed.), Blackwell Science, Oxford, p. 174-212.

Thorez, J. & Bless, M.J.M. (1977) *On the possible origin of the Lower Westphali-an D Neeroeteren Sandstone (Campine, Belgium).* Meded. Rijks Geol. Dienst, N.S., 28, p. 128-134.

TNO-NITG (2001a) *Geological Atlas of the Subsurface of the Netherlands: Explanation to map sheets XIII and XIV: Breda-Valkenswaard and Oss-Roermond.* Utrecht, 149 pp.

Tucker, M.C. (1991) *Sequence stratigraphy of carbonate-evaporite basins: models and application to the Upper Permian (Zechstein) of northeast England and adjoining North Sea.* Journal of the Geological Society, 148, p. 1019-1036.

Underhill, J.R. & Partington, M.A. (1993) *Jurassic thermal doming and deflation in the North Sea: implications for sequence stratigraphic evidence.* In: Parker, J.R. (ed.), *Petroleum Geology of Northwest Europe.* Graham & Trotman, London, p. 697-706.

Vail, P.R., Mitchum, R.M. Jr. & Todd, R.G. (1977) *Eustatic model for the North Sea during the Mesozoic.* N.P.F. Mesozoic Northern North Sea Symposium, Oslo, MNNSS/12, p. 1-12.

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P. (1993-1997) *Stratigraphic nomenclature of the Netherlands revision and update by RGD and NOGEPA.* Meded. Rijks Geol. Dienst 50.

Van Amerom, H.W.J. & Pagnier, H.J.M. (1990) *Palaeoecological studies of Late Carboniferous plant macrofossils from borehole Kemperkoul-1 (Sittard, the Netherlands).* Meded. Rijks Geol. Dienst, 44-4, p. 43-61.

Van Balen, R.T., Van Bergen, F., de Leeuw, C., Pagnier, H., Simmelink, H., Van Wees, J.D. & Verweij, J.M. (2000) *Modelling the hydrocarbon generation and migration in the West Netherlands Basin, the Netherlands.* Geol. Mijnbouw/ Neth. Journ. Geosc. 79, p. 29-44.

Van der Baan, D. (1990) *Zechstein reservoirs in The Netherlands.* In: Brooks, J. (ed.) – *Classic Petroleum Provinces;* Geol. Soc. Spec. Publication nr. 50, p. 379-398.

Van de Laar, J.G.M. & van der Zwan, C.J. (1996) *Palynostratigraphy and palynofacies reconstruction of the Upper Carboniferous of borehole 'De Lutte-6' (East Twente, the Netherlands).* Meded. Rijks Geol. Dienst, 55, p. 61-82.

Veevers, J.J. & Powell, C.Mc.A. (1987) *Late Palaeozoic glacial episodes in Gondwanaland reflected by transgressive-regressive depositional sequences in Euramerica.* Geological Society of America Bulletin, 98, p. 475-487.

Vercoutere, C. & van den Haute, P. (1993) *Post-Palaeozoic cooling and uplift of the Brabant Massif as revealed by apatite fission track analysis.* Geol. Mag., 130, p. 639-646.

Verdier, J.P. (1996) *The Rotliegend sedimentation history of the southern North Sea and adjacent countries.* In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds) *Geology of Gas and Oil under the Netherlands,* Kluwer, Dordrecht, p. 45-56.

Whiteman, A., Naylor, D., Pegrum, R. & Rees, G. (1975) *North Sea troughs and plate tectonics.* Tectonophysics, 26, p. 39-54.

Wouters, L. & Vandenberghe, N. (1994) *Geologie van de Kempen.* NIRAS, Brussel, 208 pp.

Wuster, P. (1968) *Palaeogeografie der Deutschen Trias und die palaeogeografische Orientierung der Lettenkohle in Sudwestdeutschland.* Eclog. Geol. Helv., 61, p. 157-166.

Zagwijn, W.H. (1989) *The Netherlands during the Tertiary and the Quater-nary: A case history of Coastal Lowland evolution.* Geol. Mijnbouw, 68, p. 107-120.

Ziegler, P.A. (1990) *Geological Atlas of Western and Central Europe.* Shell Int. Petrol. Mij., 2nd ed., 239 pp, 56 encl.

RGD 1983, *Geologische en hydrologische inventarisatie van Tertiaire en Onder-Kwartaire afzettingen in Midden-Nederland t.b.v. ondergrondse opslag en winning van warm water.* Rapport no. 83KA20EX.

RGD 1984, *Voorkomen en winningsmogelijkheden van thermisch mineraalwater in de ondergrond van Oploo (N.Br.).* GB 2001/GD 20139.

RGD 1986a, Lissenberg, Th. & Herngreen, G.F.W. *Stratigrafische interpretatie van een twaalftal monsters uit het Mesozoische traject van de boring Rustenburg-1.* Micropal. Mes. 438.

RGD 1986b, Herngreen, G.F.W. *Resultaten van het palynologisch onderzoek van de boring Rustenburg-1, traject 1120-1230 m.* Palyn. Mes. 2198.

RGD 1986c, Lissenberg, Th. & Herngreen, G.F.W. *Stratigrafische interpretatie van een achttal monsters uit het Kaenozoische en Mesozoische traject van boring Middelie-103.* Micropal. Mes. 439.

RGD 1986d, Lissenberg, Th. & Herngreen, G.F.W. *Stratigrafische interpretatie van het Mesozoicum van boring Middelie-201.* Micropal. Mes. 440.

RGD 1987, Lissenberg, Th. & Witte, L.J. *Stratigrafische interpretatie van het Mesozoicum van boring Bergermeer-1.* Micropal. Mes 448.

RGD 1990a, Herngreen, G.F.W. *Resultaten van het palynologisch onderzoek van boring Bergermeer-1, traject 840-1315 m.* Palyn. Mes. 2228.

RGD 1990b, Lissenberg, Th. & Witte, L.J. *Biostratigrafische interpretatie van het traject 1270-1400 van boring Middelie-301.* Micropal. Mes. rap. 513.

RGD 1990c, Herngreen, G.F.W. *Resultaten van het palynologisch onderzoek van boring Middelie-301, traject 1300-1385.* Palyn. Mes. 2230.

RGD 1995a, Herngreen, G.F.W. *Palynologisch onderzoek van de boring Ridderkerk-01, kerntrajekt 2177-2183 m.* Palyn. Mes. 2313.

RGD 1995b, Herngreen, G.F.W. *Palynologisch onderzoek van de boring IJsselmonde-64, trajekt 2080-2150 m.* Palyn. Mes. 2312.

RGD 1995c, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van een traject uit de Midden Jura (2090 m t/m 2419.75 m) van boring RKK-01 (Ridderkerk-1, Kaartblad VII).* Micropal. Mes. 589.

RGD 1995d, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van een traject uit de Midden Jura (2080 m t/m 2290 m) van boring IJS-64 (IJsselmonde-64, Kaartblad VII).* Micropal. Mes. 628.

RGD 1995e, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van een traject uit de Midden Jura (1815 m t/m 1995 m) van boring IJS-03 (IJsselmonde-3, Kaartblad VII).* Micropal. Mes. 629.

RGD 1996a, Herngreen, G.F.W. *Palynologisch onderzoek van trajekt 2040-2070 m van de boring IJsselmonde 64.* Palyn. Mes. 2312a.

RGD 1996b, Herngreen, G.F.W. *Palynologisch onderzoek van de boring Ridderkerk-01. 2120-2140 m.* Palyn. Mes. 2313a.

RGD 1996c, Herngreen, G.F.W. *Palynologisch onderzoek van de boring Lekkerkerk-01, trajekt 1260-1744 m.* Palyn. Mes. 2314.

RGD 1996d, Herngreen, G.F.W. *Palynologisch onderzoek van het trajekt 1845-1881 m van de boring IJsselmonde-3.* Palyn. Mes. 2321.

RGD 1996e, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van een traject uit de Midden Jura (1350 t/m 1744 m) van boring LEK-01 (Lekkerkerk-1, Kaartblad VII).* Micropal. Mes. 640.

RGD & TNO 1996, Wildenborg, A.F.B. et al. *Inventarisatie van mogelijkheden voor CO2-opslag in de Nederlandse ondergrond,* 95KAR12.

NITG-TNO 1997, Rijkers, R. & Van Doorn, Th.H.M. *Atlas of geothermal resources in the European Community, the Netherlands,* NITG 97-24-A.

NITG-TNO 1998, Van Bergen, F. *Basin modelling and hydrocarbon generation in the WNB – an organic petrological and organic geochemical approach,* NITG 98-148-B.

NITG-TNO 1999, Herngreen, G.F.W. *Palynologisch onderzoek van boring Voorthuizen-1, traject 1080-1753 m.*, NITG 99-107-B.

TNO-NITG 2001b, Lokhorst. A. et al. *Aardwarmte in Nederland; verslag van het onderzoeksprogramma "Instandhouding Kennis Aardwarmte Exploratie en Exploitatie in Nederland (1997-2000)"*, 00-331-A.

TNO-NITG 2001c, Doornenbal, J.C. *Regionale snelheidsmodellen van het Nederlandse territoir,* NITG 01-116-B.

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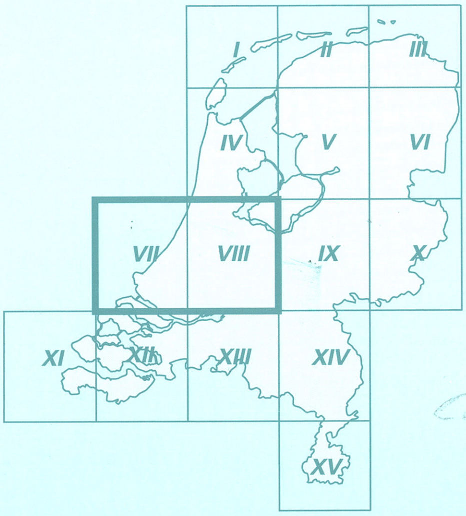
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