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

Explanation to map sheets XI and XII Middelburg-Breskens and Roosendaal-Terneuzen

TNO

Geological Atlas of the Subsurface of the Netherlands

Explanation to map sheets XI and XII Middelburg-Breskens and Roosendaal-Terneuzen

Netherlands Institute of Applied Geoscience TNO – *National Geological Survey*, Utrecht 2003

Geological Atlas of the Subsurface of the Netherlands

"Het Verdronken land van Saeftinge"
Photograph courtesy Paul Paris

Contents

The publication of map sheets XI and XII by the Netherlands Institute of Applied Geoscience TNO - *National Geological Survey* almost completes the Geological Atlas of the Subsurface of the Netherlands. This series makes available unique map sheets of the subsurface of the Netherlands, presenting an overview of potential exploitation opportunities. TNO-NITG's wide-ranging regional-geological knowledge of the subsurface of the Netherlands and surrounding countries, clearly enhances 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) used to be restricted because of the confidential status of the data required. These data are obtained from seismic surveys and deep drilling, which activities were 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 TNO-NITG in accordance with the regulations laid down in the Mining Act.

The mining legislation applicable to the Dutch territory prior to 2003 did not permit the general release of classified information. Agreements with industry concerning the use of this information enabled TNO-NITG to evaluate it and publish the results, provided the data had been acquired more than ten years before. However, for concession areas the classified period used to be five years. In the new Mining Act, all concession areas are referred to as production licences. The agreements with industry enabled TNO-NITG to make the geology of the deeper subsurface of the Netherlands known to the general public.

On 1 January 2003 the new Mining Act came into effect. The new mining legislation permits the immediate release of data concerning the Dutch Territory that were acquired (more then) ten years previously. Data acquired more recently are subject to transitional provisions. Data acquired less than five years ago may now be released as soon as the five-year classified period has ended. The modified provisions laid down in the new Mining Act and accompanying further rules did not affect production of the present map sheets or explanation.

The Middelburg-Breskens and Roosendaal-Terneuzen map sheets of the Geological Atlas of the Subsurface of the Netherlands are the thirteenth and fourteenth sheets to be published in the framework of the systematic mapping of the deep subsurface of the Netherlands. For this purpose the Netherlands has been divided into 15 map sheets to be published on a scale of 1:250 000 (see fig. 1.1 for an overview of the area of the map sheets).

Each map sheet has its characteristic features. The map sheets presented here outline the geology of the province of Zeeland as well as parts of the provinces of Zuid-Holland and Noord-Brabant. Maps and explanation reveal that the geology of these provinces is dominated by the northward extension of Brabant Massif.

The Brabant Massif, consisting of Cambro-Silurian deposits, was deformed during the Acadian phase of the Caledonian Orogeny, which took place during the Early Devonian. During the Middle and Late Devonian, the area was eroded and new sediments were deposited on the entire eroded massif area. To the north of the Brabant Massif the Campine Basin is present. This basin probably formed during the Middle Devonian under the influence of Early Variscan tectonics. The northern boundary of this basin is formed by the Zandvoort-Krefeld High, a string of horst structures, which formed a major structural zone well into the Tertiary.

The north-eastern corner of the map area just includes a part of the Mesozoic West Netherlands Basin, a NW-SE-oriented basin, which experienced a period of rapid subsidence during the Kimmerian tectonic phases, resulting in the deposition of a fairly complete succession of Triassic, Jurassic and Lower Cretaceous sediments. The boundary between the West Netherlands Basin and the Brabant Massif is formed by the Zeeland Platform, where the Chalk Group unconformably overlies Carboniferous and thin Permo-Triassic deposits. During the Late Eocene, inversion tectonics prevailed as a result of Alpine compression. This only affected the northernmost part of the map sheet area. During the inversion of the West Netherlands Basin, a subsiding area developed along the southern edge of the basin, commonly known as the Voorne Trough.

The text comprises three main parts. The first part describes the research set-up (Chapter 1), followed by an account of the exploration for hydrocarbons (Chapter 2) and the structural framework (Chapter 3). The second part comprises lithostratigraphic descriptions of the rocks (Chapters 4-14) and the geological history of the map sheet area (Chapter 15). 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 includes a section devoted to the depositional environment and the palaeogeography. In the third part (Chapter 16) special attention is given to various aspects of economic and applied geology, such as hydrocarbons, geothermal energy, hydrogeology and infrastructural works.

TNO-NITG expects that these map sheets, together with those already published or in progress, will contribute to a greater understanding of the structure and configuration of the deep subsurface of the Netherlands. This is important, not only to companies which are active in exploration for and production of mineral and natural resources, but also to various government authorities and other interested parties. The published maps may also be viewed digitally. TNO-NITG has developed a 3D viewer enabling the maps to be seen in three dimensions (see: http://dinoloket.nitg.tno.nl).

As well as the people acknowledged in the credits, who have been directly responsible for compiling these map sheets, many other employees of TNO-NITG have been involved, and their efforts are greatly appreciated. Regular consultations have been held with Dr M. Dusar and Dr W. De Vos of the Belgian Geological Survey on the harmonisation of these map sheets with the Belgian maps. Their expertise on the pre-Silesian in particular has contributed much to a proper description of that subject. Special thanks are due to the companies which provided the exploration data used in these map sheets.

Utrecht, November 2003

1 Research set-up

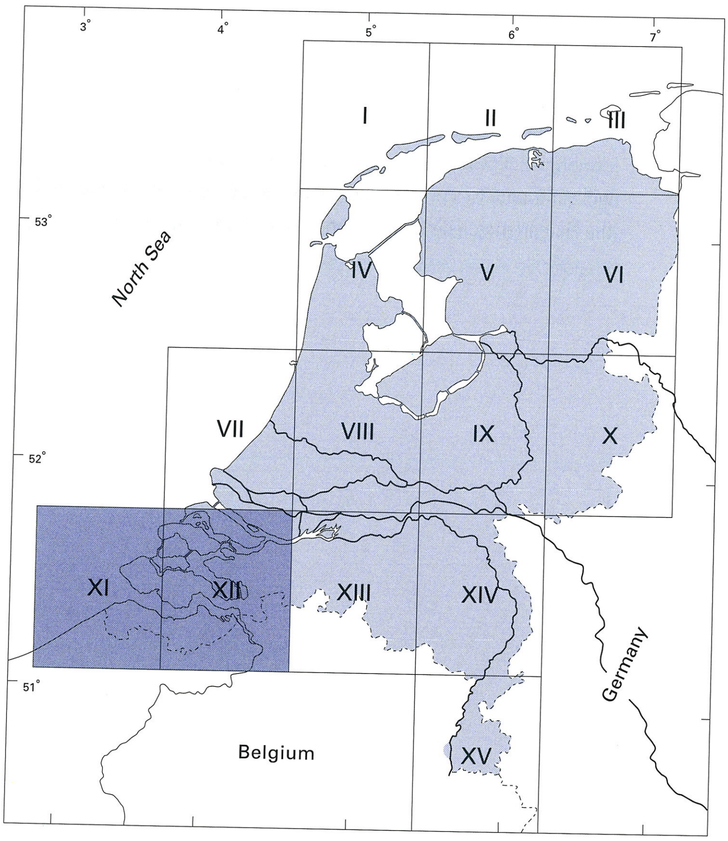
1.1 Extent of area studied

The area covered by map sheets XI (Middelburg-Breskens) and XII (Roosendaal-Terneuzen) of the Geological Atlas of the Subsurface of the Netherlands comprises the province of Zeeland and parts of the provinces of Zuid-Holland and Noord-Brabant (fig. 1.1). The area is bordered by the Dutch part of the Continental Shelf in the west and by the Belgian provinces of West Flanders, East Flanders and Antwerp in the south. 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. Mapping of these sheets relied mainly on 2D seismics. Seismic mapping of the adjoining continental shelf was also carried out. Only for the north eastern part of map sheet XII was 3D seismics available

Figure 1.1 Subdivision of the map sheets of the deep subsurface of the Netherlands showing the location of map sheets XI and XII.



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

(fig. 1.2, Appendix A). A total of 100 wells were selected for the area covered by the map sheets (fig. 1.3, Appendix B).

1.3 Geological research

The geological research focused on the lithostratigraphic configuration of the rock formations present in the map sheet area (fig. 1.4) and their geological history in the context of a regional-geological framework. Use was made of the seismic sections and well-log data referred to above. The lithostratigraphic units, which are indicated in fig. 1.4, are discussed in detail in the relevant chapters. The geological time scale applied in this research is according to Harland et al. (1990).

1.4 Seismic mapping

The mapping made use of almost all available seismic data. The seismic data used were shot between 1974 and 1991. In the southern part of the map sheet area the density of the seismic lines is extremely sparse. The interpretation is mainly based on 2D seismics and to a lesser extent on 3D seismics (fig. 1.2, Appendix A). The interpretation made use of a total of over 500 km^2 of 3D seismics and over 1700 km of 2D seismics.

The mapped reflectors form the boundaries between the lithostratigraphic units (groups and formations). The seismic data were calibrated against a number of wells, 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). This method is based on the assumption that for each layer a linear relationship exists between the velocity and the depth of the layer (Table 1.1).

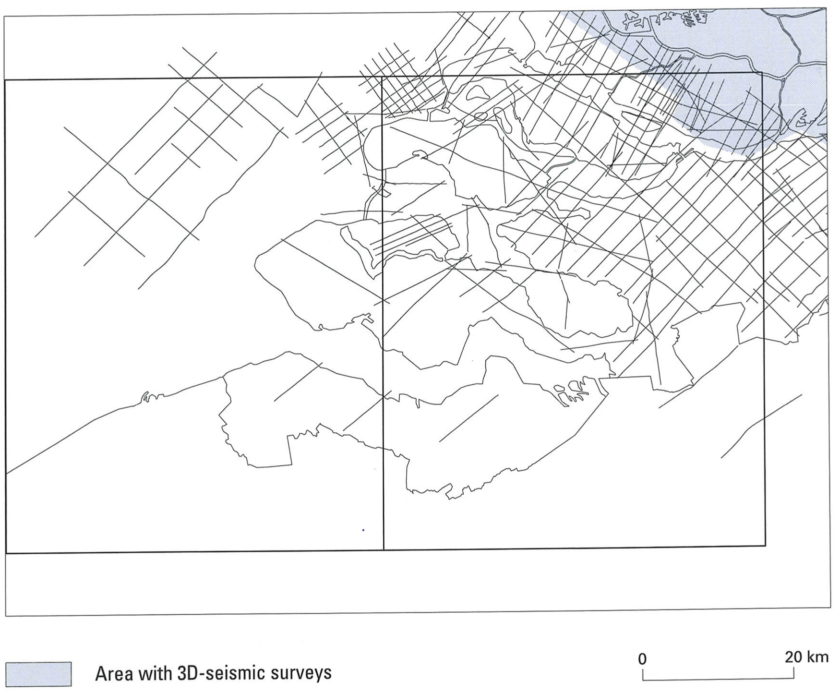


Figure 1.2 Locations of the seismic lines used for the mapping. Appendix A contains additional information on the vintage and ownership of the various surveys.

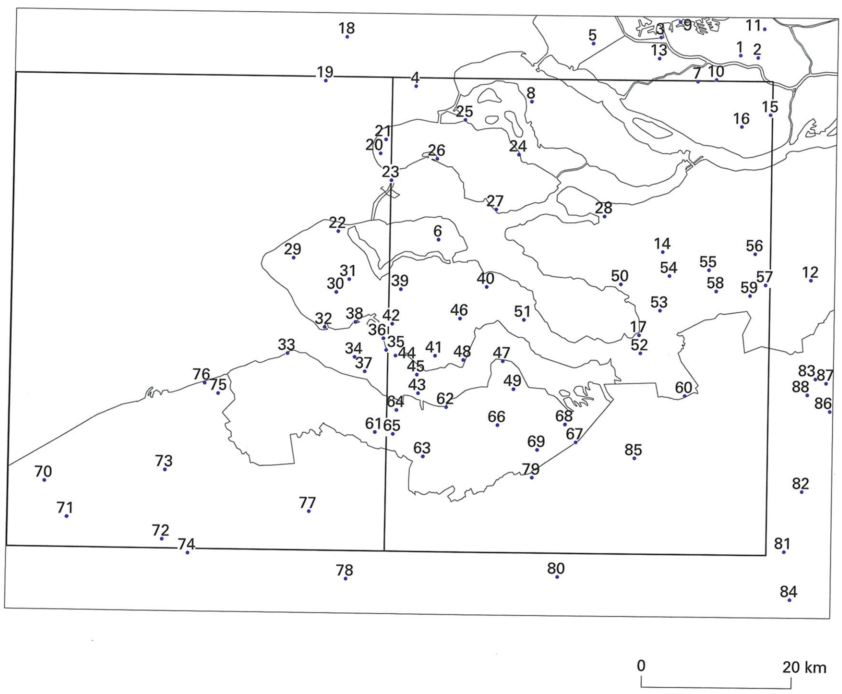
To ensure consistency between adjacent map sheets, a single velocity equation was derived for the whole of the Netherlands, which is to be applied to all the map sheets of the Geological Atlas of the Subsurface of the Netherlands. The parameters of this countrywide equation were determined from the acoustic data from 61 representative wells drilled all over the Netherlands. Application of this velocity distribution, however, gave rise to large discrepancies in the depths of the base of the Rijnland Group, the Altena Group and the Lower Germanic Trias Group, particularly in the inverted areas, and consequently the equation was revised. A regional velocity distribution (*TNO-NITG, 2001a*) was determined from the acoustic data from over 600 wells located in the Netherlands on- and offshore areas. For the present map sheet area, this produced the velocity equation given in Table 1.1.

The interpreted seismic horizons are delineated by the bases of lithostratigraphic groups, i.e., the Upper North Sea Group, the North Sea Supergroup, the Chalk Group, the Rijnland Group, the Schieland Group, the Altena Group, the Permo-Triassic groups and the Limburg Group (figs 1.4, 3.2, 5.4 and 15.6).

The Upper North Sea Group is the youngest seismic unit and is characterised by typical seismo-stratigraphic phenomena such as downlaps, toplaps and onlaps, which are associated with a prograding sedimentary system. In the southern part of the map sheet area, this horizon is too shallow to show on seismics. Mapping of this horizon in this area is therefore based on a large number of shallow wells. The Lower and Middle North Sea Groups constitute a comparatively uniform unit, containing distinct, continuous reflectors.

The Chalk Group also constitutes a uniform unit, characterised by distinct, continuous reflectors. In the southern part of the map sheet area, where the Chalk Group overlies the Limburg Group, the base of the Chalk Group is a distinct angular unconformity.

Figure 1.3 Locations of the wells used for the mapping. Please refer to Appendix B for the numbering and the name, owner, total depth and year of drilling of each well. In case of wells drilled outside the Netherlands, total depths and literature references are listed.



The Rijnland, Schieland and Altena Groups only occur in the north-eastern part of the map sheet area. The base of the Rijnland Group is often difficult to trace. Occasionally, a clear reflector shows up, but this horizon is usually vague and indistinct. The base of the Rijnland Group is marked by the sand bodies of the Vlieland Formation and the Nieuwerkerk Formation, which are each other's lateral equivalents. The lower part of the Schieland Group is a unit containing many continuous reflectors. The base of the Altena Group is usually a prominent and continuous reflector.

The Permo-Triassic groups have been interpreted as a single seismic unit, frequently 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 sections. The thickness maps of both these groups have therefore been derived from 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 distinct angular unconformity.

Figure 1.4 Diagram of the litho-stratigraphic units and the major tectonic phases that have affected the geological evolution of the map sheet area.

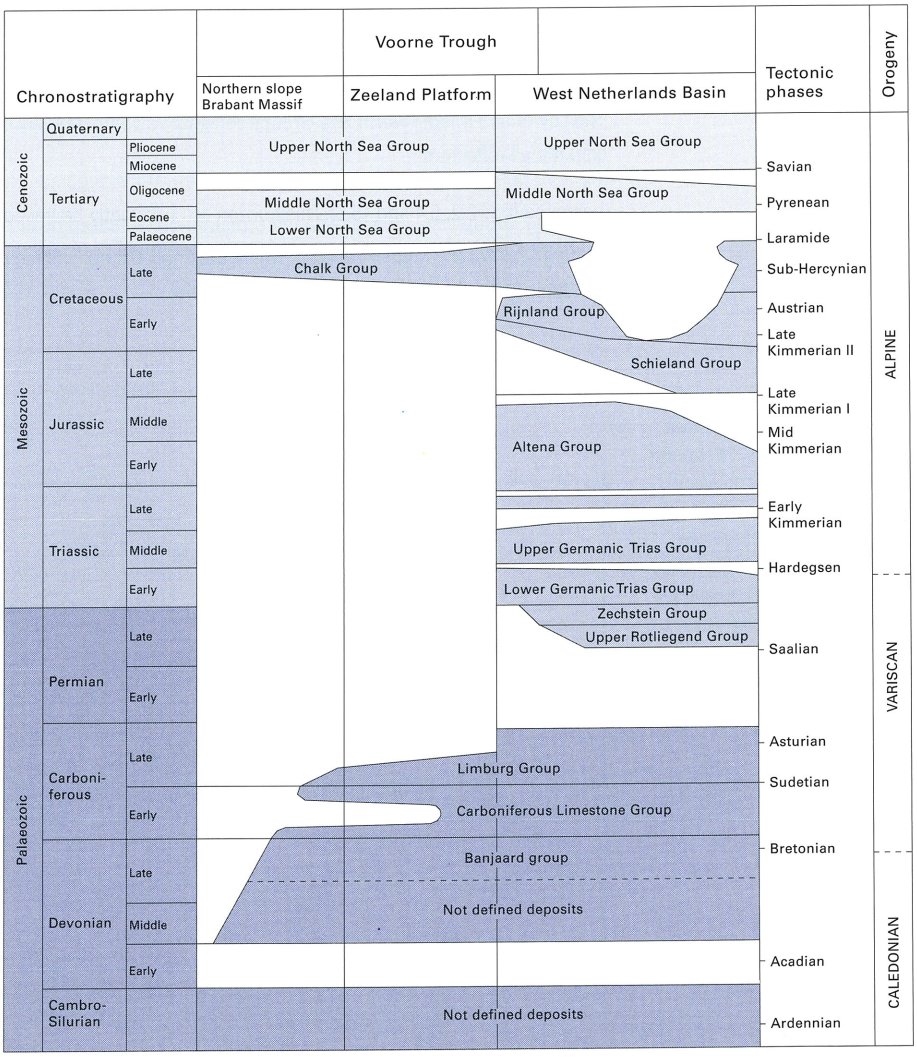


Table 1.1 Velocity distributions applied

The velocity distributions applied in the map sheet area are based on $V_z = V_0 + k.z$
V_z: average velocity at depth z (m/s)
V_o: 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
Limburg Group	3443	0.25

The base of the Limburg Group has been interpreted on a large number of seismic lines in the map sheet area (figs 3.2, 5.4 and 15.6). This horizon can frequently be traced as a strong, prominent reflector, on top of which onlap may be observed in places. A number of seismic lines show the underlying deposits of the Carboniferous Limestone Group, as an acoustically transparent unit characterised by discontinuous reflectors. The lower boundary of the Carboniferous Limestone Group also shows as a strong, sometimes very wide, prominent reflector, characterised by an angular unconformity.

1.5 Biostratigraphic research

To support the geological research, use was made of a large number of biostratigraphic studies (*RGD, 1964, RGD 1973a,b; RGD, 1975, RGD, 1978, RGD, 1981; RGD, 1990; RGD, 1995a,b,c; RGD, 1996a,b,c; NITG-TNO, 1999; TNO-NITG, 2002; TNO-2003a,b*).

1.6 Petrophysical research

The petrophysical characteristics of the reservoir rocks in the map sheet area have also been evaluated. Well-log data and core analyses of one well (Oud-Beijerland-Zuid-1) have been processed to calculate porosities; these are listed in Appendix C. Appendix D shows the test data.

1.7 Maps and cross-sections

The results of the mapping are presented on a scale of 1:250 000 in a series of depth maps and thickness maps of the lithostratigraphic groups, on subcrop maps and in cross-sections (Maps XI-1 to XI-7 and Maps XII-1 to XII-19). An overview of the stratigraphy is given in figure 1.4.

Depth maps have been prepared for the bases of the Upper Rotliegend, the Zechstein, the Lower Germanic Trias, the Altena, the Schieland, the Rijnland and the Chalk Groups, the North Sea Supergroup and the Upper North Sea Group. The Upper Rotliegend and Zechstein Groups are only thinly developed (0-50 m) in the map sheet area. The seismic resolution is insufficient to allow these intervals to be mapped separately. 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 thickness of the Zechstein Group and that of the Upper Rotliegend Group have been added.

Thickness maps have been prepared for the Zechstein, the Lower and Upper Germanic Trias, the Altena, the Schieland, the Rijnland and the Chalk Groups. The depth and thickness maps only show those wells in which the interval in question has been fully penetrated (see section 1.2).

Subcrop maps have been made for the major unconformities: at the bases of the Schieland Group, the Rijnland Group/Chalk Group, the Chalk Group and the North Sea Supergroup. These give an idea of the degree of erosion that preceded deposition of these groups.

Finally, two structural cross-sections are included for map sheet XI and three structural cross-sections for map sheet XII.

1.8 Explanation

This explanation supplements the information provided by the geological maps and sections to provide as complete a picture as possible of the geological configuration and history of the map sheet area. In the first part of this explanation, Chapters 4-14, a description is given of the lithological successions, including an account of the lithostratigraphy and sedimentary development. The second part, Chapter 15, describes the geological history of the area. This relates to basin development and tectonic events in the context of the regional tectonics. In the last part, Chapter 16, special attention is given to various aspects of economic and applied geology, such as hydrocarbons, geothermal energy, hydrogeology and infrastructure.

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. Their distribution is generally related to the major structural elements of the map sheet area, which are described in Chapter 3. Figure 1.5 shows the geological timescale and the main tectonic phases as used in this explanation. References to internal reports within the body of the text are printed in italics.

The Quaternary deposits are only briefly referred to in this explanation. A detailed description has been published in Fischer (1997) and the "Toelichtingen bij de Geologische Kaart van Nederland 1:50 000 [Explanation to the Geological map of the Netherlands 1:50 000], map sheets Goeree-Overflakkee West, Zeeuws-Vlaanderen East and West, Schouwen-Duivenland East and West, Willemstad East, Walcheren West and Beveland East (Rijks Geologische Dienst [Geological Survey of the Netherlands], resp. 1964, 1965, 1970, 1971, 1972 en 1978).

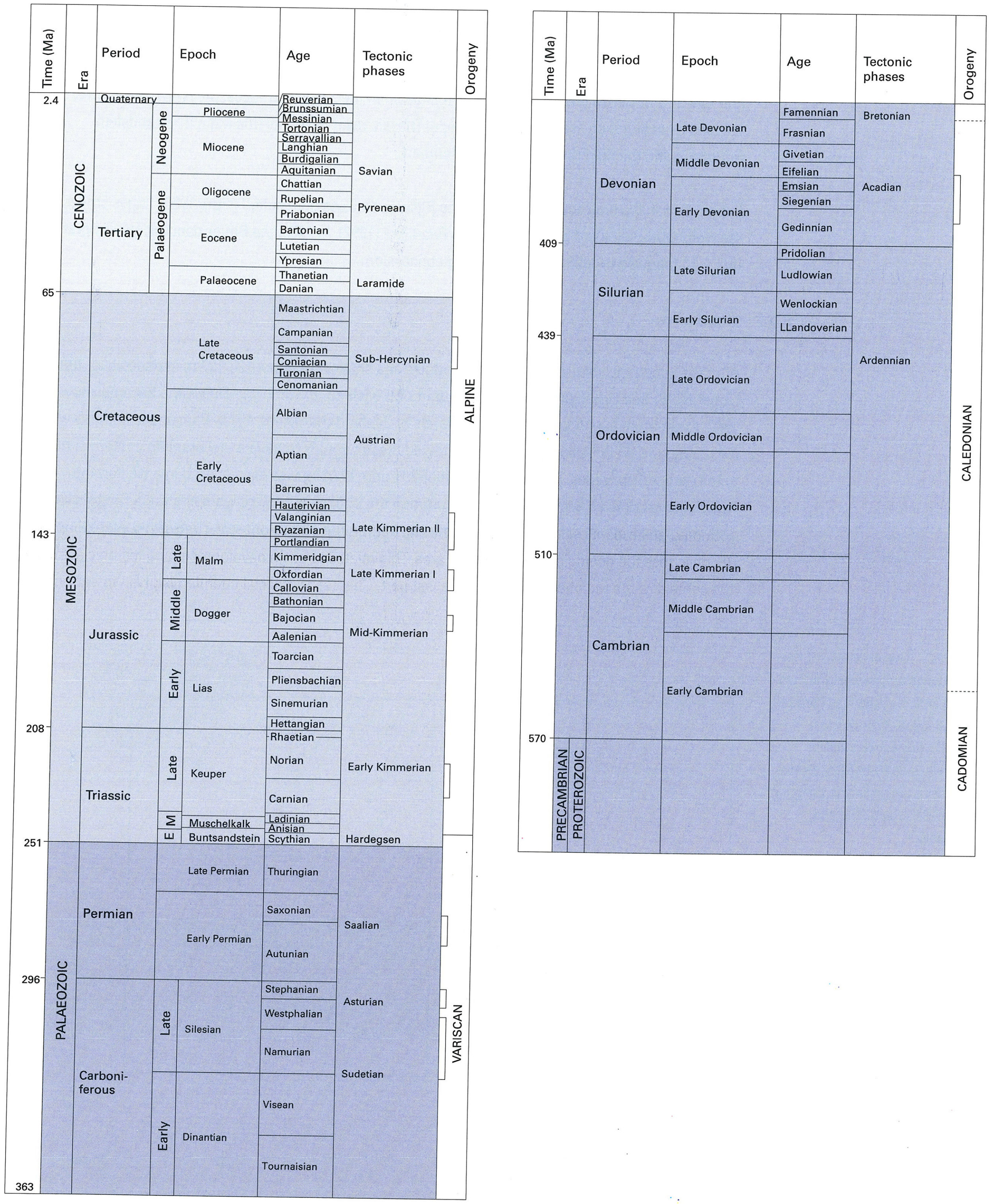


Figure 1.5 Geological timescale as used in this explanation. The tectonic phases mentioned in the text are indicated in this figure.

2 Exploration history

2.1 Hydrocarbons

The north-eastern part of the map sheet area just touches on the West Netherlands Basin, one of the Netherlands' more prospective areas for oil and gas. Following the discovery of several Upper Jurassic and Lower Cretaceous oil and gas fields in this basin in the 1950s and 1960s, the NAM successfully focused its exploration activities on the deeper Triassic reservoir rocks (the Main Buntsandstein Subgroup and the Röt Fringe Sandstone Member).

Exploration in the area south and east of the Rijswijk concession resulted in the 1980s in gas strikes in the wells Oud-Beijerland-Zuid-1 (1990) and Reedijk-1 (1992). In 1991, the Botlek concession was granted (fig. 2.1), followed in 1996 by the Beijerland concession.

2.2 Uranium

After the occurrence of uranium-bearing nodules at a shallow depth of 123-137 m in deposits of the Upper North Sea Group under the western part of the island of Schouwen-Duiveland became known in 1969, exploration expanded to the other islands of Zeeland (Harsveldt, 1973). Phosphatic nodules were also found in several wells and analyses showed these nodules to have a low uranium content similar to the earlier discoveries. The highest grade of 291 ppm (0.03%) was encountered in a well on the western coast of Walcheren. Both the uranium and the phosphor content were analysed. The results of both analyses were so disappointing that mining of uranium and/or phosphor was not contemplated.

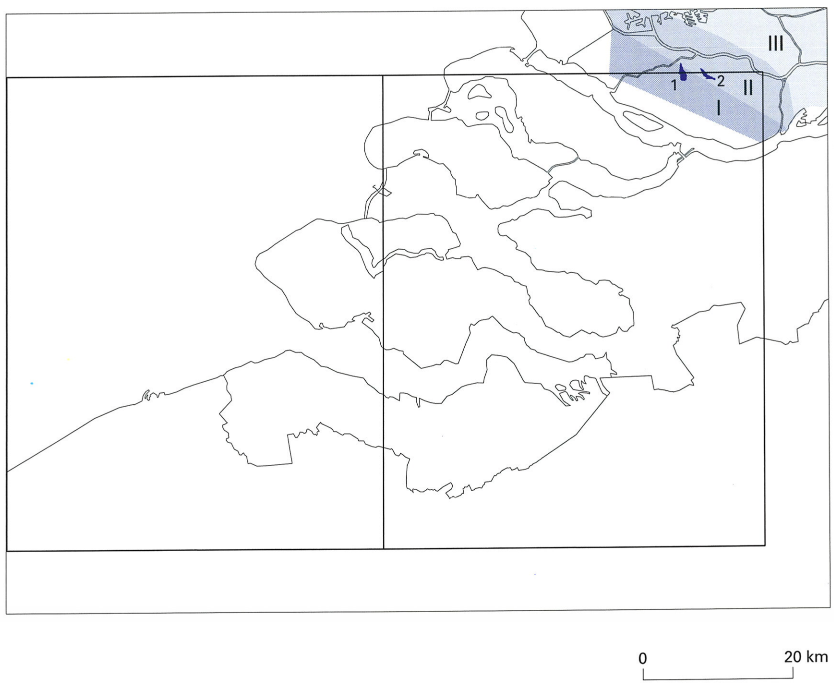


Figure 2.1 Overview map of the concession areas within the map sheet area. I = Beijerland concession, II = Botlek concession and III = Rijswijk concession. The following hydrocarbon accumulations are present in the area: 1. Oud-Beijerland-Zuid and 2. Reedijk.

3 Structural framework

In this chapter, the structural elements differentiated in the map sheet area (fig. 3.1a,b,c) 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** consists of folded deposits of Cambro-Silurian age. Deformation took place during the Acadian or Brabantian phase of the Early-Devonian Caledonian Orogeny (Verniers et al., 2002). The massif was eroded later in the Devonian, while, as from the Late Devonian onwards, sediments were deposited in the south. The entire Brabant Massif was once covered by Carboniferous sediments and probably also by Permian and Triassic sediments. This sequence was eroded during the Jurassic as indicated by fission track studies (Vercoutere & Van den Haute, 1993). This resulted in truncation of the Palaeozoic and Triassic deposits. The Early Palaeozoic deposits of the massif are now unconformably overlain by Chalk Group deposits. In the north-west, the Brabant Massif meets the London Massif. The entire structure is referred to as the London-Brabant Massif (Ziegler, 1990).

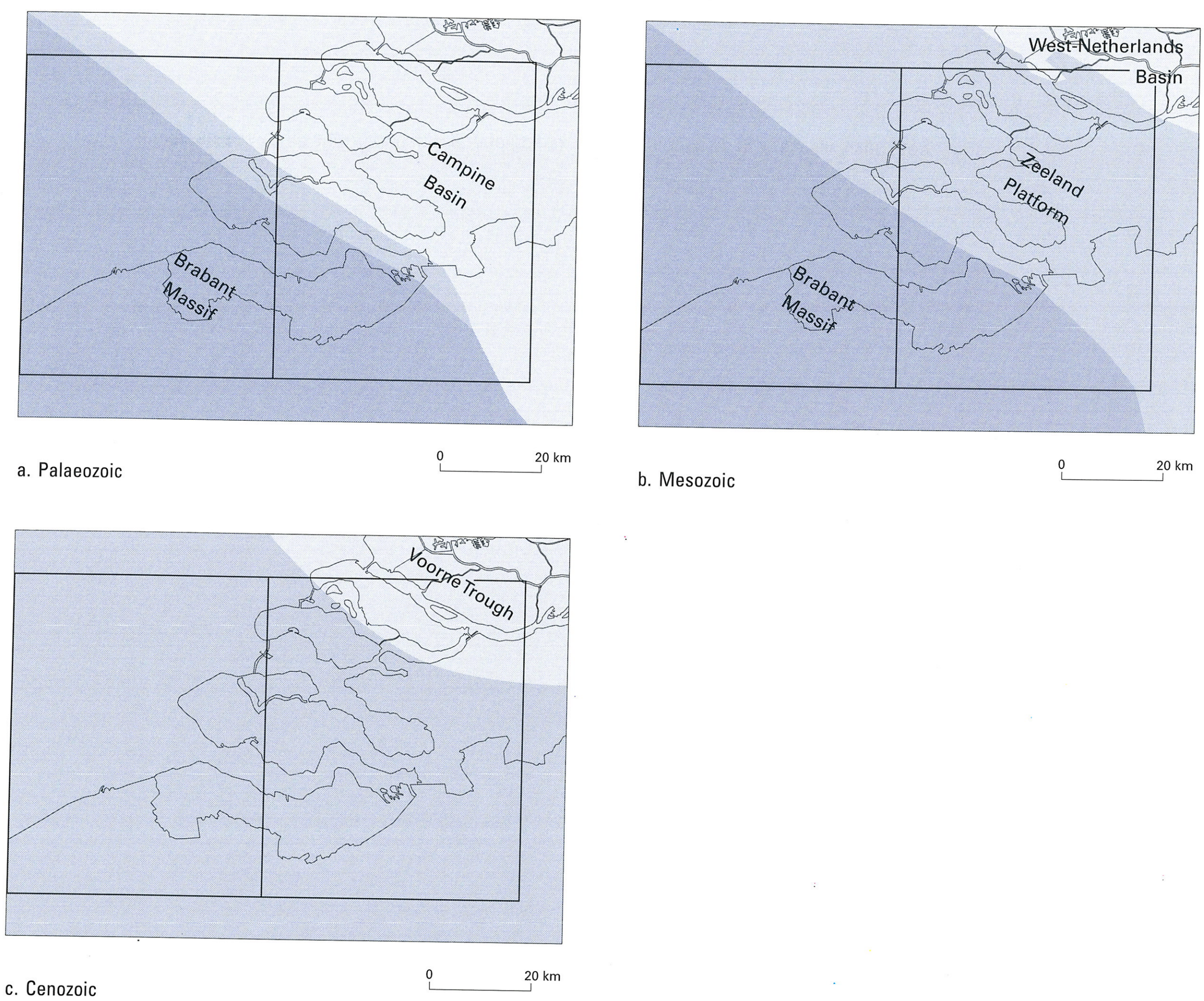


Figure 3.1 Overview of the evolution of the structural elements present in the map sheet area.

The **Campine Basin** is located to the north of the Brabant Massif. The Campine Basin probably formed during the Middle Devonian as a result of Early Variscan tectonics (Bless et al., 1980). Owing to uplift of the Brabant Massif, the original southern limit of the basin cannot be determined. The northern boundary is formed by the Zandvoort-Krefeld High, a string of horst structures (Bless et al., 1980), which formed a major structural zone well into the Tertiary.

The north-eastern corner of the map sheet area just covers a part of the Mesozoic **West Netherlands Basin**, a NW-SE-trending basin which experienced a period of rapid subsidence during the Kimmerian tectonic phases, resulting in the deposition of a fairly complete succession of Triassic, Jurassic and Lower-Cretaceous sediments. The boundary between the West Netherlands Basin and the Brabant Massif is formed by the **Zeeland Platform**, where the Chalk Group unconformably overlies Carboniferous and thin Permo-Triassic deposits (figs 3.2 and 15.6).

Up to the Late Oligocene, the Cenozoic was characterised by inversion tectonics as a result of Alpine compression. This tectonic activity only affected the northernmost part of the map sheet area. During the inversion of the West Netherlands Basin, a subsiding area developed during the Sub-Hercynian phase along the southern edge of the basin, which is commonly known as the **Voorne Trough**.

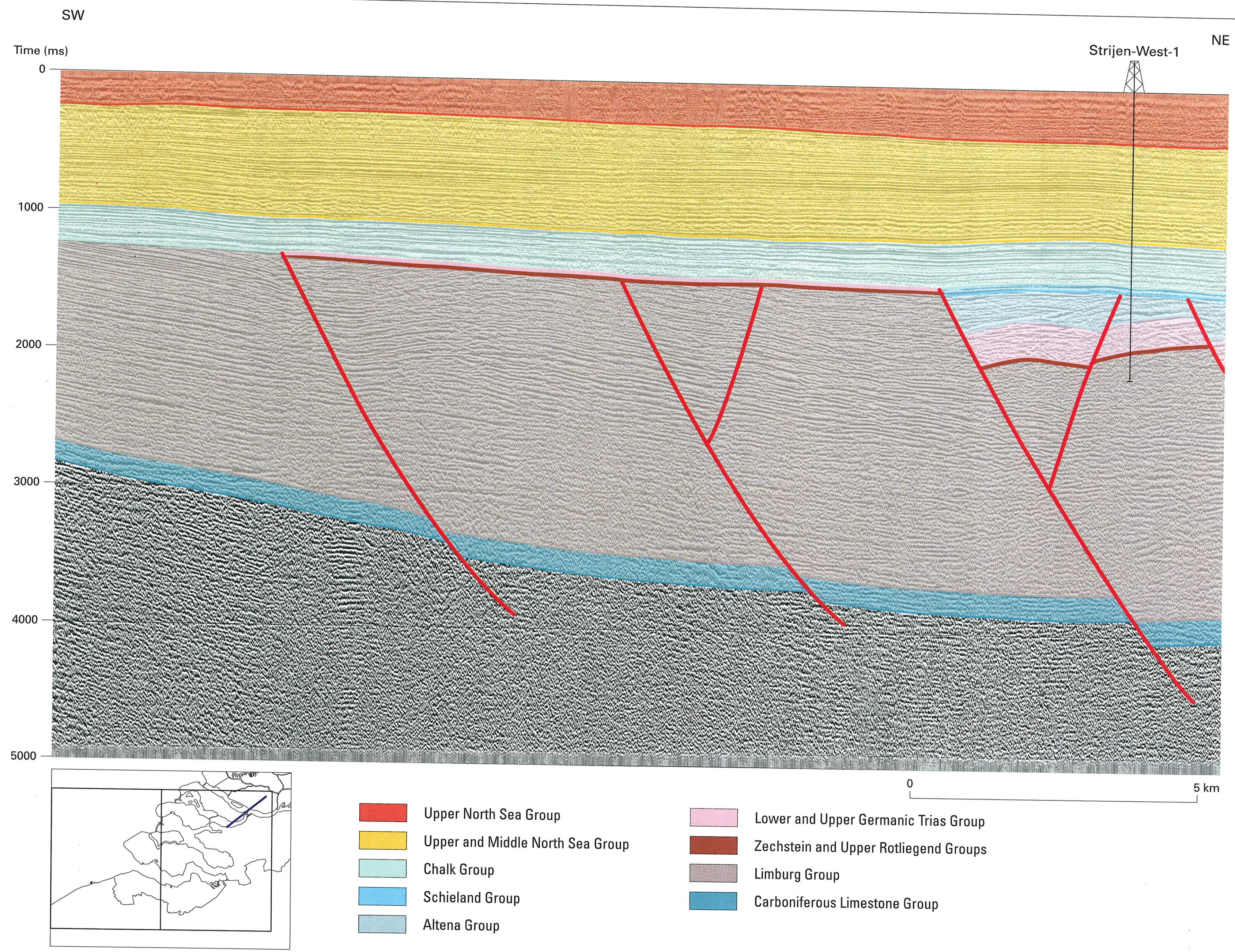


Figure 3.2 Seismic section through the Zeeland Platform and the southern edge of the West Netherlands Basin.

4 Cambro-Silurian and Banjaard group

4.1 Stratigraphy

The oldest deposits penetrated in the wells in the map sheet area are shales and sandstones of Silurian age. These deposits are uncomformably overlain by the Late Devonian Banjaard group. In wells in the adjoining parts of Flanders, Cambro-Ordovician sediments have been penetrated. It is assumed these Cambro-Ordovician deposits also occur below the map sheet area. A lithostratigraphic timescale of the Cambro-Silurian sediments was published recently (Verniers et al., 2001).

4.1.1 Cambro-Ordovician

Deposits of Cambrian and Ordovician ages have been penetrated in the Brabant Massif (Eeklo, Knokke and Knokke-Heist; see: Legrand, 1968; De Vos et al., 1993). The Cambrian deposits consist of shales, sandstones and quartzites, which were deformed during the Caledonian Orogeny. The presence of Ordovician rocks in Belgium has been documented extensively (Legrand, 1968; Servais et al., 1993; Van Grootel et al., 1997). The Ordovician sequence comprises dark, fine-grained shales with intercalated thin, fine-grained sandstones. This sequence is overlain by Silurian deposits, either conformably or disconformably.

4.1.2 Silurian

During the Silurian, sediments were deposited both on top of the Brabant Massif and to the north of it. In two cores from well Kortgene-1, deposits of a Wenlockian to ?Pridolian age were encountered. These deposits consist of grey, fine-grained sandstones, siltstones and shales. The fossil content and sedimentological features are indicative of deposition by turbidity currents in a deep-water environment and are comparable with the Belgian examples described by Verniers & Van Grootel (1991).

4.1.3 Devonian

During the Early Devonian, there was no deposition on either the Brabant Massif or to the north of it. The coarse-clastic sediments encountered in the Namur Basin to the south of the Brabant Massif were laid down during the Middle and earliest Late Devonian. These deposits have not been defined in the Dutch lithostratigraphy (fig. 4.1), but have been penetrated in well Kortgene-1 (fig. 4.2.). Unlike the sediments of the Namur Basin, the deposits north of the Brabant Massif consist of fine-grained shales and siltstones. These deposits are overlain by the Banjaard group.

4.1.3.1 Middle and earliest Late Devonian

On the northern flank of the Brabant Massif, a 400-m-thick conglomerate sequence, preserved in half-graben structures, was penetrated in well Booischot-132 (Legrand, 1968; Kimpe et al., 1978). This conglomerate is partly of Givetian and Frasnian age. These clastic deposits are overlain by a 100-m-thick sequence consisting of reef and nodular limestone, dolomite and claystone (well Loenhout-Heibaart-129; Kimpe et al., 1978). The carbonate content of this sequence increases upward and its age is predominantly Frasnian. This sequence was deposited on top of a vast carbonate platform north of the Brabant Massif (Drozdzewski et al., 1998). Well Kortgene-1 (fig. 4.2) penetrated an approximately 350 m long sequence of Eifelian to Frasnian age (Middle to early Late Devonian). As described above, these deposits consist of fine-grained shales and siltstones, but part of this sequence may be of Silurian age (*TNO-NITG, 2003a*).

4.1.3.2 Banjaard group

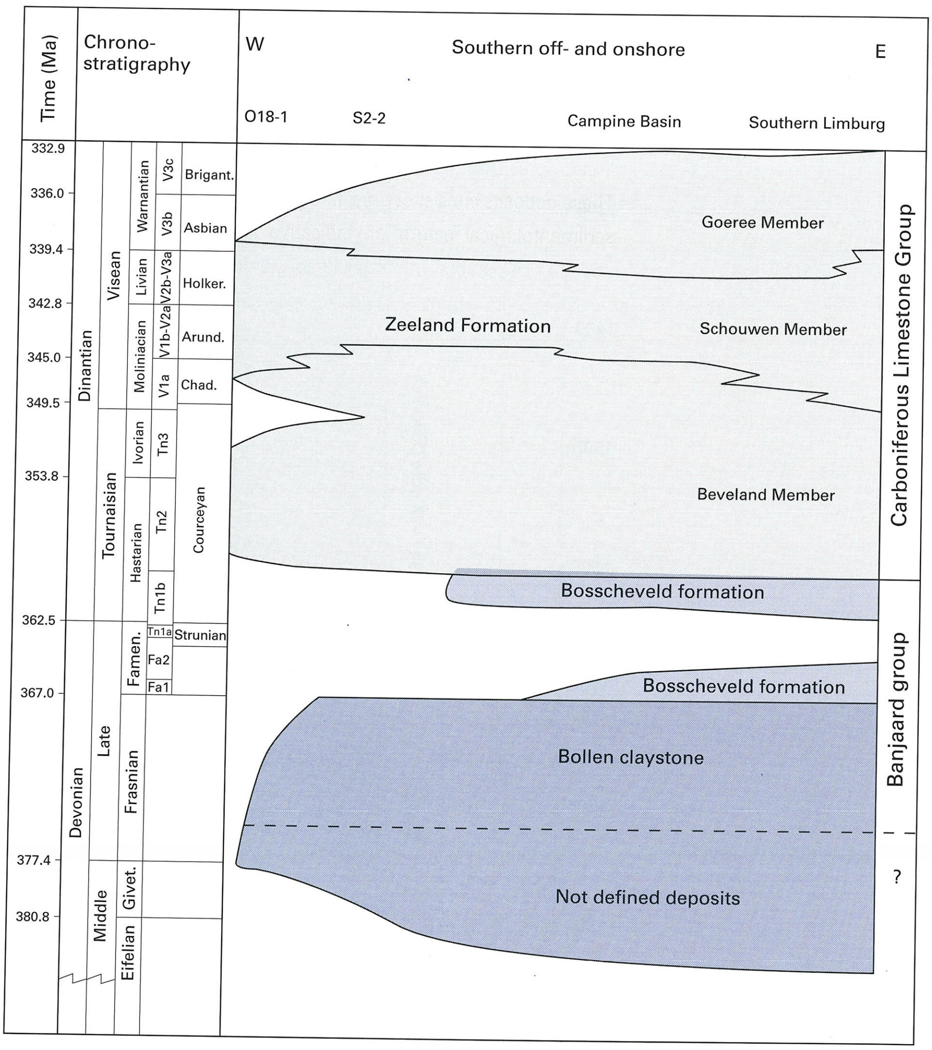
The top of the Banjaard group has been penetrated in several wells on the flank of the Brabant Massif. The group is subdivided lithostratigraphically into the Bollen claystone and the Bosscheveld formation.

The Bosscheveld formation grades into Lower-Carboniferous carbonates. The most complete Devonian succession was found in well Kortgene-1 and has a thickness of approximately 300 m at that location.

Bollen claystone

The Bollen claystone, of Frasnian age, is a monotonous, approximately 300-m-thick, succession consisting of grey to dark-grey clays with thin intercalations of siltstones and fine-grained sandstone horizons. The section is an accumulation of both fining- and coarsening-upward, clay-dominated units. The dark-grey to black claystone intervals demonstrate little evidence of bioturbation, whereas the lighter clays and silty intervals are clearly bioturbated. The siltstone and fine-grained sandstone horizons vary in thickness (from cm- to dm-thick) and show horizontal lamination, current ripples en locally "hummocky cross-stratification". Some intervals show chaotic slump structures: the sediments show both plastic deformation and small-scale fracturing.

Figure 4.1 Stratigraphy of the Banjaard group.



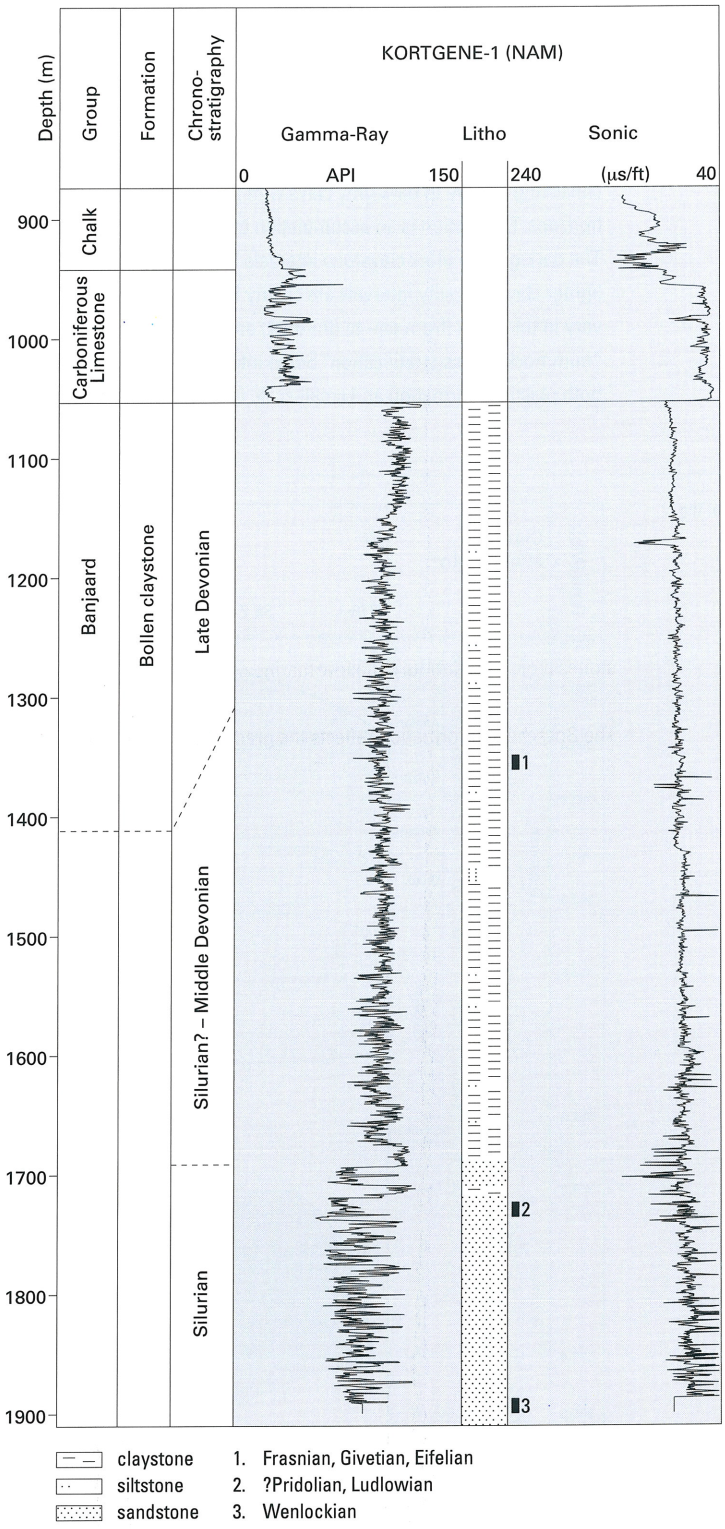


Figure 4.2 Stratigraphic subdivision and log characteristics of the Banjaard group and older Devonian and Silurian units in well Kortgene-1 (TNO-NITG, 2003a).

Bosscheveld formation

The Bosscheveld formation represents the transition from Bollen claystone to the Lower-Carboniferous (Dinantian) carbonates. Dark-grey clays alternate with siltstone and sandstone layers and limestone layers, the latter are commonly nodular. No cores have been cut from this interval in the map sheet area. Gamma-ray logs show that this interval is approximately 30 m thick.

4.2 Sedimentary development and palaeogeography

During the Silurian, deep-marine deposits were laid down in the foreland basin of the present-day Ardennes. This basin extended over part of the map sheet area. During the Early Devonian no deposition took place and during the Middle Devonian the Brabant Massif was inundated by the sea. The first sediments laid down by this sea were coarse clastics, gradually increasing in carbonate content upward as a result of the progradation of the carbonate platform north of the Brabant Massif. These carbonates were not encountered in the map sheet area.

The Bollen claystone formed in a fairly shallow-marine depositional environment. The virtually ubiquitous presence of current ripples indicates deposition above storm base. The alternation of dark clays with siltstones and fine-grained sandstones, both showing ripples is indicative of deposition during storms at depths below fair-weather wave base. The absence of well-developed sands in the Bollen claystones indicates that truly shallow-marine conditions did not occur during the latest Devonian.

The Bosscheveld formation reflects the gradual shallowing and filling of the marine basin by a mixture of clastic and carbonate deposits. The transition to carbonates in combination with this shallowing could be related to the transition to a tectonically quieter period.

5 Carboniferous Limestone Group

5.1 Stratigraphy

The Carboniferous Limestone Group, of Early Carboniferous (Dinantian) age (fig. 5.1), underlies most of the area of map sheet XII. The group was penetrated and cored in wells S2-2, S5-1, Woensdrecht-1, Kortgene-1 and Brouwershavense Gat-1. The depth to the top of the unit increases in a north-easterly

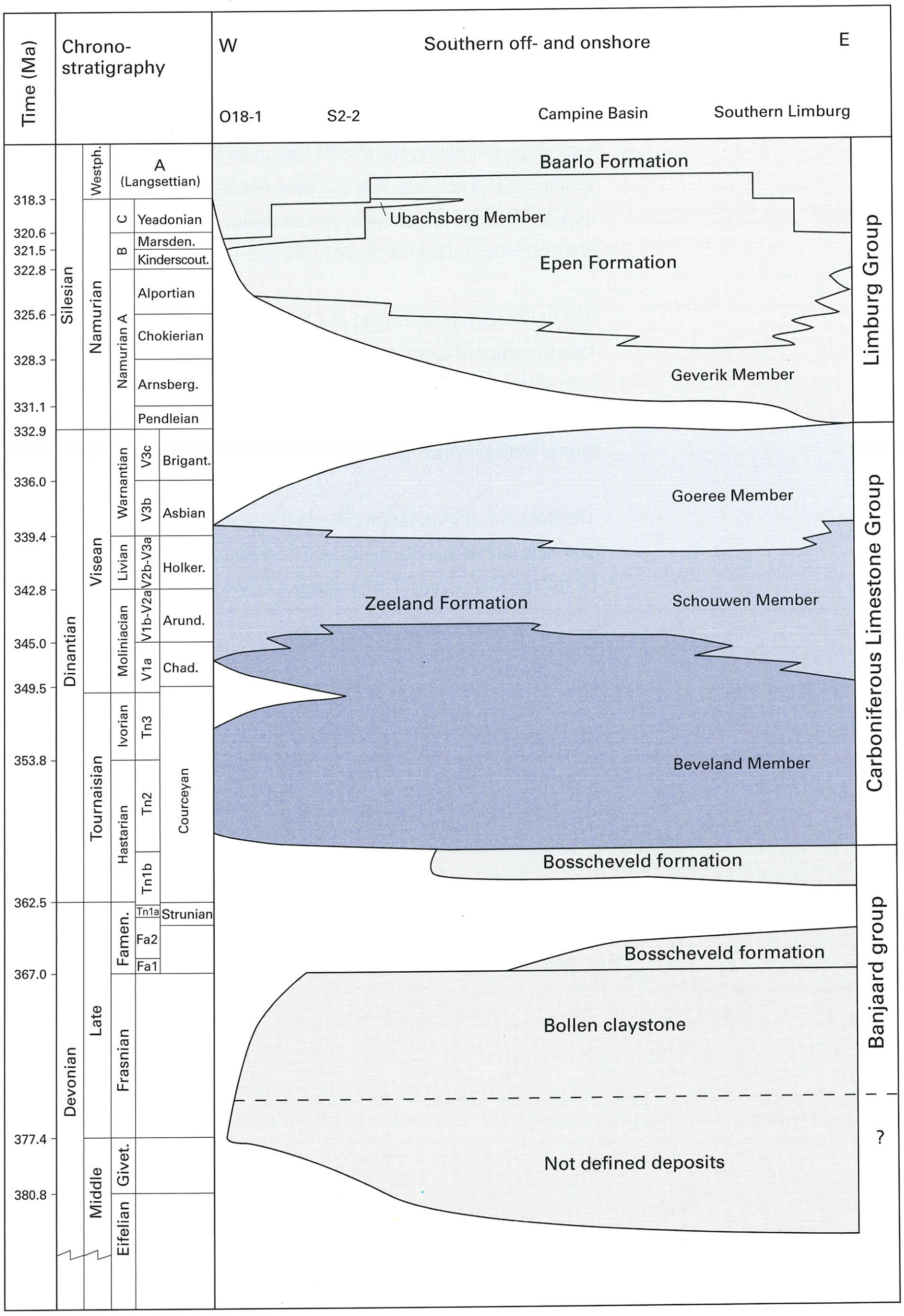


Figure 5.1 Stratigraphy of the Carboniferous Limestone Group.

direction from 1000 to 6500 m (figs 5.2 and 5.4). The thickness of the Carboniferous Limestone Group varies from 500 to 1300 m (fig. 5.3). The group comprises the Zeeland Formation, which is subdivided into the Beveland, Schouwen and Goeree Members. The Carboniferous Limestone Group overlies the Devonian either conformably or disconformably and is overlain, either disconformably or locally unconformably, by the Namurian (Limburg Group).

5.1.1 Zeeland Formation

5.1.1.1 Beveland Member

The *Beveland Member* has a thickness of approximately 200 - 300 m in the map sheet area. Part of the member was cored in well S5-1, the core consist of light-grey limestone, characterised by ubiquitous small shells and intense bioturbation. The rocks are mostly fine-grained limestones containing thin horizons of coarse-grained bioclastic limestone.

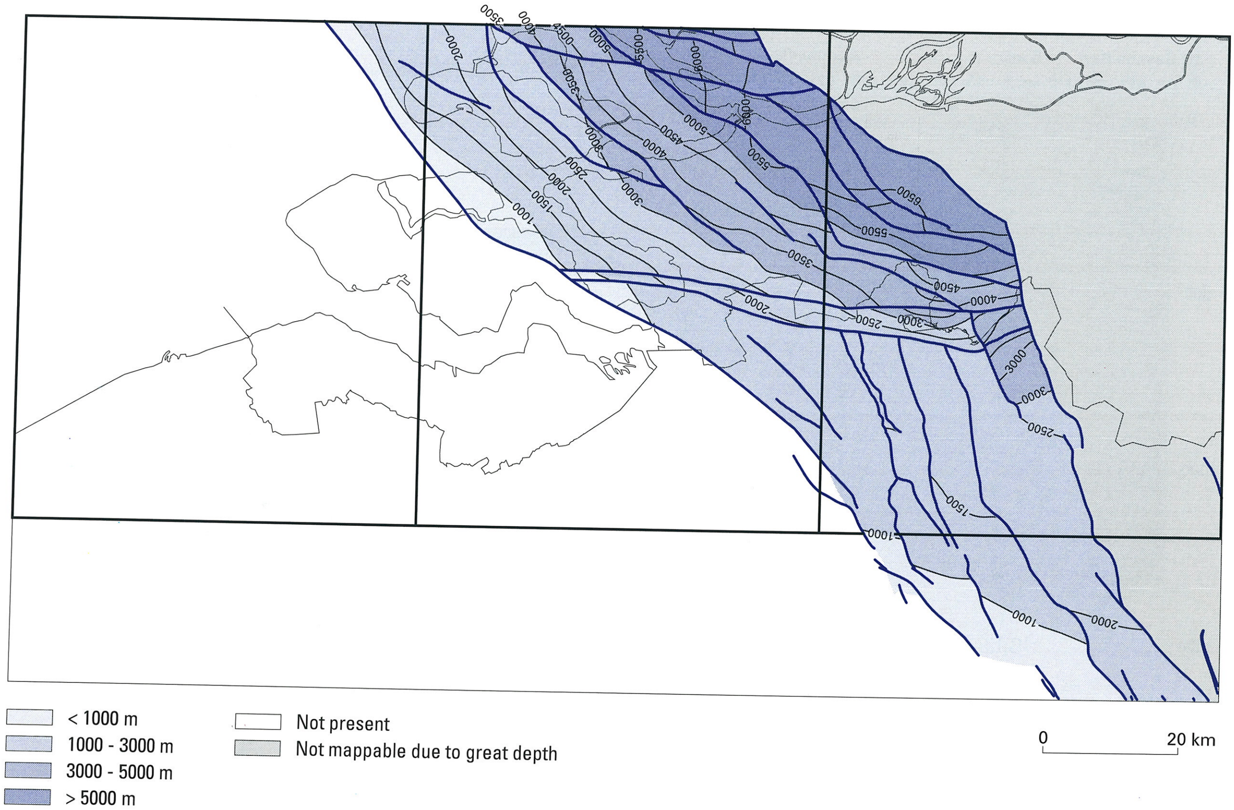


Figure 5.2 Depth map of the top of the Carboniferous Limestone Group. This map is based on seismic interpretation, with additional information from well data and literature (Bless et al., 1976; Rijks Geologische Dienst, 1984).

5.1.1.2 Schouwen Member

The *Schouwen Member* is the thickest unit in the Dinantian and ranges in thickness from approximately 75 m in well Brouwershavense Gat-1 to approximately 800 m in well O18-1. The member is characterised by well-developed limestones with a few claystone intercalations; the member can be recognised in logs by its constant, low level of natural radioactivity. In well S5-1 the lowermost part of the sequence consists of mainly pale-grey to grey, fine-grained limestones with shell and crinoid fragments. Locally, thin, black, clayey limestones occur. These can be recognised on gamma-ray logs by a higher reading. The upper part of the member comprises mainly cream-coloured, coarse-grained, well-sorted, bioclastic limestones. These may contain reef-like accumulations with microbial mats and algal boundstones at structurally high positions. They also contain grey to blackish clayey limestones.

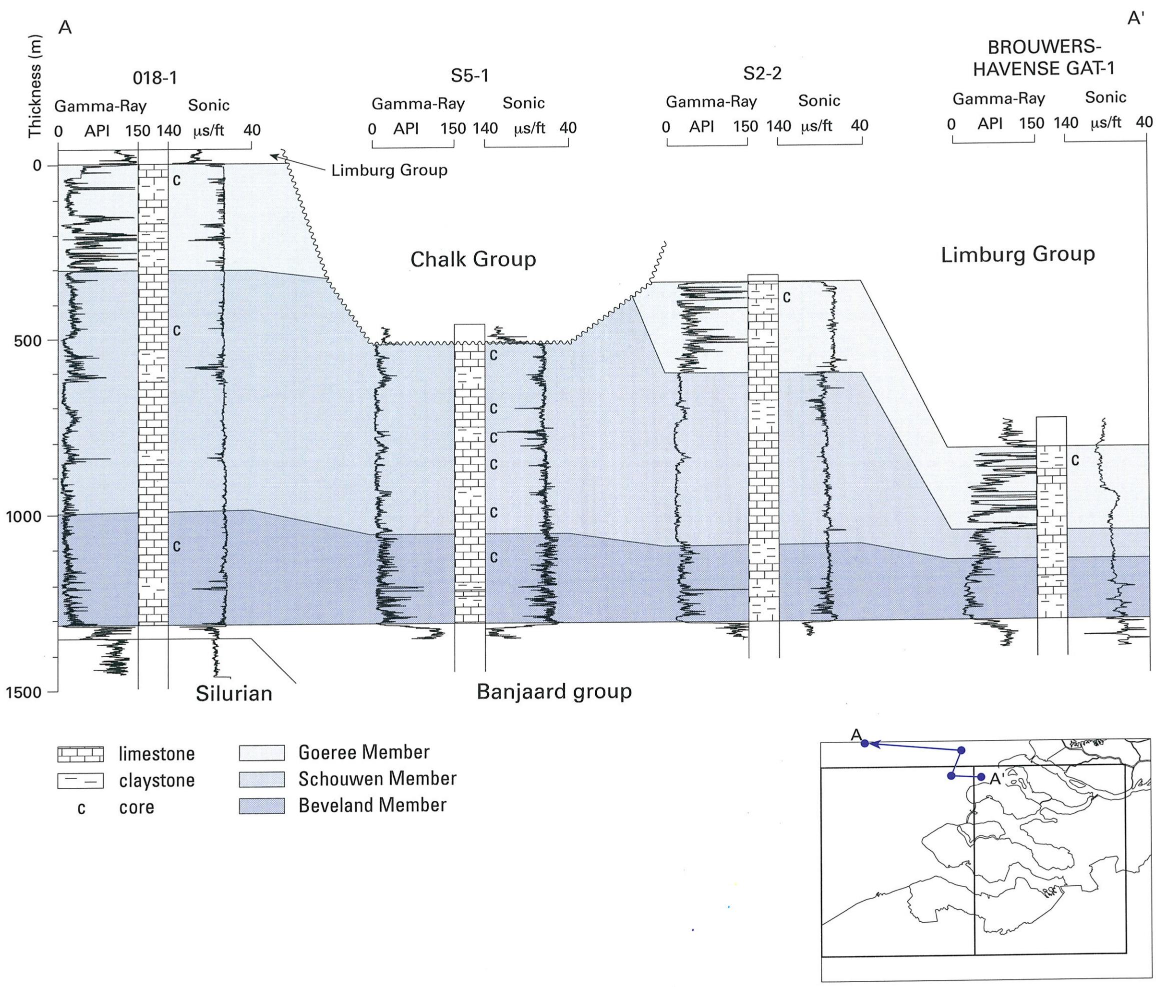


Figure 5.3 Stratigraphic correlation of the Carboniferous Limestone Group along line A-A' between wells O18-1, S5-1, S2-2 and Brouwershavense Gat-1. The correlation clearly shows that the thickness of the Beveland and Schouwen Members decrease towards the east.

5.1.1.3 Goeree Member

The *Goeree Member* consists mainly of a succession of grey and black clayey limestones and shales, which are locally silicified. Cored intervals from the map sheet area and the adjoining offshore area also show light-grey, fine-grained bioclastic limestone, which locally contains coarse-grained peloid-packstone layers. In well Brouwershavense Gat-1 this interval is strongly fractured and brecciated.

5.2 Sedimentary development and palaeogeography

The great variation in thickness of the carbonates of the Zeeland Formation indicates an aggrading carbonate platform north of the Brabant Massif. In this area, limestone deposition kept pace with basin subsidence. More towards the north, in the deeper part of the basin, sedimentation could not keep up with basin subsidence. Here, relatively deep-water limestones accumulated, in particular in the upper part of the sequence, while shallow-water sediments were deposited along the margins of the basin.

Whereas the Beveland and Schouwen Members gradually wedge out eastward, the thickness of the Goeree Member is amazingly constant. The constant thickness of this sequence suggests that the difference in water depths, which was responsible for the thickness variations of the underlying deposits, was less pronounced at the end of the Early Carboniferous. The entire map sheet area may have been covered by fairly deep water. During the transition from the Visean to the Namurian the area fell dry. This caused deep erosion of the carbonate platform resulting in a typical karst landscape.

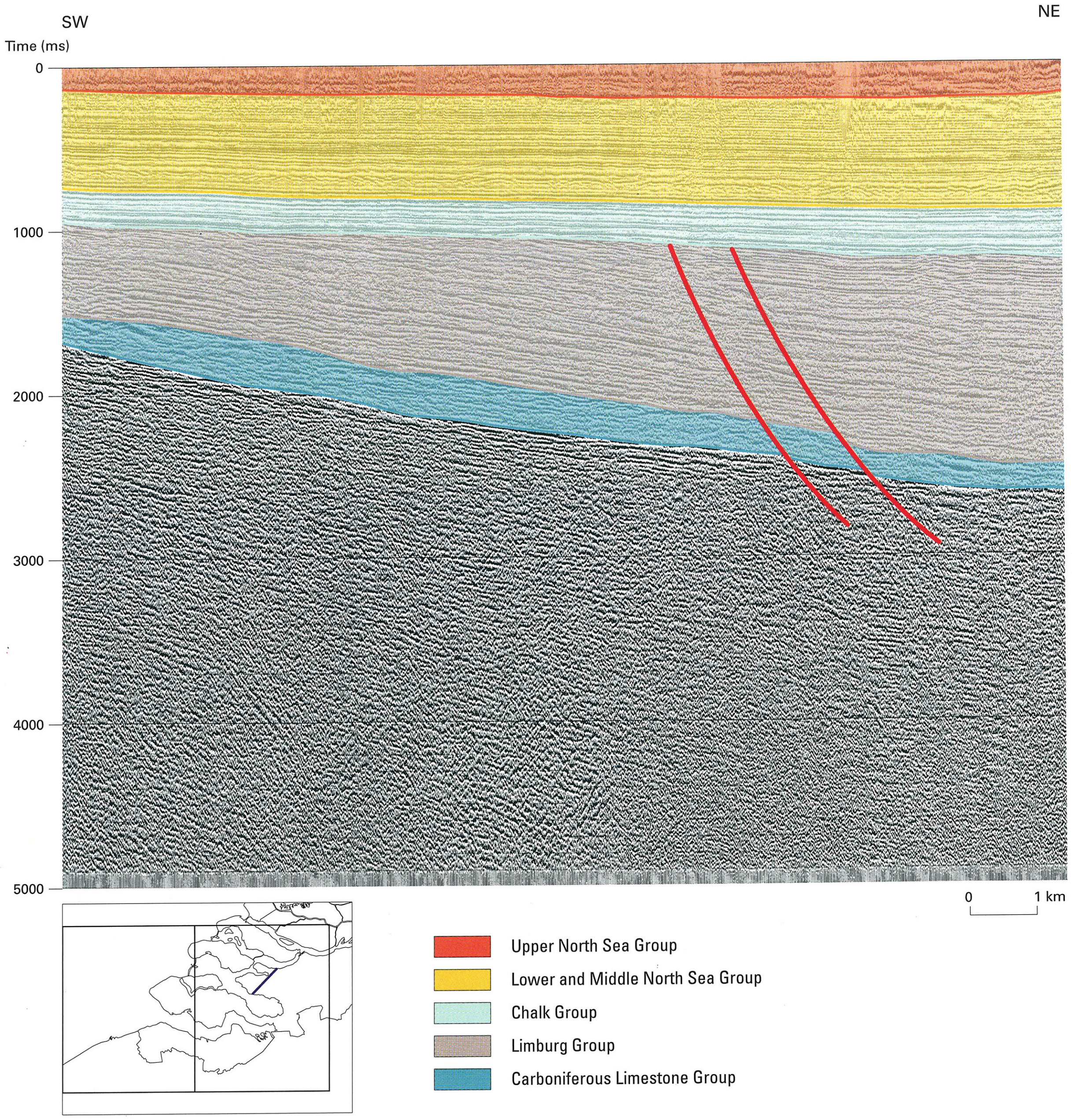


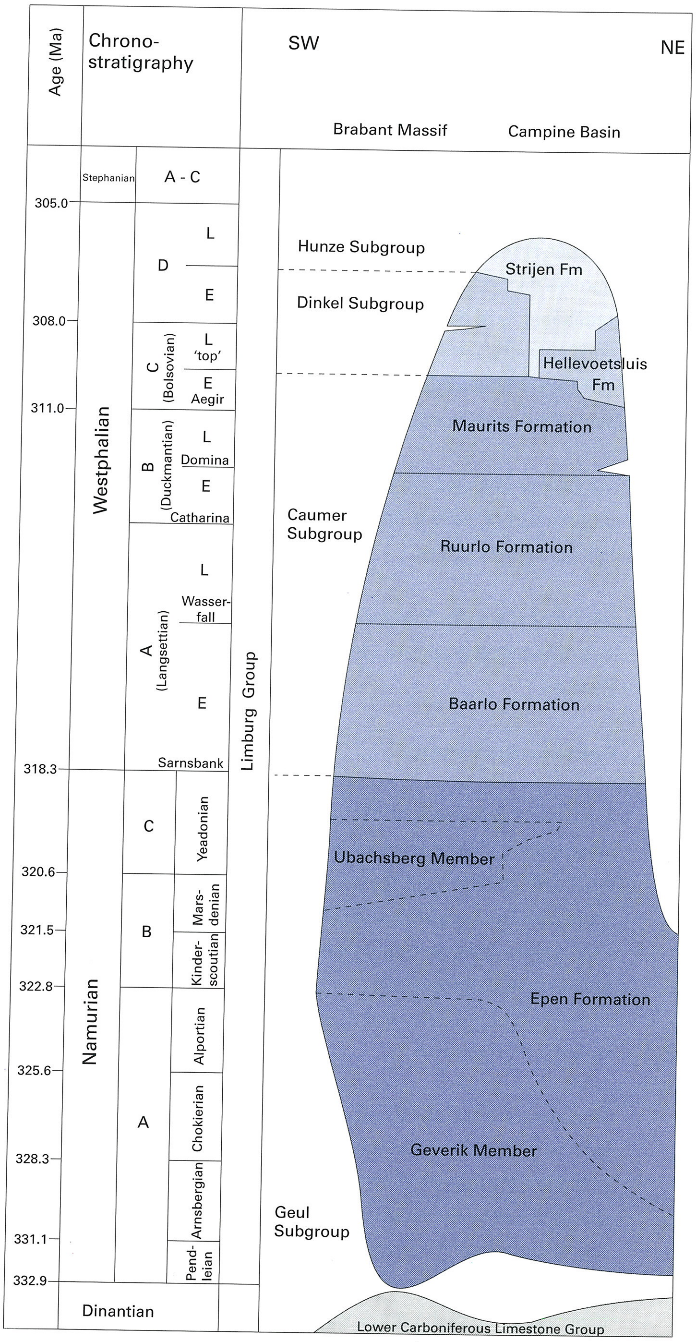
Figure 5.4 This SW-NE seismic line clearly shows that the top of the Carboniferous Limestone Group is located progressively deeper towards the NE.

6 Limburg Group

6.1 Stratigraphy

Unlike the other map sheets, the present map sheet area comprises mainly the lower part of the Limburg Group, represented by the clay-dominated Geul Subgroup and the Caumer, Dinkel and Hunze Subgroups consisting of coal-bearing alternations of sandstone, siltstone and claystone (fig. 6.1). Each subgroup reflects a phase of the Late Carboniferous regressive megasequence.

Figure 6.1 Stratigraphy of the Limburg Group.



The Limburg Group rests disconformably upon the Carboniferous Limestone Group and is overlain unconformably by the Chalk Group in most of the map sheet area (Maps XI-5 and XII-17). In the north-eastern part of the map sheet area, the Upper Rotliegend Group unconformably overlies the Limburg Group (Map XII-1). The group dips at 10° away from the Brabant Massif towards the north-east (fig. 15.6). As a result of erosion during the Jurassic, the Limburg Group is not present on the Brabant Massif. The Limburg Group increases in thickness eastward, attaining a thickness of over 3 km in well Rijsbergen-1 (*TNO-NITG 2003b).* This is partly due to better preservation, but largely to the increased thickness of the Epen Formation (fig. 6.2).

6.1.1 Geul Subgroup

The Geul Subgroup consists predominantly of dark-coloured claystones and siltstones with a minor percentage of sandstone. The subgroup consists solely of the Epen Formation of Namurian age.

6.1.1.1 Epen Formation

The Epen Formation is present throughout the distribution area of the Limburg Group. The formation's thickness decreases towards the Brabant Massif owing to truncation. The Epen Formation consists predominantly of dark-coloured claystones and siltstones with only a very small percentage of sandstones. The formation is characterised by stacked, coarsening-upward sequences of 50 to 100 m thick each. Within the formation, two members are distinguished: the Geverik and the Ubachsberg Members. A maximum thickness of 1500 m was penetrated in well Rijsbergen-1.

The *Geverik Member:* the base of the Epen Formation is formed by black bituminous shale. In the northern part of the map sheet area this shale is only locally present. The member is characterised by high gamma-ray values.

The *Ubachsberg Member:* locally, the Epen Formation contains 10 to 20 m thick sandstone bodies at the tops of coarsening-upward sequences. These sand bodies are collectively known as the Ubachsberg Member.

6.1.2 Caumer Subgroup

The Caumer Subgroup, of Westphalian A-C age, 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 Formation. The Caumer Subgroup is present in the northern part of the map sheet area. The subgroup is unconformably overlain by the Chalk Group, except in the north-east, where a thin Upper-Rotliegend sandstone overlies the subgroup. The maximum thickness of the subgroup is 1200 m in well Rijsbergen-1.

6.1.2.1 Baarlo Formation

The Baarlo Formation, of Early Westphalian A age, consists of stacked, coarsening-upward sequences, varying in thickness from some tens of metres to over 100 m. These consist of dark claystones and siltstones, the tops of which often contain fine-grained sandstones. Some of the basal claystones are characterised by the presence of marine or brackish-water fossils, such goniatites and *Lingula.* Coal seams occur throughout the formation, but are less numerous than in the overlying formations of the Limburg Group. Most coal seams are a few decimetres thick, they gradually increase in frequency towards the top of the sequence. The sandstones can be up to 30 m thick and are present at the tops of coarsening-upward sequences. The maximum thickness of the formation is approximately 800 m.

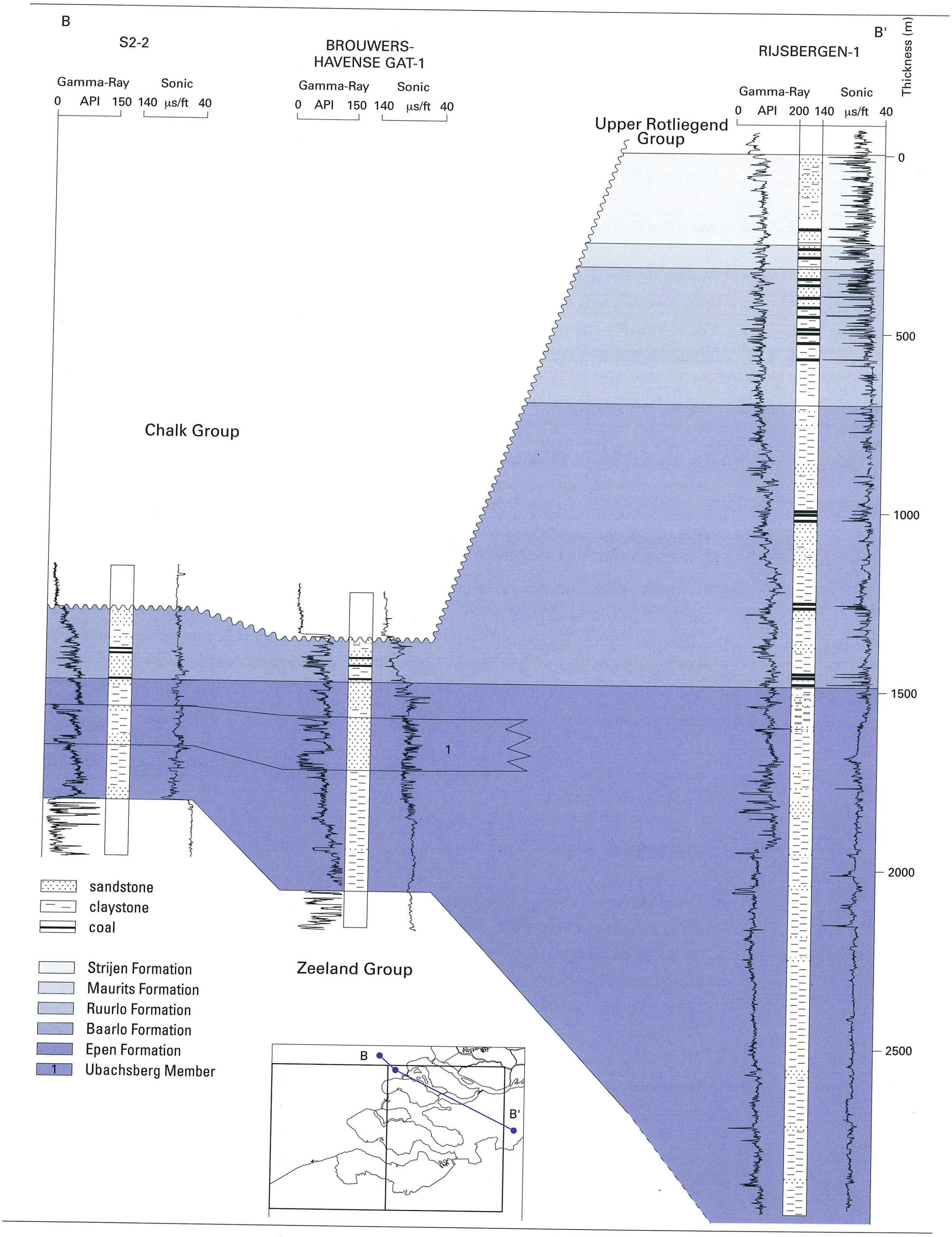


Figure 6.2 Stratigraphic correlation of the Limburg Group along line B-B′ between wells S2-2, Brouwershavense Gat-1 and Rijsbergen-1. Reference level is the base of the Baarlo Formation.

6.1.2.2 Ruurlo Formation

The Ruurlo Formation, of Late Westphalian A up to and including Early Westphalian B age, is present in the northern part of the map sheet area where it has a thickness of 400-500 m. The formation rests conformably on the Baarlo Formation. The Ruurlo Formation consists of alternating clays, sands and coals seams. Locally, the formation contains coarsening-upward sequences with a thickness of a few tens of metres each.

6.1.2.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Early Westphalian C age, was only penetrated in wells in the adjoining map sheets. There, the formation is dominated by light-grey claystones with abundant coal seams. A few rare sandstone layers are up to 10-15 m thick. The formation is unconformably overlain by the Hellevoetsluis Formation of the Dinkel Subgroup.

6.1.3 Dinkel Subgroup

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

6.1.3.1 Hellevoetsluis Formation

The Hellevoetsluis Formation, of Early Westphalian C up into Early Westphalian D age, consists of an alternation of thick sandstones and claystones and rest disconformably on the Maurits Formation. Coal seams are rare. The formation is present in the Campine Basin and its maximum thickness in the map sheet area is approximately 250 m. The formation is conformably overlain by the Strijen Formation.

6.1.4 Hunze Subgroup

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

6.1.4.1 Strijen Formation

The Strijen Formation is found in the Campine Basin. In the map sheet area this formation was only penetrated in well Strijen-West-1. The formation consists of a succession of red-brown, sometimes beige to green-grey, silty to fine-grained sandy claystones. The claystone sequences contain up to 20 m thick sandstones that display good lateral continuity. The formation is overlain unconformably by the Upper Rotliegend Group. Just north of the map sheet area, the Strijen Formation is up to approximately 700 m thick.

6.2 Sedimentary development and palaeogeography

The sedimentary succession of the Limburg Group is characterised by a large-scale regressive trend from a fairly deep-water deltaic facies in the Namurian to a fluviatile facies in the Late Westphalian. During the Namurian, the relatively deep marine basin that came into being during the Early Carboniferous was filled up by repeated phases of deltaic progradation. Along the northern flank of the Brabant Massif, where a shallow carbonate platform was situated during the Early Carboniferous, relatively shallow-water conditions prevailed, enabling the deposition of stacked deltaic cycles of approximately 100 m thick each. Further towards the north, in the deeper part of the Campine Basin, these cycles are poorly developed.

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 ubiquitous 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 across the basin (Thorez & Bless, 1977; Wouters & Vandenberghe, 1994). The abundant coal seams are the consequence of a humid, tropical climate in combination with deposition around sea level. The gradual transition to the red clays of the Hunze Subgroup 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 point to a more seasonal, tropical, semi-arid climate (Pagnier & Van Tongeren, 1996).

7 Upper Rotliegend Group

7.1 Stratigraphy

The Upper Rotliegend Group, of a Late Permian age, consists, in the map sheet area, entirely of sandstones of the Slochteren Formation (fig. 7.1) (Van Adrichem Boogaert & Kouwe, 1993-1997).

The Upper Rotliegend Group (Map XII-1) rests unconformably on the Limburg Group and is disconformably overlain by the Zechstein Group. Situated along the southern edge of the West Netherlands Basin, the Upper Rotliegend Group wedges out towards the south and is absent in most of the map sheet area. Where present, the formation is encountered at a depth of 1400 to 3000 m. In the map sheet area, the formation is 10 to 15 m thick.

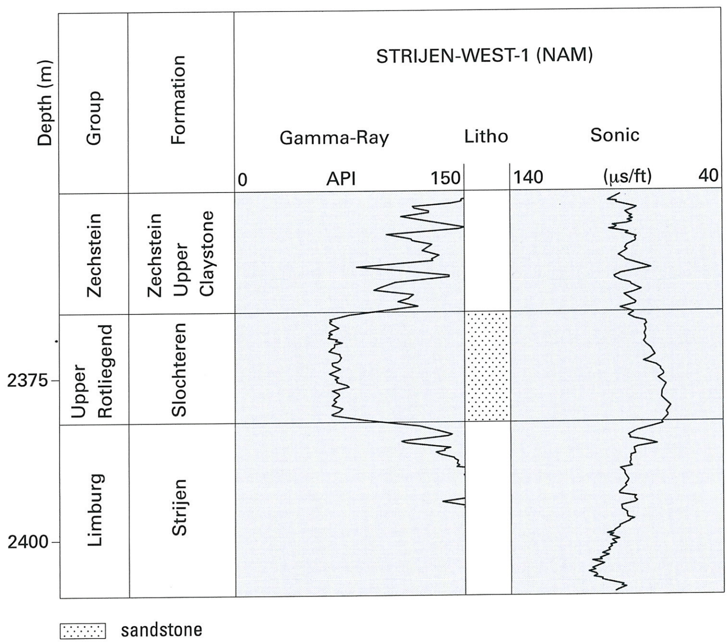
7.1.1 Slochteren Formation

The Slochteren Formation consists of red to grey sandstones possibly with conglomerates at its base. Its thickness is only 10 to 15 m.

7.2 Sedimentary development and palaeogeography

The coarse-clastic material of the Slochteren Formation originates from the southern Brabant Massif and the Variscan hinterland. The condensed thickness of the Slochteren Formation in the map sheet area is predominately due to its depositional position proximal to the Zeeland Platform and the Brabant Massif, which formed the southern edge of the basin.

Figure 7.1 Stratigraphic subdivision and log characteristics of the Upper Rotliegend Group in well Strijen-West-1.



8 Zechstein Groep

8.1 Stratigraphy

The Zechstein Group, of Late Permian age, comprises only the Zechstein Upper Claystone Formation in the map sheet area, and is only present in the north-eastern corner (Map XII-2). The group rests here on the Upper Rotliegend Group. Towards the south, the group's distribution is partly fault-controlled.
The thin Zechstein Upper Claystone (fig. 8.1) rests unconformably on deposits of the Slochteren Formation. The Zechstein Group is conformably overlain by the Lower Germanic Trias Group.

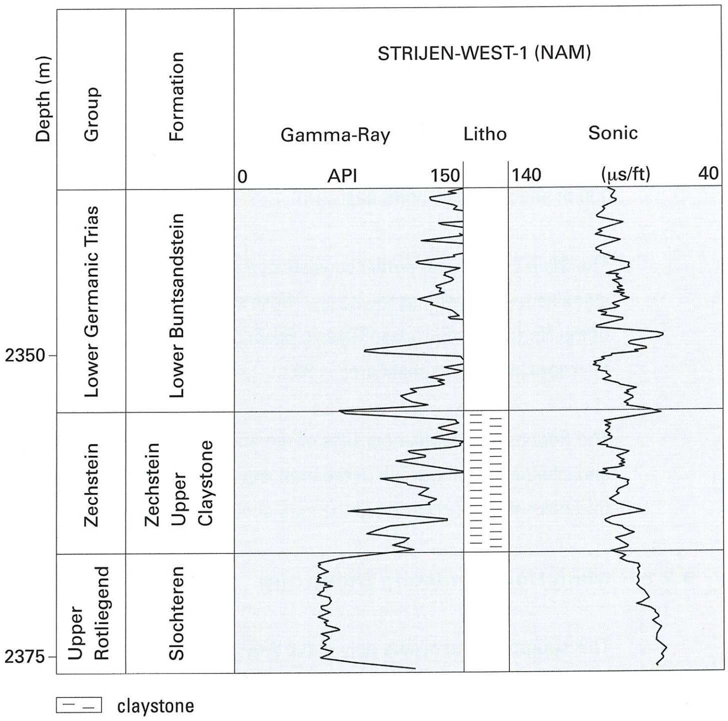
8.1.1 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation, of Late Permian age, is a claystone with thin sand intercalations with a thickness of a few metres to approximately 15 m (Map XII-3, Geluk, 1999 and TNO-NITG, 2001).

8.2 Sedimentary development and palaeogeography

The palaeogeography of the maps sheet area was a mud plain on which hardly any sedimentation took place. The sea-level rise towards the end of the Zechstein resulted in an increase in sedimentation area, with deposition of clay and sand.

Figure 8.1 Stratigraphic subdivision and log characteristics of the Zechstein Group in well Strijen-West-1.



9 Lower and Upper Germanic Trias Groups

9.1 General

The Triassic deposits, of youngest Late Permian to Norian age, consist predominately of grey, red and green clastic sediments and grey limestones, marls and evaporites. The Triassic is subdivided into the Lower and Upper Germanic Trias Groups. Triassic deposits are present in the southern part of the West Netherlands Basin (Maps XII-4, 5).

9.2 Lower Germanic Trias Group

9.2.1 Stratigraphy

Within this group, four formations are distinguished: i.e., the Lower Buntsandstein, the Volpriehausen, the Detfurth en the Hardegsen Formations (fig. 9.1). The Lower Buntsandstein Formation is predominantly fine-grained. The other formations consist predominantly of sandstone with claystone and siltstone intercalations. The Volpriehausen, Detfurth and Hardegsen Formations together make up the Main Buntsandstein Subgroup. Unconformities at the bases of the Volpriehausen and Detfurth Formations reflect non-deposition or minor erosion. The most complete sequences are found in the West Netherlands Basin (Ziegler, 1990; Geluk & Röhling, 1997).

The Lower Germanic Trias Group rests conformably on the Zechstein Group and is overlain uncomformably by the Upper Germanic Trias Group or the Schieland, Rijnland or Chalk Groups. The age of the Lower Germanic Trias Group is Late Permian tot Scythian (Kozur, 1999).

9.2.2 Lower Buntsandstein Formation

A thin erosion remnant of the formation is present in the eastern part of the map sheet area. This formation consists of the Main Claystone and the Rogenstein Members and is overlain by the Main Buntsandstein Subgroup, separated by a sharp boundary. The thickness of the formation is just over 130 m and increases north-eastward.

The *Main Claystone Member* consists of a cyclic succession of 20 to 35 m thick, fining-upward, clay-siltstone sequences with sandy bases. These sequences show a very uniform character over large parts of the North-West European Triassic Basin (Ziegler, 1990; Geluk & Röhling, 1997). The maximum thickness in the map sheet area is 80 m.

The *Rogenstein Member* consists of red and green fine-grained sandy, thinly laminated claystones and siltstones. In the south of the area, several thin sandstone layers are intercalated. The maximum thickness of the succession in the map sheet area is approximately 50 m.

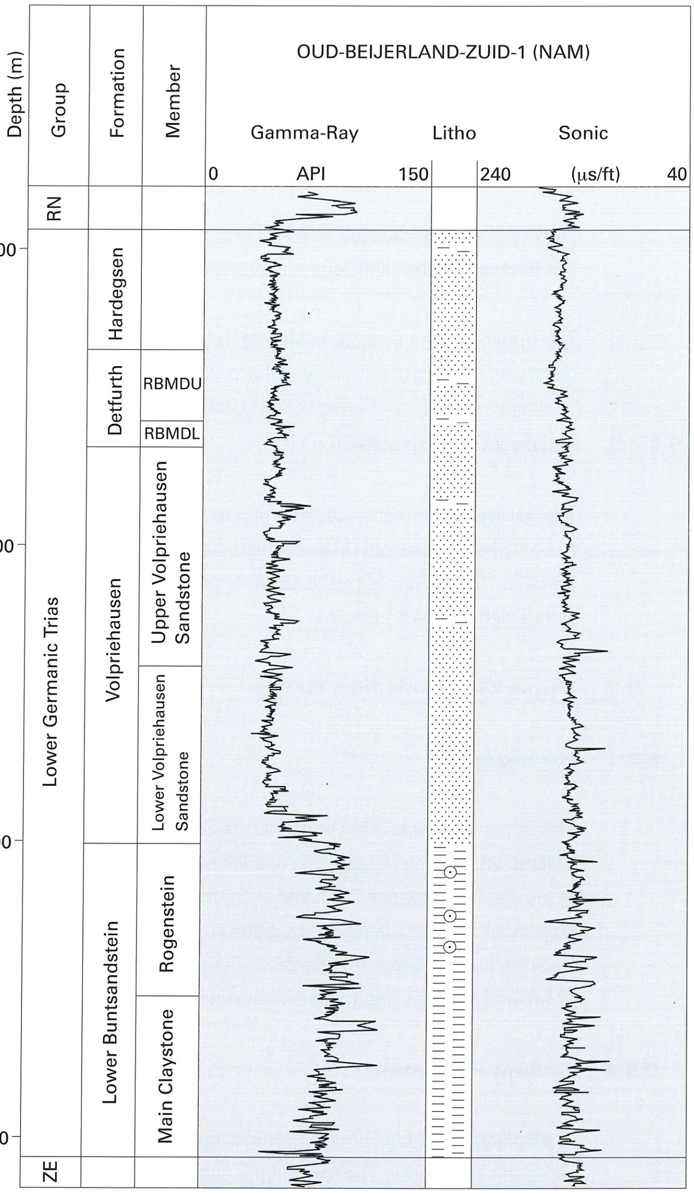
9.2.3 Main Buntsandstein Subgroup

This subgroup also occurs only in the West Netherlands Basin. The subgroup is almost 200 m thick (fig. 9.1). Within the subgroup, three formations are distinguished: the Volpriehausen, the Detfurth and the Hardegsen Formations. In the purely sandy basin-edge facies, the subdivision is predominantly based on log characteristics. In the eastern part of the map sheet area, in particular, the Main Buntsandstein Subgroup overlies the Lower Buntsandstein Formation with a sharp contact, which represents a minor unconformity. The Subgroup is unconformably overlain by the Upper Germanic Trias Group.

9.2.3.1 Volpriehausen Formation

The Volpriehausen Formation comprises in the map sheet area the Lower Volpriehausen Sandstone and the Upper Volpriehausen Sandstone Members (fig. 9.1). The formation overlies the Lower Buntsandstein Formation either conformably or unconformably (Geluk & Röhling, 1997) and is overlain by the Detfurth Formation. The formation has its maximum thickness, over 130 m, along the southern edge of the West Netherlands Basin.

Figure 9.1 Stratigraphic subdivision and log characteristics of the Lower Germanic Trias Group in well Oud-Beijerland-Zuid-1.



RN Upper Germanic Trias Group
ZE Zechstein Group
RBMDU Upper Detfurth Sandstone Mb
RBMDL Lower Detfurth Sandstone Mb

sandstone
claystone
oolite

The *Lower Volpriehausen Sandstone Member* rests on the underlying Rogenstein Member, the contact being marked by a sharp contact. The member consists of a sandstone unit showing a blocky gamma-ray pattern. Its thickness is approximately 60 m.

The *Upper Volpriehausen Sandstone Member* consists of a succession of light-coloured sandstone and siltstone beds. The base of this member is formed by a thinly laminated siltstone that can be correlated regionally. The most complete succession is 80 m thick.

9.2.3.2 Detfurth Formation

The Detfurth Formation comprises in the map sheet area the Lower and the Upper Detfurth Sandstone Members (fig. 9.1). The Detfurth Formation rests on the Volpriehausen Formation with an abrupt contact. The formation is conformably overlain by the Hardegsen Formation and has a maximum thickness of over 30 m.

The *Lower Detfurth Sandstone Member* consists of medium-grained to coarse-grained sandstone. The thickness of the sandstone is approximately 10 m.

The *Upper Detfurth Sandstone Member* is composed of two sandstone intervals, separated by claystone. The thickness is fairly uniform: 25 m throughout the map sheet area.

9.2.3.3 Hardegsen Formation

The Hardegsen Formation consists of grey to pink, medium-grained sandstone (fig. 9.1). The formation has only been preserved in the southern part of the West Netherlands Basin. The thickness of the formation is determined by the extent of pre-Solling erosion and is up to approximately 43 m in well Oud-Beijerland-Zuid-1 (fig. 9.1).

9.3 Upper Germanic Trias Group

9.3.1 Stratigraphy

The Upper Germanic Trias Group, of Late Scythian to Norian age, consists of four formations: the Solling, the Röt, the Muschelkalk and the Keuper Formations. The group is encountered most completely in the West Netherlands Basin and unconformably overlies the Lower Germanic Trias Group (fig. 9.2). It is overlain by the Altena Group, either conformably or slightly disconfomably, or unconformably by the Schieland Group, the Rijnland Group or the Chalk Group. Figure 9.2 shows the thickness of the group and provides information on the lithostratigraphic composition.

9.3.2 Solling Formation

The Solling Formation, of Late Scythian age, is present in the entire distribution area of the Upper Germanic Trias Group. The formation is subdivided into the Basal Solling Sandstone and Solling Claystone Members (fig.9.2). The formation rests unconformably on the Main Buntsandstein Subgroup. The maximum thickness of the formation in the map sheet area is 20 m.

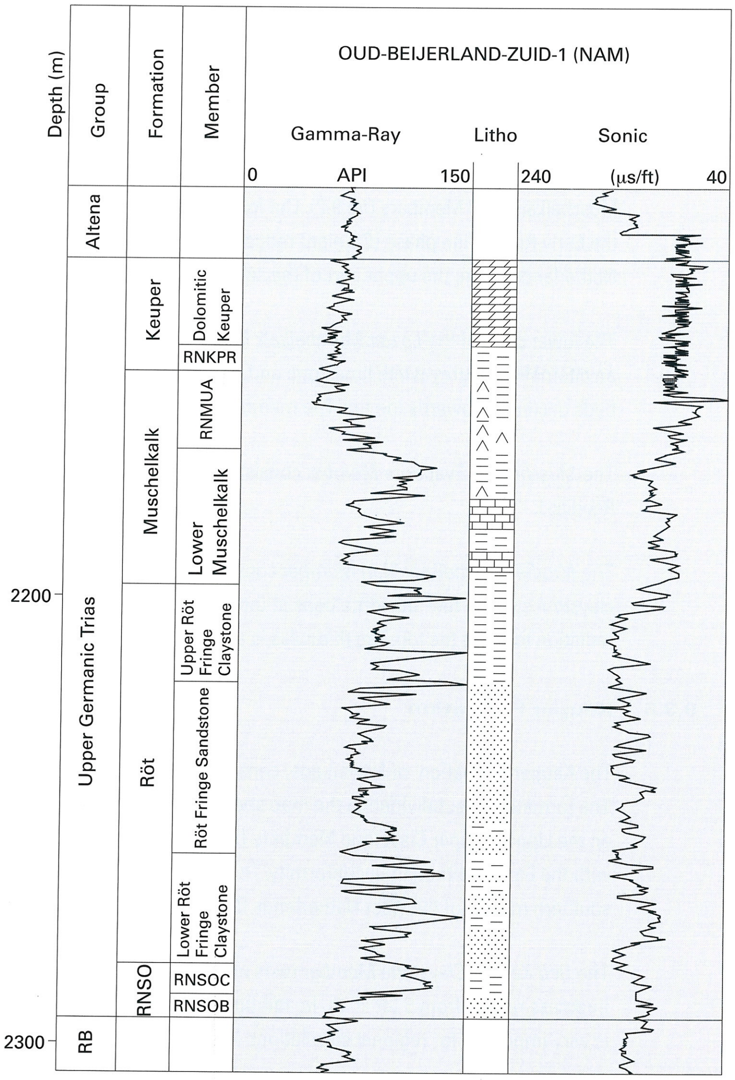
The *Basal Solling Sandstone Member* consists of a succession of one or more fine-grained sandstone layers and thin claystone layers. The unit is only a few metres thick.

The *Solling Claystone Member* makes up the greater part of the formation and consists of red-brown to green-mottled claystone. The sequence is up to 14 m thick.

9.3.3 **Röt Formation**

The Röt Formation, of Early Anisian age, consists in the map sheet area of the Lower and Upper Röt Fringe Claystone Members that are separated by the Röt Fringe Sandstone Member (fig.9.2).
The Röt Formation occurs throughout the distribution area of the Upper Germanic Trias Group and its maximum thickness is 100 m.

Figure 9.2 Stratigraphic subdivision and log characteristics of the Upper Germanic Trias Group in well Oud-Beijerland-Zuid-1.



RNKPR	Red Keuper Claystone Mb
RNMUA	Middle Muschelkalk Marl Mb
RNSO	Solling Formation
RNSOC	Solling Claystone Mb
RNSOB	Basal Solling Sandstone Mb
RB	Lower Germanic Trias Group

dolomite
claystone
anhydrite
sandstone
limestone

The *Lower Röt Fringe Claystone Member* consists of a red-brown, silty claystone. At the southern limit of the member's distribution area, its thickness is over 20 m.

The *Röt Fringe Sandstone Member* consists of an alternation of grey, arkosic sandstone and red-brown claystone beds. Its distribution is parallel to the southern boundary faults of the West Netherlands Basin and, outside the map sheet area, it grades laterally into the Röt Claystone in a northerly direction (Geluk et al., 1996; TNO-NITG, 2001). The maximum thickness is found in the south-east and is approximately 50 m.

The *Upper Röt Fringe Claystone Member* consists of a silty, sometimes sandy claystone. The member contains a few thin dolomite horizons. The unit's thickness is a few tens of metres.

9.3.4 Muschelkalk Formation

The Muschelkalk Formation, of Early Anisian to Early Ladinian age, rests conformably on the Röt Formation and is unconformably or slightly disconformably overlain by the Keuper Formation.
The formation is subdivided here into the Lower Muschelkalk, the Muschelkalk Evaporite and the Middle Muschelkalk Marl Members (fig.9.2). The formation ranges in thickness from 4 to 50 m. Erosion during the Early Kimmerian phase (Carnian) reduced the formation's thickness; at the southern edge of the West Netherlands Basin, the upper part of the sequence is missing as a result of erosion.

The lower parts of the *Lower Muschelkalk Member* consist of limestone beds. These are overlain by an alternation of grey-white limestone and dolomite beds and grey marls. The proportion of dolomite beds decreases towards the top. The member is approximately 30 m thick.

The *Muschelkalk Evaporite Member* consists of an anhydrite with a thickness of a few meters in well Reedijk-1.

The *Middle Muschelkalk Marl Member* consists of light-grey, sometimes green tot brown-grey marls and claystones with a few anhydrite beds at the base. This sequence shows a typical increase in gamma-ray radiation towards the top. The thickness is approximately 10 m.

9.3.5 Keuper Formation

The Keuper Formation, of Norian age, consists predominantly of claystones and dolomite layers.
The formation is subdivided in the map sheet area into the Red Keuper Claystone, the Dolomitic Keuper en the Upper Keuper Claystone Members (fig. 9.2). The base of the Red Keuper Claystone coincides with the Early Kimmerian unconformity. The formation's thickness ranges from 20 to 40 m along the southern margin of the West Netherlands Basin.

The *Red Keuper Claystone Member* rests unconformably on the Muschelkalk Formation. The member's thickness ranges from 5 tot 20 m. In addition to red claystones, green claystones occur. This member is very important for regional correlations (Geluk, 1999b).

The *Dolomitic Keuper Member* is composed of an alternation of claystones and several anhydrite and dolomite layers. The dolomite is characterised by its conspicuous light colour. The member's maximum thickness is approximately 20 m.

The *Upper Keuper Claystone Member* mainly comprises grey, silty claystones and marls and is a few meters thick in well Reedijk-1.

9.4 Sedimentary development and palaeogeography

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

The increased supply of clastics resulted in deposition of the sandy Main Buntsandstein Subgroup. This sandy unit was deposited by fluvial systems which regularly prograded basinward. The sandy material, which originated from the Variscan massifs to the south, was transported to the basin by braided river systems via the Trier Graben and the Ruhr Valley Graben (Wuster, 1968). At the edge of the lake in the centre of the basin, sand was deposited in fluvial fan systems, which prograded into the shallow, ephemeral, playa lake. The regular advances and retreats of this arid fluvial system may reflect fluctuations in climate. Following 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 eroded material (TNO-NITG, 2001).

The overlying Solling Claystone and Röt Claystone represent a return to sedimentation in a shallow lake environment. Some of these sediments may have been deposited 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 resulted in an influx of sand from the Brabant Massif. This depositional environment is interpreted as a braided-river system that fanned out distally at the margin of the playa lake (Geluk, 1999b).

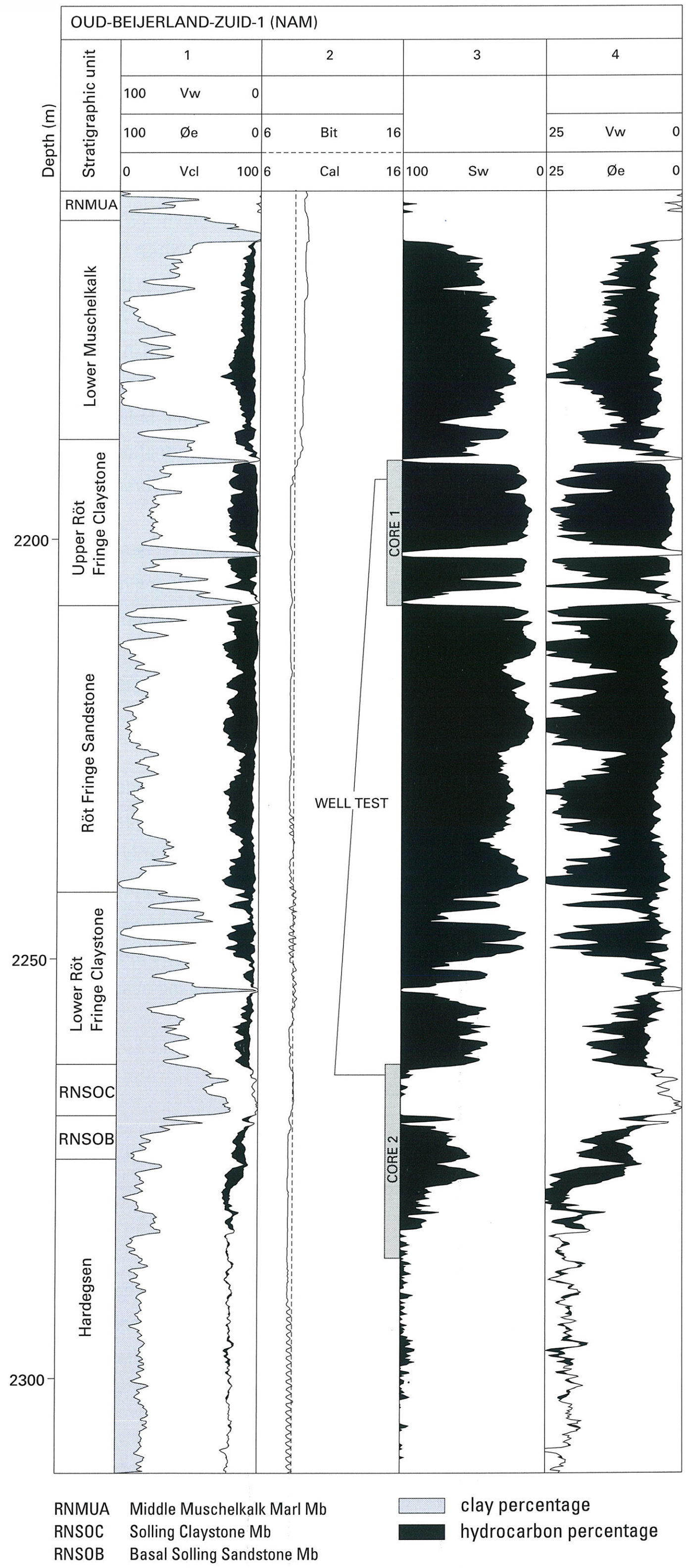
The sediments of the Muschelkalk succession were predominantly deposited in shallow-marine waters, near the tidal zone. Deposition of anhydrite and rock salt (Muschelkalk Evaporite Member) indicates that connections with the Tethys Ocean were temporarily restricted. Towards the end of the Muschelkalk, an open-marine environment prevailed again. A, possibly eustatically induced, regional regression resulted in renewed fine-grained clastic and evaporite sedimentation during the Keuper (Ziegler, 1990). The Red Keuper Claystone, the Dolomitic Keuper and the Upper Keuper Claystone Members were deposited under continental to marginal-marine and evaporitic conditions, possibly in a tidal flat or sabkha environment.

9.5 Petrophysical evaluation

Commercially significant amounts of liquid and gaseous hydrocarbons are present north of the map sheet area and have been produced for quite some time. The Botlek and Beijerland concessions are partly located within the map sheet area (see chapter 2).

The Triassic deposits in one well in the map sheet area have been petrophysically evaluated (Appendix C). In well Oud-Beijerland-Zuid-1 the reservoir was extensively tested and cored. In the Oud-Beijerland-Zuid field, both oil and gas have been discovered. The field has not yet been taken in production. Figure 9.3 shows an example of a log evaluation of the reservoir sequence of the Lower and Upper Germanic Trias Groups in well Oud-Beijerland-Zuid-1.

Figure 9.3 Petrophysical evaluation of the sandstones of the Lower and Upper Germanic Trias Groups in well Oud-Beijerland-Zuid-1. Column 1: clay content V_{cl}, effective porosity Φ_e and pore volume water V_w, all in percentages. The clay content was determined from the gamma-ray log. The effective porosity was obtained using the *shaly sand model* (density log/neutron log), in which the calculated log porosity was corrected for the clays and hydrocarbons present. Column 2: well diameter (Cal) and bit diameter (Bit), both in inches; the cored interval is also shown. Column 3: water saturation S_w, in percentages. The water saturation was determined according to the Indonesian formula (Fertl, 1987). Column 4: effective porosity Φ_e (left curve) and pore volume water V_w (right curve), both in percentages. The formation boundaries are indicated in the left column. All depths are true vertical depths.



10 Altena Group

10.1 Stratigraphy

The Altena Group, of Rhaetian to Late Bajocian (possibly up to Early Bathonian) age, consists predominantly of dark-coloured claystones with intercalated sandstone, limestone and marl layers in the upper part. The group is subdivided into five formations, which all occur within the map sheet area: the Sleen, the Aalburg, the Posidonia Shale, the Werkendam and the Brabant Formations. The stratigraphically most complete sequence was penetrated in well Reedijk-1 (fig. 10.1).

Within the map sheet area, the Altena Group rests conformably or slightly disconformably on the Upper Germanic Trias Group. The deposits are only present along the southern margin of the West Netherlands Basin at depths ranging from 1800 to 3100 m (Map XII-6). Erosion and syn-sedimentary subsidence have resulted in large variations in thickness, from a few metres to 800 m (Map XII-7). The deposits are unconformably overlain either by the Schieland, the Rijnland, or the Chalk Group.

10.1.1 Sleen Formation

The Sleen Formation, of Rhaetian age, is present throughout the distribution area of the Altena Group. The formation rests disconformably on the underlying Upper Germanic Trias Group and is conformably overlain by the Aalburg Formation. The deposits consist of dark-grey to black, sometimes bituminous, claystone and shales, locally containing abundant pyrite, as well as fossil and plant remains. The formation is divided into two parts by a thin sandstone unit. The upper part of the formation may be red-brownish. The formation is 20 to 40 m thick.

10.1.2 Aalburg Formation

The Aalburg Formation, of Hettangian to Pliensbachian age, is also present throughout the distribution area of the Altena Group. The formation rests conformably on the Sleen Formation and is conformably overlain by the Posidonia Shale Formation or unconformably either by the Schieland, the Rijnland or the Chalk Group. The formation has a monotonous lithology and comprises greenish-grey to black, sometimes calcareous claystone with thin limestone beds. The thickness of the Aalburg Formation varies greatly as a result of syn-sedimentary faulting and erosion. The maximum thickness is 200 m.

10.1.3 Posidonia Shale Formation

The Posidonia Shale Formation, of Toarcian age, consists of dark, bituminous shales containing a few limestone beds. The high organic content makes this shale the most important oil source rock in the Netherlands. The formation rests conformably on the Aalburg Formation and is, also conformably, overlain by the Werkendam Formation. In the map sheet area, the formation is only present in the West Netherlands Basin (Reedijk-1 and Strijen-West-1). The formation has a thickness of approximately 30 m.

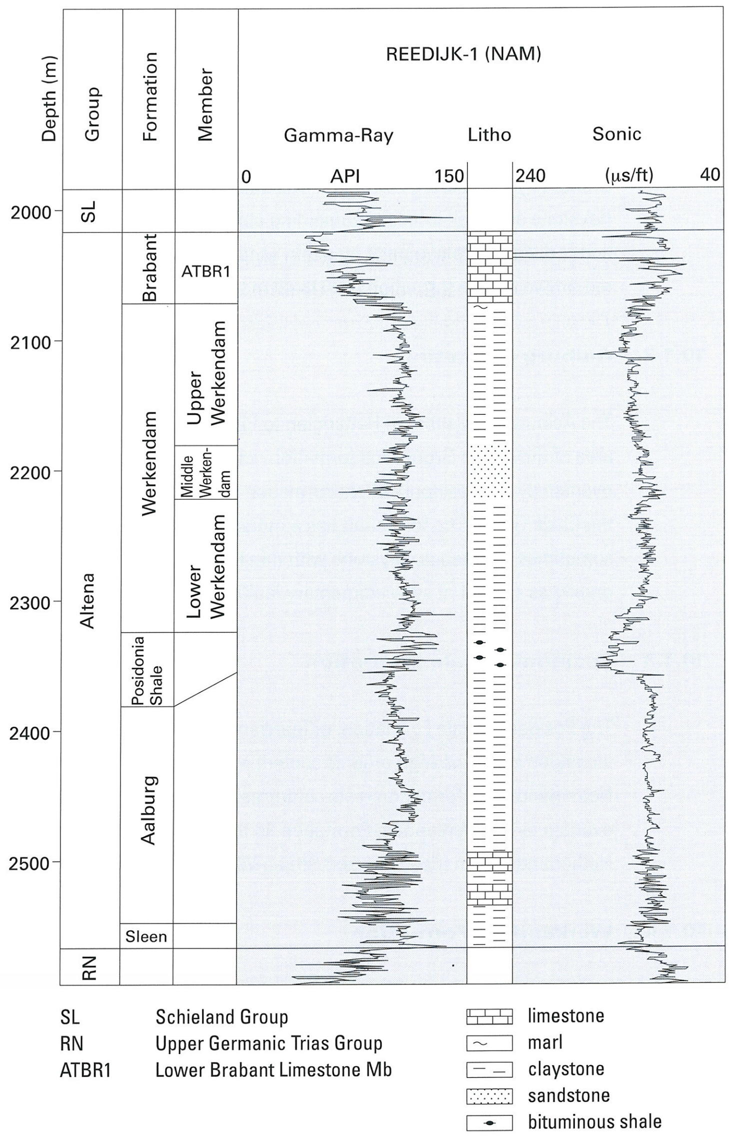
10.1.4 Werkendam Formation

The Werkendam Formation, of Late Toarcian up to and including Early Bathonian age, consists of grey, marly claystones with an interval of limestone beds and siltstone in the middle of the sequence. The formation has approximately the same distribution as the Posidonia Shale and Aalburg formations. The Werkendam Formation rests conformably on the Posidonia Shale Formation and is overlain conformably by the Brabant Formation or unconformably by the Schieland Group. The thickness varies greatly as a result of erosion and the maximum thickness is approximately 250 m. The formation is subdivided into three members (fig. 10.1).

The *Lower Werkendam Member,* of Late Toarcian to Middle Bajocian age, consists of grey, occasionally silty claystone, frequently containing characteristic siderite concretions and/or iron oolites. Locally, a few bituminous intercalations are present at the base. The thickness is variable and is up to 100 m.

The *Middle Werkendam Member,* of Middle Bajocian age, consists of sandstones with limestone beds and siltstone intercalations and has distinctly lower sonic-log responses than the underlying and overlying members. Its thickness is 40 m. The basal part of the member is usually marked by a sandstone sequence.

Figure 10.1 Stratigraphic subdivision and log characteristics of the Altena Group in well Reedijk-1.



The *Upper Werkendam Member,* of Middle Bajocian to latest Bajocian or earliest Bathonian age, is a homogenous sequence of grey, slightly marly claystones. Its thickness is up to 100 m.

10.1.5 Brabant Formation

In the far north-eastern corner of the map sheet area, only the lowest member of the Brabant Formation, the Lower Brabant Limestone Member, was penetrated (well Reedijk-1). The other members of the Brabant Formation are missing as a result of erosion. The formation conformably overlies the Werkendam Formation. The formation is unconformably overlain either by the Schieland, the Rijnland or the Chalk Group.

The *Lower Brabant Limestone Member,* of Early Bathonian (possibly also Late Bajocian) age, is an alternation of marls and limestones, the latter increasing in number towards the top of the member. The thickness is 50 m. The transition from the Upper Werkendam Member to the Lower Brabant Limestone Member is gradual, via a marl sequence containing thin limestone beds to a limestone sequence.

10.2 Sedimentary development and palaeogeography

After a long period of continental and shallow-marine depositional conditions, a transgression during the Late Triassic (Rhaetian) resulted in an open-marine depositional area, which extended over large parts of North-West Europe. This transgression marks the beginning of the deposition of the Altena Group. The remarkable uniformity of the sediments over a wide area indicates that they were deposited in a single large basin. The uniform, fine-grained composition of the Altena Group indicates that its absence on the highs is not a depositional feature, but the consequence of subsequent erosion predominantly related to Late Kimmerian uplift.

The start of the above-mentioned transgressive cycle resulted in deposition of the Sleen Formation. The fairly constant thickness of this formation is indicative of a steadily subsiding area. A brief regressive period following the deposition of this formation gave its upper part a lagoonal character. Subsequently, sea level rose again and the open-marine sediments of the Aalburg Formation were deposited, predominately below wave base. The presence of bituminous layers indicates that anoxic conditions periodically prevailed in the basin. The thickness variation within the formation reflects differential subsidence in this area.

The Posidonia Shale Formation is a pelagic deposit with a bituminous character, deposited under anoxic conditions. These may have been due to stagnation in deep-water circulation, probably caused by a combination of a deep basin and an intensely faulted basin floor and a restriction of the seaway to the open ocean. This could account for the reducing conditions.

Open-marine conditions returned during deposition of the Werkendam Formation. This formation was deposited in a shallow, open-marine environment; several sea-level fluctuations must have caused facies variations in the more tidal areas. During the deposition of the Brabant Formation there was a slight drop in sea level. The fossil content of the Brabant Formation indicates deposition under brackish-water conditions (*RGD, 1995a,b; 1996b*).

11 Schieland Group

11.1 Stratigraphy

The Schieland Group comprises the Delfland Subgroup, which, here, consists predominantly of an alternation of dark to variegated claystones and sandstones containing lignite beds. The subgroup is represented by the Nieuwerkerk Formation (fig. 11.1). In the map sheet area, the depth of the base of the Schieland Group is to be found between 1700 and 2100 m deep (Map XII-8). The maximum thickness is 175 m (Map XII-9). The Schieland Group rests unconformably on the Altena Group or on the Upper Germanic Trias Group and is conformably overlain by the Rijnland Group or unconformably by the Chalk Group. The sediments range in age from Kimmeridgian to Barremian making the group partly the time equivalent of the Rijnland Group.

11.1.1 Nieuwerkerk Formation

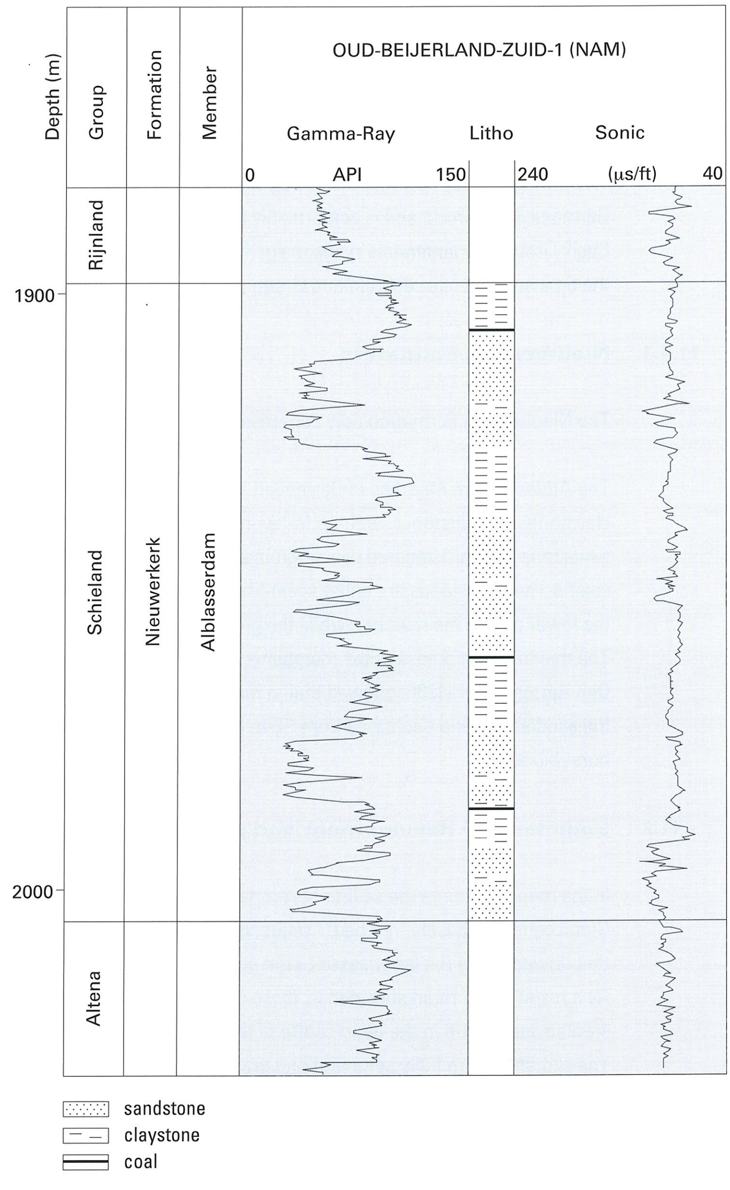
The Nieuwerkerk Formation only comprises the Alblasserdam Member in this map sheet area (fig. 11.1).

The *Alblasserdam Member,* of Barremian age, consists of succession of grey, red and mottled claystones and siltstones, with up-to-few-metres-thick intercalations of fine-grained to medium-grained sandstone and thick-layered coarse-grained sandstone. The claystones and siltstones contain coal seams. The sandstones are either sheet-like or channel shaped. The reddish sediments are restricted to the lower part of the member, while the grey, organic-rich sediments predominate in the upper part. The maximum thickness of the member is 175 m. The sandstones generally show little lateral continuity. Den Hartog Jager (1996) showed that in the West Netherlands Basin to the north of the map sheet area, the sand/shale ratio decreases from SE to NW. The same trend can be observed close to the adjacent horst blocks.

11.2 Sedimentary development and palaeogeography

In the map sheet area the sediments of the Nieuwerkerk Formation were deposited during the Early Cretaceous. The basal ("red bed") sequence represents a depositional environment of braided rivers that flowed along the length axes of the grabens, resulting in rapid deposition of channel sands. As a result of the rapid subsidence, these channel sand bodies had a limited lateral extent and formed a stacked succession in the depo-centre of the rift basin, which was located north of the map sheet area. The climate was initially semi-arid and gradually became more humid (Den Hartog Jager, 1996; *NITG-TNO, 1999*; Herngreen et al., 2000). Furthermore, differential subsidence ceased and was followed by gradual regional subsidence. The braided-river system was replaced by a system of meandering rivers flowing through wide, flat valleys. Sand was deposited in the river channels, but sands (in the form of crevasse splays), clays and peat layers were also deposited in the flood-plain areas. The river systems discharged into a shallow sea located towards the north-west. The provenance areas of the sands were the Brabant Massif and possible the Rhenish Massif as well.

Figure 11.1 Stratigraphic subdivision and log characteristics of the Schieland Group in well Oud-Beijerland-Zuid-1.



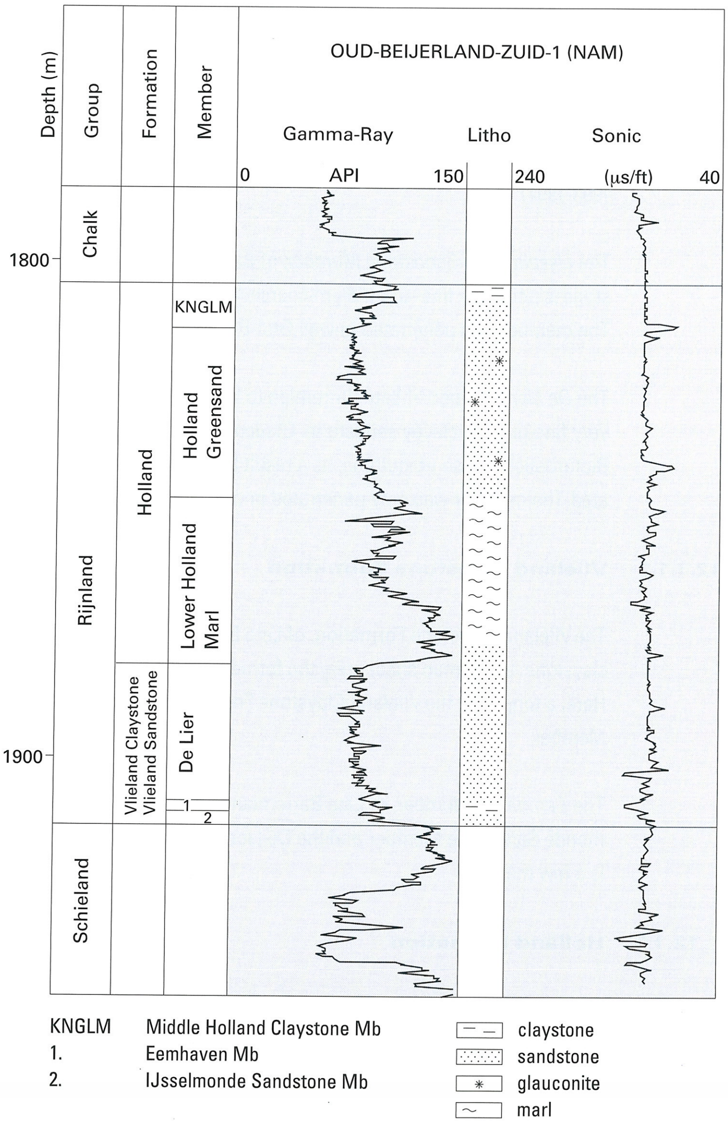
12 Rijnland Group

12.1 Stratigraphy

The Rijnland Group, of Barremian to Albian age, consists of glauconitic sandstones, siltstones, claystones and marls. The group is subdivided into the Vlieland Sandstone, Vlieland Claystone and Holland Formations. The first two formations together form the informal Vlieland subgroup.

The Rijnland Group is only present in the north-eastern part of the map sheet area. The group has not been deposited in the south-west, on the Brabant Massif and on the Zeeland Platform. The Rijnland Group has been penetrated in two wells only in the map sheet area, i.e., Reedijk-1 and Oud-Beijerland-Zuid-1 (fig. 12.1). The base of the group is located at a depth of 1800 to 1900 m (Map XII-10). The group's maximum thickness is approximately 100 m (Map XII-11). During deposition of this group, the marine depositional area expanded from the West Netherlands Basin, located to the north of the map sheet

Figure 12.1 Stratigraphy and log characteristics of the Rijnland Group in well Oud-Beijerland-Zuid-1.



area, across the neighbouring highs. As a result only the younger part of the sequence is present in the map sheet area. The group is overlain either unconformably or disconformably by the Chalk Group and rests conformably or slightly disconformably on the Schieland Group, or unconformably either on the Altena Group or the Upper Germanic Trias Group.

12.1.1 Vlieland subgroup

The Vlieland subgroup, of Barremian to Early Aptian age, is only present in a small area in the north-eastern part of the map sheet area. The subgroup is overlain either conformably or slightly disconformably by the Holland Formation. The subgroup's maximum thickness is attained north of the map sheet area in the West Netherlands Basin. The subgroup is thinner on the highs, located to the south and south-east of this basin, and the age of the base of the subgroup on the Zeeland Platform is progressively younger towards the south. Within the subgroup, the Vlieland Sandstone Formation and the Vlieland Claystone Formation are distinguished. These formations are each other's lateral equivalents.

12.1.1.1 Vlieland Sandstone Formation

In the map sheet area the Vlieland Sandstone Formation consists of only two sand bodies: i.e., the IJsselmonde Sandstone Member and the De Lier Member (Van Adrichem Boogaert & Kouwe, 1993-1997).

The *IJsselmonde Sandstone Member,* of Barremian age, is a light-grey, massive sandstone. This sandstone is generally fine- to medium-coarse-grained, with locally some conglomeratic sandstone. The member was penetrated in well Oud-Beijerland-Zuid-1 and its thickness is a few metres.

The *De Lier Member,* of Late Barremian to Early Aptian age, is an alternation of thin-bedded, fine- to very fine-grained clayey sandstone. Glauconite, siderite, lignite and shell fragments are common. Bioturbation is also ubiquitous; as a result the original sedimentary structures have largely been obliterated. The member was only penetrated in well Oud-Beijerland-Zuid-1 and its thickness is almost 30 m.

12.1.1.2 Vlieland Claystone Formation

The Vlieland Claystone Formation, of Late Barremian age, consists of dark-brown to dark-grey, silty claystone. In the map sheet area, the formation grades laterally into the Vlieland Sandstone Formation. Here, a tongue of the Vlieland Claystone Formation is intercalated in the sandstones: the Eemhaven Member.

The *Eemhaven Member,* of Late Barremian age, is a thin claystone intercalation between the IJsselmonde Sandstone Member and the De Lier Member. The maximum thickness of the Eemhaven Member is a few metres.

12.1.2 Holland Formation

The Holland Formation, of Aptian to Middle Albian age, consists primarily of grey and red-brown marls and claystones. The formation is subdivided into the Lower Holland Marl, the Holland Greensand en the Middle Holland Claystone Members. The Upper Holland Marl Member is missing in the map sheet area (fig. 12.1). The Holland Formation rests conformably on the Vlieland subgroup and is overlain unconformably by the Chalk Group.

The *Lower Holland Marl Member*, of Aptian age, consists of grey, sometimes, red, brown or yellowish marly claystone (*RGD, 1990*). The member's thickness is over 30 m in well Oud-Beijerland-Zuid-1.

The *Holland Greensand Member*, of Late Aptian to Early Albian age, consists of an alternation of dark, silty and sandy clayey and glauconitic sands (greensands) containing limestone beds. The unit rests on the Lower Holland Marl Member and is overlain by the Middle Holland Claystone Member. The unit is over 30 m thick.

The *Middle Holland Claystone Member* consists of grey, marly, clays. The clay content is higher than that of the underlying and overlying members. The unit's maximum thickness is approximately 20 m. The member is unconformably overlain by the Chalk Group. Biostratigraphic studies have shown that the lower part of the member is of Late Aptian age (*RGD, 1990*), which is contrary to the generally accepted Early to Middle Albian age.

12.2 Sedimentary development and palaeogeography

When deposition of the Rijnland Group commenced, the landscape was dominated by the subsiding West Netherlands Basin to the north of the map sheet area. The advancing transgression eventually terminated the lacustrine and fluvial conditions that prevailed during deposition of the Schieland Group and heralded a long period of marine sedimentation. The resulting deposits of the Vlieland subgroup are, in the map sheet area, only represented by shallow-marine sediments, generally beach barriers and tidal deposits.

On the Zeeland Platform, the base of the subgroup is progressively younger towards the south. This reflects the onlap of the Cretaceous transgression onto the flanks of the Brabant Massif.

During deposition of the Holland Formation, clayey marls and clays were deposited along the southern margin of the West Netherlands Basin (Lower Holland Marl Member and Middle Holland Claystone Member). In a shallow marine environment glauconitic sands of the Holland Greensand Member were deposited at the same time.

13 Chalk Group

13.1 Stratigraphy

The Chalk Group, of Cenomanian up to and including Danian age, consists predominantly of light-coloured, hard, fine-grained bioclastic chalks and marly limestones. Intercalations of marls, calcareous claystones and, at the base, glauconitic greensands are also present. Chert nodules are numerous and occur both isolated and in bands. The Chalk Group is subdivided into the Texel, Ommelanden and Houthem Formations (fig. 13.1).

The Chalk Group has originally been deposited throughout the map sheet area In Zeeuws-Vlaanderen, the group rests unconformably on Silurian and Devonian rocks. Further to the north and north-east the following groups subcrop successively: Banjaard, Zeeland, Limburg, Upper Rotliegend, Zechstein, Lower and Upper Germanic Trias and the Rijnland Groups (Maps XI-5 and XII-17). The Chalk Group is overlain throughout the maps sheet area by the Lower North Sea Group. The depth of the group ranges form 400 to 1800 m (Maps XI-1,2 and XII-12,13). Its thickness ranges from 100 m in Zeeuws-Vlaanderen to over 700 m in the north-eastern part of the map sheet area.

13.1.1 Texel Formation

The Texel Formation, of Cenomanian to possibly earliest Turonian age, is only present along the southern margin of the West Netherlands Basin in the north-eastern part of the map sheet area The formation consists here of the Texel Greensand Member. Its maximum thickness is 10 m.

Texel Greensand Member consists of glauconitic sands and is only present in the proximity of the Rijen Fault and along the southern margin of the West Netherlands Basin. The thickness ranges from a few metres to 10 m.

13.1.2 Ommelanden Formation

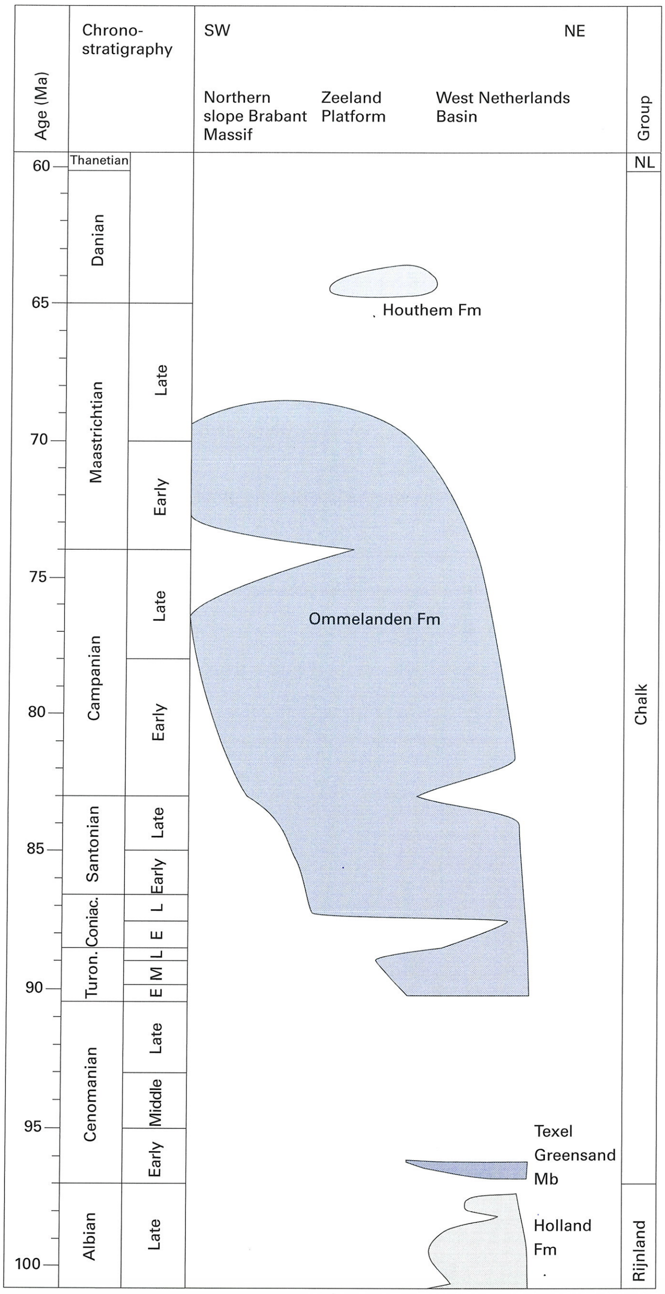
The Ommelanden Formation is present in virtually the entire distribution area of the Chalk Group. The formation consists of white, fine-grained limestone, which may be clayey or marly locally. Horizons containing chert concretions are common. The rock consists predominantly of pelagic bioclastic material. The formation has not been subdivided into members, but log correlations, supported by age dating, enabled the identification (fig. 13.2) and correlation (fig. 13.3) of several Cretaceous stages.

The lower part of the formation consists of massive limestones of Turonian age, succeeded by marly sequences of Coniacian and Santonian age. This is overlain by a marly to slightly sandy, calcareous sequence of Campanian age, which grades upward into a massive limestone containing numerous chert nodules. Chalks of Maastrichtian age occur at the top of the Ommelanden Formation. The thickness of the Ommelanden Formation can be up to 700 m in the north-eastern part of the map sheet area. Along the southern margin of the West Netherlands Basin, the Ommelanden Formation rests unconformably on the Holland Formation or the Schieland Group. The rocks underlying the unconformity are progressively older towards the south (fig.13.3). The formation is overlain in the northern part of the map sheet area by the Houthem Formation and in the southern part by the Lower North Sea Group.

13.1.3 Houthem Formation

The Houthem Formation, of Danian age, consists of soft, pale-grey to pale-yellow, fine- to coarse-grained chalks. The formation is distinguished lithologically from the underlying Maastrichtian by ubiquitous clayey intervals, one of which is found immediately at the base of the interval. The formation contains calcite concretions, hardgrounds and fossil debris horizons. The lower part of the formation is characterised by the presence of glauconite. The formation is present in the northern part of the map sheet area where its thickness is up to approximately 70 m.

Figure 13.1 Stratigraphy of the Chalk Group.



NL Lower North Sea Group

13.2 Sedimentary development and palaeogeography

The Early Cretaceous was marked by a worldwide sea-level rise. Maximum sea level was reached during the Late Cenomanian (Haq et al., 1987; Ziegler, 1990). The sea level remained high up to the end of the Cretaceous. The sea-level rise resulted in the transgressive sequences at the base of the Chalk Group.

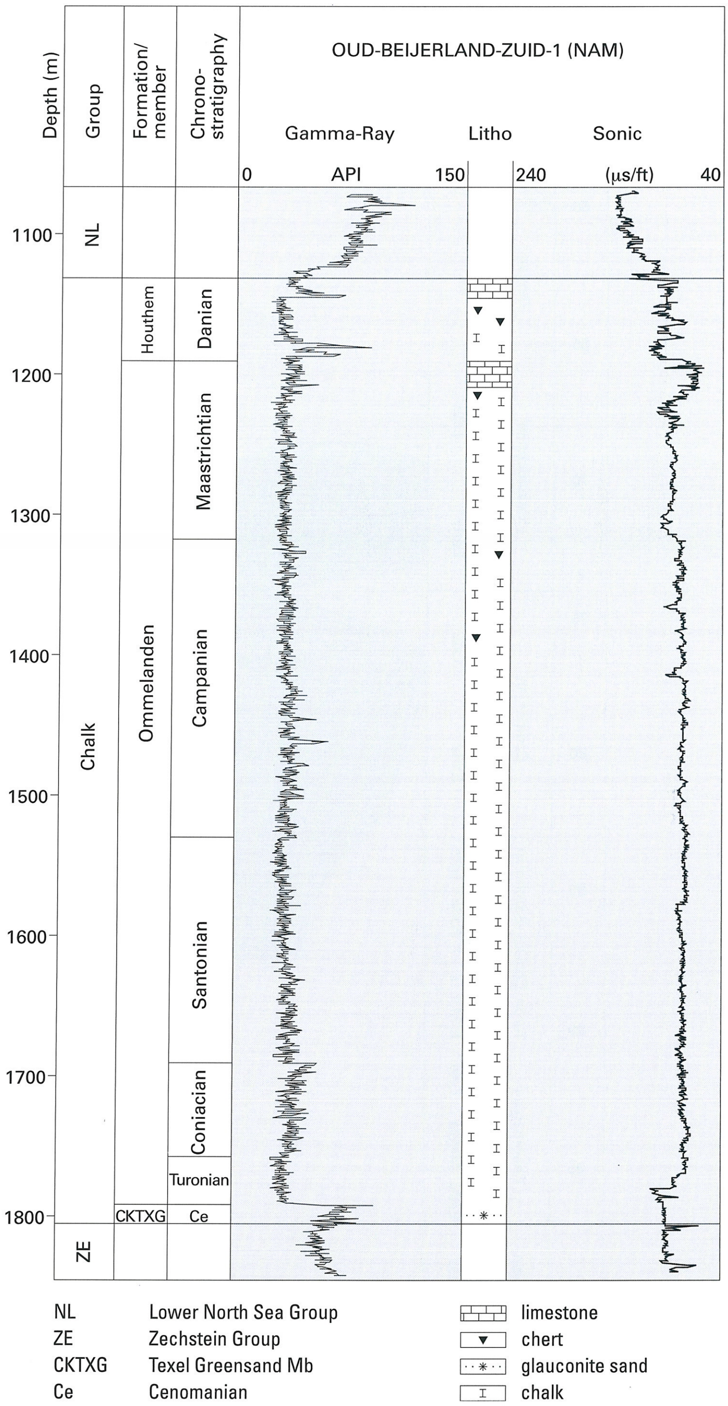


Figure 13.2 Stratigraphic subdivision and log characteristics of the Chalk Group in well Oud-Beijerland-Zuid-1.

The greensands of the Texel Formation were deposited along the basin margin by a coastline that migrated progressively southward. The younger parts of the Texel Formation, which overlie the greensands elsewhere, are not developed in the map sheet area. The high glauconite content of the sands belonging to the Texel Greensand indicates a low sedimentation rate and considerably biogenic activity, which confirms the transgressive character of the Texel Greensand sequence.

During the Turonian, a pure limestone sequence was deposited. The low clay content is attributed to a highstand, resulting in flooding of the former provenance areas of clastic sediments and an increased distance to new provenance areas. From the Late Turonian onwards, the clay percentage gradually increased again. The increase in the supply of clastics was due to uplift of the former basins to the

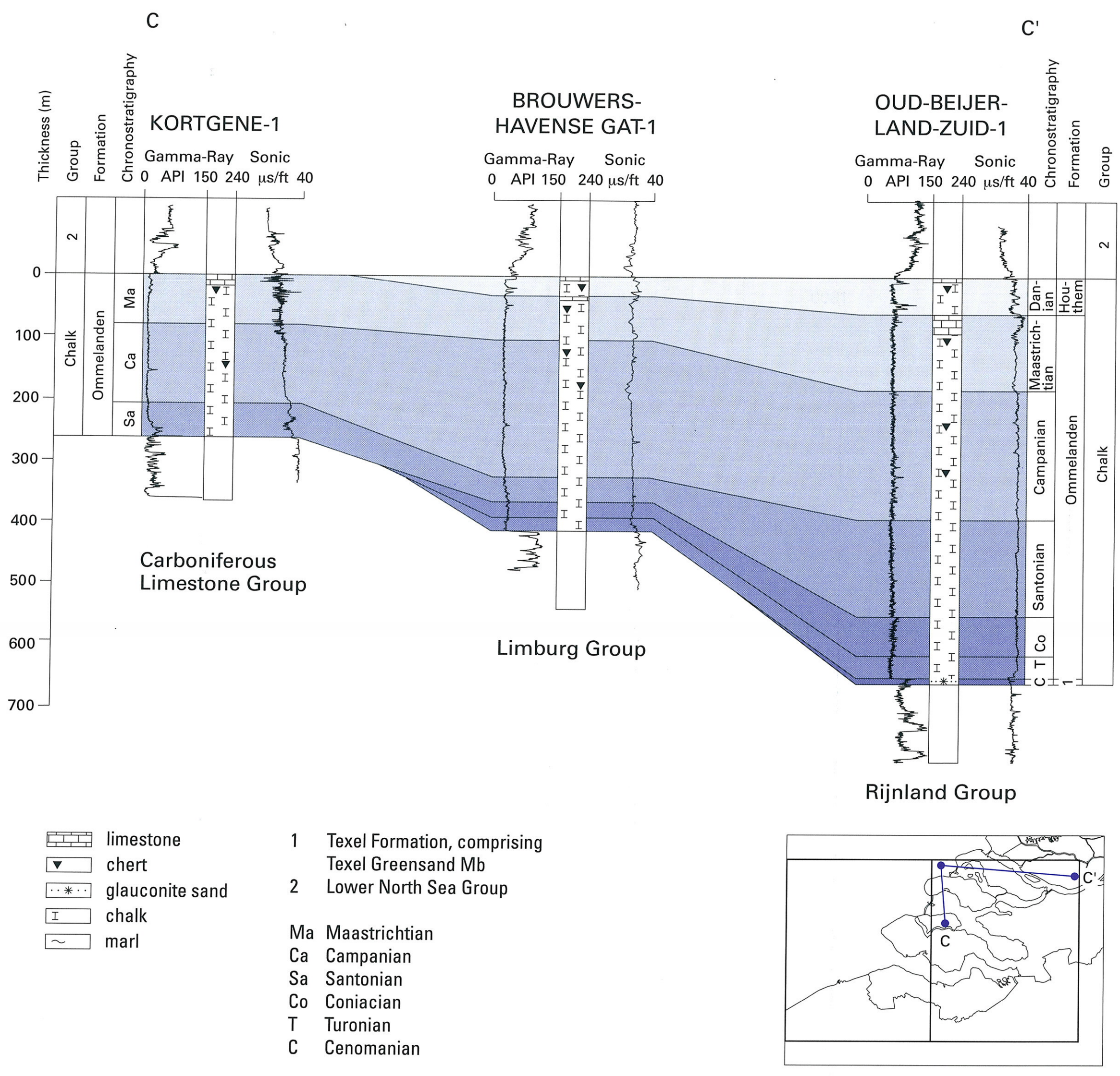


Figure 13.3 Stratigraphic correlation of the Chalk Group along line C-C′ between wells Kortgene-1, Brouwershavense Gat-1 and Oud-Beijerland-Zuid-1. Reference level is top Chalk Group.

north and east of the map sheet area during the Sub-Hercynian inversion phase in the Santonian and Early Campanian. The gradual southward thinning of the Chalk Group stages indicates that the Sub-Hercynian phase did not directly affect these deposits, except in the south on the northern flank of the Brabant Massif. Here, only syn- and post-inversion deposits are encountered of Santonian to Maastrichtian age (Legrand, 1968).

After a short break in deposition at the end of the Cretaceous, the Houthem Formation was deposited in a similar shallow-marine carbonate facies during the earliest Tertiary. These deposits are only present in the northern part of the map sheet area.

14 North Sea Supergroup

14.1 Stratigraphy

The North Sea Supergroup is subdivided into the Lower, Middle and Upper North Sea Groups (see fig. 14.1) and consists virtually solely of sands and clays fig. 14.2). The three groups are separated by unconformities from each other. The North Sea Supergroup rests conformably to slightly unconformably on the Chalk Group. Sedimentation was strongly influenced by the combined effects of regional tectonics and eustatic sea-level fluctuations. In the map sheet area, marine conditions prevailed while the supergroup was being deposited (Letsch & Sissingh, 1983; Zagwijn, 1989).

The thickness of the North Sea Supergroup ranges from less than 300 m in the south to over 1150 m on the southern margin of the Voorne Trough (Maps XI-3 and XII-14). Only the Middle North Sea Group is missing in the western part of Zeeuws-Vlaanderen. In Zeeuws-Vlaanderen the Upper North Sea Group only comprises Quaternary deposits. In this explanation, the Quaternary deposits are discussed only briefly, but they are described in detail by Fischer (1997) and in the "Toelichtingen bij the Geologische Kaart van Nederland 1:50.000" (Rijks Geologische Dienst, 1965, 1970, 1971, 1972, 1978) [Explanation to the Geological Map of the Netherlands 1:50.000" (Geological Survey of the Netherlands, 1965, 1970, 1971, 1972, 1978)]. Where the younger Tertiary and the Quaternary deposits are located at depths that are too shallow to allow mapping by the methods normally used for the deep subsurface, the above-mentioned explanation and accompanying maps and sections have been used. *TNO-NITG (2002)* contains additional biostratigraphic information.

14.1.1 Lower North Sea Group

The Lower North Sea Group, of Late Palaeocene and Eocene age, consists of the Landen Formation and the Dongen Formation, and is present throughout the map sheet area. The entire group is present, showing that erosion, caused by uplift during the Pyrenean tectonic phase (Late Eocene to Early Oligocene), has hardly affected this area. This is in sharp contrast to large areas in the southern and central Netherlands. The deposits rest conformably to slightly unconformably on the Chalk Group. The maximum thickness of the group is 500 m in the north-east; in the south the thickness is approximately 400 m.

14.1.1.1 Landen Formation

The Landen Formation, of Late Palaeocene age, comprises the Heers Member, the Gelinden Member and the Landen Clay Member.

The *Heers Member* is a very fine-grained, green-grey, glauconitic sand, locally cemented into sandstone by a calcite cement. The unit is present throughout the map sheet area, with the possible exception of the south-western part. The maximum thickness is 42 m.

The *Gelinden Member* consists of grey-white to yellow-brown, clayey marls. Its distribution is limited to the south-eastern and eastern parts of the map sheet area and, westward and northward, the marls merge laterally into the Landen Clay Member. The member has a slightly wider distribution than the underlying Heers Member. The thickness ranges from 12 to 15 m.

The *Landen Clay Member* generally consists of a dark-grey, pyritic and glauconitic clay sequence. However, towards the south-east, the facies changes into a fine-grained sandy deposit containing humic intercalations. Thickness ranges from less than 17 m in the south-eastern part to almost 60 m in the north-western part of the map sheet area on the southern side of the Voorne Trough.

14.1.1.2 Dongen Formation

The Dongen Formation, of Eocene age, comprises the Basal Dongen Sand Member, the Ieper Member, the Brussels Sand Member and the Asse Member. The formation is present throughout the map sheet area.

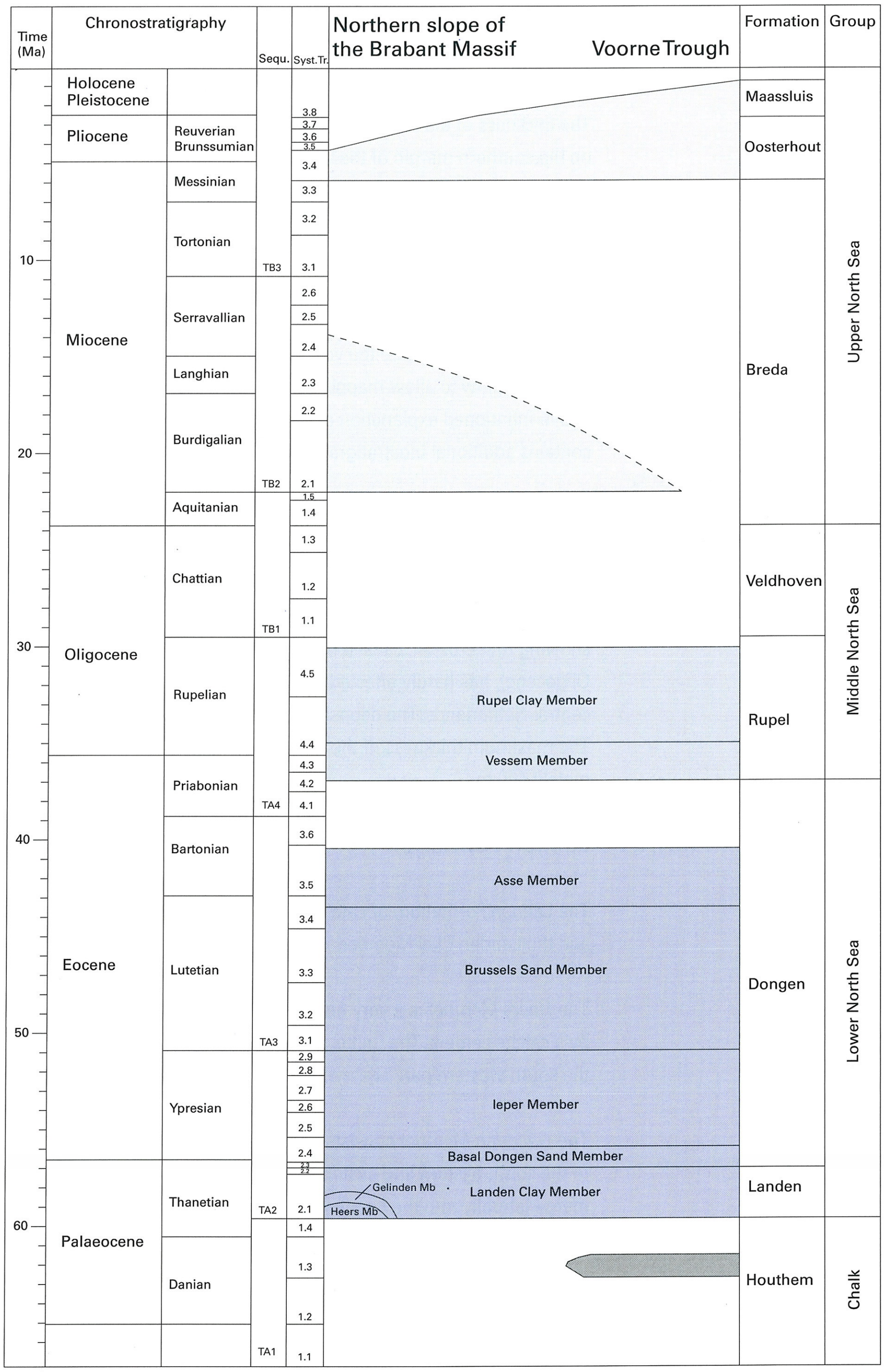


Figure 14.1 Stratigraphy of the North Sea Supergroup.

The *Basal Dongen Sand Member,* of Ypresian age, consists of fine-grained, brown, humic, sometimes glauconitic sands. The member is present throughout the map sheet area, with the exception of the south-eastern part. Its thickness is only 25 to 35 m. There are local indications of thin volcanic ash beds, however, these are not sufficient to distinguish this member from the overlying and in part also laterally equivalent *Basal Dongen Tuffite Member.*

The *Ieper Member,* of Ypresian age, consists of brown-grey to red-brown clay at the base, and sandy clay at the top and may locally contain pyrite, shells, coalified plant remains, and benthic foraminifers. The clays contain sandy and silty horizons. The upper part of the unit is characterised by the presence of green-grey, glauconitic and marly sand intercalations. In the south-eastern part of the map sheet area, only the youngest part of the member is present. The member ranges in thickness from 66 m in the south-east to over 275 m on the southern side of the Voorne Trough in the north-west of the map sheet area.

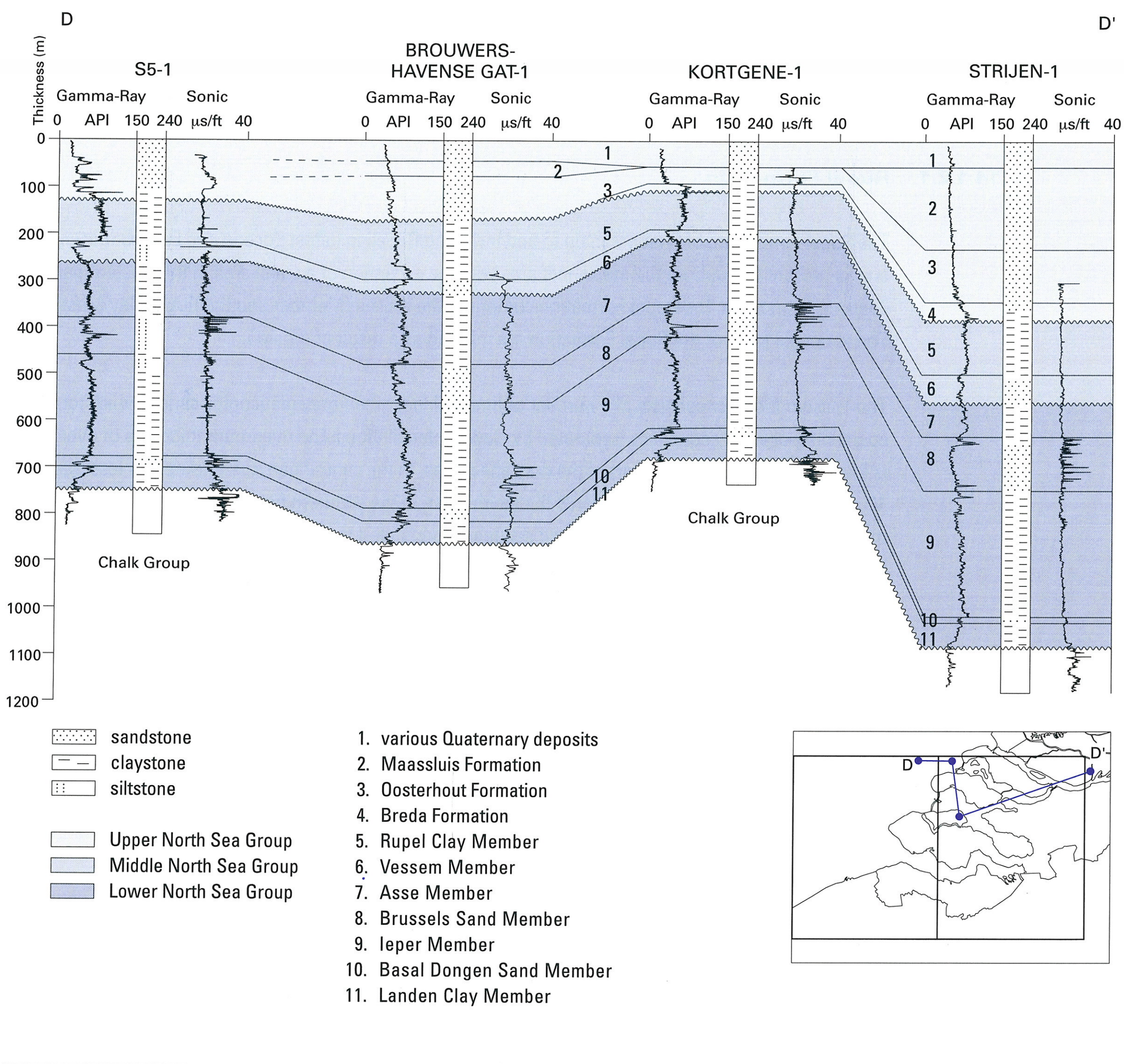


Figure 14.2 Stratigraphic correlation of the North Sea Supergroup along line D-D' between wells S5-1, Brouwershavense Gat-1, Kortgene-1 and Strijen-1. Reference level is the top of the Quaternary deposits.

The *Brussels Sand Member*, of Lutetian age, consists of fine-grained, glauconitic sands, containing numerous thin limestone and sandstone beds especially in its upper part. The unit's thickness ranges from over 40 m on the southern side of the Voorne Trough to almost 130 m in the eastern part of the map sheet area.

The *Asse Member,* of Bartonian age, is a highly plastic, green-grey to blue-grey, calcareous clay. The member is up to 30 m thick in the eastern part of the map sheet area while on the southern side of the Voorne Trough in the north-western part of the map sheet area the member's thickness is slightly over 150 m.

14.1.2 Middle North Sea Group

In the map sheet area, the Middle North Sea Group, of Late Eocene to Late Oligocene age, only comprises the Rupel Formation. With the exception of a small area in the western part of Zeeuws-Vlaanderen, the group is present throughout the map sheet area. The maximum thickness of approximately 250 m is found in the Voorne Trough. The Middle North Sea Group rests conformably or slightly uncomformably on the Lower North Sea Group and is in turn unconformably overlain by the Upper North Sea Group. The group's thickness ranges from 150 m to 200 m in the north-eastern part of the map sheet area.

14.1.2.1 Rupel Formation

The Rupel Formation, of Priabonian up to and including Rupelian (latest Eocene and Early Oligocene) age, is present throughout the map sheet area with the exception of a small area in the western part of Zeeuws-Vlaanderen. The Rupel Formation comprises the Vessem Member and the Rupel Clay Member. The youngest parts of the Rupel Formation are missing as a result of erosion.

The *Vessem Member* consists of a number of fine-grained, green-grey glauconitic sands, which form coarsening-upward sequences, separated by clayey intercalations. The maximum thickness of over 70 m is found in the north-eastern part of the map sheet area. In the central part, the thickness is less than 40 m. The member pinches out towards the south-west. In the southern part of the map sheet area, the Vessem Member consists of two sand sequences separated by a clay layer. Here, a local subdivision is used, which are consistent with the Belgian stratigraphy, i.e.: the *Bassevelde Sand Member*, the *Watervliet Clay Member* and the glauconitic *Ruisbroek* S*and Member* (see fig. 16.3, Wouters & Vandenberghe, 1994). In Belgium, these members are included in the Zelzate Formation, which is part of the Tongeren Group.

The *Rupel Clay Member* consists of a succession of brown to grey-brown stiff clays, characterised by pyrite nodules and horizons containing septarian nodules. The Rupel Clay has a thickness of 110 m in the north-eastern part of the map sheet area and gradually decreases in thickness towards the south-west down to zero in the western part of Zeeuws-Vlaanderen.

14.1.3 Upper North Sea Group

In the map sheet area, the Upper North Sea Group, ranging in age from Miocene to Holocene, comprises the Breda, Oosterhout and Maassluis Formations and younger, both marine and continental, Quaternary deposits (Doppert et al., 1975). The group rest unconformably or disconformably on the Middle North Sea Group. The group was recorded the deepest in the north-eastern part of the map sheet area: at a depth of almost 400 m (Maps XI-4 en XII-15). The shallowest depth of the group was recorded in the south-western part of Zeeuws-Vlaanderen; here the depth is a mere 15 m.

14.1.3.1 Breda Formation

The base of the deposits of the Breda Formation is characterised by a clayey section with a maximum thickness of 25 m. In the eastern part of the map sheet area, this sequence is overlain by silty deposits with a maximum thickness of 50 m. The thick, prograding sand sequences that are so well known in the Ruhr Valley Graben are absent here. These deposits are absent in the far north-west of the map sheet area and in Zeeuws-Vlaanderen. The Breda Formation is of Miocene age (*RGD, 1983*; TNO-NITG, 2001).

14.1.3.2 Oosterhout Formation

The Oosterhout Formation, of latest Miocene to Pliocene age, is a predominantly sandy, glauconitic formation. In the north-eastern part of the map sheet area, the unit is up to 125 m thick. It wedges out towards the south-west, and is absent in Zeeuws-Vlaanderen. The formation consists of prograding sands in the north-eastern part of the map sheet area.

14.1.3.3 Maassluis Formation

The Maassluis Formation, of Pleistocene age, is present in the centre and north of the map sheet area. The formation's thickness is approximately 150 m in the north-eastern part of the map sheet area, thinning to 50 m towards the north-west. In the south, the formation is missing as a result of erosion. The formation consists of fine- to coarse-grained sands with shell fragments and local intercalations of sandy clay layers and clay lenses.

14.2 Sedimentary development and palaeogeography

The southern margin of the North Sea Basin was located either in or just to the south of the map sheet area during deposition of the North Sea Supergroup. The sedimentation pattern was largely controlled by tectonic movements, eustatic sea-level fluctuations and in the south by the palaeogeographic relief. Subsidence of the Voorne Trough was the key feature affecting deposition of the Lower North Sea Group.

The Palaeocene Laramide phase marks the transition from carbonate deposition to a period during which clastic sediments were deposited under largely marine conditions. The first major sedimentary sequences following the Laramide phase resulted in the deposition of the marine sediments of the Landen Formation during the Late Palaeocene. This was followed by the also marine sands and clays of the Dongen Formation. The Pyrenean phase did not cause any erosion in the map sheet area.

The Rupel Formation was deposited in initially shallow-marine conditions. The basin became gradually deeper resulting in deposition of the Rupel Clay. There are no indications of differential subsidence and the homogenous character of the Rupel Clay indicates deposition in an extensive marine basin.
Sea level fell again towards the end of the Early Oligocene. No sediments have been preserved that date from the Late Oligocene, a period of relatively low sea level. It is assumed that sediments were in fact deposited at the time, but were removed by subsequent erosion.

At the time of the transition from the Oligocene to the Miocene, regional uplift resumed during the Savian phase. As a result of a brief rise in sea level, followed soon by a fall, solely the oldest sediments of the Breda Formation were deposited, while in the south-west and north-west, no sediment was deposited at all. The prograding system of the northern offshore, which was part of the major advancing NW European coastal system from the Middle Miocene right up to the Pleistocene (Bijlsma, 1981; Zagwijn, 1989), is, therefore, only represented by the latest Miocene to Pliocene sands of the Oosterhout Formation.

During deposition of the Quaternary Maassluis Formation, marine conditions still prevailed in most of the map sheet area, with the exception of the southern part. However, as a result of increased uplift of the hinterland, the younger Quaternary sediments are largely continental. The uplift resulted in partial erosion of the sediments of the Maassluis Formation.

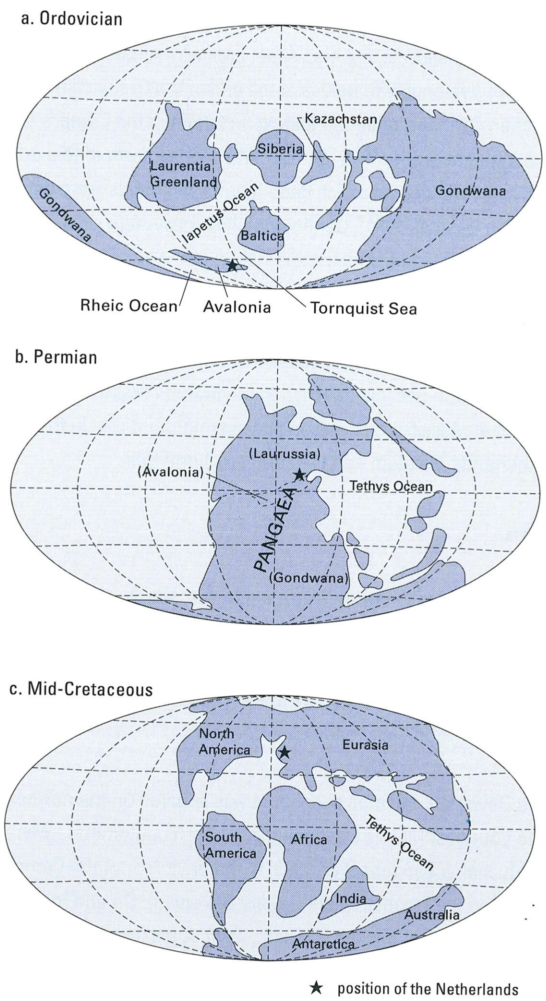
15 Geological history

15.1 Introduction

This chapter describes the geological history of the map sheet area, from the Cambro-Silurian to the Quaternary (fig. 15.1). Very few data are available for the pre-Carboniferous in the map sheet area. For this period, the description is based partly on publications describing the surrounding areas. For details of the Quaternary in the map sheet area, please refer to the publications by Zagwijn (1989), Fischer (1997) and the "Toelichtingen bij de Geologische Kaart van Nederland 1:50 000" [Explanation to the Geological Map of the Netherlands 1:50 000], sheets Goeree-Overflakkee 43 West, Zeeuws-Vlaanderen 54/44 East and West, Schouwen-Duivenland 42 East and West, Willemstad 43 Oost, Walcheren 48 West and Beveland 48 East (Rijks Geologische Dienst, resp. 1964, 1965, 1970, 1971, 1972 en 1978).

The geological history of each period is described in chronological order in the context of the different tectonic phases that affected the map sheet area and the surrounding areas (fig. 1.5). During the Early Palaeozoic, these phases were the Ardennian and Acadian phases, both characterised by compressional

Figure 15.1 Locations of the continents and oceans during the Ordovician, Permian and Middle Cretaceous (after Scotese, 1991; Scotese & McKerrow, 1990). The middle picture shows (between brackets) the names of the elements that made up Pangaea.



stress fields. These phases resulted in the consolidation of the Brabant Massif. During the Late Carboniferous and earliest Permian, the Variscan mountain belts to the south and east of the map sheet area were formed during the Variscan Orogeny. During these tectonic phases, the broad outlines of the regional structural framework evolved. The Late Triassic to earliest Cretaceous period was characterised by the Kimmerian extensional tectonic phases, which were related to the break-up of Pangaea and were responsible for the formation of major Mesozoic structural units, such as the West Netherlands Basin. The Sub-Hercynian phase during the Late Cretaceous was characterised by a compressional stress field, causing a brief inversion of the direction of movement of the major fault systems and structural elements. The Tertiary tectonic phases (Laramide, Pyrenean and Savian phases) were associated with the opening of the Atlantic Ocean and the Alpine Orogeny. The geology of the map sheet area was not shaped by tectonics only, but also by climate changes and associated sea-level fluctuations (Haq et al., 1987).

Figure 15.2 shows the geographical position of the map sheet area in a regional context. The principal structural elements discussed in this chapter are outlined in figure 3.1.

15.2 Basin development, sedimentation and tectonics

15.2.1 Cambro-Silurian

During the Early Palaeozoic, the map sheet area was situated on the micro-continent Avalonia (fig. 15.1). The collision of Avalonia with Baltica at the end of the Ordovician resulted in the Ardennian phase of the Caledonian Orogeny, initiating folding and uplift of the Cambro-Ordovician Ardennes Basin (Wouters & Vandenberghe, 1994; De Vos, 1998). To the north of this uplifted area, the Brabant Depression developed, as a foredeep, in which deep-marine sediments were deposited by turbidity currents (Verniers & Van Grootel, 1991). Continuing plate movement closed the Iapetus Ocean and merged Laurentia-Greenland and Fennoscandia-Baltica into a single continent, Laurussia (Ziegler, 1989). This was associated with further Late Caledonian deformation. The Acadian phase in the Early Devonian resulted in folding and uplift of the Brabant Depression creating the Brabant Massif (Van Grootel et al., 1997; De Vos, 1998; Verniers et al., 2002). In the north-west, the incipient Cadomian (Precambrian) Midland microcraton became attached to the Brabant Massif (Ziegler, 1990). Together, they formed the London-Brabant Massif, which was to play an important role in the subsequent geological development of the Netherlands, Belgium and the southern North Sea.

15.2.2 Devonian

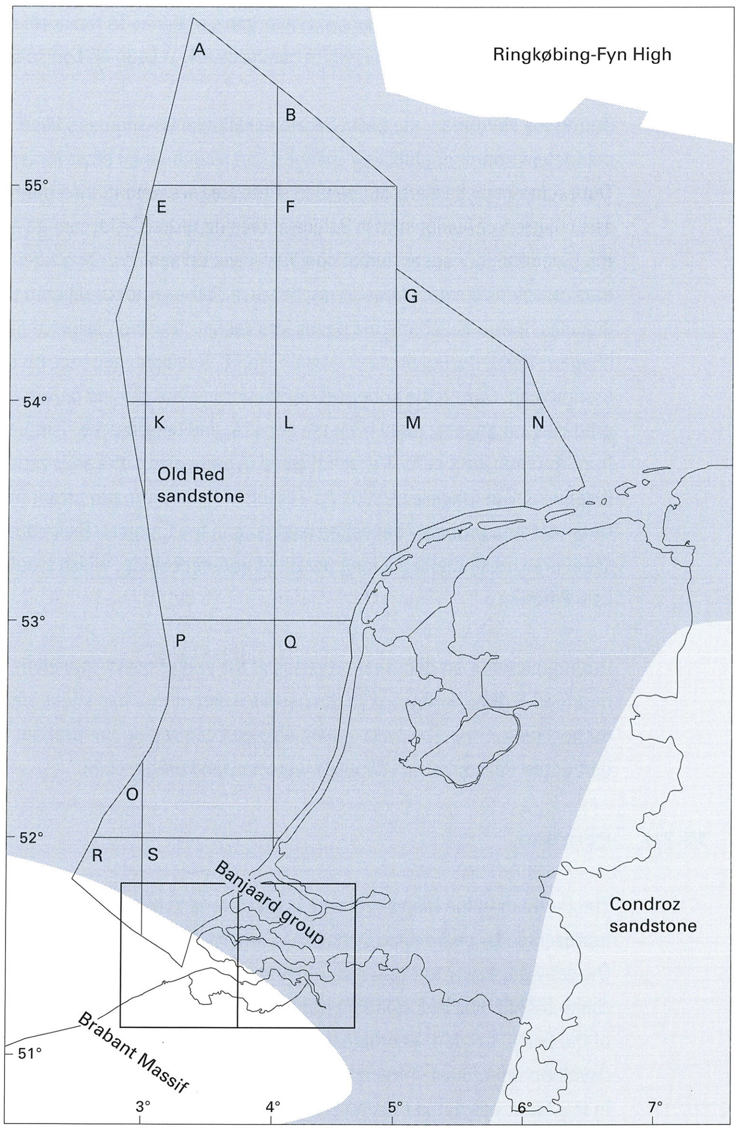
During the Caledonian Orogeny, a vast landmass, which is known as the *Old Red Continent*, was formed in the present-day North Sea region. During the Early Devonian, a regime of extensional stresses in a back-arc position, initiated the formation of a large basin in Central Europe, the Rhenohercynian Basin (Ziegler, 1990). Increased subsidence and cyclic sea-level rises expanded the area of marine sedimentation during the Middle and early Late Devonian.

During the Devonian, the map sheet area was situated on the northern side of the Brabant Massif. During the youngest Middle Devonian (Givetian), conglomerate was deposited in grabens or half-grabens (Muchez & Langenaeker, 1993) in the precursor of the Campine Basin. A major transgression occurred during the Frasnian (earliest Late Devonian). On and to the north of the Brabant Massif, clays and limestones were deposited (Ribbert, 1998). A fall in sea level at the beginning of the Famennian (Kimpe et al., 1978) terminated carbonate sedimentation. East of the map sheet area, sands of the Condroz Sandstone were deposited in a shallow-marine environment (fig. 15.2).

15.2.3 Carboniferous

Geological developments in the map sheet area were largely dominated by the Variscan Orogeny. The main phase of this orogeny took place during the Late Carboniferous: the collision of Gondwana and Laurussia created the supercontinent Pangaea, the contours of which are shown in figure 15.1b. The first contact with Laurussia occurred at the end of the Devonian (Wouters & Vandenberghe, 1994), heralding the Variscan Orogeny. In this orogeny, three orogenic deformation phases can be identified in North-West Europe: the Bretonian, Sudetian and Asturian tectonic phases, in the course of which the deformation front migrated progressively further to the north. This was reflected in the northward migration of the depo-centres, from the Ruhr Basin to the east of the map sheet area during the Namurian and oldest Westphalian into the Campine Basin in the the northern part of the map sheet area during the youngest Westphalian and Stephanian (Drozdzewski, 1992).

Figure 15.2 Facies distribution during the Late Devonian.
The location of the map sheet area is outlined.



In the vicinity of the Brabant Massif, the first phase of the Variscan Orogeny, the Bretonian phase, only caused minor local uplifts and hiatuses in the sedimentary succession. During the Early Carboniferous, a further rise in the sea level drastically reduced the influx of clastic material. Around the Brabant Massif, a vast carbonate platform of several hundred meters thick developed. Minor cyclic sea-level fluctuations resulted in temporary emergence and karstification. North of the map sheet area, the carbonate platform gradually gave way to deeper water (Ziegler, 1990).

The Sudetian phase of the Variscan Orogeny occurred at the beginning of the Late Carboniferous. The N-S-oriented compressional stress field initiated the development of an E-W trending mountain belt extending throughout Europe. In isostatic response to this load, the foreland basin to the north of this mountain chain deepened. This basin included the Ruhr Basin and extended westwards into the Campine Basin. The Brabant Massif was also part of this basin (Drozdzewski & Zeller, 1998). The orientation of the Campine Basin is controlled by the structure of the Brabant Massif, which was a rigid element on the southern margin of the foreland basin (fig. 15.3). In this basin, the erosion products from the Rhenohercynian mountain chain were deposited. Initially, during the Namurian, these consisted of marine clays, rich in organic material. To the north of the Brabant Massif, the Campine Basin became rapidly deeper, which can be clearly recognised on seismic sections (fig. 15.6).

During the Namurian, the basin became shallower having been filled by clastic sediments, and the marine environment gradually changed into a continental environment (Langenaeker & Dusar, 1992). The sediment was clearly supplied by a provenance area to the south. During the Westphalian A, B and early C, predominantly lacustrine clays were deposited, alternating with deltaic and fluvial sands and massive peat sequences, which coalified into coal seams during later burial. Episodically, ephemeral transgressions covered large areas, because of the very low relief in the basin (fig. 6.1). The resulting deposits, the so-called marine bands, are seen as the expression of glacio-eustatic sea level rises (Ziegler, 1990). During the later Westphalian C, fluviatile influence on sedimentation became even more pronounced. During the youngest Carboniferous, the climate became drier because the area drifted gradually northward, away from the equator, and because the rising mountain chains shielded the area from the monsoon rains. This is reflected in particular in the soils represented in the succession (Pagnier & Van Tongeren, 1996). As a result of the deformation front migrating northward, little or no sediment was probably deposited any more in the Campine Basin during the Stephanian. In the map sheet area, this heralded a long period of non-deposition, which would continue well into the Late Permian.

During the Asturian deformation phase at the end of the Westphalian, the Variscan orogenic front migrated further northward. In the northern part of the map sheet area, a northerly dipping, faulted, monocline formed. The most severe erosion occurred on the Brabant Massif, from which the major part of the Carboniferous deposits were stripped off (fig 15.6).

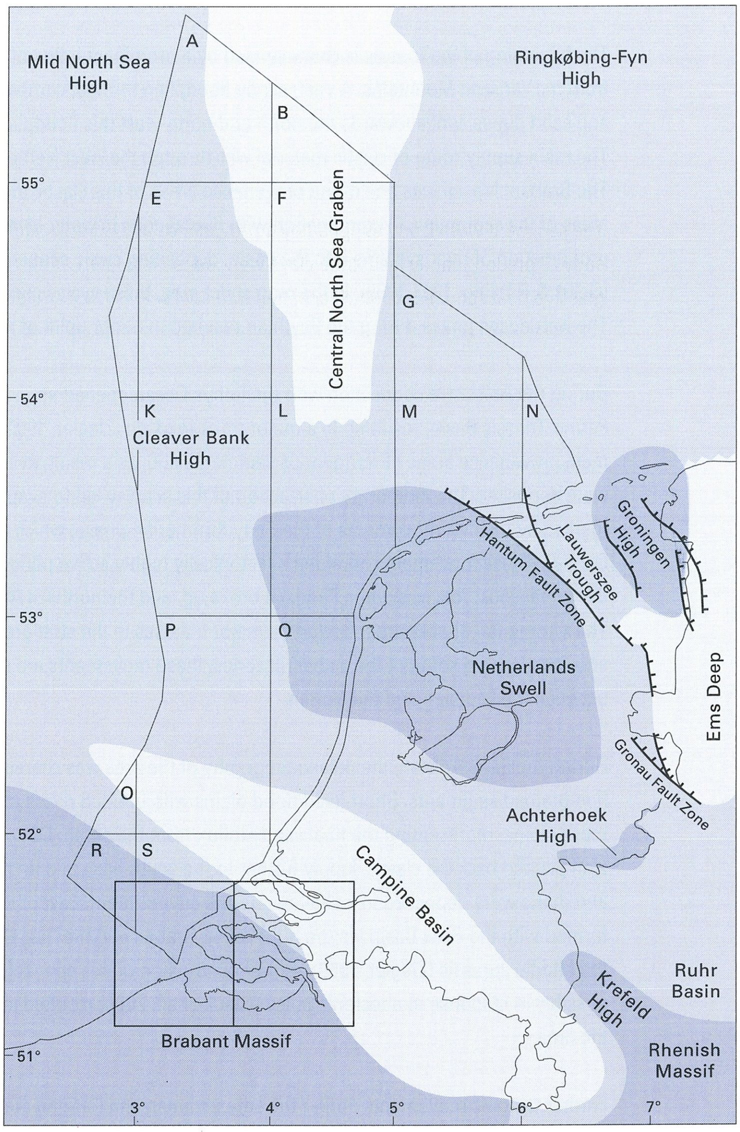
15.2.4 Permian

The Permian in the map sheet area is characterised by a large hiatus; only the youngest Permian is represented by sediments. During the Early Permian, the compressional stress fields of the Variscan Orogeny gave way to east-west trending extensional stresses. To the north of the Variscan mountain chain, NW-SE and W-E trending transverse wrench fault systems developed (Ziegler, 1990). At the end of the Early Permian, a combination of extensional stresses and cooling of volcanic rocks led to the development of vast, intracratonic, continental basins: the Northern and the Southern Permian Basins. In this latter basin, the erosion products originating from the Variscan Mountains were deposited in a continental environment. The oldest sediments in this basin have been penetrated in North-East

Germany, from where the sedimentation area expanded to the west and south during the Late Permian (Plein, 1995). During the hiatus that spans the entire Early Permian and the oldest part of the Late Permian, a number of tectonic pulses occurred: the Saalian and the Altmark I, II and III pulses (Plein, 1995). These pulses together resulted in the unconformity at the base of the Upper Rotliegend Group. Only the youngest sediments of this group, conglomerates and sands transported by wadis, have been deposited in the map sheet area. In depressions in the northern part of the map sheet area, aeolian sands accumulated.

Graben development in the North Atlantic and Arctic region, combined with a eustatic sea level rise as a result of the melting of the Gondwana ice cap (Ziegler, 1990), opened up a new seaway between the present-day Barentsz Sea area in the north and the intracratonic Northern and Southern Permian Basins.

Figure 15.3 Overview map showing the main structural elements in the Netherlands during the Late Carboniferous. The location of the map sheet area is outlined.



The basins had subsided to below the palaeo sea level, and the transgression by Arctic waters was therefore very rapid indeed (Glennie, 1998). A large inland sea formed, in which cycles of carbonates and evaporites were deposited, as a result of a combination of the arid climate on the one hand and a variable influx of seawater from the Arctic area on the other. Major transgressions mark the bases of the different cycles. Owing to the position of the map sheet area, on the edge of this inland sea, only an incomplete succession was deposited here, consisting predominantly of clastics.

15.2.5 Triassic

The Triassic was characterised initially by extremely uniform basin subsidence. The Southern Permian Basin basically persisted and is therefore often referred to as the Permo-Triassic Basin. The area of sedimentation extended southwards. The Triassic is characterised by two phases of extensional tectonics (Ziegler, 1990), associated with the break-up of the supercontinent Pangaea. Because the map sheet area was located at the edge of this basin, the local effects were minimal.

The beginning of the Triassic is characterised by a prominent influx of clastic material, originating from the Variscan Mountains. A vast, sandy floodplain formed, comprising a combination of wadis and sand dunes, while towards the north and north-west this floodplain graded into a playa lake. The main supply route of clastic material was through the West Netherlands Basin (Geluk et al., 1996). The Brabant Massif was one of the provenance areas of this clastic material. Uplift of the provenance areas of the sediments, in combination with fluctuations in water level in the basin, resulted in episodic progradation of river systems into the basin, depositing cyclic sequences of sand and clay/silt (Geluk & Röhling, 1997, 1999). In the map sheet area, these cycles consist mainly of sands. The Hardegsen phase during the Scythian resulted in minor uplift of the West Netherlands Basin.

During the Anisian, a connection with the Tethys Ocean opened up in the eastern part of the Permo-Triassic Basin, resulting in a major transgression (Ziegler, 1990). This transgression flooded the main provenance areas of terrigenous sediments and, as a result; eventually only carbonates and marls were deposited. The temporary obstruction of this seaway led to evaporite deposition. The Anisian was marked by the first movements of the Early Kimmerian phase, which would culminate during the Carnian. These movements heralded a tectonically highly active period, which was to continue well into the Cretaceous. This was when Pangaea broke up, and the northern Atlantic Ocean started to open up. The Kimmerian phases are reflected by major hiatuses in the stratigraphic succession. As the map sheet area was located south of the active rift zones, these movements are reflected only in a marked hiatus between the Ladinian and the Norian.

During the Early Anisian, the palaeogeography of the area was characterised by vast plains with fine-grained sediments. Short-lived flood plains with braided rivers and sand dunes spread across these plains, representing the final sandy influx from the south. During the Late Anisian, the transgression pushed back the clastic supply further to the south-east, and in the map sheet area, limestones and marls were deposited in a shallow-marine environment. East of the map sheet area, a connection formed with the Paris Basin via the Ruhr Valley Graben and the Trier Graben, which was to persist until the Middle Jurassic (Ziegler, 1990). A brief obstruction of this connection with the Tethys Ocean, possibly in response to a tectonic pulse (Geluk et al., 2000) resulted in anhydrite deposition throughout the area.

Further tectonic movements during the Late Ladinian and Carnian are difficult to reconstruct owing to the absence of sediments. However, during the Norian, tectonic activity decreased sharply and sedimentation resumed. The deposits of the Red Keuper Claystone and the Dolomitic Keuper Members mark the

Early Kimmerian unconformity. During the Rhaetian, a conspicuous transgression heralded a long period of marine sedimentation that was to continue well into the Middle Jurassic.

15.2.6 Jurassic

During the Jurassic, the regional subsidence of a large part of northern Europe, which had started at the end of the Triassic, initially continued. A connection with the Arctic Sea was established via the North Sea rift system, which, in combination with a sea-level rise, resulted in deposition of fine-grained marine sediments. These deposits, of Early and earliest Middle Jurassic age, were deposited in a single, vast, continuous basin, encompassing the area of both the Permo-Triassic Basin and the Paris Basin. This can be inferred from the uniform and fine-grained character of the deposits. The Brabant Massif was also covered by the sea at that time. During the Hettangian to Pliensbachian, clays and silts were deposited in an open-marine environment, below wave base. Some stagnation in the circulation in the basin resulted in euxinic depositional conditions.

During the Toarcian, a period of stagnation affected the marine basin, presumably owing to a thermo-haline stratification of the water (Ziegler, 1990), causing deposition of the bituminous clays of the Posidonia Shale Formation in large parts of North-West Europe. During the Middle Jurassic, the circulation in the basin was restored and during the Aalenian to Bajocian, clays and sands were deposited in a marine environment. These sands are probably related to the Mid-Kimmerian uplift of the highs (Brabant Massif, Rhenish Massif) surrounding the basin. During the Bathonian to earliest Oxfordian, limestones, marls and clays were deposited in a shallow marine environment. The excellent correlatability of these deposits with those in the Sole Pit Basin reveals that sedimentation essentially occurred in a large sea embracing the Sole Pit Basin, the West Netherlands Basin, the Central Netherlands Basin, the Ruhr Valley Graben and the Paris Basin. Sedimentation ceased when the area fell dry as a result of a regression (Gianolla & Jacquin, 1998).

The Late Jurassic is a period characterised by major tectonic events: the Late Kimmerian phase, with a primary pulse occurring at the onset of the Late Jurassic, and a second at the Ryazanian-Valanginian boundary in the earliest Cretaceous (=Late Kimmerian I and II; Rijks Geologische Dienst, 1991). Extension of the crust under the graben was accommodated by transtensional, dextral wrench fault movements along a system of reactivated NW-SE-striking fault systems. This initiated a further structural modification of the West Netherlands Basin.

The Late Kimmerian rift phases caused significant uplift of the areas on the edges of the rifts as well as of the Brabant Massif (Vercoutere & van den Haute, 1993). Deep-cutting erosion also affected the Zeeland Platform. During the Kimmeridgian, transtensional movements triggered the formation of small rift basins in the north and north-west of the map sheet area, where thick sequences of fluvial sands and lacustrine clays were deposited. During the Portlandian, differential subsidence diminished and sedimentation expanded from these basins and spread further across the area.

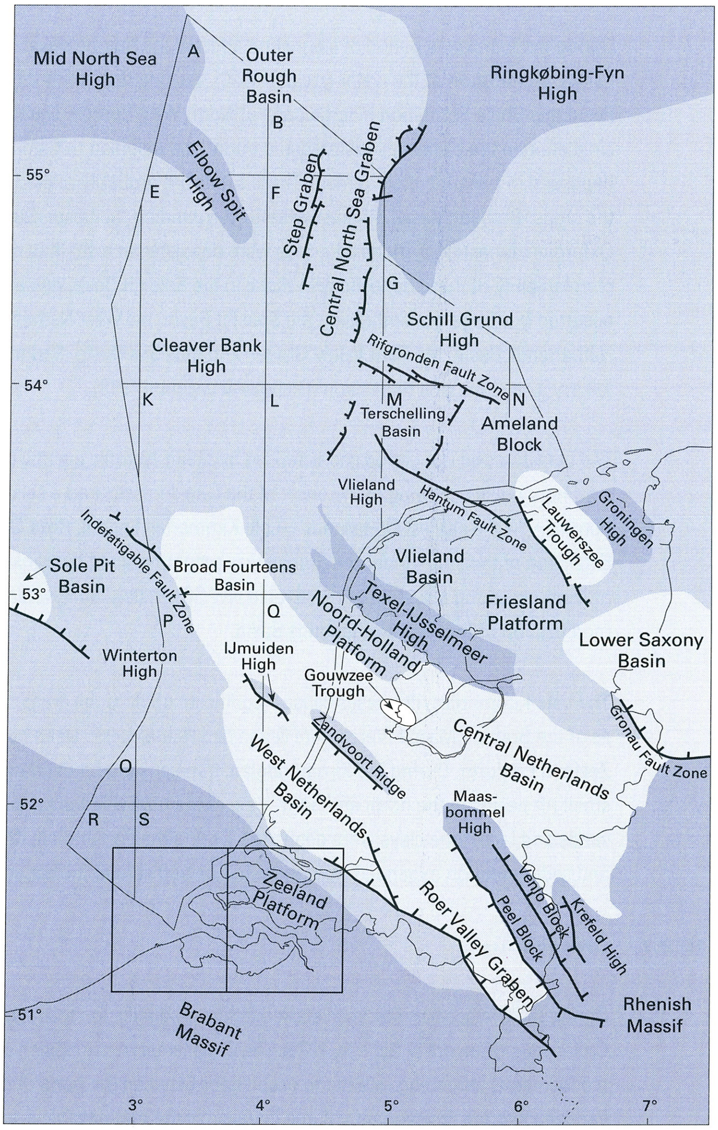
15.2.7 Cretaceous

During the Cretaceous, sea level started to rise gradually, to reach a maximum high stand in the Late Cretaceous (Hancock & Scholle, 1975). The Cretaceous transgression presumably occurred in response to the increased spreading rate of the ocean floor between the parts of the broken-up supercontinent Pangaea and the consequent volume increase of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979).

The second pulse of the Late Kimmerian phase accentuated the highs around the basins during the Valanginian as well as other regional uplifts in North-West Europe. In the map sheet area, the Zeeland Platform was uplifted significantly. After that, differential tectonic movement decreased.

During the Cretaceous, the map sheet area was situated on the southern perimeter of the West Netherlands Basin. A transgression approached from the north, but it only reached the northern part of the map sheet area by the Barremian. During the Aptian, a brief regression occurred, coinciding with the Austrian tectonic pulse (Ziegler, 1990), which resulted in the deposition of greensands along the margins of the West and Central Netherlands Basins. During the Albian, the transgression spread more widely owing to a significant sea-level rise (Crittenden, 1987).

Figure 15.4 Overview map showing the main structural elements in the Netherlands during the Late Jurassic to Early Cretaceous. The location of the map sheet area is outlined.



During the Late Cretaceous, the transgression advanced further. Consequently, the distance between the map sheet area and the provenance areas of clastics increased, and, moreover, the provenance areas decreased in size. The period of regional subsidence came to an end during the Coniacian. Europe went through a major plate reorganisation (fig. 15.1c) induced by an extensional stress regime and graben formation associated with the sea-floor spreading in the Arctic and northern Atlantic Oceans (Coward, 1991), the incipient collision of Africa and Europe (Ziegler, 1990) as well as a number of local factors (Baldschuhn et al., 1991). This initiated a compressional tectonic regime. During the Coniacian to Early Campanian, this led to a reversal in the direction of movement along faults, which in turn resulted in inversion of the former Upper Jurassic/Lower Cretaceous basins in the area and pronounced subsidence of the former highs. This inversion occurred in a series of pulses: the Sub-Hercynian pulse during the Santonian and Campanian, the Laramide pulse at the beginning of the Tertiary and the Pyrenean pulse at the end of the Eocene, the latter two being marked by after-movements of the inverted basin, which were, however, not accompanied by any significant faulting.

The inversion of the West Netherlands Basin occurred in the Santonian and Early Campanian (Kuyl, 1983; Bless et al., 1987; Gras & Geluk, 1999). During this period, the non-uplifted areas surrounding the former basin started to subside significantly. The inverted basins became a divide between the now subsiding former highs and started to act as sediment sources. During the Santonian, the sea spread over the adjacent areas and in the map sheet area marine greensands were deposited. During the Campanian, the proportion of the Brabant Massif that was covered by the sea increased.

15.2.8 Cenozoic

During the Cenozoic, the Atlantic Ocean continued to open up. The sea between Norway and Greenland was formed and graben formation in the North Sea area ceased. On the other hand, the collision of the Eurasian and the African lithosphere plates continued, reflected in the main Alpine Orogeny. This resulted in a NW-oriented compressional stress field.

Initially, during the Early Palaeocene, chalk deposition continued. After the Laramide tectonic phase at the start of the Late Palaeocene, which was accompanied by a significant fall in sea level, the North Sea Basin formed. The widespread carbonate sedimentation came to an abrupt end. Only in the north of the map sheet area did the tectonic phase cause any after-movements in the inverted basins. These movements, which occurred virtually without any fault activity, culminated in the erosion of the post-inversion deposits of the Chalk Group in the Central and West Netherlands Basins. In the Palaeocene and the Early Eocene, the North Sea Basin was still connected to the Paris Basin, but this seaway became blocked by the uplift of the Artois Axis (Ziegler, 1990).

During the Late Palaeocene, lacustrine and lagoonal sediments were initially deposited. The expanding transgression subsequently deposited marine sands, clays and marls. At the end of the Eocene, the Pyrenean tectonic phase caused the uplift of a NW-SE-trending zone in the centre and south-east of the Netherlands, referred to as the Southern Early Tertiary High in Van Adrichem Boogaert & Kouwe (1993-1997). This was followed by the Eocene sedimentary cycle, during which the marine sands and clays of the Dongen Formation were deposited. The Pyrenean tectonic phase caused hardly any erosion in the map sheet area. Simultaneous with the after-movements in the West Netherlands Basin, a subsiding area formed along the southern margin of the basin: the Voorne Trough (fig. 3.1c and 15.5).

The Rupel Formation was deposited by the succeeding sedimentary cycle during the latest Eocene and Early Oligocene. Initially, shallow-marine conditions prevailed, which gradually became fully open-marine in most of the map sheet area. There are no indications of differential subsidence of the area and the homogenous lithology of the Rupel Clay indicates deposition in a vast marine basin, the furthest margin of which was probably located in the western part of present-day Zeeuws-Vlaanderen. During the Late Oligocene, no deposition took place; the map sheet area may even have suffered erosion as a result of a fall in sea level.

At the transition of the Oligocene to the Miocene, regional uplift occurred again, related to the Savian phase. A short-lived rise in sea level, followed by a fall, resulted in deposition of only the oldest part of the Breda Formation, while in the south-west and north-east no sediment was deposited at all. The mainly Pliocene sands of the Oosterhout Formation are therefore the only sediments that represent the prograding system that was part of a large-scale NW European coastal system, which continued to build out from the Middle Miocene right up to the Pleistocene in the northern part of the offshore (Bijlsma, 1981; Zagwijn, 1989).

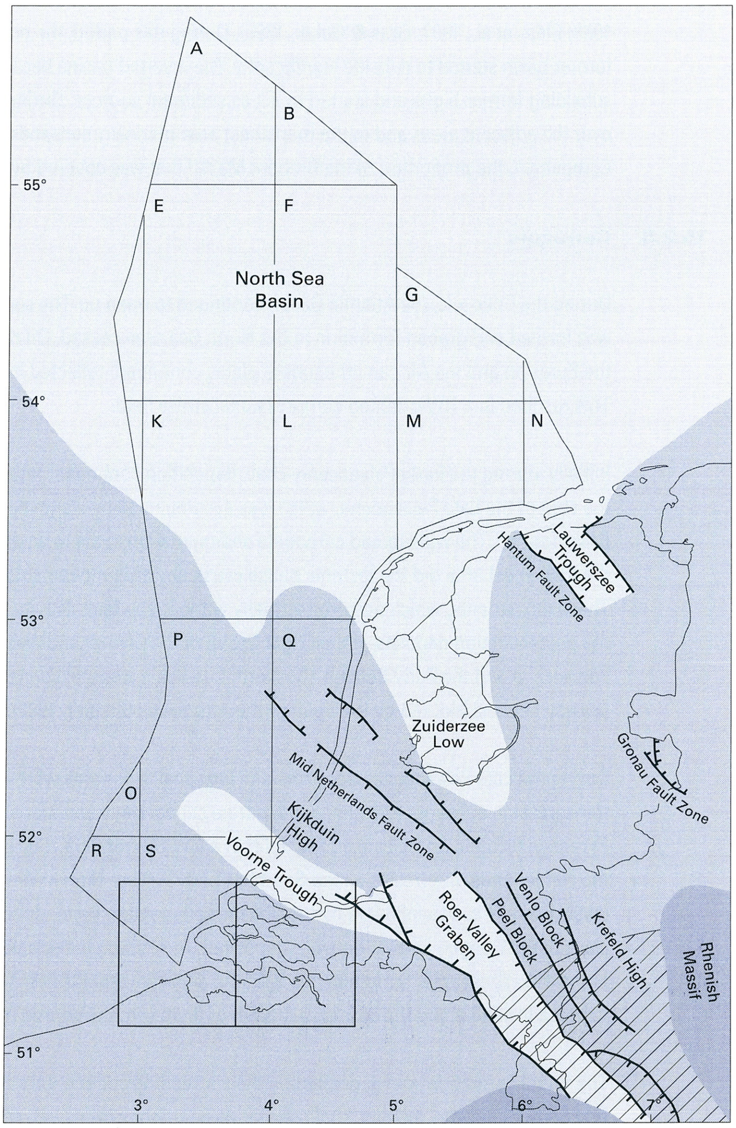


Figure 15.5 Overview map showing the main structural elements in the Netherlands during the Cenozoic. The location of the map sheet area is outlined.

During the Quaternary, when the Maassluis Formation was deposited, marine conditions persisted in the map sheet area, with the exception of the southern part. However, owing to intensified uplift of the hinterland, the later Quaternary deposits are largely continental. This uplift was the reason that the sediments of the Maassluis Formation were partly eroded again.

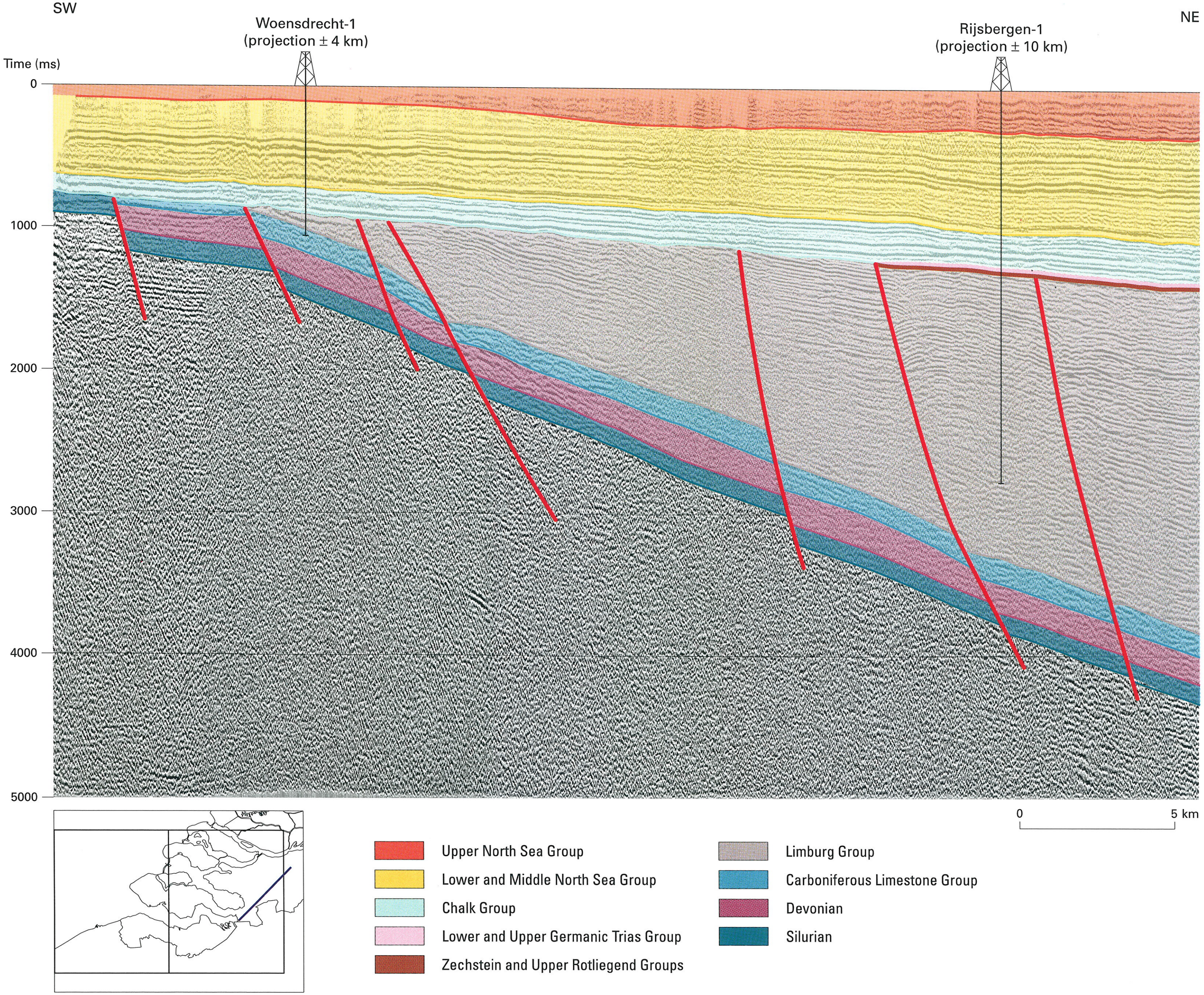


Figure 15.6 SW-NE seismic section across the northern edge of the Brabant Massif and the Zeeland Platform. The section clearly shows the difference between the virtually horizontal Devonian-Silurian deposits on the Brabant Massif and the northerly dipping Carboniferous-Silurian deposits on the Zeeland Platform.

16 Applied geology

16.1 Introduction

In addition to being a source of fossil energy, the subsurface can also be used for other purposes. The possibilities of exploiting geothermal energy (using the heat that is present within the earth) and the potential storage of waste materials in the subsurface have been looked into by various authorities (Novem, 2001; *TNO-NITG, 2001b*). A potential geothermal resource could be the production of warm groundwater or the extraction of energy by circulating surface water to the deeper, warmer parts of the subsurface. The extraction of groundwater and the construction of infrastructure works such as the Westerschelde tunnel are also relevant in the context of this map sheet area. Finally, the karstified Dinantian limestones might offer future possibilities for the exploitation of geothermal energy or for gas storage, as is currently practised at Loenhout, in Belgium, just across the border.

16.2 Hydrocarbons

16.2.1 Introduction

Commercially significant hydrocarbon accumulations are rare in the map sheet area. The main reason is the virtual absence of the prospective Permian and Mesozoic deposits from the map sheet area. Only in the northernmost part of the map sheet area, along the southern margin of the West Netherlands Basin, in the Oud-Beijerland-Zuid and Reedijk gas fields, are hydrocarbon-bearing Triassic structures present. These Triassic structures contain mainly gas, locally associated with minor quantities of oil (De Jager et al., 1996). The main source rocks of the gas are probably the Westphalian coal seams, but recent modelling studies (Van Balen et al., 2000; TNO-NITG, 2002) imply that part of the trapped gas may have been derived from Namurian source rocks. The Triassic gas accumulations are located in tilted fault blocks that formed during the Late Jurassic rifting phase and were further affected by the Late Cretaceous to Middle Tertiary inversion.

In addition to the above-mentioned Triassic gas play in the southern part of the West Netherlands Basin, another potential play concept that is currently being investigated by several major oil companies should be mentioned. We refer to the "pre-Silesian play" which assumes that hydrocarbons, generated from pre-Westphalian source rocks have been trapped in Devonian or Lower and Upper Carboniferous sediments. This model is outlined in section 16.2.2.

The presence of coal-bearing Westphalian deposits in the north-eastern part of the map sheet area might enable the production of coalbed methane in the future. This might be enhanced by injecting CO_2, the CO_2 replacing the coalbed methane. The permeabilities and depths of the Westphalian deposits, however, preclude exploitation in the short term.

16.2.2 Petroleum systems on the Zeeland Platform

Cameron & Ziegler (1997) postulated the concept of a potential petroleum system in the UK quadrant 53 (fig. 16.1). This quadrant comprises the British part of the Zeeland Platform. The concept claims that reservoirs might be formed by structural "traps" in deposits of a Devonian to Westphalian age, which developed as a result of Variscan compression along the northern flank of the Londen-Brabant Massif. This concept assumes that the oil source rocks were of Carboniferous or Devonian age, and had been deposited in basins north of the Massif. The generated hydrocarbons would have been forced out by expulsion during inversion periods.

In Belgium, some traces of oil have actually been encountered north of the London-Brabant Massif (Van Riessen & Vandenberghe, 1996). These authors interpreted a "chocolate-coloured" sandstone interval of Oligocene age as a fossil "oil seepage". Previous studies explained this phenomenon as the result of soil processes. As there are no known (mature) oil source rocks on this part of the Brabant Massif, the authors postulate long-distance migration, following the Pyrenean tectonic phase, from the oil reservoirs located some 100 km to the north in the West Netherlands Basin or from the south-western part of the Netherlands. If indeed, oil did migrate from the south-western parts of the Netherlands towards the flank of the London-Brabant Massif, potential "traps" may have become charged with oil along the way as well (Van Riessen & Vandenberghe, 1996). Such "traps" might then be located in the map sheet area. This could also explain the presence of minor oil shows encountered in the Carbonifeous interval in several wells in the adjoining offshore S quadrant.

The values for coalification at the top of the Carboniferous deposits, as measured in a few wells in the map sheet area, correspond to the onset of what is referred to as the 'oil window' (Table 16.1). This degree of coalification is lower than that at the top of the Carboniferous deposits in the West Netherlands Basin, north of the map sheet area. The difference in degree of coalification is even greater if we take into account the difference in age between the top Carboniferous in the map sheet area (Westphalian B-Early Westphalian C) in comparison with the West Netherlands Basin (Westphalian C and D).

The degrees of coalification of some samples from Carboniferous deposits from various depths from well Overflakkee-1 have been analysed. The coalification trend at this location suggests that gas may have been generated from the coal seams located at a depth of 2000 to 2500 m. The burial history of the deposits encountered in this well, has also been reconstructed and calibrated on the basis of the coalification values measured (vitrinite reflections and Rock Eval T_{max}). This reconstruction (fig. 16.2)

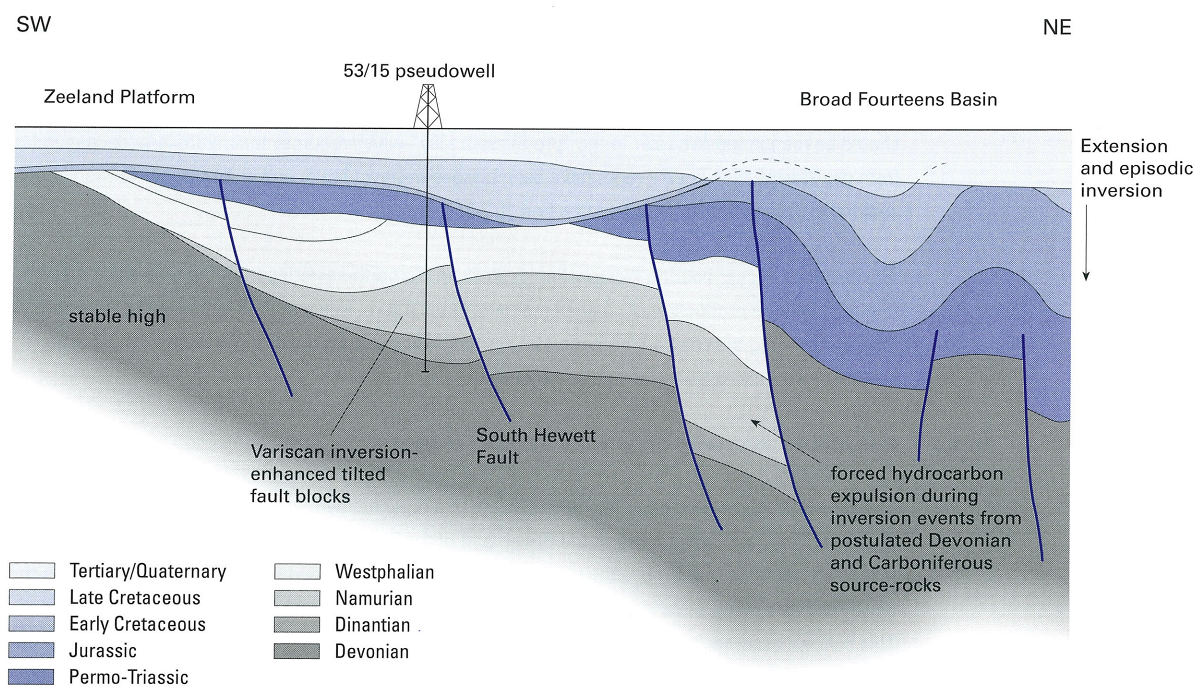


Figure 16.1 'Play concept' on the Zeeland Platform. Palaeozoic-sourced hydrocarbons migrated updip along the northern flank of the London-Brabant Massif during inversion periods (after Cameron & Ziegler, 1997).

assumes that, originally, 500 m of Westphalian C and 500 m Westphalian D sediments had been deposited. These sediments would have been eroded during the Saalian phase at the end of the Carboniferous. Any sediments that may have been deposited during the Permian, Triassic and Jurassic, would have been eroded during the Late Kimmerian tectonic phase. During that same phase, the clayey sediments of the Altena Group (approximately 400 m thick) were also eroded. It is assumed that during the Late Jurassic and Early Cretaceous, no sedimentation took place on the site of well Overflakkee-1. The presence of the Chalk Group indicates that, unlike in the West Netherlands Basin, during the Sub-Hercynian and Laramide phases, erosion was limited. It is assumed that only a thickness of 100 metres has been eroded off from the original succession. During the Early Tertiary the site of well Overflakkee-1 was located close to the centre of the Voorne Trough. This location resulted in deposition of a 1100-m-thick sediment sequence belonging to the North Sea Supergroup.

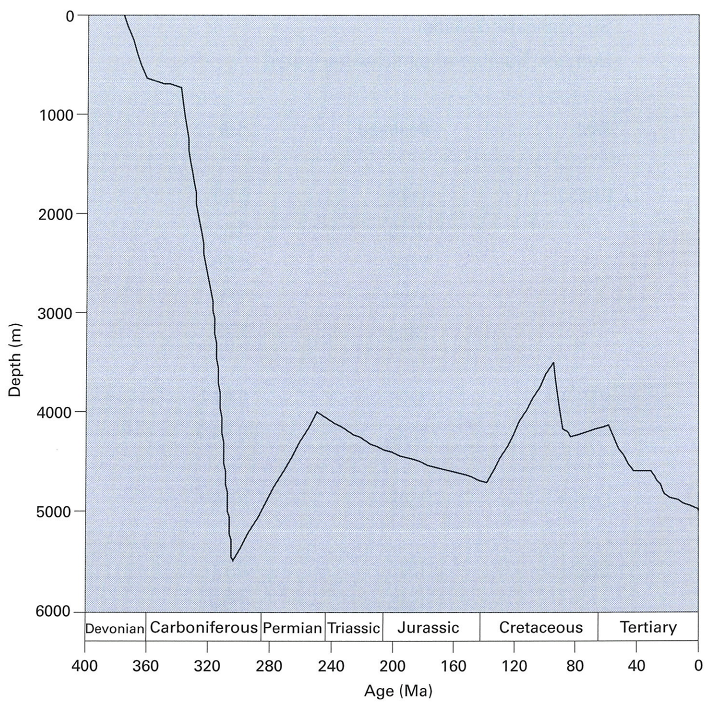
Unlike the equivalent sediments in the West Netherlands Basin, the deposits penetrated in well Overflakkee-1 appear to be at their maximum burial depth.

16.3 Geothermal energy

16.3.1 Introduction

Geothermal energy is a sustainable form of energy, which can be exploited without causing any CO_2 emissions. Geothermal energy can be used to provide space heating, for example in greenhouse complexes and for district heating. An inventory study was conducted for the western part of the map sheet area a few years ago to evaluate the potential of the area for geothermal energy applications. (*TNO-NITG, 2001b*).

Figure 16.2 Burial history of the Limburg Group in well Overflakkee-1.



16.3.2 Aquifers

In the north-eastern part of the map sheet area (southern part of the province of Zuid-Holland), there are some aquifers in Triassic sequences (Main Buntsandstein Subgroup) that might provide suitable conditions for geothermal energy production. These aquifers are located along the south-western boundary of the distribution area of this subgroup. The most suitable areas are those with a temperature exceeding 40 °C, and a heat content of at least $20x10^9$ J/m^2. The map sheet area comprises only 30 km^2 of this type of aquifers in the southernmost part of the province of Zuid-Holland. The Dinantian might also offer some potential, as shown by a pilot project in the Campine Basin in Belgium (Lie Sun Fan & Vandenberghe, 1989; Vandenberghe et al., 2001).

Main Buntsandstein (Triassic)

The top of the Main Buntsandstein Subgroup in the map sheet area is strongly faulted and is found at depths ranging, within a very short distance, from approximately 1700 m to, locally, over 3000 m. The temperature at the top of the Volpriehausen Sandstone Member in the map sheet area ranges from 65 to 70° C at a depth of approximately 1700 m to locally over 100° C at a depth of 3000 m. The total thickness of the Main Buntsandstein Subgroup in the map sheet area is approximately 175 m. Calculated porosity values are around 18% (*TNO-NITG, 2001b*).

Table 16.1 Vitrinite reflection in %Rr in de wells Brouwershavense Gat-1 Strijen-1, Overflakkee-1 en S2-2.

%Rr: Vitrinite reflection in %
SD: Standard deviation
Number: Number of particles measured

Well	*Depth(m)*	*%Rr*	*SD*	*Number*
BHG-1	1478	0.89	0.06	100
	1700	0.86	0.24	100
	2198	0.96	0.19	100
	2398	1.64	0.42	100
	2888	1.73	0.62	100
STR-1	2223	0.59	0.27	100
	2232	0.84	0.33	100
OVE-1	1508	0.76	0.06	100
S2-2	1375	0.71	0.14	100
	1515	1.04	0.13	100
	1810	1.68	0.30	100
	1850	2.04	0.34	100
	2735	1.96	0.32	100

16.3.3 Effects and risks

Interference in the deep subsurface may occur if a geothermal energy exploitation site is located too close to an oil or gas field or near to a gas or CO_2 storage facility. In that case, geothermal energy exploitation could affect the pressure distribution in the oil or gas field or in the storage facility.
There are no known risks related to geothermal energy exploitation. When drilling a well for geothermal energy exploitation, and if there is any chance of striking oil or gas, the same safety procedures should be observed as in drilling an oil or gas well. Geothermal energy exploitation is sustainable and environmentally friendly.

16.4 Hydrogeology

16.4.1 Introduction

Because of their distribution, depths, hydraulic properties and composition of the pore water, the sediments of the North Sea Supergroup that have been deposited since the Eocene should not be overlooked in the hydrogeological explanation of these map sheets. This includes the Quaternary deposits. However, only the Tertiary hydrology will be described in the context of this explanation.
For the stratigraphic and lithological configuration of the Tertiary, please refer to chapter 14 and figures 14.1 and 14.2.

16.4.2 Hydrogeological configuration of the Tertiary

The hydrogeological configuration of the Tertiary in this map sheet area is characterised by three aquifers, separated by aquicludes, which increase in thickness in a NNE direction and dip down under the younger Quaternary deposits (fig. 16.3).

The following hydrogeological units can be distinguished:

- A hydrogeological basis, consisting of clays of the Ieper Member of the Dongen Formation;
- An aquifer that coincides with the Brussels Sand Member;
- An aquiclude formed by the clays of the Asse Member;
- A multi-layered aquifer within the Vessem Member of the Rupel Formation; this aquifer can be subdivided into the Bassevelde Sand Member, the Watervliet Clay Member and the glauconitic Ruisbroek Sand Member;
- An aquiclude formed by the Rupel Clay Member;
- A multi-layered aquifer consisting of deposits of the Breda, Oosterhout and Maassluis Formations.

Aquifers

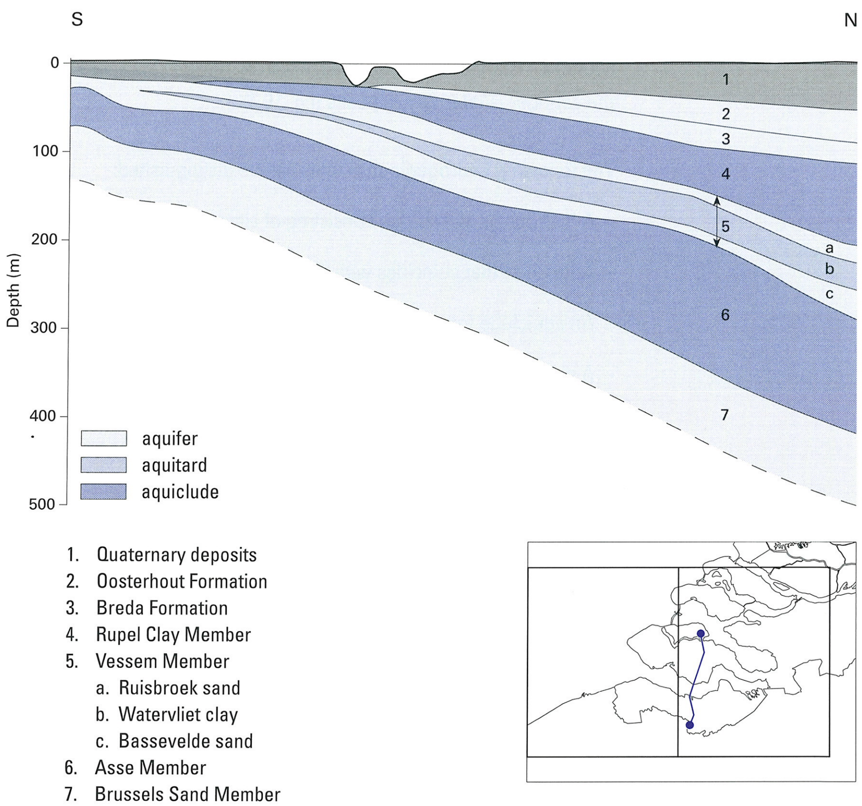
The deposits of the Breda, Oosterhout and Maassluis Formations form the major aquifers in the map sheet area. Especially in the western part of the province of Noord-Brabant, large-scale water extraction takes place from the permeable, shell-rich, deposits of the Oosterhout Formation. The average values for the horizontal permeability of this aquifer range from 3.0 meters/day (m/d) for moderately fine-grained sands, to 40 metres/day for shell deposits, see *TNO-GG, 1990*. In the northern part of the map sheet area and in the province of Zeeland, however, this aquifer frequently contains brackish to salt groundwater and is therefore of minor importance. The area around St. Jansteen is an exception. In the dune areas of

Walcheren and Schouwen-Duiveland, fresh-water lenses have formed till the uppermost part of the aquifer. The aquifer is missing in the southern part of Zuid-Beveland and Walcheren and in the western part of Zeeuws-Vlaanderen. In part of the area, clay layers are present within the aquifer in the top of the Oosterhout Formation, which act as aquitards and protect against pollution. The average values for the vertical permeability of these clays range from 0.002 to 0.011 metres/day (*TNO-GG, 1990*).

Because the shallower aquifers contain so little fresh water, the fine-grained sands of the Vessem Member and the Brussels Sand Member are only of importance in Zeeuws-Vlaanderen, Walcheren and Zuid-Beveland. The Vessem Member forms a multi-layered aquifer, consisting of fine-grained sands, separated by a clay horizon. The sands are moderately permeable. Literature data (Vermoortel, 1994) quote a horizontal permeability ranging from 0.23 to 4.88 m/d. The studies preceding the construction of the Westerschelde tunnel, found vertical permeabilities of $8.9x10^{-4}$ and $2.5x10^{-4}$ m/d (Vermoortel, 1994).
The aquifer is generally overlain by the poorly permeable Rupel Clay Member, which forms an aquiclude. However, near Terneuzen and in the south-western part of Zeeuws-Vlaanderen, this clay layer is absent as a result of later erosion and the aquifer is in direct contact with the overlying Quaternary aquifer.

The aquifer of the Vessem Member is underlain by the aquifer of the Brussels Sand Member from which it is separated by the extremely poorly permeable clays of the Asse Member. The sediments of the Brussels Sand Member are also fine-grained and have a poor permeability. In the literature permeabilities are quoted ranging from 0.6 to 4.25 metres/day (Vermoortel, 1994). The overlying Asse

Figure 16.3 Hydrogeological section across Zeeuws-Vlaanderen and Zuid-Beveland.



Member is only absent in a narrow zone along the Belgian border in the south-western part of Zeeuws-Vlaanderen.

Because of the high hydraulic resistances of both the Rupel Clay Member and the Asse Member, the underlying aquifers of the Vessem Member and the Brussels Sand Member would under natural conditions constitute confined aquifers. In the south-western part of the map sheet area, these aquicludes are missing and, depending on the hydrogeological characteristics of the Quaternary deposits, the aquifers in that area are semi-confined or phreatic.

According to Vermoortel (1994) the infiltration areas of both aquifers are located in Belgium, in the hills near Odelgem-Zomergem and in the southern part of the Land van Waas. The aquifers became partly fresh-water-bearing from a southerly direction. Figure 16.4 shows the chloride content of the aquifer of the Vessem Member. According to Van Camp & Walraevens (1999) these aquifers contain fresh water as far as 30 km away from the infiltration area where the sealing clay layers are absent, most likely owing to conditions prevailing during the youngest Ice Ages.

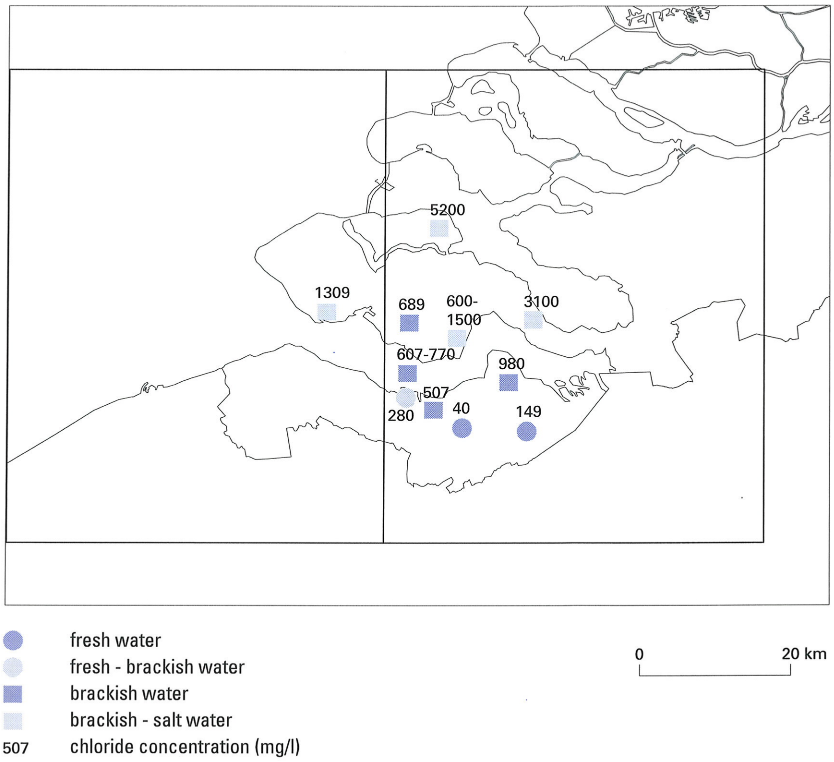


Figure 16.4 Chloride content in the aquifer of the Vessem Member (Bassevelde and Ruisbroek Sands, after Vermoortel & Mahauden, 1996). The hydrochemical classification into main types is taken from Stuyfzand (1986).

16.5 Infrastructure

16.5.1 Introduction

In March 2003, the Westerschelde tunnel was opened. The tunnel forms a permanent bank-to bank connection between Zeeuws-Vlaanderen and Zuid-Beveland. From south to north, the tunnel trajectory runs beneath: the Pas van Terneuzen, the Middelplaat and the Everingen towards the northern bank of the Westerschelde (fig. 16.5). The tunnel has a length of 6.6 km and transects Quaternary sediments and the Tertiary Rupel, Breda and Oosterhout Formations.

Prior to construction of the tunnel, the subsurface was studied in detail by wells, soundings and seismic surveys. This section describes the geology, including the applied engineering-geological studies carried out for the construction of the drilled tunnel and the transverse tunnels connecting the two tubes of the tunnel (Van Beek et al., 1999).

16.5.2 Geology of the Westerschelde

In the subsurface underneath the Westerschelde, the Dongen, Rupel and Breda Formations are unconformably overlain by Quaternary sediments. These sediments dip approximately 2° N, as a result of the regional uplift of the Brabant Massif and subsidence of the North Sea Basin. In the deepest channels of the Westerschelde, deposits of Rupel Clay Member and of the Breda and Oosterhout Formations are being eroded by the tidal currents. In the subsurface of Zuid-Beveland, Pleistocene sediments are also present. The Quaternary tidal deposits consist of marine sands and clays, alternating with peat layers

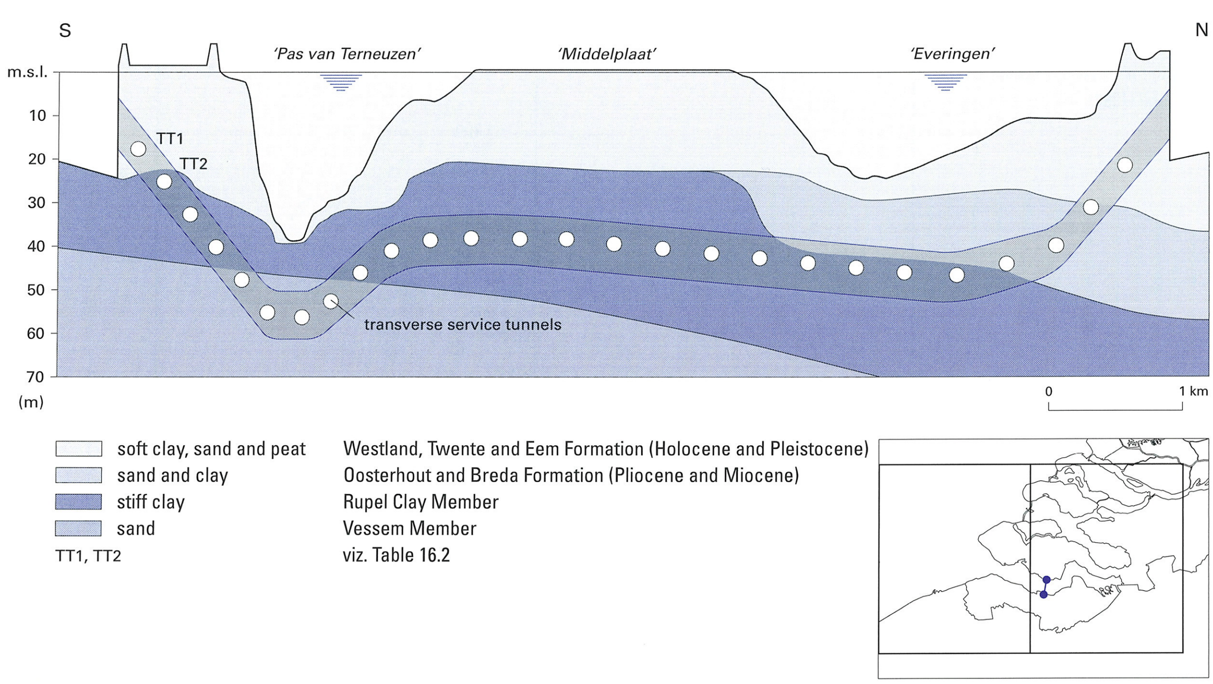


Figure 16.5 Geological cross-section of the Westerschelde tunnel trajectory showing the locations of the 26 transverse tunnels.

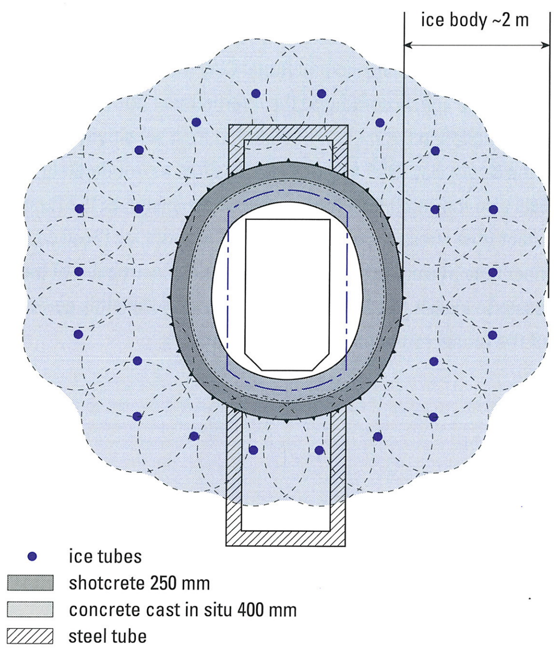
(Fischer, 1997). The Quaternary sequences were deposited during transgressive and regressive sea-level fluctuations, during which Zeeland was flooded regularly. This resulted in the present-day geography of Zeeland, a typical pattern of estuaries and islands.

The studies for the construction of the Westerschelde tunnel yielded a considerable amount of data along the tunnel trajectory. These data include the exact depths of lithostratigraphic units, as well as geological, geotechnical and geohydrological data. The existing knowledge of the geological development of the Holocene sequences in Zeeland is based on the mapping programmes of the Geological Survey of the Netherlands, which were carried out between 1950 and 1990. The Holocene palaeogeographic development is reported in full in Fischer (1997).

16.5.3 Transverse tunnels of the Westerschelde tunnel

The tunnel has a length of 6.6 km and consists of two parallel tubes with two road lanes each. The internal diameter of each tunnel tube is 10.10 m. To ensure safety, transverse tunnels were constructed every 250 m, which serve as escape routes in case of accidents. Construction of the transverse tunnels started from the drilled tunnels by artificially freezing the ground (AGF) enabling underground excavation under atmospheric conditions. The natural (unfrozen) properties of all soil types through which the tunnel had been drilled were considered insufficiently strong to allow open excavation of the transverse tunnels at a depth of 55 m below the bottom of the Westerschelde. The ground was frozen using 22 ice lances through which a brine solution ($CaCl_2$), which had been cooled by a refrigeration unit to approximately –38 °C, was pumped (fig. 16.6). After excavation of the frozen ground, the ceiling, floor and walls of the excavated section were reinforced by spraying concrete and the tunnels were completed by building a concrete support structure.

Figure 16.6 Using AGF (artificial ground freezing) during construction of transverse tunnels by 22 ice lances.



The risk inventory for the design and construction of the transverse tunnels listed the following risks (Rijkers et al., 2002):

- Tunnel deformation: movement of the tunnel segments and failure of the tunnel constructions;
- The frozen ground being insufficiently water-tight;
- Instability and leakage of frozen ground during excavation under normal atmospheric conditions;
- Shrinkage of the subsoil as a result of freezing-thawing consolidation;
- Surface subsidence as a result of the freezing-thawing consolidation of the frozen ground.

Before the first two transverse tunnels (TT1 en TT2) were constructed, extensive laboratory studies analysed the geomechanical behaviour and the expansion of frozen ground (Côté et al, 2000; Rijkers et al., 2000). During construction work of the transverse tunnels, an extensive measuring programme carefully monitored the progress (Rijkers et al., 2002). The two soil types in which TT1 (sand) and TT2 (clay) were excavated, are very different in their geomechanical characteristics, such as plasticity and hydraulic conductivity (Table 16.2). The strength and cone resistance of the Rupel Clay Member is also significantly higher that of the sands of the Westland Formation.

Because a high salt content of the soil could result in insufficient freezing (as a result of the lower freezing point of salt water), the salt content of the Z1 unit (Holocene sand), and the BK1 and BK2 units (Rupel Clay Member) was analysed. The salt content of the permeable Holocene sands on the bottom of the Westerschelde is identical to that of normal seawater. The very low salt content of the (fresh-water) aquifer underneath the Rupel Clay Member (fig. 16.5) was remarkable. Both the tops of BK2 and Z1 contain significant salt concentrations of 2000-13000 Cl^- mg/l. This makes it likely that the (marine) Rupel Clay Member, from which salt was leached away during the Tertiary, became salty again after the Holocene marine flooding of the coastal zone.

De axis of transverse tunnel TT1 is located at a depth of NAP 17.5 m and was constructed in unconsolidated Holocene sand (unit Z1). The axis of transverse tunnel TT2 is located at a depth of NAP 28.7 m and was constructed in overconsolidated Rupel Clay Member, here referred to as Boom clay (units BK1 and BK2) of Oligocene age. According to the international norms of the ISSMFE (International Society Soil Mechanics Foundation Engineering) related to frost sensitivity, Z1 (sand) is classified as "negligible", whereas the Boom clay (BK1 and BK2) is classified as 'moderately to severely' frost sensitive. The laboratory tests also indicated that in case of frost expansion of the Rupel Clay Member, the development of significant frost stress should be taken into account, as these could cause deformation of the (drilled) main tunnel tube (Rijkers et al., 2002). During the construction of the transverse tunnels in clay, frost stresses in excess of 1400 kPa have been measured; this corresponds to a displacement of over 18 mm of the tunnel segments in the main tunnel.

Table 16.2 Geomechanical properties of units of the Westland Formation (Z1), Rupel Clay Member (BK1 and BK2) and Vessem Member (GZ2).

Soil properties	*Unit*	*Z1* *Westland Fm*	*BK1* *Rupel Clay Mb*	*BK2* *Rupel Clay Mb*	*GZ2* *Vessem Mb*
lithology	NEN 5104	fine-grained sand	silty clay	silty clay sandy intercalations	silty fine-grained sand
clay fraction (average)	%	0	81.2	62.2	7.9
sand fraction (average)	%	100	18.8	37.8	92.1
water content	%	22	25.3	23.8	19.4
γ wet	kN/m^3	-	19.4	19.3	19.7
γ dry	kN/m^3	15.5			
porosity p	%		~ 50	~ 50	~ 47
k_v hydraulic conductivity	m/s	1.3E-4 - 1.9E-4	1.5E-9 - 2.4E-11	-0.17 x 10E-9	0.4E-4 - 0.6E-4
W_p plasticity limit	%		30	25	
W_l liquid limit	%		91	76	
I_p plasticity-index	-		61	51	
τ shear strength (torvane)	kN/m^2		~ 220	~ 100	
salinity					
	Cl^- mg/l	3400-6600	2000-13000	< 1000	< 1000
cone resistance	MPa	17 (heart TT1)	4 (heart TT2)		
friction ratio	-	1 - 1.2 (heart TT1)	4 - 5.4 (heart TT2)		
effective (grain)	kPa	170 (heart TT1)	310 (heart TT2)		
waterpressure-hydrostatic	kPa	150 (heart TT1)	290 (heart TT2)		

Appendices

Overview of seismic data used

Survey	*Jaar*	*Eigenaar*	*2D/3D*
7420*	1974	NAM	2D
7490*	1974	NAM	2D
7591*	1975	NAM	2D
7610*	1976	NAM	2D
7920*	1979	NAM	2D
7990*	1979	NAM	2D
7998*	1979	NAM	2D
80*	1980	BGD	2D
8011*	1980	NAM	2D
8111*	1981	NAM	2D
BR81-*	1981	ELF	2D
ANE81-3*	1981	AMC	2D
BR84-*	1984	ELF	2D
8460*	1984	NAM	2D
8462*	1984	NAM	2D
8520*	1985	NAM	2D
8521*	1985	NAM	2D
85H5*	1985	NAM	2D
NNS-*	1985	WGC	2D
8621*	1986	NAM	2D
8726*	1987	NAM	2D
LSC-89-*	1989	BGD	2D
Rotterdam	1985	NAM	3D
Biesbosch	1986	NAM	3D
Oud-Beijerland	1987	NAM	3D
Dordrecht	1988-1990	NAM	3D
Monster-Land	1990-1991	NAM	3D
Mookhoek	1991	NAM	3D

AMC	Amoco Netherlands Petroleum Co
BGD	Belgische Geologische Dienst (Belgian Geologic Survey)
ELF	Elf Petroland B.V.
NAM	Nederlandse Aardolie Maatschappij B.V.
WGC	Western Geophysical Company

Appendix B

Overview of wells used

No.	*Name well*	*Code*	*Owner*	*Total depth (m)*	*Year*
1	Barendrecht-1	BRT-01	NAM	3365	1984
2	Barendrecht-Ziedewij-1	BRTZ-01	NAM	3259	1993
3	Botlek-1	BTL-01	NAM	3290	1984
4	Brouwershavense Gat-1	BHG-01	NAM	2907	1978
5	Hellevoetsluis-1	HVS-01	NAM	3841	1969
6	Kortgene-1	KTG-01	NAM	1900	1982
7	Oud-Beijerland-Zuid-1	OBLZ-01	NAM	2745	1990
8	Overflakkee-1	OVE-01	CHE	1800	1969
9	Pernis-West-1	PRW-01	NAM	3460	1987
10	Reedijk-1	RDK-01	NAM	3053	1992
11	Ridderkerk-32-S3	RKK-32-S3	NAM	3691	1990
12	Rijsbergen-1	RSB-01	NAM	4645	1970
13	Spijkenisse-1	SPK-01	NAM	3276	1960
14	Steenbergen-1	STB-01	NAM	1314	1949
15	Strijen-1	STR-01	AMS	2779	1964
16	Strijen-West-1	STW-01	NAM	3101	1987
17	Woensdrecht-1	WDR-01	ROvD	1205	1912
18	S2-2	S02-02	MOB	2878	1983
19	S5-1	S05-01	NAM	2230	1981
20		42B0006	Delta	138	1912
21		42B0053	RWS	156	1969
22		42D0127	RWS	96	1967
23		42D0146	RWS	116	1976
24		42F0023	RWS	215	1964
25		42F0024	RWS	216	1964
26		42G0022	RWS	165	1964
27		42H0039	RWS	157	1964
28		43D0017	RWS	211	1900
29		48A0126	RWS	64	1982
30		48B0136		114	1981
31		48B0141	PWZ	66	1982
32		48C0081		72	1940
33		48C0105	RWS	38	1957
34		48D0141	RWS	26	1968
35		48D0152	RWS	19	1971
36		48D0274	RWS	63	1991
37		48D0314	RWS	29	1977
38		48D0335	RWS	52	1957
39		48E0135	RWS	74	1967
40		48F0114	RWS	106	1967
41		48G0059	RWS	56	1967
42		48G0060	RWS	59	1967
43		48G0137	RWS	22	1991
44		48G0162	RWS	30	1978
45		48G0192	RWS	47	1994
46		48H0124	RWS	80	1967

No.	Name well	Code	Owner	Total depth (m)	Year
47		48H0216	RWS	62	1981
48		48H0226	RWS	113	1969
49		48H0291	Waterschap	156	1996
50		49B0369	Delta	155	1978
51		49C0115	RWS	240	1985
52		49D0050	RWS	110	1967
53		49E0065	RWS	192	1965
54		49E0301	RGD	211	1997
55		49F0073	RGD	218	1915
56		49F0240	WLM	265	1973
57		49F0378		250	1989
58		49F0435	WLM	235	1997
59		49F0436	RGD	238	1997
60		49G0160	WZWN	95	1979
61		54B0050	RWS	28	1959
62		54E0131	RWS	28	1960
63		54E0144	RGD	27	
64		54E0146	RGD	29	1960
65		54E0285	Waterschap	179	1995
66		54F0066	RWSZ	31	1987
67		55A0206	RGD	28	
68		55A0215	DGV	41	1981
69		55A0340	Waterschap	216	1995

Belgian wells

No.	Name	Total depth (m)	Source
70	Oostende	376	BGD (GeoDoc databank)
71	Oudenburg-Westkerke	267	BGD (GeoDoc databank)
72	Oostkamp	259	BGD (GeoDoc databank)
73	Koolkerke(Brugge)	335	BGD (GeoDoc databank)
74	Beernem(Oedelem)	352	BGD (GeoDoc databank)
75	Knokke	440	Laga & Vandenberghe (1990)
76	Knokke-Zoute	455	BGD (GeoDoc databank)
77	Eeklo	378	BGD (GeoDoc databank)
78	Vinderhoute	266	BGD (GeoDoc databank)
79	Stekene	506	BGD (GeoDoc databank)
80	Hamme	383	BGD (GeoDoc databank)
81	Kessel-bij-Lier-38	704	Bless et al. (1976)
82	Zandhoven-39	851	BGD (GeoDoc databank)
83	Loenhout-Heibaart-129	1638	Legrand (1968), BGD (GeoDoc databank)
84	Beerzel-130	481	Legrand (1968), BGD (GeoDoc databank)
85	Kallo-133	622	Gulinck et al. (1969)
86	Rijkevorsel-204	1600	Distrigaz (DZH18)
87	Rijkevorsel-213	1580	Distrigaz (DZH24)
88	St.Lenaarts-214	1642	Distrigaz

Belgian wells
(used for depth map of the top of the Carboniferous Limestone Group, see figure 5.2)

No.	*Name*	*Total depth (m)*	*Source*
89	Oostmalle-210	1480	Distrigaz (DZH26)
90	Booischot-132	1330	Bless et al. (1976), BGD (GeoDoc Databank)
91	Meer-149	2517	Vandenberghe et al.(1988)
92	Beerse-Merksplas-165	1761	Vandenberghe et al. (2001)
93	Poederlee-170	1137	Langenaeker & Dusar (1992)
94	Rillaar-128	372	Bless et al. (1976), BGD (GeoDoc Databank)
95	Turnhout-120	2706	Delmer (1962), Bless et al. (1976)
96	Loksbergen-127	422	Bless et al. (1976), BGD (GeoDoc Databank)
97	Halen-131	1367	Bless et al. (1976), BGD (GeoDoc Databank)
98	Mol-107	2034	Van Waterschoot van der Gracht (1936), BGD (GeoDoc databank)
99	Leopoldsburg-118	1754	Delmer (1951), Legrand & Tavernier (1950)
100	Zolder-Wijvenheide-86	1912	Stainier (1922)

AMS	American Overseas Petroleum Ltd.
BGD	Belgische Geologische Dienst (Belgian Geological Survey)
CHE	Chevron Oil Company of the Netherlands
MOB	Mobil Producing Netherlands Inc.
NAM	Nederlandse Aardolie Maatschappij B.V.
ROvD	Dienst der Rijksopsporing van Delfstoffen (State Service for the Exploration of Mineral Sources)
Delta	Delta Nutsbedrijven (Delta Public Utilities)
DGV	Dienst Grondwater Verkenning TNO (TNO-DGV Institute of Applied Geoscience)
PWZ	Provinciale Waterstaat Zeeland (Provincial Department of Public Works Zeeland)
RGD	Rijks Geologische Dienst (Geological Survey of the Netherlands)
RWS	Rijks Waterstaat Deltadiensten (State Departement of Public Works section Delta Works)
RWSZ	Rijks Waterstaat Zeeland (State Departement of Public Works section Zeeland)
WLM	Waterleidingsmaatschappij Noord-West Brabant (Waterworks North-West Brabant)
WZWN	Waterleidingsmaatschappij Zuid-West Nederland (Waterworks North-West Netherlands)

Reservoir calculations and averages Lower and Upper Germanic Trias Groups

The calculations and averages reported in the tables below have been calculated for the Lower and Upper Germanic Trias Groups. In addition to a gas zone, a thin oil-bearing horizon is present in well Oud-Beijerland-Zuid-1.

Calculations were carried out and averages were calculated for the gas zone and for the oil zone. The gas zone includes the RNMUL up to and including the RNSOC members with the gas/oil contact at 2270.3 m. The oil zone includes the RNSOB Member and the topmost metres of the RBMH Member with the oil/water contact at 2278.3 m. Since the oil zone is a mere eight metre thick, it is part of the hydrocarbon transition zone where water saturation is still high owing to capillary action.

The following cut-off values were used: clay content Vcl=50%; effective porosity=6%.
The 50% cut-off for the clay content is customary in the industry. De 6% cut-off for the porosity is derived from a cross-plot of core permeabilities, 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 percent)
Vclm = average clay content (in percent)
Swm = average water saturation (in percent) (Hydrocarbon saturation = 100 - Sw)

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

Lower and Upper Germanic Trias Groups

Well	*Unit*			*Reservoir*		
		Gross	*Net*	*Øem*	*Vclm*	*Swm*
OBLZ-1	RNMUL	26.78	21.56	15.7	21.0	36
	RNROY	19.73	14.90	19.3	28.6	19
	RNROF	34.50	34.50	19.9	16.3	21
	RNROL	19.70	15.36	14.1	32.2	40
	RNSOC	6.89	0.98	12.1	38.2	58
	RNSOB	4.92	4.43	15.6	21.3	64
	RBMH	42.32	37.35	21.5	16.8	93
	Total/Average for all units	159.81	129.09	18.7	20.9	50
	Gas zone	108.87	88.09	17.6	22.7	27
	Oil zone	7.98	7.98	19.2	18.0	65

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

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
OBLZ-1	Oil/gas	S	3-Rate well test	2203-2276	Gas	3300	RNROL, RNROF, RNROY

Legend Appendices C and D

Status:
S = suspended

Interval:
Interval in metres log depth

Flow:
Gas, Q50, in 1000 m^3/day

Eenheid:

RNMUL	Lower Muschelkalk Member
RNROY	Upper Röt Fringe Claystone Member
RNROF	Röt Fringe Sandstone Member
RNROL	Lower Röt Fringe Claystone Member
RNSOC	Solling Claystone Member
RNSOB	Basal Solling Sandstone Member
RBMH	Hardegsen Formation

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