Netherlands Institute of Applied Geoscience TNO

Explanation to Map Sheet VI Veendam-Hoogeveen

TNO

Geological Atlas of the Subsurface of The Netherlands

Explanation to Map Sheet VI
Veendam-Hoogeveen

Netherlands Institute of Applied Geoscience TNO - *National Geological Survey*, Utrecht 2000

Geological Atlas of the Subsurface of The Netherlands

Oil production near Schoonebeek.
Courtesy Nederlandse Aardolie Maatschappij B.V.

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The publication of Map Sheet VI by the Netherlands Institute of Applied Geoscience TNO - *National Geological Survey* marks a continuation of the map sheets constituting the Geological Atlas of the Subsurface of The Netherlands.

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

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

The Veendam-Hoogeveen map sheet of the Geological Atlas of the Subsurface of The Netherlands is the eighth sheet to be published in the framework of the systematic mapping of the subsurface of The Netherlands, for which purpose The Netherlands has been divided into 15 map sheets published on a scale of 1:250 000 (see figure 1.1 for an overview of the area of the map sheets). The Annual Report of the TNO-NITG gives an up-to-date overview of the progress of this mapping.

Each map sheet has its own features. This map sheet outlines the geology of the province of Drenthe and parts of Groningen and Friesland. Certain modifications have been made to the layout of the explanation compared with previous map sheets. The text broadly comprises three parts. The first part explains the research set up (Chapter 1), followed by an account of the exploration of mineral and natural resources (Chapter 2) and the structural framework (Chapter 3). The second part consists of a lithostratigraphic description of the rocks (Chapters 4 - 13) and the geological history of the map sheet area (Chapter 14). The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members, which are related to the major structural elements of the map sheet area. Each chapter devotes one section to the depositional environment and the palaeogeography. Finally, additional attention is given to a number of important reservoir rocks (the Limburg Group, the Upper Rotliegend Group, the Z2 and Z3 Carbonate Members, the Lower and Upper Germanic Trias Groups and the Rijnland Group) as well as the gas-source rock in the Limburg Group and the oil-source rock in the Niedersachsen Group.

The geological setting of Map Sheet VI, Veendam-Hoogeveen, is largely determined by the location of the map sheet area on the western margin of the Lower Saxony Basin, an elongated E-W-orientated sedimentary basin extending far into Germany. The Friesland Platform was situated to the west of this basin. This platform and the aforementioned basin developed already during the Triassic. This basin underwent major subsidence, continuing into the Cretaceous. The thicknesses and extent of the older units were not determined by this basin, but by the N-S oriented Ems Low (Maps 1 & 2, Chapter 4-6). The influence of the Lower Saxony Basin on the setting of the map sheet area is clearly indicated in the depth and thickness maps of the Altena, Niedersachsen and Rijnland Groups (Maps 8-13). These maps also clearly demonstrate that the Lower Saxony Basin did not constitute a uniform entity, but was built up of a number of smaller subbasins. This subdivision was strongly affected by the mobility of the underlying Zechstein salt; during the course of geological history, this salt accumulated in a number of structures, even piercing the sediment sequence in some places (Maps 4, 5, 20 & 21). As a result, accumulations of rock salt may be encountered locally in the near surface.

The map sheet area is rich in minerals and natural resources and gas is exploited from many geological zones (Figure 2.2). Underground storage of gas is also conducted in this area. While oil production from the Schoonebeek oil field has for the present, been discontinued, this field still contains potentially exploitable amounts of oil. Efficient and economic exploitation will present a great technological challenge in years to come. In addition to hydrocarbons, in this area rock salt and potassium-magnesium salt are also exploited. The explanation concludes with a chapter focusing specifically on the opportunities for applications afforded by the subsurface of this area in the future (Chapter 15), including the exploitation of thermal energy and thermal water. The subsurface of this area also offers potential for the storage of various substances.

The TNO-NITG anticipates that this map sheet, together with those already published or in progress, will contribute to a greater understanding of the structure and composition of the subsurface of The Netherlands. This is important not only to companies which are active in the fields of exploration and exploitation for mineral and natural resources, but also various governmental institutions and other interested parties.

As well as those people acknowledged in the credit column who are directly responsible for compiling this map sheet, many other employees of the TNO-NITG have been involved, whose efforts are all greatly appreciated. Many thanks are due to the companies which provided exploration data used in this map sheet.

Utrecht, November 2000

1 Research set up

1.1 Extent of the area studied

The map sheet area comprises the southern part of the province Groningen, the province of Drenthe and the northeastern part of the province of Overijssel. The area is bordered by the German federal state of Niedersachsen (fig. 1.1).

1.2 Data base

The mapping of this map sheet area is based mainly on seismic data and well data acquired by industry within the framework of the exploration and exploitation of mineral and natural resources. For mapping purposes, predominant use was made of 3D seismics (fig. 1.2; appendix A). In addition, data from 217 wells were used (fig. 1.3; appendix B).

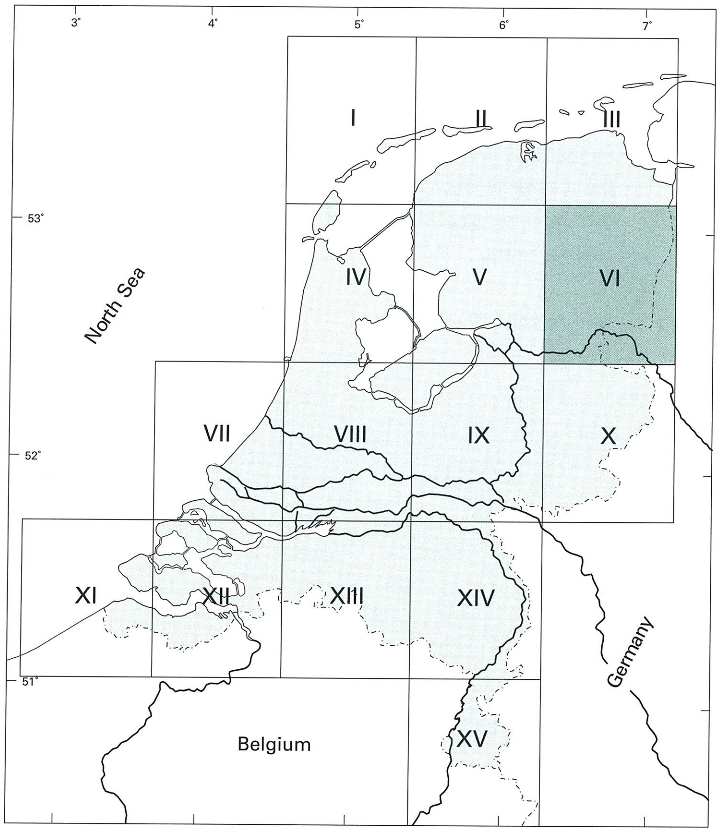


Figure 1.1 Subdivision of the regional map sheet areas of the subsurface of The Netherlands and geographical position of map sheet VI.

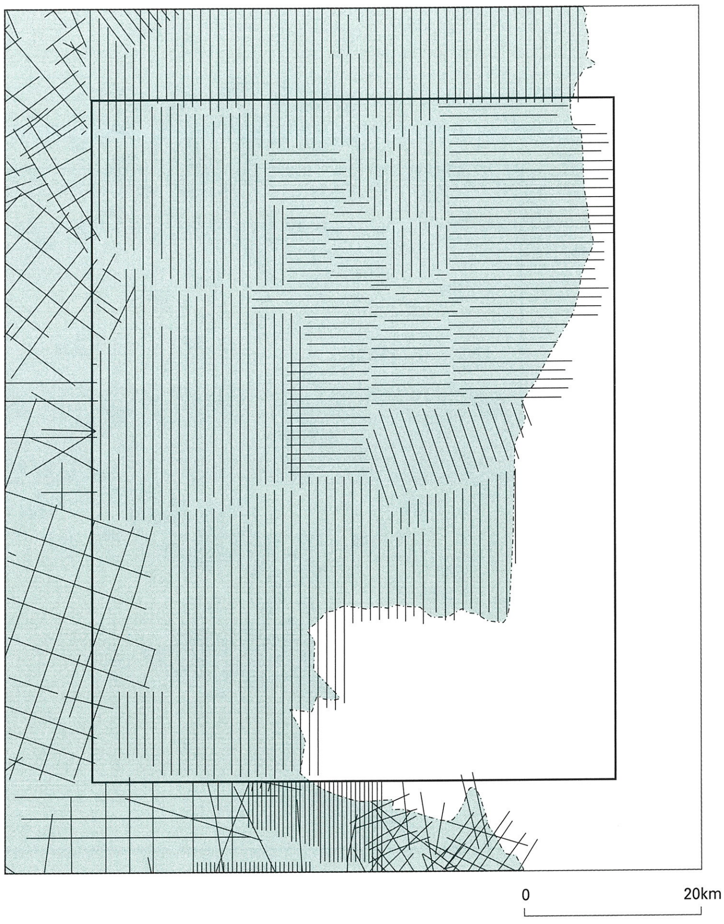
I	Vlieland-Terschelling	IX	Harderwijk-Nijmegen
II	Ameland-Leeuwarden	X	Almelo-Winterswijk
III	Rottumeroog-Groningen	XI	Middelburg-Breskens
IV	Texel-Purmerend	XII	Roosendaal-Terneuzen
V	Sneek-Zwolle	XIII	Breda-Valkenswaard
VI	Veendam-Hoogeveen	XIV	Oss-Roermond
VII	Noordwijk-Rotterdam	XV	Sittard-Maastricht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

1.3 Geological research

The geological research focused on the lithostratigraphic, structural-geological and sedimentological analysis of the rocks present in the map sheet area (fig. 1.4). Seismic sections and well-log data were used, supplemented with data derived from the literature. The most relevant regional-geological publications are those by Betz et al. (1987), Ziegler (1990) and Baldschuhn et al. (1991, 1996, 1999). In order to acquire a better understanding of the geological structure, the area across the German border has also been closely examined.

Unless specifically stated, the nomenclature and age applied conform to the stratigraphic nomenclature (Van Adrichem Boogaert & Kouwe, 1993-1997). Figure 1.5 gives a list of the stage names used by the TNO-NITG occurring in this explanation.

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

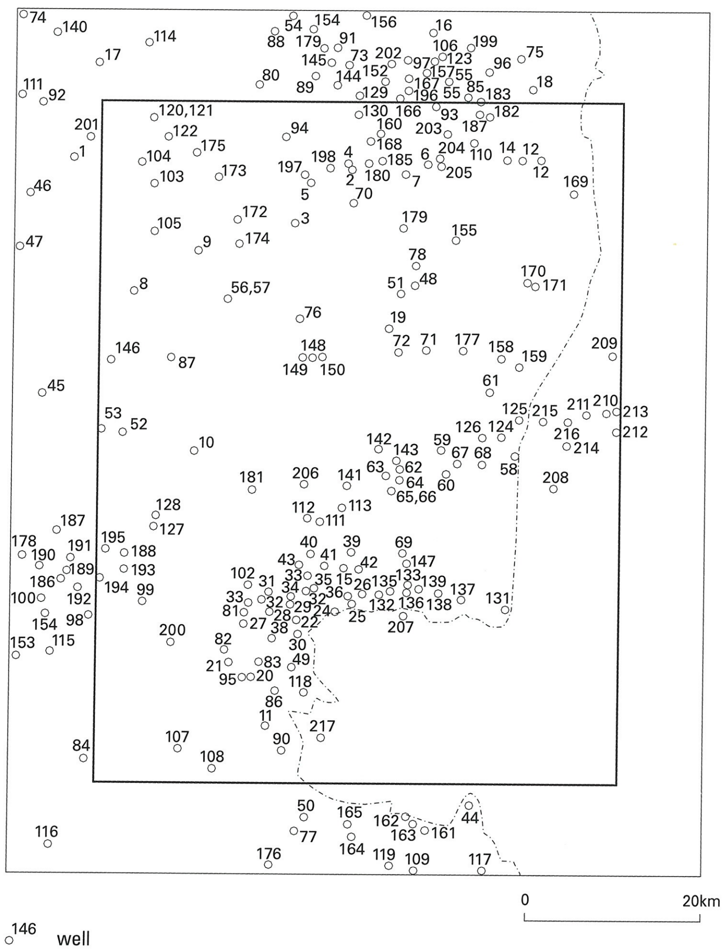


1.4 Seismic mapping

The mapping was carried out mainly with 3D seismics and focused in particular on the structural-geological composition. Over 95% of the map sheet area was covered with 3D-surveys (fig. 1.2; appendix A). In each 3D survey, every fortieth line was interpreted, achieving a seismic coverage of 1 by 1 km. An interpretation was made of a total of approximately 3700 km^2 of 3D seismics in the mapping.

The mapped reflectors form the boundaries between the lithostratigraphic units (groups and formations). Calibration of the seismic data was performed by means of acoustic logs and check-shot surveys. The time-depth conversion of the seismic data was carried out per layer (the so-called layer-cake method). For this, a linear equation between the velocity and the depth of the layer was taken (table 1.1a). In view of the specific lithostratigraphic composition of the Zechstein Group, an exception was made in this case, and a linear equation between the thickness and the time interval was adopted. (table 1.1b).

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



To achieve consistency between the depth maps of adjacent map sheets, a countrywide velocity distribution was made and applied to all the map sheets. The parameters of the regional velocity distribution were determined from the acoustic data from 61 wells located throughout The Netherlands. Application of this velocity distribution resulted in large deviations in the depths of the base of the Altena Group and the Lower Germanic Trias Group. Better results were obtained by taking a modified V_0 and a k for the Altena and Niedersachsen Group. A variable V_0 for the Lower and Upper Germanic Trias Group was applied. The applied velocity distribution is stated in table 1.1.

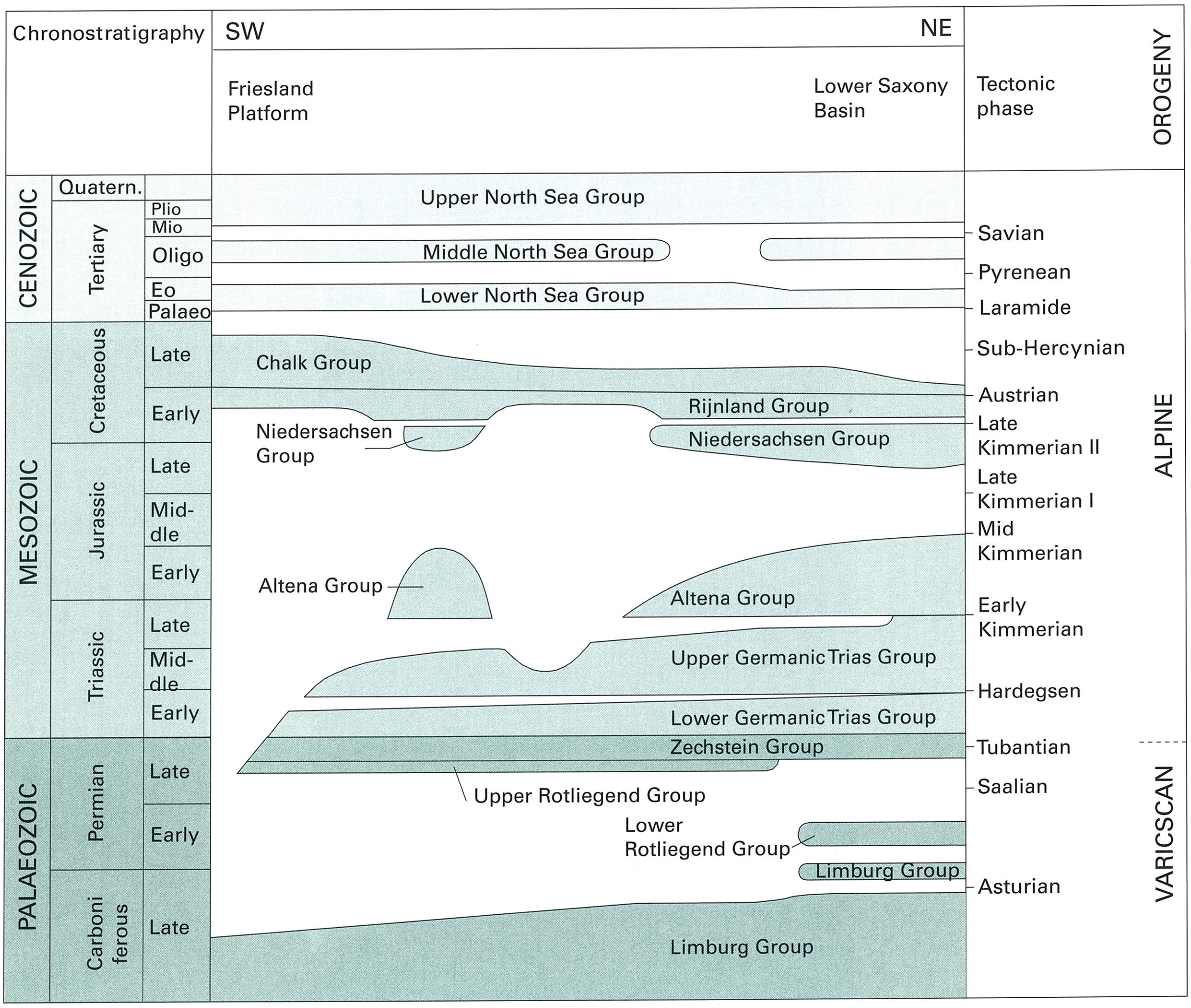


Figure 1.4 Diagram of the lithostratigraphic units and the main tectonic events for the geological development of the map sheet area.

Figure 1.5 Geological timetable as used in the explanation. The tectonic phases which are referred to have been indicated in the figure.

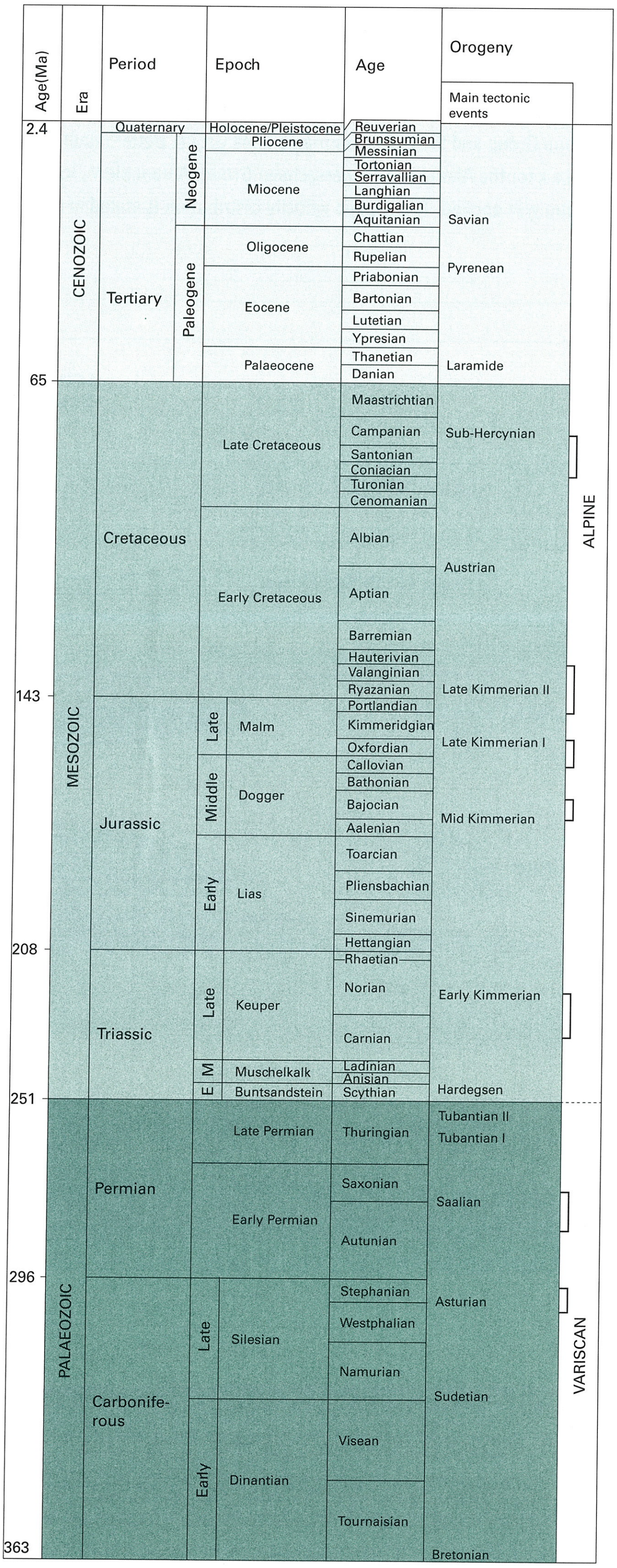


Table 1.1 Applied velocity distribution

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

Unit	V_0	*k*
North Sea Supergroup	1696	0.49
Chalk Group	2092	1.08
Rijnland Group	2020	0.63
Niedersachsen Group	2285	0.57
Altena Group	2093	0.48
Lower and Upper Germanic Trias Groups	2293-2950	0.69

b. The velocity distribution for the Zechstein Group is based on $d = (V_h * \Delta t) + c$
d = thickness (m)
V_h = interval velocity halite (4402 m/s
Δt = time interval Zechstein (s)
c = constant (25.7 m)

1.5 Biostratigraphic research

To clarify the geological research and the geophysical mapping, supplementary micropalaeontological and palynological studies were performed on units of the Limburg, the Altena, the Niedersachsen, the Rijnland and the Chalk Groups. In addition, relevant existing biostratigraphic reports were already available in the case of this map sheet area. The results of these studies have been incorporated in the explanation.

1.6 Petrophysical research

The map sheet area contains a great variety of oil and gas-bearing rocks (see section 2.1.1). Petrophysical research was conducted on the sandstones of the Limburg, the Upper Rotliegend, the Lower Germanic Trias, the Upper Germanic Trias and the Rijnland Groups and all the limestones and dolomites of the Zechstein Group. The petrophysical characteristics were determined from well-log data, from which the porosity, water saturation and hydrocarbon content were calculated. The calculations were calibrated on a basis of core analyses. For the petrophysical evaluation use was made of the single porosity model with the density log as porosity log, with the exception of the Zechstein Group. The gamma-ray log serves as clay indicator.

The evaluation of the Zechstein Group has been carried out with the aid of a complex-lithology-model specially developed for the petrophysical evaluation of limestone/dolomite reservoirs. First, the porosity and the dolomite, carbonate and anhydrite content are derived from log-curve comparisons (density, sonic and neutron). Next, the effective porosity is calculated, followed by the dolomite content and finally, the remaining contents are calculated.

Eight wells of the Limburg Group in the southern part of the map sheet area have been petrophysically evaluated (appendix C). In three of these, the sandstones of the Limburg Group have been found to be gas-bearing (appendix D). This will be discussed in section 4.5.

Reservoir rocks of the Upper Rotliegend Group have been evaluated in thirteen wells (appendix E). In ten of these, the sandstones have been found to be gas-bearing (appendix D). This evaluation is examined in section 6.3.

Fifteen wells of the Zechstein Group (Z2 and Z3 Carbonate) have been evaluated (appendix G). In five of these, the carbonates were gas-bearing (appendix H). These evaluations are discussed in section 7.3.

Sandstones of the Lower and Upper Germanic Trias Group have been evaluated in five wells (appendix I). In three wells, the sandstones were gas-bearing (appendix J). Section 8.5 discusses the evaluations.

Finally, sandstones of the Rijnland Group have been evaluated in ten wells (appendix K). In one case, these sandstones were oil-bearing and in another case, gas-bearing (appendix L). Section 11.3 discusses these evaluations.

1.7 Geochemical research

To pursue the geochemical research, fifteen wells in this map sheet area have been analysed. The coalification (vitrinite content) of the samples has been measured and the burial history of the map sheet area modelled. The procedure, the results of the analyses and the modelling are discussed in section 14.3.

1.8 Maps and sections

The results of the seismic mapping are shown in a series of depth maps, thickness maps and subcrop maps on a scale of 1:250.000. Depth maps have been plotted of the base of the Lower Rotliegend, the Upper Rotliegend, the Zechstein, the Lower Germanic Trias, the Altena, the Niedersachsen, the Rijnland and the Chalk Groups as well as of the North Sea Supergroup and the Upper North Sea Group. In addition, a depth map has been plotted of the top of the Zechstein Group. The depth maps of the bases of in particular the Upper Rotliegend, the Zechstein and the Lower Germanic Trias Group give an impression of the structural trend of the area, which is predominantly WNW-ESE and N-S-oriented. Subcrop maps have been made of the major unconformities, which are on the base of the Niedersachsen Group, Rijnland Group and North Sea Supergroup. The depth maps do not depict all the faults, but only a selection. The selection has been made on a base of the offset and the length of the faults and the fault pattern.

Thickness maps have been plotted of all the above-mentioned stratigraphic units, with the exception of the Lower Germanic Trias Group and the North Sea Supergroup. The Lower Germanic Trias and the Upper Germanic Trias Groups are presented in combination as one single map. A thickness map of the North Sea Supergroup may be obtained by adding the present-day surface altitude to the depth map.

Because of the reduced thickness, the base of the Lower and Upper Rotliegend Group was not able to be seismically mapped everywhere. The depth map of these groups is based on the seismic depth map of the base of the Zechstein Group, to which the thickness grid of the Lower and Upper Rotliegend Group respectively has been added, based on well-log data, (fig. 5.1 and 6.1).

The depth and thickness maps do not show wells containing a fault in the particular group or where the final depth of this group is located.

The subcrop maps of the base of the Niedersachsen Group, Rijnland Group and North Sea Supergroup (Maps 18, 19 & 20) illustrate the stratigraphic units situated below the unconformities and give an impression of the extent of erosion preceding the deposition of these groups.

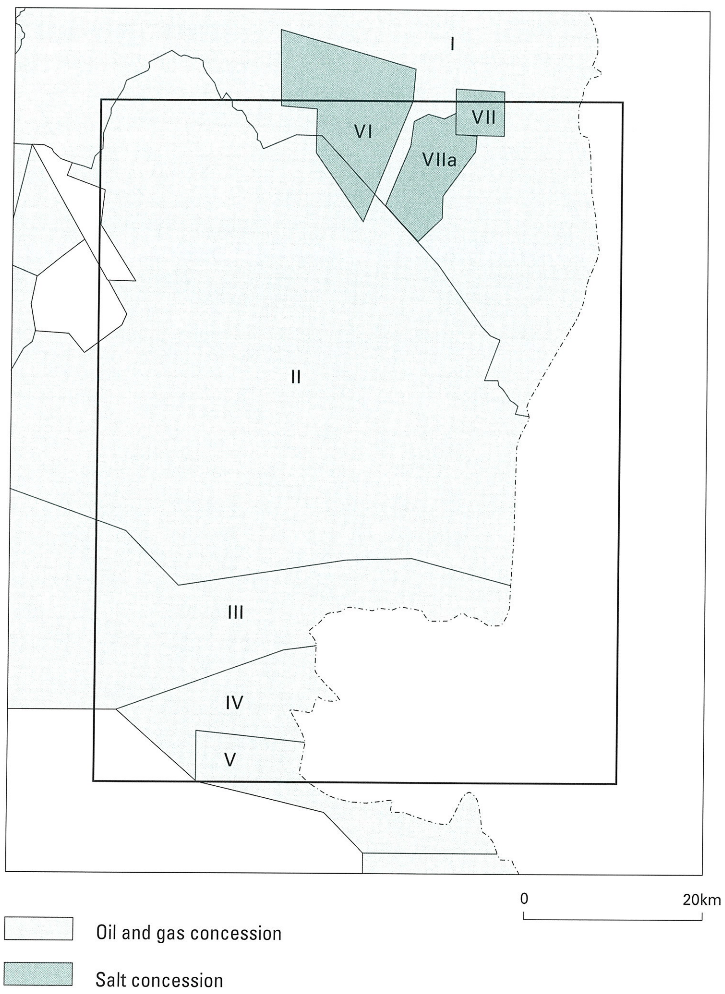
Finally, three structural sections are depicted on a separate map (Map 21). These sections, with a NW-SE and SW-NE orientation, have been selected in such a way as to link up with sections of the adjacent map sheets.

2 Exploration history

2.1 Introduction

The exploration of mineral and natural resources in this map sheet area commenced during the thirties, since which time oil, gas and salt have been successfully exploited. The map sheet area contains parts of the concession areas 'Drenthe', 'Groningen', 'Schoonebeek', 'Hardenberg' and 'Tubbergen', granted to the Nederlandse Aardolie Maatschappij B.V. Wthin these concession areas, targeted at bitumina, two salt concessions are also situated, 'Veendam' granted to Nedmag Industries and 'Adolph van Nassau', granted to Akzo Nobel Salt B.V. (fig. 2.1).

Figure 2.1 Overview map of the concession licence areas within the map sheet area. I: Groningen; II: Drenthe; III: Schoonebeek; IV: Hardenberg; V: Tubbergen; VI: Veendam; VII Adolph van Nassau; VIIa: Extension Adolph van Nassau.



In the map sheet area, 979 oil and gas boreholes have been drilled by the Bataafsche Petroleum Maatschappij (BPM), NAM, Elf Petroland and Hardy Oil and 32 salt wells by Shell Delfstoffen Nederland N.V. (Billiton Delfstoffen), Noordelijke Zoutwinning, Nedmag Industries and the Koninklijke Nederlandse Zoutindustrie, now Akzo Nobel Salt.

2.1.1 Hydrocarbons

A large number of oil and gas fields are situated in the map sheet area and its immediate vicinity (fig. 2.2 a-d).

The exploration of hydrocarbons in the map sheet area began in 1935 when a gravimetric survey was carried out by the Bataafsche Petroleum Maatschappij (BPM). In order to investigate in greater detail a number of the anomalies encountered, from 1937 onwards 12 core boreholes were drilled, the Noord-Nederland boreholes. As these boreholes were drilled with equipment of limited capacity, the Chalk Group was not penetrated. Despite the valuable geological information provided by these boreholes, they may not be regarded as valid tests for the observed gravimetric anomalies.

2.1.1.1 Crude oil

During the German occupation, the oil exploration was undertaken by the BPM/Elwerath consortium. Drillings were principally targeted at occurrences of oil in the Lower Cretaceous sands, by analogy with the discoveries in Emsland in Germany, (including Dalum, Lingen, Georgsdorf; Lögters, 1951). The gas find in the vicinity of Bentheim (1938) had previously revealed the probable occurrence of natural gas in the deeper units, for example the Zechstein, but there was a lack of interest in gas during the war period.

After a number of dry wells had been drilled, oil was encountered in the Bentheim Sandstone in 1944, in what would later be known as the Schoonebeek field. Up to now, this field is the largest oil field in northwest Europe situated on land, with a total reserve of 165 million m^3. More or less simultaneously, drilling was carried out in the German part of the field (Emlichheim) somewhat further to the south. The development of the field did not get properly underway until the end of the Second World War, after the Nederlandsche Aardolie Maatschappij (NAM) had been founded by Shell and Esso in 1947. In 1948, the NAM was granted the 'Schoonebeek' concession.

In view of the unique character of this oil field, additional data are given here (Mulder, 1950b; Visser & Sung 1958): The field is situated at a depth of 800 to 950 m (Oil-Water Contact at a depth of 880 m) and extends E-W over a length of 17 km. The field consists of two compartments, a gas-driven and a water-driven part. The API gravity of the oil is 25°. Approximately 40 million m^3 of oil have been produced from 599 wells in the field; at present around 120 million m^3 remain. In 1957, the maximum daily oil production of 3700 m^3 was reached. Oil production was discontinued in 1997, for economic reasons. The oil field also overlies a gas field in the Z2 Carbonate (fig. 2.2c, d).

2.1.1.2 Natural gas

After the war, the NAM also commenced the exploration of natural gas. Ten years after the discovery of the Bentheim field, the Z2 Carbonate was found to be gas-bearing in the Coevorden-2 well. In 1949, the De Wijk gas field was discovered, followed by the Staphorst and Wanneperveen fields. Reservoir rocks from these gas fields are present in several formations, including oolites in the Lower Buntsandstein, sandstone in the Volpriehausen, the Solling and the Vlieland Sandstone Formation, limestone in the Muschelkalk Formation and tuffite in the Basal Dongen Tuffite. These discoveries led to an enlargement of the 'Schoonebeek' concession in a westerly direction.

Figure 2.2 Overview map of the hydrocarbon occurrences per stratigraphic unit. Names of fields within the map sheet area and German fields have been given. For other field names, reference should be made to the adjacent map sheets.

a. Carboniferous fields.
1. Grollo; 2: Emmen; 3: Oosterhesselen; 4: Geesbrug; 5: Dalen; 6: Coevorden; 7: Hardenberg; 8: Den Velde. German fields: 9: Rütenbrock; 10: Fehndorf; 11: Annaveen; 12: Emslage; 13: Adorf; 14 Emlichheim-Nord en Emlichheim; 15: Kalle; 16: Esche; 17: Ratzel; 18: Uelsen; 19: Wielen.

b. Rotliegend fields:
1: Groningen; 2: Annerveen; 3: Oude Pekela; 4: Blijham; 5: Midlaren; 6: Roden; 7: Norg; 8: Vries; 9: Norg Zuid; 10: Assen; 11: Appelscha; 12: Eleveld; 13: Geesbrug.

c. Zechstein fields.
1: Gieterveen; 2: Stadskanaal; 3: Gasselternijveen; 4: Exloo; 5: Valtermond; 6: Vlagtwedde; 7: Emmen; 8: Oosterhesselen; 9: Geesbrug; 10: Dalen; 11: Emmen-Nieuw Amsterdam; 12: Schoonebeek; 13: Coevorden; 14: Collendoorner veen; 15: Den Velde; 16: Hoogeweg German fields: 17: Rütenbrock; 18: Annaveen; 19: Emslage; 20: Adorf; 21 Emlichheim en Emlichheim-Nord; 22: Kalle; 23: Esche; 24: Ratzel; 25: Uelsen; 26: Wielen.

d. post-Zechstein fields.
1: Sleen; 2: Roswinkel; 3: De Wijk; 4: Coevorden; 5: Schoonebeek. German fields: 6: Fehndorf; 7: Hebelermeer; 8: Meppen; 9: Rühle; 10: Emlichheim; 11: Adorf; 12: Varloh; 13: Lingen; 14: Scheerhorn; 15: Georgsdorf; 16: Hohenkörben; 17: Ratzel.

Gas fields are found in Triassic reservoirs, oil fields in Lower Cretaceous reservoirs.

The exploration of natural gas in the map sheet area received a considerable impetus with the discovery of the Groningen field in 1959. The southern part of this field is situated within the map sheet area. In 1963, the Annerveen field was discovered, which, with $75*10^9$ m^3 GIIP, was the third largest gas field in the Netherlands (Veenhof, 1996). This formed the basis for the allocation of the 'Drenthe' concession to the NAM in 1969.

Forty years of exploration resulted in the discovery of a large number of oil and gas fields in the area. These fields are found in various reservoirs. In the northern part, the reservoirs occur predominantly in the sandstones of the Upper Rotliegend Group (fig. 2.2b). In the eastern part, the gas fields are in the Zechstein Group, in addition to two occurrences of oil (Stadskanaal and Gieterveen). In the southern part of the map sheet area, the gas fields are situated in the Zechstein as well as the Limburg Group (fig 2.2a and c). In addition, a number of discoveries were made in the sandstones of the Lower and Upper Germanic Trias Group in Sleen, Roswinkel and De Wijk. The Sleen-2 well (1965) experienced what was, in the Dutch perspective, a great calamity, when gas escaping along the drill pipe caused a huge collapse crater, into which the entire derrick disappeared (Milius & Van der Vlugt, 1967; Brouwer & Coenen, 1968).

More than 50 fields in seven different stratigraphic units have been found in the map sheet area. Besides gas exploitation, underground gas storage has been carried out in the Norg field since 1997 (see also Chapter 14).

Other consequences of gas exploitation besides surface subsidence are the earthquakes which have regularly occurred since 1986 in the vicinity of Eleveld, Roswinkel, and others. As this area is considered a non-seismic area, the occurrence of earthquakes gave rise to considerable disquiet. To gain a better understanding of the mechanisms of the earthquakes in the North Netherlands, a number of seismometers were placed in the area. The findings have revealed that while many earthquakes do occur in the area, the majority are not perceptible. Multidisciplinary investigations have established a relation between the occurrence of earthquakes and gas exploitation. The magnitude of the strongest earthquakes is 2 to 3.4 on the Richter scale. Because of the shallowness of the focal depth of the earthquakes (from 1 to 3 km), they are of relatively great intensity (the observed surface sensation, Mercali scale). The earthquakes in the vicinity of Roswinkel, in particular, have considerable magnitudes. Despite research by various institutes, no undisputed explanation for this has as yet been found (Begeleidingscommissie Onderzoek Aardbevingen, 1993). An up-to-date overview of the earthquakes can be obtained at http://www.knmi.nl.

2.1.2 Salt

The results of the gravimetric survey carried out by the BPM in Drenthe at the end of the 1930s had already suggested the presumed occurrence of a number of salt structures within the map sheet area. The presence of these structures was revealed in three wells in the Schoonlo salt dome (Mulder, 1950a).

The salt exploration commenced in 1951, when the NAM was commissioned by the Koninklijke Nederlandse Zoutindustrie (KNZ) to drill three boreholes in the Winschoten salt dome. Accordingly, the 'Adolph van Nassau' concession was granted to the KNZ in 1954. This concession was expanded southwards in 1967, after the presence of rock salt was demonstrated by a well in the Zuidwending salt dome (Harsveldt, 1980), since when over 20 salt wells have been placed in this concession. Around 2500 kilotons of rock salt are produced from the Z2 (Stassfurt) Formation on an annual basis.

On account of the results from the exploration wells drilled by Billiton, the 'Veendam' concession was granted to the Noordelijke Zoutwinning B.V. in 1980. A unique occurrence of magnesium-rich layers was found in the Veendam salt pillow in the Z3 (Leine) Formation (Coelewij et al., 1978). Nowadays, production of these salts is carried out by Nedmag Industries. The annual production (1997) is approximately 180 tons of potassium-magnesium salt, of which 145 tons were magnesium salt. Wells have revealed magnesium-rich layers in several salt pillows within the map sheet area. In both concession areas, the salt exploitation is carried out by solution mining.

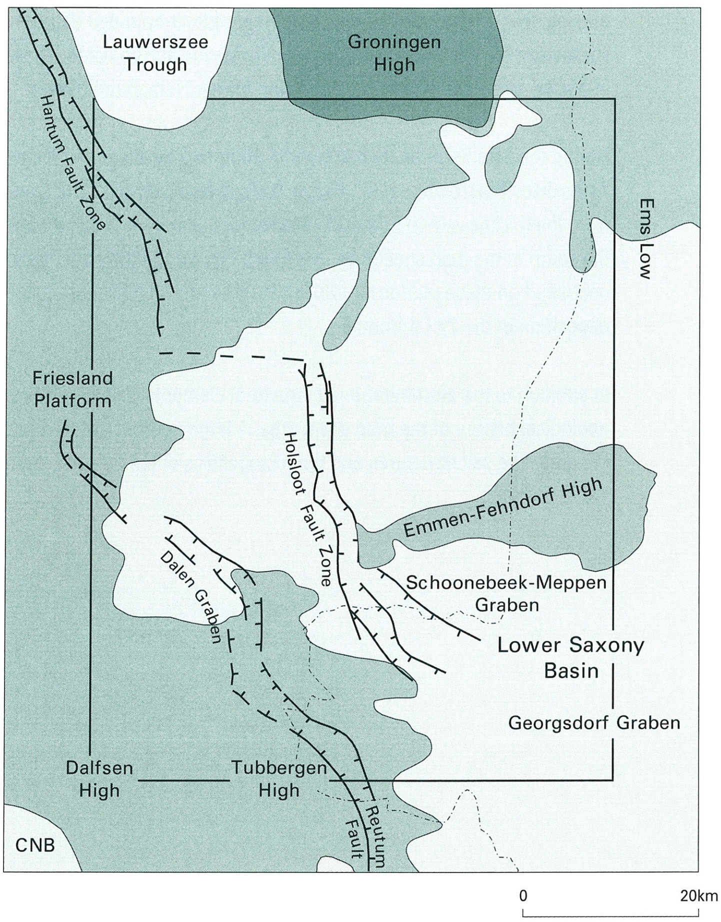
3 Structural framework

The geological history is illustrated by the structural elements differentiated in the map sheet area (fig. 3.1). These units comprise, to a greater or lesser degree, Variscan elements that were reactivated and modified during later tectonic phases.

The **Lower Saxony Basin** is one of the most conspicuous elements within the map sheet area. The basin is characterised by differential subsidence during the Late Jurassic and the Late Cretaceous. The subsidence was strongly determined by differential salt movements. Basin inversion occurred during the Sub-Hercynian phase (Coniacian-Campanian). The map sheet area was situated on the northwest margin of this basin, as a result of which the subsidence and inversion movements were slight here in comparison with the movements observed in Germany. Within the basin, a number of E-W-oriented depocentres and highs can be differentiated, which are mainly manifested in the southeast of the map sheet area. The **Schoonebeek-Meppen Graben**, the **Georgsdorf Graben** and the **Emmen-Fehndorf High** are the most important of these.

The **Friesland Platform** and the **Groningen High** formed the highs to the north, west and south of the Lower Saxony Basin. These highs constituted a major source area for sediments during the Valanginian and Hauterivian. During the Hauterivian to Aptian, the high was then overlain by sediment. The highs are characterised by relatively major subsidence during the Sub-Hercynian phase. The erosion of the highs cut deep down as far as the deposits of the Lower or Upper Germanic Triassic Group, even

Figure 3.1 Structural units in the map sheet area.



reaching as far as the Zechstein Group locally. In the south of the map sheet area, two subelements are identified within the Friesland Platform, namely the Tubbergen High and the Dalfsen High. The **Dalfsen High** is characterised by the subcropping of the Carboniferous beneath the Rijnland Group (Map19). The **Tubbergen High**, to the east of the Dalfsen High, is the southeasternmost part of the Friesland Platform (fig. 3.1). The highs situated to the west and north of the Lower Saxony Basin are also referred to as the **North Netherlands High**. Besides the highs mentioned, this unit also contains the Lauwerszee Trough.

The **Lauwerszee Trough** is a Tertiary subsidence area associated with the Hantum Fault Zone. Also during the Late Permian and the Early Cretaceous, this area was distinguished from the Groningen High and the Friesland Platform by the more pronounced subsidence. The **Hantum Fault Zone** forms the western boundary of the trough. The Hantum Fault Zone forms part of a Tertiary fault system of which the **Holsloot Fault Zone**, the **Dalen Graben** and the **Reutum Fault** are also part.

The **Ems Low**, in the east of the map sheet area, is a distinctive structure. During the course of geological history, the structure has undergone pronounced modification. During the Westphalian C and, probably, the Stephanian, pronounced substance occurred in this then N-S oriented area. The area was subjected to volcanic activity during the Early Permian, while forming a high in the Late Permian. During the Early Triassic, the NNE-SSW oriented area was characterised by a thick deposition of the Main Buntsandstein Subgroup (fig. 8.2b). The western part of the map sheet area was part of the **Netherlands Swell**, containing a succession of the Main Buntsandstein Subgroup attenuated by erosion. During the Late Triassic, a number of fault-bounded depressions were formed, in which a thick succession of sediments of the Keuper Formation accumulated. These structures were N-S oriented and, in places, also encompassed parts of the former Netherlands Swell.

During the Late Permian, two anhydrite platforms developed in the map sheet area, the **Kloosterhaar Anhydrite Platform** and the **Exloo Anhydrite Platform**. The contours of these areas can be deduced from the thickness map of the Z1 (Werra) Formation (fig. 7.2a); the Kloosterhaar Platform is situated in the south of the map sheet area, the Exloo Platform in the east. Thick sequences of anhydrite were deposited on these platforms, which also played a significant role in the facies distribution during deposition of the Z2 Carbonate.

In addition to the aforementioned structural elements, salt structures are also of great importance in the geological history of the map sheet area. A large number of salt domes and salt pillows are found within the area. The salt structures and the tectogenesis of the area are described in greater detail in Chapter 14.

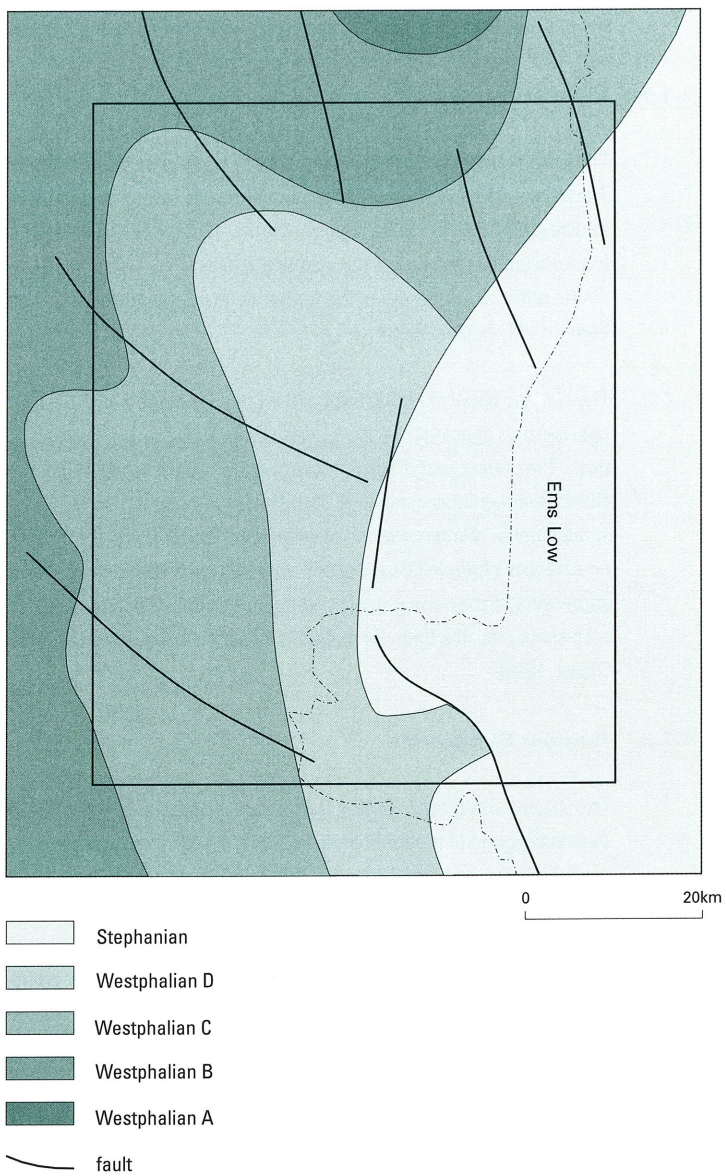
4 Limburg Group

4.1 Stratigraphy

The Limburg Group, of Namurian to, presumably, Stephanian age, consists of a thick succession of predominantly grey to black, fine-grained siliciclastic and organic sediments, but which are also red coloured in the youngest part. The group represents virtually the entire Upper Carboniferous and is subdivided into four subgroups, each representing a particular phase of the Late Carboniferous regressive megasequence. From bottom to top, these are the Geul, Caumer, Dinkel and Hunze Subgroups.

In the map sheet area, the Limburg Group is unconformably overlain by the Lower Rotliegend, the Upper Rotliegend or the Zechstein Group (Maps 1, 2 & 3). In the extreme southwest, the group is unconformably overlain by the Rijnland Group (Map 18).

Figure 4.1 Subcrop map of the top of the Limburg Group.



Deposits of the Limburg Group are found throughout the map sheet area. The thickness of the entire Limburg Group is approximately 3000 m in the west to probably well over 6000 m in the east. This strong variation is largely the consequence of post-depositional erosion during the Late Carboniferous and Early Permian. The map sheet area then encompassed the Netherlands High and the Groningen High, two areas where intense uplift and erosion occurred, and the Ems Low, where major subsidence occurred. This is illustrated by the age of the top of the Limburg Group. (fig. 4.1 & 4.2).

The thickness of the top of the Limburg Group increases towards the east from 2000 m to over 5200 m in the Lower Saxony Basin (Maps 1 & 2). The fault pattern exhibits an interference of an overall N-S-trend with EW directions. In the northwest of the area, NW-SE orientations also occur.

4.1.1 Geul Subgroup

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

4.1.1.1 Epen Formation

The Epen Formation, of Namurian A to Late Namurian C age, is present throughout the map sheet area. The formation has not been encountered in wells owing to its great depth (Van Adrichem Boogaert & Kouwe 1993-1997; Rijks Geologische Dienst, 1995; NITG-TNO, 1998). The formation is, however, known from documentation on the surrounding areas (NITG-TNO, 1998; Rijks Geologische Dienst, 1993a, 1995). To the north, the thickness of the formation increases from 2000 to a probable 3000 m (Stancu-Kristoff & Stehn, 1984; Ziegler, 1990).

The *Geverik Member*, at the base of the Epen Formation and of earliest Namurian A to Late Namurian C age, consists of hot shales, claystones with a high organic material content. The unit is 50 to 100 m thick. The greater part of the Epen Formation consists predominantly of dark coloured claystone and siltstone, sometimes containing abundant organic material. This fine-grained succession exhibits a small number of intercalations of sandstone layers. The member is characterised by the frequent occurrences of marine beds containing goniatites and bivalves. The sequence comprises a cyclical succession of coarsening-upward sequences, 50 to 100 m thick (NITG-TNO, 1998). To the north of this map sheet area, the Epen Formation may also contain some carbonaceous material (Rijks Geologische Dienst, 1995).

4.1.2 Caumer Subgroup

The Caumer Subgroup, ranging from Late Namurian C to Early Westphalian C in age, is composed of a thick succession of predominantly fine-grained siliciclastic sediments and frequent occurrences of coal seams. Within the map sheet area, this is the oldest unit to have been penetrated. The Caumer Subgroup comprises three formations, the Baarlo, the Ruurlo and the Maurits. In the greater part of the map sheet area, the subgroup is unconformably or disconformably overlain by the Tubbergen Formation. In the north and west of the map sheet area the subgroup is unconformably overlain by deposits of the Upper Rotliegend Group, and in the southwest unconformably by deposits of the Rijnland Group. The subgroup has not been completely penetrated in any of the wells, but from literature sources it can be inferred that the Caumer Subgroup may achieve a thickness of 2000 m (Stancu-Kristoff & Stehn, 1984).

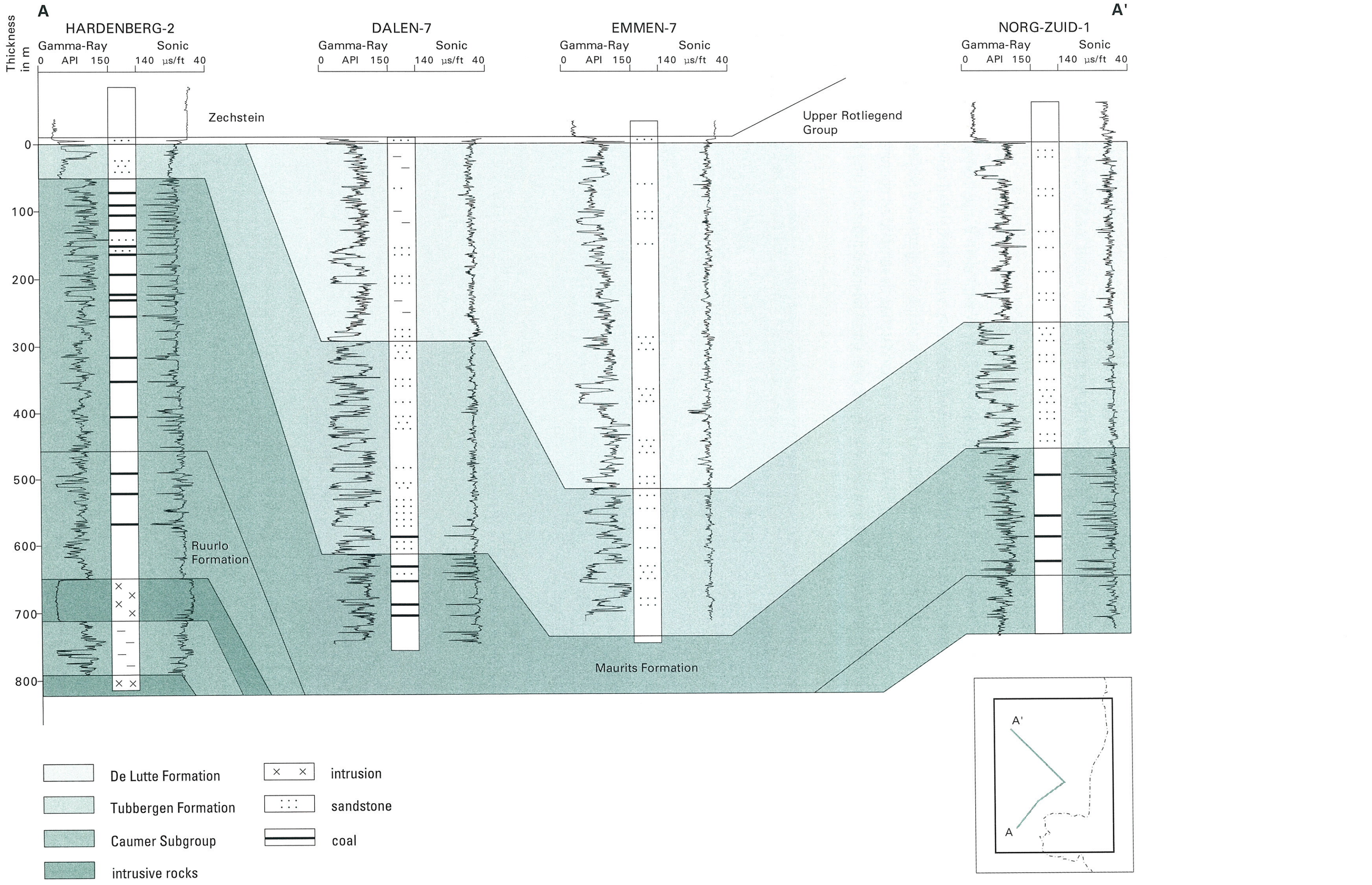


Figure 4.2 Stratigraphic section A-A' of the Limburg Group between the Hardenberg-2, Dalen-7, Emmen-7 and Norg-Zuid-1 wells. This section displays the units at the top of the Limburg Group, becoming younger in a northerly direction, and the unconformable, overlying Upper Rotliegend Group. The reference level is formed by the base of the last-mentioned group.

4.1.2.1 Baarlo Formation

The Baarlo Formation, Westphalian A in age, consists of dark coloured claystone, with frequent occurrences of coal seams and sandstones. The formation is present throughout the map sheet area, but has only been encountered in wells to the north and west of the area (Rijks Geologische Dienst, 1993a, 1995). To the north of the map sheet area, the formation achieves a thickness in excess of 1000 m (Tjuchem-2 well; Rijks Geologische Dienst, 1995).

The sandstones in this formation occur predominantly in coarsening-upward sequences. These sequences achieve a thickness ranging from some tens of metres to 300 m on occasion. The base of such sequences contain claystones with marine to brackish-water fossils (goniatites, *Lingula*).

4.1.2.2 Ruurlo Formation

The Ruurlo Formation, of Late Westphalian A to Early Westphalian B age, comprises a succession of predominantly light-grey silty or argillaceous claystones, with intercalated coal seams and grey to poorly sorted pink sandstone beds. In the formation, while fining-upward sequences prevail, there are also a few coarsening-upward sequences. The sandstones developed as channel sandstones, mini deltas in fresh-water lakes and as sand layers with good lateral continuity. The formation rests

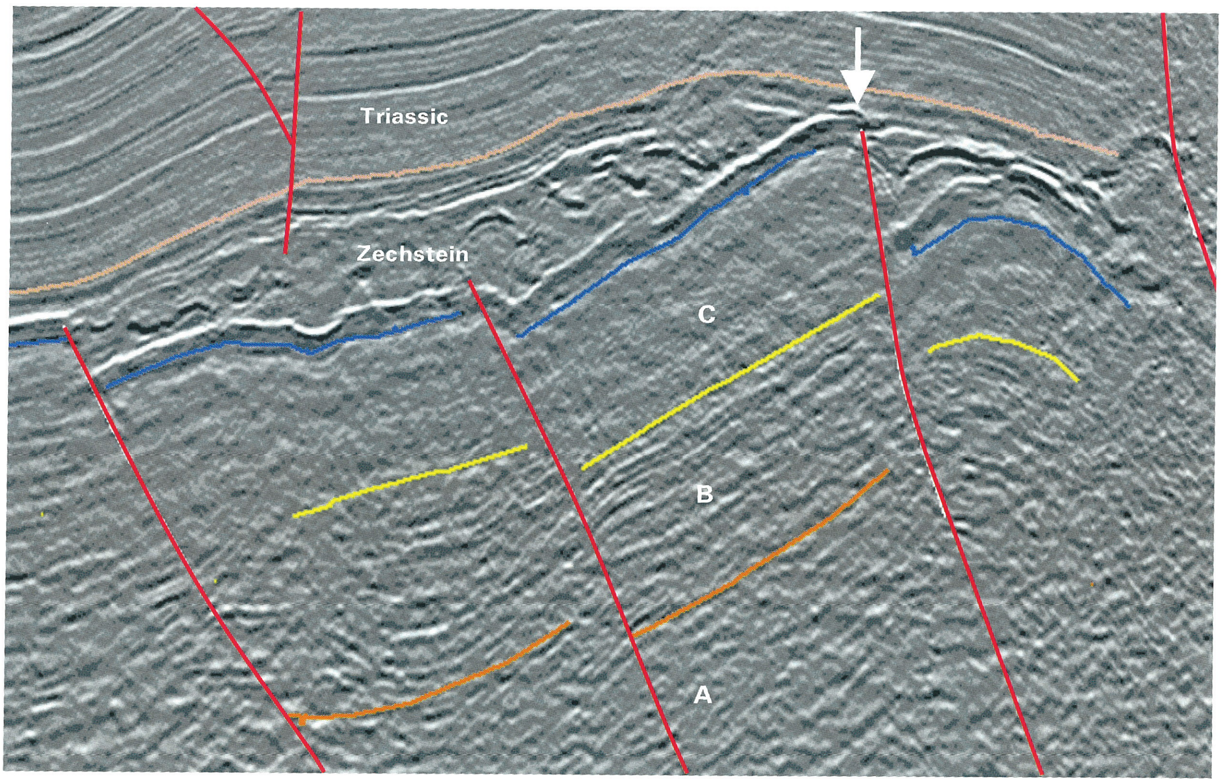


Figure 4.3 Example of the seismo-stratigraphic facies of the Limburg Group, showing a N-S running section from the Hoogenweg 3D survey (line 8920). A, B and C refers to the seismic facies of the Limburg Group (section 4.4). A corresponds to the Namurian to Westphalian A deposits, B to the coal-bearing Westphalian B to Early Westphalian C deposits and C to the youngest Carboniferous deposits. The arrow indicates the place where the Zechstein Upper Claystone Formation rests immediately upon the basal units of the Zechstein Group.

conformably on the Baarlo Formation and is also overlain conformably by the Maurits Formation (fig. 4.2, Hardenberg-2). The formation is found throughout the map sheet area. To the west of the map sheet area, the thickness is over 750 m.

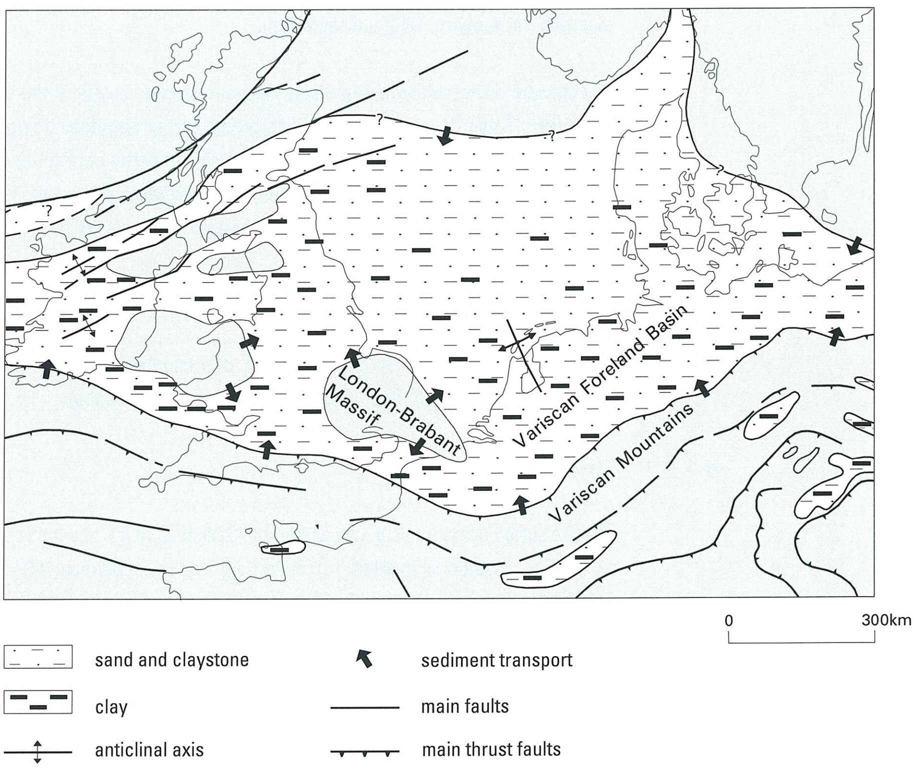
The Ruurlo Formation contains the equivalents of two important marine bands, namely the Catharina horizon, which defines the Westphalian A/B boundary, and at the top of the formation the Domina horizon, at the boundary of the Lower and Upper Westphalian B This horizon also forms the boundary with the Maurits Formation.

4.1.2.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Early Westphalian C age, mainly comprises light-grey claystones with abundant coal seams. In addition, thin (<5 m) layers of fine to coarse-grained sandstone are found. The formation is differentiated from the underlying formation by its fine-grained character and higher abundance of coal, which is clearly demonstrated on well logs (fig. 4.2). The formation is conformably or unconformably overlain by the Tubbergen Formation, or by the Upper Rotliegend, the Zechstein or the Rijnland Group (fig. 4.2, Map 19).

Within the map sheet area there are various indications that the base of the overlying Tubbergen Formation is erosional. The Maurits Formation contains two distinctive marine bands: at the base, the Domina Marine Band, (the boundary between the Lower and Upper Westphalian B), and near the top, the Aegir Marine Band (boundary Westphalian B-C).

Figure 4.4 Palaeogeography of Northwest Europe during the Late Carboniferous (after Ziegler, 1990).



The Maurits Formation is found throughout the map sheet area, but has only been penetrated in the western part (fig. 4.2). The thickness of the Maurits Formation in the map sheet area is approximately 400 m.

4.1.3 Dinkel Subgroup

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

4.1.3.1 Tubbergen Formation

The Tubbergen Formation, of Westphalian C to Early Westphalian D age, consists of a succession of thick sandstone bodies, separated by thin, fine-grained deposits. The formation lies on the Maurits Formation, separated by a hiatus or a minor unconformity and is found in the greater part of the map sheet area (fig. 4.1). In the extreme east of the map sheet area the formation is overlain conformably by the De Lutte Formation, and elsewhere unconformably by the Upper Rotliegend, the Zechstein or the Rijnland Group (fig. 4.2, Map 19). The thickness of the formation is a maximum of 350 m in the central part of the map sheet area, and is determined by the degree of erosion during the Early Permian.

The formation comprises successions of sandstone bodies 10-30 m thick, as much as 100 m in the central part of the formation. The sandstones are separated by 5 to 40 m thick claystone/siltstone intervals (fig. 3.5 & 3.7). Sandstone constitutes 50 to 80% of the formation. The sand percentage decreases in a northerly direction. The sandstones are medium-coarse, very coarse to conglomeratic and immature with poorly rounded grains. They are predominantly light-grey in colour. The sandstone bodies display good lateral continuity and constitute the reservoir rocks of several gas fields (for example Hardenberg, Dalen, Coevorden).

The claystones in the formation display a greenish-grey colour at the bottom, where a few coal seams also occur. Towards the top, the reddish-brown colour begins to be dominant and the formation becomes devoid of coal seams. The red colouring is partly of primary origin (Selter, 1990; Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996; Van der Meer & Pagnier, 1996). The thickness of the formation is approximately 475 m, but is thought to be greater in the Ems Low.

4.1.4 Hunze Subgroup

The Hunze Subgroup, Early Westphalian D to (presumably) Stephanian in age, comprises the De Lutte Formation. The base of the formation is somewhat diachronous.

4.1.4.1 De Lutte Formation

The De Lutte Formation is a succession of reddish-brown and occasionally greenish-grey, silty to very fine-sandy claystones. In addition, red and light-grey sandstones with thicknesses up to 15 m are found. The only coal-bearing bed in the formation, known in Germany as the *Itterbeck-Horizon* (Tantow, 1993), occurs a few metres above the base. This bed marks the boundary between the part with gley soils below and the part with caliche and ferruginous soils above. The caliche levels are dominant in the uppermost part of the formation (Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996; Van der Meer & Pagnier, 1996).

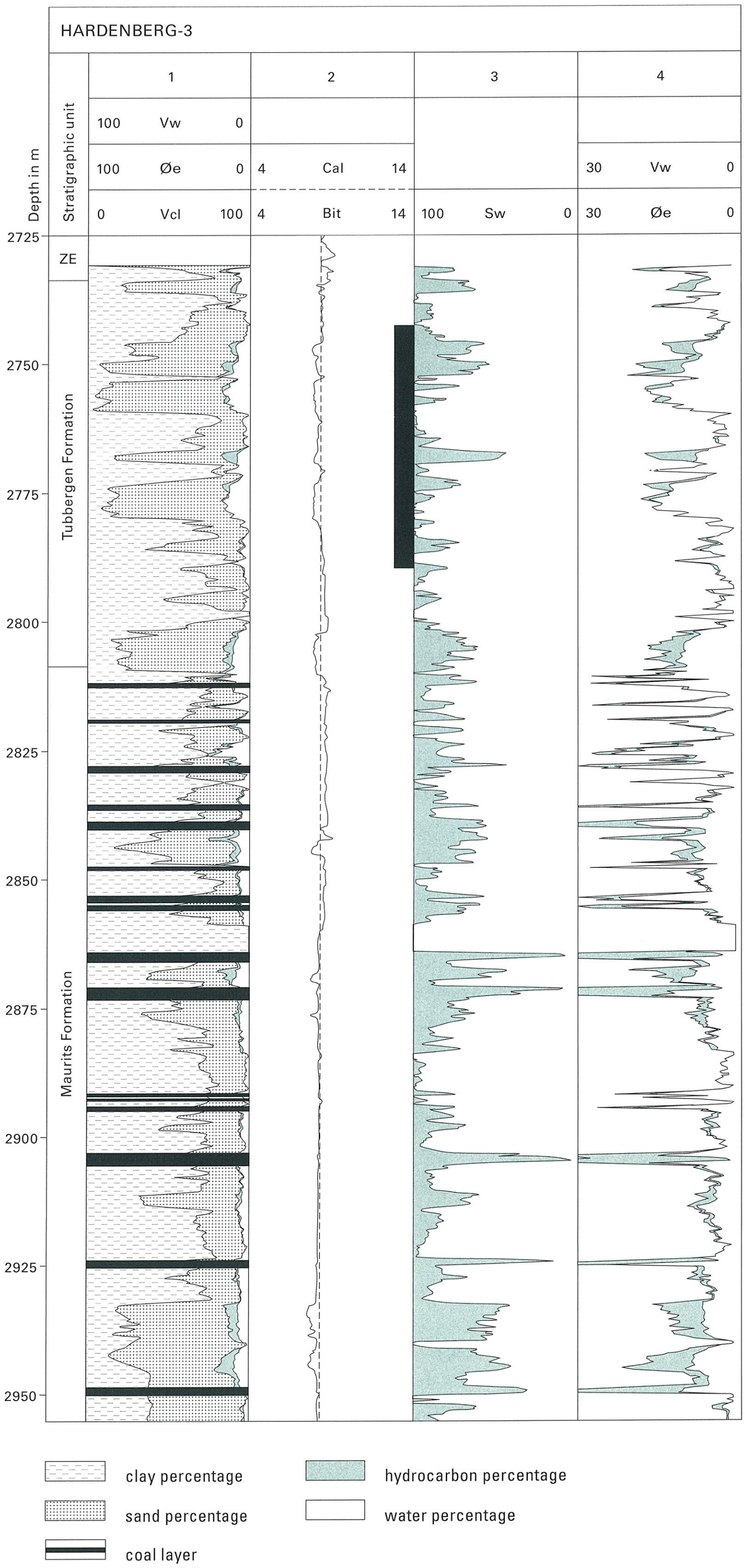
Figure 4.5 Petrophysical evaluation of the sandstones of the Limburg Group in the Hardenberg-3 well.

Column 1: clay content V_{cl}, effective porosity $Ø_e$ and pore volume water V_w, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained by the use of a shaly sand model (density log/neutron log), in which the calculated log porosity was corrected for the clay and the hydrocarbons present.

Column 2: drill hole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the cored interval is indicated by a black bar.

Column 3: water saturation S_w in percentages. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987).

Column 4: effective porosity $Ø_e$ (left curve) and the volume of water in the pores V_w (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated.
The depths are the true depths.



The De Lutte Formation is found in the central and eastern part of the map sheet area (fig. 4.1). The formation rests conformably upon the Tubbergen Formation and is unconformably overlain by the Lower Rotliegend, the Upper Rotliegend or the Zechstein Groups. The maximum thickness of the formation is nearly 800 m (Grollo-1); in the east, the thickness ranges from 650 to over 700 m.

4.2 Intrusive rocks

Intrusive rocks have been penetrated in several places in the map sheet area. In the Dwingelo-2 well, an olivine gabbro has been encountered at 3754 to 3792 m (Thiadens, 1963). This plutonic rock has been dated at 322±15 Ma and was described in detail by Eigenfeld & Eigenfeld-Mende (1986). In the Hardenberg-2 well (fig. 4.2), an olivine gabbro of roughly the same age has been recovered (290±16 Ma). These rocks have also been found in wells in the vicinity of De Wijk and Wanneperveen.

4.3 Sedimentary development and palaeogeography

The deposits of the Limburg Group reflect the regressive accumulation of the Late Carboniferous foreland basin (Van Wijhe & Bless, 1974; Ramsbottom, 1979). This basin was E-W trending and covered the area from England to Poland (fig. 4.4). The thick succession of the Limburg Group contains gradual transitions of the various facies as well as intra-formational hiatuses and unconformities. The sediment source area was situated in the south. (David, 1990; Selter, 1990).

The basal part of the regressive megasequence (Epen Formation) contains marine and deltaic deposits. The characteristic coarsening-upward successions represent protruding deltas. The middle part of the megasequence (Caumer Subgroup) is characterised by the transition from pro-delta deposits to delta plains and river deposits. The marshes on the delta plain are the initial setting for peat formation. Sandy deposits are formed in a meandering or braided river and crevasse depositional environment. In the upper part of the megasequence (Tubbergen Formation), the predominantly fine-grained deposits passed into coarse-grained braided river deposits. The erosive incision of channels, the large amounts of coarse-grained material and the small internal unconformities indicate tectonic uplift of the hinterland during the deposition of this formation (Pagnier & Van Tongeren, 1996). The fine-grained De Lutte Formation represents mainly flood-plain deposits, with thin, coarse-grained, braided river deposits.

The Limburg Group exhibits frequent occurrences of marine horizons, which decrease in frequency upwards. These marine or marginal marine deposits were of short duration. Sediments, flora and fauna dating from the Namurian and the Westphalian A, B and C indicate a continuous tropical humid climate. The development of the soil types (ranging from ferruginous to caliche) indicates that the climate slowly became drier during the Late Westphalian C and D, and the Stephanian (Hedeman & Teichmüller, 1971; Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996). The red colour of the sediments, the calcareous soils and sparse vegetation indicate a more tropical, semi-arid climate.

4.4 Seismic facies

In the map sheet area, the Limburg Group is characterised by three seismic facies (fig.4.3). These were mapped on 3D seismics and calibrated with the aid of approximately 35 wells. Similar seismic facies have been identified in the Carboniferous in adjacent areas (Tantow, 1993; Van Tongeren 1996) and on the Cleaver Bank High in the North Sea (Quirk, 1993). In the north of the map sheet area, these seismostratigraphic units are not always well traceable owing to the strongly disrupted seismic signal caused by the salt domes.

Seismic facies A is characterised by on average low frequency amplitudes of reasonable continuity. The surroundings of Dwingelo display occasional strong amplitudes, which may have been caused by parallel-bedded volcanic intrusions. This facies corresponds with the Epen and Baarlo Formations, which contain relatively few coal seams (Namurian to Westphalian A).

Seismic facies B consists of strongly continuous and parallel reflections with high amplitudes and corresponds with the Ruurlo and Maurits Formations (Westphalian B to Early Westphalian C). These formations are characterised by a rapid vertical alternation between claystone, sandstone and coal seams. The typical character of this seismic facies is attributed to interference of a rapid vertical alternation of coal, claystone and sandstone.

Seismic facies C is more or less transparent and generally has low amplitude and low frequency reflections. This uppermost interval is characterised by a somewhat high amplitude and discontinuous reflections, which may point to intra-formational hiatuses. This facies corresponds with the Tubbergen and the De Lutte Formation (Early Westphalian C to probably Stephanian).

4.5 Petrophysical evaluation

In and around the map sheet area, eight wells were petrophysically evaluated (appendix C). Out of six wells, core analysis data are available. The porosity measured from cores lies between 1-21%, whereas permeabilities reach a maximum of 200 mD. The sandstones of the Tubbergen Formation form a major target for exploration in the southern part of the map sheet area. Here and in the adjacent area of Germany, several gas fields have been discovered (fig. 2.2a). In addition, parts of the underlying and overlying formations have been included in the evaluation.

In the Tubbergen Formation, the net/gross ratio decreases in a northerly direction; the highest values are observed in the northern part of Twente (Tubbergen-Mander-1), the lowest value in southern Drenthe (Dalen-7). This is commensurate with the sedimentary model for this formation, in which braided fluvial systems extend from a southerly direction across the area, passing northwards into flood plains and fluvial deposits (Selter, 1990). However, a certain amount of caution should be observed, as this decrease may also have been caused by the fact that the Dalen-7 well is situated more on the margin of the fluvial system or by the occurrence of secondary porosity (Van der Meer & Pagnier, 1996).

The porosities of the sandstones in the formations lie between 10 and 13%, the average value in the Tubbergen Formation being slightly higher and more constant than in the De Lutte Formation. The sandstones in the Maurits Formation display a striking range, with an exceptionally high value of 19.8% in a thin sandstone in the Dalen-7. To illustrate a log-evaluation of the Limburg reservoir sequence, figure 4.5 shows the results in the case of the Hardenberg-3 well.

5 Lower Rotliegend Group

5.1 Stratigraphy

The Lower Rotliegend Group in the map sheet area, of Early Permian age, is represented by the Emmen Volcanic Formation. These deposits are only found in the Ems Low (Map 1) this also being their only known occurrence under the onshore area of The Netherlands (fig. 5.1) and the westerly prolongation of a much larger area in Germany. In view of the low drilling density in the southeast of the map sheet area, their presence in this area should nonetheless be assumed.

The Lower Rotliegend Group in the map sheet area rests unconformably upon the Hunze Subgroup and is overlain, also unconformably, by the Zechstein Group. Immediately to the east of the map sheet area, the group is unconformably overlain by the Upper Rotliegend Group. The depth of the base of the group ranges from 4000 tot 5000 m (Map 1). The thickness of the group is a maximum of 75 m in the east of the map sheet area.

5.1.1 Emmen Volcanic Formation

The Emmen Volcanic Formation, of Early Permian age and considered to be probably the oldest part (Asselian-Artinskian; Plein, 1995), consists of a rapid, alternation of reddish-brown, greenish-green

Figure 5.1 Thickness map of the Emmen Volcanic Formation in the map sheet area, based on well log data. The data from the German part have been derived from Plein (1995) and Lokhorst (1998).

coloured, coarse and fine-grained siliciclastic deposits, tuffs and layers of spilitic basalt (fig.5.2). These basaltic layers are clearly identifiable on well logs. The succession has been cored to the east of the map sheet area in the Oberlanger Tenge Z1 well (Fabian et al., 1962). Here, the formation consists of a succession of (sandy) claystones and spilite (albitised basalt). Tephra layers are scarcely found.

The volcanic deposits have been encountered in the Ems Low (fig. 3.1). It is notable that, while no sediments of the Upper Rotliegend Group have been found here, their presence has been recorded immediately beyond the map sheet (Plein, 1995) and they may possibly also occur in the southeast of the area. The thickness of the formation is the greatest in the eastern part of the map sheet area, namely over 75 m, and beyond, the thickness increases to over 100 m (fig. 5.2).

Correlation of the basalts in the Emmen Volcanic Formation with the gabbro plutonic rocks in the Limburg Group (found in the De Wijk, Dwingelo-2 and Hardenberg-2 wells) seems obvious, but cannot be proved.

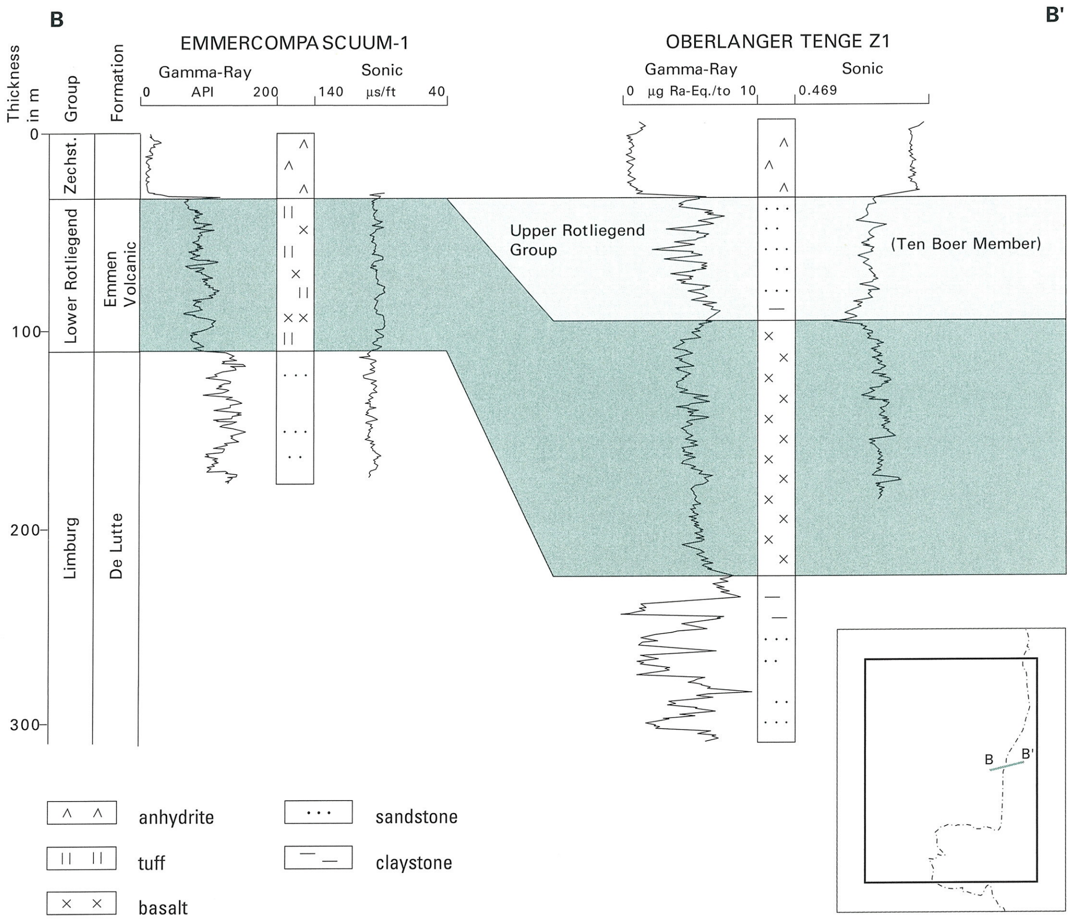


Figure 5.2 Stratigraphic section B-B' of the Lower and Upper Rotliegend Group in the Emmercompascuum-1 and Oberlanger Tenge Z1 wells (after Fabian et al. 1962). In the Emmercompascuum-1 well, the Lower Rotliegend Group comprises an alternation of basalt and tephra layers. The sequences containing spilite (albitised basalt) are characterised by a high interval velocity on the sonic log. In the Oberlanger Tenge Z1 well, the Lower Rotliegend Group is composed entirely of spilite.

5.2 Sedimentary development and palaeogeography

The formation was formed in a terrestrial depositional environment under dry climatological conditions, in which lava flows with a basaltic composition pours out from fault zones into the Ems Low. The coarse-grained deposits represent wadis in which deposition of erosional material from the surrounding highs occurred.

6 Upper Rotliegend Group

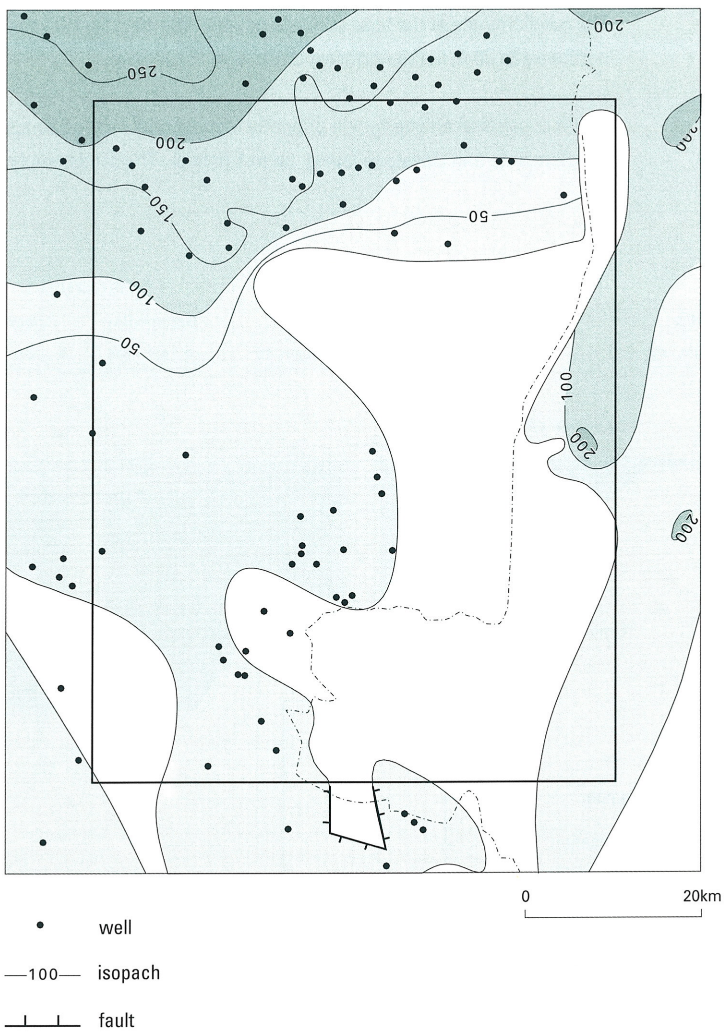
6.1 Stratigraphy

The Upper Rotliegend Group is represented by sands and conglomerates of the Slochteren Formation. In the northern part of the map sheet area, claystones of the Silverpit Formation occur at the top. According to the latest perceptions, the group within The Netherlands is Late Permian in age (Van Adrichem Boogaert & Kouwe, 1993-1997; Geluk, 1997, 1999b).

The Upper Rotliegend Group rests unconformably upon the Limburg Group and is overlain conformably by the Zechstein Group (Map 3) or, in the extreme southwest, unconformably by the Rijnland Group (Map 19). Immediately to the east of the map sheet area, the group rests unconformably upon the Lower Rotliegend Group; this may possibly also be the case in the southeast of the map sheet area. The group is absent in the Ems Low and on the Dalfsen High. The depth of the base of the group ranges from under 2000 m in the west to over 4000 m in the centre and northeast of the map sheet area (Map 2).

The group reaches its greatest thickness, over 200 m, in the north and to the east of the map sheet area. In the greater part of the area, the thickness is under 50 m (fig. 6.1).

Figure 6.1 Thickness map of the Upper Rotliegend Group in the map sheet area, based on wells. The claystones of the Ten Boer Member only occur in the north of the map sheet area. Data from the adjacent area of Germany have been taken from Lokhorst (1998).



6.1.1 Slochteren Formation

The Slochteren Formation consists of purple to reddish-brown and yellowish-grey sandstones and conglomerates with thin intercalations of reddish-brown and grey silty claystones. In the north of the map sheet area, the uppermost part of the Slochteren Formation grades latterally into the silty claystones of the Silverpit Formation.

The thickness of the Slochteren Formation increases in a northerly direction from a few metres in the south to over 180 m in the north. The increase in thickness occurs relatively rapidly within a narrow zone (fig.6.1). This line coincides with the aforementioned lithological transition in the uppermost part of the formation (fig. 6.2).

In the north of the map sheet area, on a basis of lithology and log pattern, three informal units can be distinguished within the Slochteren Formation, referred to as A, B and C (fig. 6.2). Unit A comprises sandy conglomerates, poorly sorted and strongly cemented with quartz and carbonates, containing moderately rounded pebbles up to a few cm in size. The grain size in this unit decreases upwardly, with increasing intercalations of sandstone and claystone layers. The composition of the rock fragments indicates a hinterland with sedimentary as well as metamorphic and granitic rocks (Van Rossum, 1978). The conglomerate at the base contains notably little clay. Unit A varies in thickness from 50 m in the northwest to 20 m in the northeast of the map sheet area.

Unit B consists of an alternation of poorly to moderately-sorted sandstone with a few intercalated conglomerate and claystone layers, up to 1 m thick. The sandstone layers are scarcely cemented, but

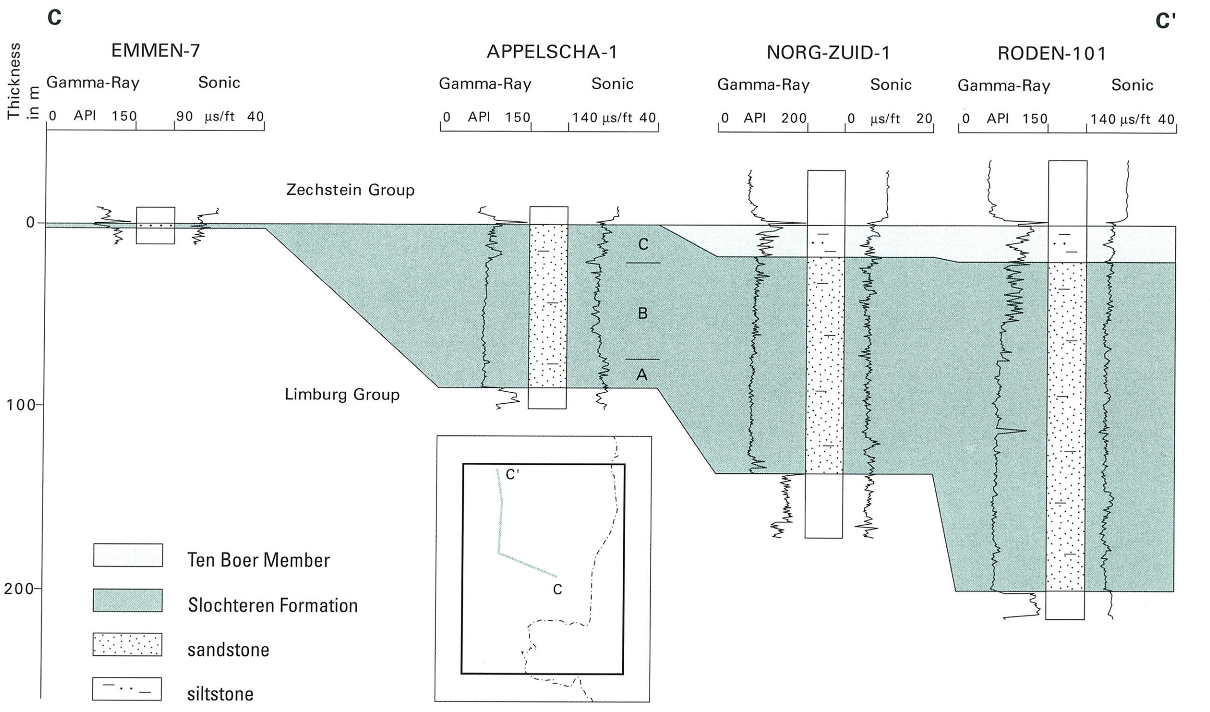


Figure 6.2 Stratigraphic section C-C' of the Upper Rotliegend Group between the Emmen-7, Appelscha-1, Norg-Zuid-1 and Roden-101 wells. The reference level is the base of the Zechstein Group. The section displays an increase in thickness in a northerly direction, where the Ten Boer Member also occurs.

early-diagenetic carbonate, kaolinite, quartz and anhydrite are found. Unit B decreases in thickness from 90 m in the west to 30 m in the east of the map sheet area.

The uppermost part of the Slochteren Formation is unit C, which forms the transition to the argillaceous facies of the Ten Boer Member. Unit C comprises a succession of claystones, moderately sorted sandstone layers and a few conglomerate layers. The thickness ranges from 50 m in the northwest to 20 m in the northeast.

In the southern part of the map sheet area, the Slochteren Formation consists only of a thin conglomerate (< 10 m). These conglomerates form the lateral equivalent of the youngest deposits of the formation.

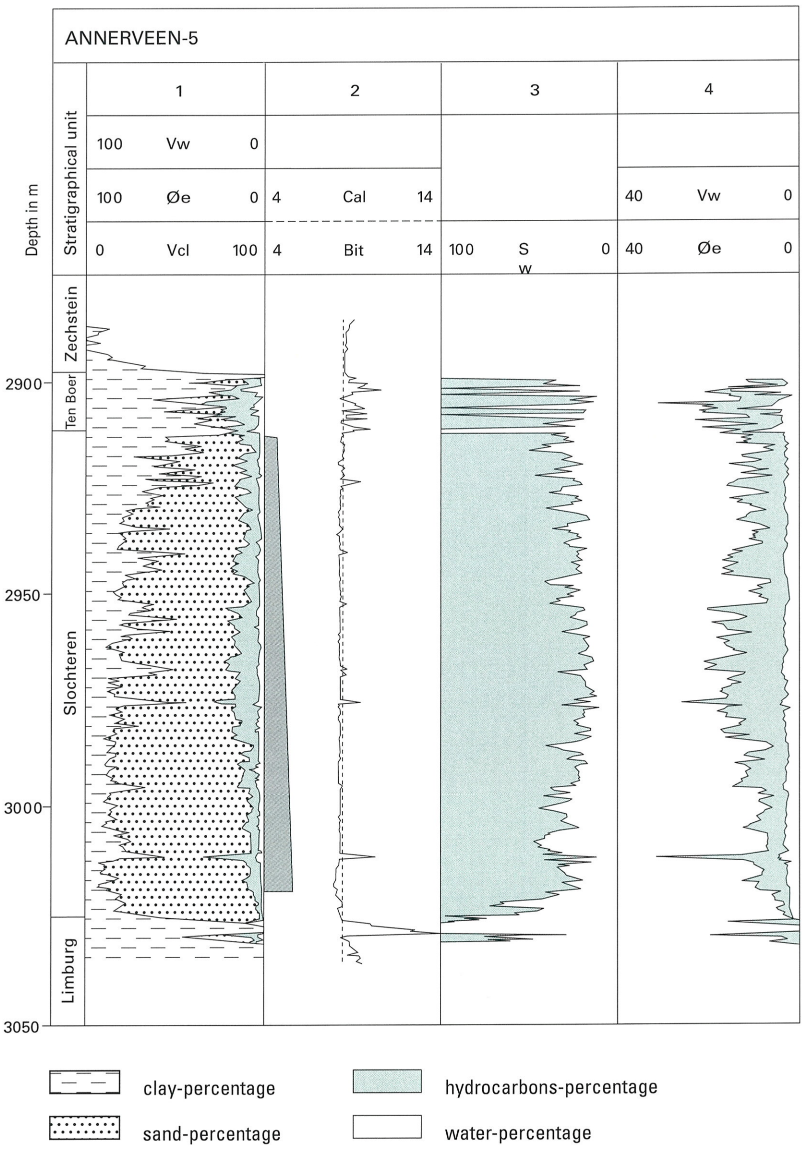
Figure 6.3 Petrophysical evaluation of the Upper Rotliegend Group in the Annerveen-5 well.

Column 1: clay content V_{cl}, effective porosity $Ø_e$ and pore volume water V_w (all given in %). The clay content was determined with the use of gamma-ray logs. The effective porosity was deduced from the sonic log, after correction for the clay content.

Column 2: borehole diameter (Cal) and bit diameter (Bit), both in inches. Furthermore, the tested interval (appendix F) is indicated here by a trapezium sign.

Column 3: water saturation S_w %. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987).

Column 4: effective porosity $Ø_e$ (left curve) and the volume of water in the pores V_w (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the true depths.



6.1.2 Silverpit Formation

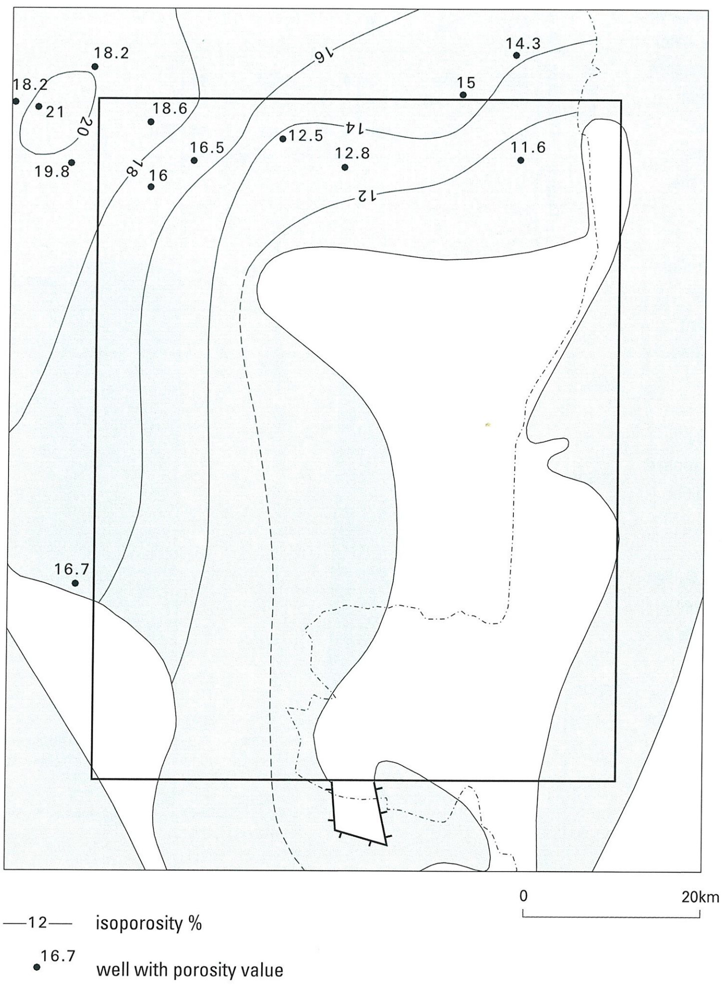
The Silverpit Formation in this area is represented by the *Ten Boer Member*. This sequence occurs at the top of the formation.

The Ten Boer Member comprises a succession of reddish-brown, sandy claystone and siltstone with thin intercalated sandstone and siltstone beds. The member is found to the north of the line Smilde-Blijham and in the map sheet area achieves a thickness of approximately 20 m (fig. 6.2).

6.2 Sedimentary development and palaeogeography

The deposits of the Upper Rotliegend Group constitute the erosional products of a Variscan hinterland. The conglomerates and sandstones of units A and B of the Slochteren Formation were deposited by braided rivers systems, wadis and sheetfloods on the margin of the Ems Low. Deposition of poorly sorted, conglomeratic thick sandstone layers followed intense, brief periods of precipitation in a warm climate. The deposits indicate mass transport of sand and gravel within a proximal fluvial range.

Figure 6.4 Schematic contour map of the average effective porosity of the Upper Rotliegend Group (appendix E).



Fine-grained sediment was transported, in suspension, further downstream, where it was deposited on the vast flood plains on the margin of the playa lake situated more to the north. The direction of flow of the fluvial systems and wadis in the map sheet area is predominantly northwards (Van Wijhe et al., 1980). The Ten Boer Member represents predominantly lacustrine sediments, deposited during periods of high stand in the playa lake. The interfingering of the Slochteren and the Silverpit Formations was caused by climatologically determined differences in the water level of the playa lake.

6.3 Petrophysical evaluation

The sandstones of the Upper Rotliegend Group form a major reservoir rock in the northern part of the map sheet area. A petrophysical evaluation of 13 boreholes of the Upper Rotliegend Group has been carried out on the reservoir rocks of the map sheet area. Appendix E contains reservoir calculations of effective porosity percentages for the entire group and for the Slochteren Formation in particular. In 10 boreholes, the group was found to be gas-bearing (appendix F). Figure 6.3 shows the petrophysical evaluation for the Annerveen-5 well.

The distribution of effective porosity of the Upper Rotliegend Group in the map sheet area displays an increase in porosity in a northwesterly direction, from 11% to over 20% (fig. 6.4). According to Van Rossum (1978), this increase reflects an improvement in the sorting of the sands. In the south, the sandstones are immature with a significant clay and gravel content. Petrophysical evaluations have not been carried out here, but, in line with the relation posited by Van Rossum (1978), a further decrease in the porosity may be expected.

7 Zechstein Group

7.1 Stratigraphy

The Zechstein Group within the map sheet area is of Late Permian age and consists of five evaporite cycles, the Z1 (Werra) to Z5 (Ohre) Formation and a sealing claystone, the Zechstein Upper Claystone Formation. The bases of the formations are characterised by transgressions.

In a large part of the map sheet area, the Zechstein Group rests conformably upon the Upper Rotliegend Group. However, in the Ems Low, the group rests locally unconformably upon the Lower Rotliegend or upon the Limburg Group (Maps 1 & 2). The Zechstein Group is conformably overlain by the Lower Germanic Trias Group (Map 6) and in the southwest and above salt structures, unconformably by the Niedersachsen, the Rijnland, or the Chalk Groups or by the North Sea Supergroup (Maps 18,19 & 20).

The base of the group is severely disrupted, its depth within the map sheet area varying from less than 2000 m in the west to over 5000 m in the east (Map 3). The depth of the top demonstrates major differences in relief initiated by salt structures (Map 4). The group varies in thickness from 300 to over 3000 m locally (Map 5). In the map sheet area, the thickness development of the group has been strongly influenced by salt flows. Halokinetic displacement of the Zechstein salt has had a considerable influence on the structural development of the map sheet area. This is discussed in detail in section 14.4.

The composition of the group is illustrated by a stratigraphic correlation section (fig. 7.1).

7.1.1 (Werra) Formation

The Z1 (Werra) Formation is composed of the Coppershale, the Z1 Carbonate, the Z1 Anhydrite and the Z1 Salt Members.

The *Coppershale* is an approximately 1-m thick, bituminous, fine-laminated brownish-black shale at the base of the Zechstein Group with a characteristic high peak on the gamma-ray log.

The *Z1 Carbonate* is a greyish-brown, dolomitic limestone with claystone intercalations, approximately 1 to 15 m thick and occurs throughout the map sheet area. Towards the top of the Z1 Carbonate, the percentage of claystone decreases, which is reflected in a drop in the gamma-ray log reading. Anhydrite nodules are found in the uppermost part of the unit.

Th *Z1 Anhydrite* comprises a 25 to nearly 300 m thick grey anhydrite. The unit contains occurrences of calcareous layers with stromatolite laminations and anhydrite modules. In the east of the map sheet area, there are two anhydrite platforms, with thicknesses of over 200 m (fig. 7.1 & 7.2a)

The occurrence of these anhydrite platforms appears to be related to older structures, an interpretation previously posited by Van der Baan (1990). The platform situated to the north coincides approximately with the areal extent of the Lower Rotliegend Group. This platform is known as the Exloo Anhydrite Platform, and the platform further to the south as the Kloosterhaar Anhydrite Platform. On the last-mentioned platform, the intercalation of the Z1 Salt subdivides the member into the *Z1 Lower Anhydrite* and the *Z1 Upper Anhydrite*.

The *Z1 Salt* predominantly consists of halite, as well as a few thin anhydrite beds. The salt only occurs in the southern part of the map sheet area (fig. 7.2a) where it achieves a maximum thickness of approximately 90 m. Locally, on the northern margin of the Kloosterhaar Anhydrite platform, the salt is present as a salt layer several metres thick (inter alia, Schoonebeek-313)

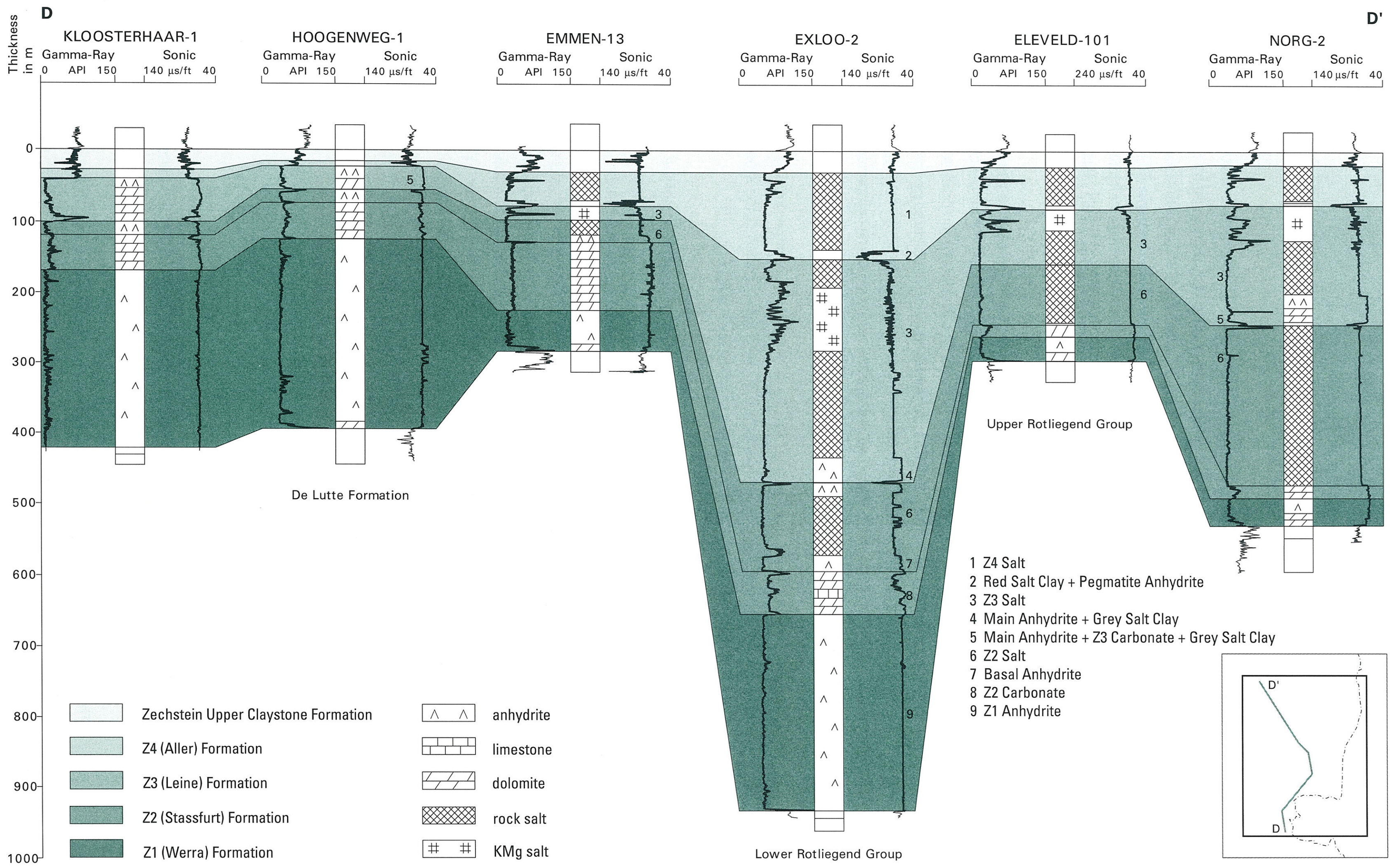


Figure 7.1 Lithostratigraphic correlation section D-D' of the Kloosterhaar-1, Hoogenweg-1, Emmen-13, Exloo-2, Eleveld-101 and Norg-2 wells.

7.1.2 (Stassfurt) Formation

The Z2 (Stassfurt) Formation is composed of the Z2 Carbonate, Z2 Basal Anhydrite, Z2 Salt and Z2 Roof Anhydrite Members.

The *Z2 Carbonate* (Main Dolomite) displays a great variation in thickness and composition within the map sheet area. The thickness pattern of the member is strongly influenced by the thickness development of the Z1 Anhydrite Member. The Z2 Carbonate Member is thickest on the slopes of the anhydrite platform. On the palaeo-platform itself, the thickness is just under 50 m, decreasing to less than 20 m to its north. The maximum thickness, over 190 m, is reached in the southeast of the map sheet area (fig. 7.2b). This thickness pattern can be mapped in detail on 3D seismics and facies information subsequently extrapolated (Van de Sande et al., 1996).

The Z2 Carbonate Member displays a considerable variation in lithological composition. In the northern part of the map sheet area, where the unit is less than 10 m thick, the member consists of a dark coloured, laminated, fine-grained dolomite with a high content of organic material. On the flanks of the anhydrite platform, the member consists predominantly of light coloured grainstones and boundstones with occurrences of oolitic and bioclastic intercalations (Clark, 1986; Van der Baan, 1990; Sannemann et al., 1978). On the platform itself, the unit is characterised by bioclastic components of bivalves and stromatolites; anhydrite is also found in the member.

The *Z2 Basal Anhydrite* is composed of a white to beige massive anhydrite. The thickness of this anhydrite in the map sheet area is less than 10 m, with the exception of the Kloosterhaar and the Exloo Anhydrite Platform, where the unit reaches a thickness of over 20 m.

The *Z2 Salt* is present throughout the map sheet area, with the exception of the extreme southwest (fig. 7.3a). Towards the north, the primary salt thickness increases from some tens of metres to over 700 m. However, this trend is strongly disrupted owing to salt flow (see section 14.3).

In the south, the Z2 Salt Member consists predominantly of light-grey, occasionally coarse-crystalline halite, a maximum of 40 m thick. At the top, thin (maximally 2 m thick) potassium-magnesium salt layers occur. The KCl content is over 18% (Brueren, 1959). In central and northern parts of the map sheet area, the salt reaches thicknesses of 500 to 700 m. Within the Z2 Salt Member, three cycles can be distinguished, separated by 1-2 m-thick polyhalite layers (Geluk, 1995). Polyhalite ($K_2Ca_2Mg(SO_4)_4 2H_2O$) can be clearly identified on well logs by its high natural radioactivity in combination with a high acoustic velocity. At the top of the member, potassium-magnesium salts are found, 10 to 25 m thick. These are the equivalent of the *Kaliflöz Stassfurt* in Germany. These layers are found in the major part of the map sheet area (fig. 7.3a).

The *Z2 Roof Anhydrite* consists of grey anhydrite, 1 to 12 m thick.

7.1.3 Z3 (Leine) Formation

The Z3 (Leine) Formation is subdivided into the Grey Salt Clay, the Z3 Carbonate, the Z3 Main Anhydrite and the Z3 Salt Members.

The *Grey Salt Clay* consists of a 1 to 8 m thick grey dolomitic claystone. This unit, with a characteristic high reading on the gamma-ray log, is highly suitable for regional correlations.

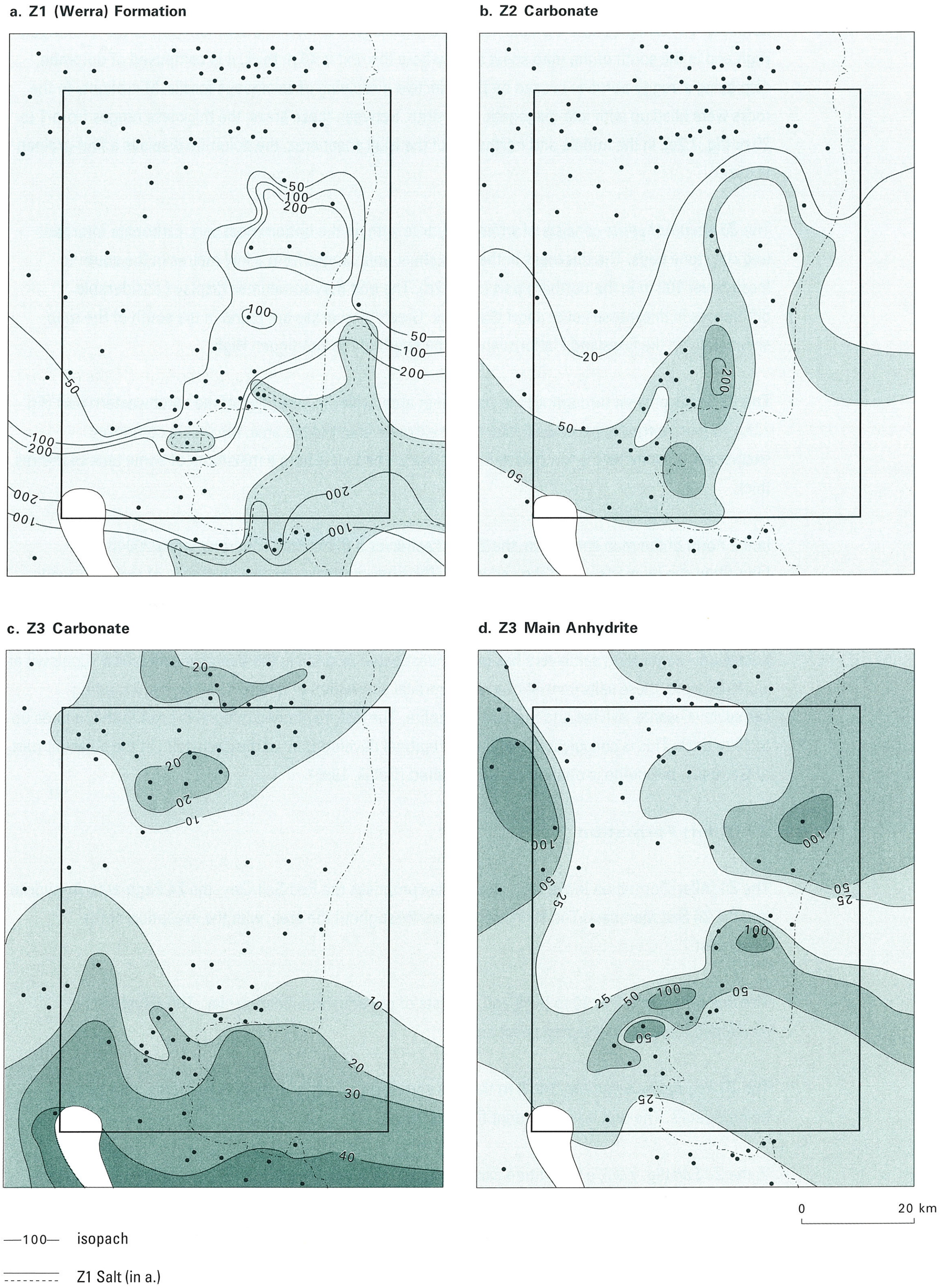


Figure 7.2 Thickness maps and platform development of (a) Z1 (Werra) Formation, (b) Z2 Carbonate, (c) Z3 Carbonate and (d) Z3 Main Anhydrite. Zechstein members have difference depocentres. Data for Germany have been derived from Baldschuhn et al. (1999).

The *Z3 Carbonate* (Platy Dolomite) is composed of a beige to light brown, strongly laminated, micritic dolomite. The Z3 Carbonate Member reaches a thickness of 25 m in the southern part of the Groningen High and in the south of the map sheet area, where the unit is 40 m thick, it is composed of dolomite, displaying a vuggy porosity caused by the selective dissolving of calcareous fossils. Microfaults in the rocks were filled up with late-diagenetic anhydrite. Between these areas, the thickness ranges from 1 to 20 m (fig. 7.2c). In the middle and northwest of the map sheet area, the dolomite displays a fine-grained texture

The *Z3 Main Anhydrite* consists of white anhydrite with, in the bottommost part, carbonate interbeds and claystone beds. The thickness in the map sheet area ranges from a few metres in the south to locally over 100 m in the northern part (fig. 7.2d). The unit may sometimes display considerable differences in thicknesses over short distances. Great thicknesses are found in the south of the map sheet area, on the Friesland Platform and to the south of the Groningen High.

The *Z3 Salt* is present throughout the map sheet area, with the exception of the southwestern part (fig 7.3b). In the Central Netherlands Basin, in the extreme south of the area, the unit is composed exclusively of halite with a few thin anhydrite beds. The unit is here a maximum of some tens of metres thick.

In the north of the map sheet area, the Z3 Salt achieves a thickness of approximately 200 m. A bipartition can be made within the sequence. The bottommost part consists mainly of rock salt, while the uppermost part is characterised by two potassium-magnesium salt layers, with rock salt in-between. These layers are found throughout the northern part of the map sheet area. The composition of the potassium-magnesium salt layers has been investigated in detail in the Veendam salt pillow (Coelewij et al., 1978).Here, these salts consist of a rapid vertical alternation of different salt layers, including carnallite, kieserite, sylvine and the rare bischofite. The last-mentioned mineral is even found in beds up to 10 m thick. This is conspicuous within the regional development of the Zechstein; in the adjacent part of Germany, bischofite is only rarely encountered (Geluk, 1995).

7.1.4 Z4 (Aller) Formation

The Z4 (Aller) Formation in the map sheet area comprises the Red Salt Clay, the Z4 Pegmatite-Anhydrite and the Z4 Salt Members. The formation occurs throughout the area, with the exception of the southwest.

The *Red Salt Clay* is 2 to 10 m thick and consists of red anhydrite-bearing clay. The claystone is developed throughout the map sheet area.

The *Z4 Pegmatite-Anhydrite*, 1 to 5 m thick, is composed of white anhydrite and large, interbedded halite crystals. The unit is clearly identifiable on logs.

In the *Z4 Salt* (fig. 7.3c), a bipartition can be made. The lower part, up to 75 m thick, consists of a pure halite, with a potassium-magnesium-rich salt layer at the top. Overlying this is an alternation of rock salt and claystone layers. The member is 10 to 100 m thick. Where the Z4 Salt is thin, only the lower part is present.

7.1.5 Z5 (Ohre) Formation

The Z5 (Ohre) Formation in the map sheet area comprises the Z5 Salt Clay and the Z5 Salt Members.

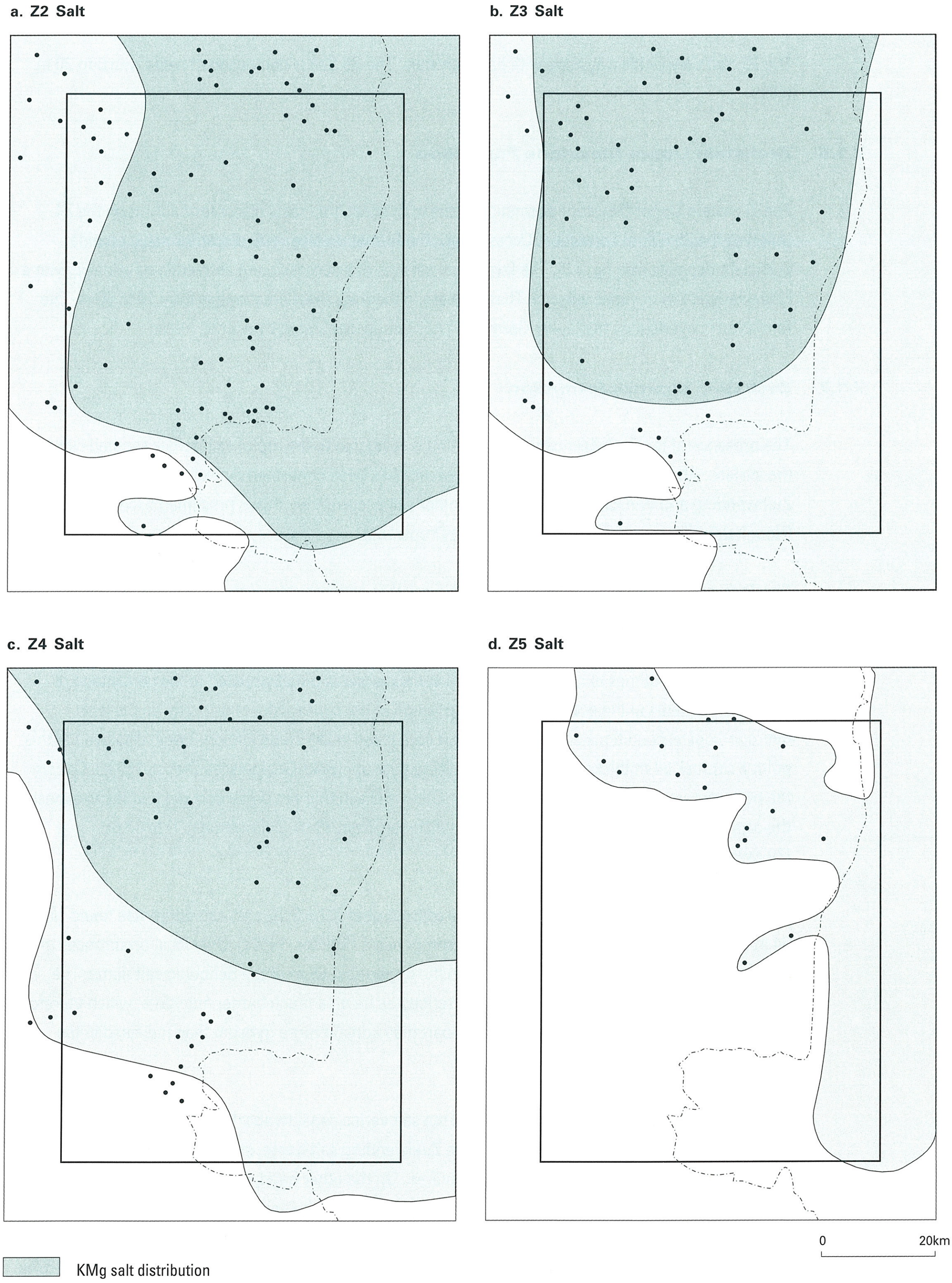


Figure 7.3 Distribution maps of (a) Z2 Salt, (b) Z3 Salt, (c) Z4 Salt and (d) Z5 Salt. The regional extent of potassium-magnesium salts is shown. Data for Germany have been derived from Best (1989).

The formation is found in the northeast of the map sheet area (fig. 7.3d).

The *Z5 Salt Clay* yields claystone with halite crystals. The *Z5 Salt* is composed of halite, van 5 to 30 m thick.

7.1.6 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation in the map sheet area rests disconformably upon the Z4 (Aller) or the Z5 (Ohre) Formation. Occasionally, the formation also rests disconformably on older Zechstein deposits (see fig. 4.3). The formation consists of a succession of anhydritic claystones, with a characteristic low acoustic velocity. The thickness in the map sheet area ranges from 10 to 50 m. The formation is overlain by the Lower Germanic Trias Group, separated by a small hiatus.

7.1.7 Zechstein caprock formation

The presence of the Zechstein caprock formation is restricted to the top of salt domes situated close to the surface. Above a number of domes, its presence has been confirmed by wells (Schoonlo, Zuidwending and Winschoten), while above other salt occurrences, this is presumed based on seismics (Hooghalen, Onstwedde, Boertange, Gasselte-Drouwen).

The Zechstein caprock formation is a residuary rock that originated from the dissolving of Zechstein evaporites. It is built up of poorly-soluble components such as anhydrite, claystone and dolomite. The aggradation of the caprock takes place on its lower surface (Battsche & Klarr, 1980). The thickness of the caprock may sometimes exhibit a pronounced variation and is directly related to the percentage of insoluble elements in the evaporite. The composition of the caprock depends partly on the local hydrogeological conditions and temperature. A core taken in the Zuidwending-9 well, displayed at this point a caprock 54 m thick, predominantly yielding gypsum (Rijks Geologische Dienst, 1993c). Only in the bottommost metres does anhydrite occur. Other wells in this salt dome showed that the thickness of the caprock may vary profoundly over a short distance, from 39 m (Zuidwending-1) to 62 m (Zuidwending-8).

In the Schoonlo-1 well, on the other hand, the caprock above the Schoonlo salt dome was found to be a 84 m-thick succession with mainly anhydrite components (Mulder, 1950a). Only local occurrences of gypsum were referred to in the description, in the uppermost 69 m of the Schoonlo salt dome. The lowest 15 m of the caprock, however, was described as being a much harder anhydrite, which therefore does not preclude the possibility that the top part may contain more gypsum than indicated in the boring record.

The contact surface between the caprock and the salt varies considerably from place to place. This is apparent within the map sheet area above the Zuidwending salt dome. In the Zuidwending-4 well, a sharp contact between both units was encountered. On the other hand, in the Zuidwending-8 well, a transitional zone a few metres thick with highly porous anhydrite sand was found, which caused considerable circulation loss. The Zuidwending-9 well, at a distance of several hundreds of metres from the previously mentioned well, only encountered the occasional decimetres-thick anhydrite sand (Rijks Geologische Dienst, 1993c).

7.2 Sedimentary development and palaeogeography

The five evaporite cycles of the Zechstein Group accumulated in a vast basin subjected to an arid

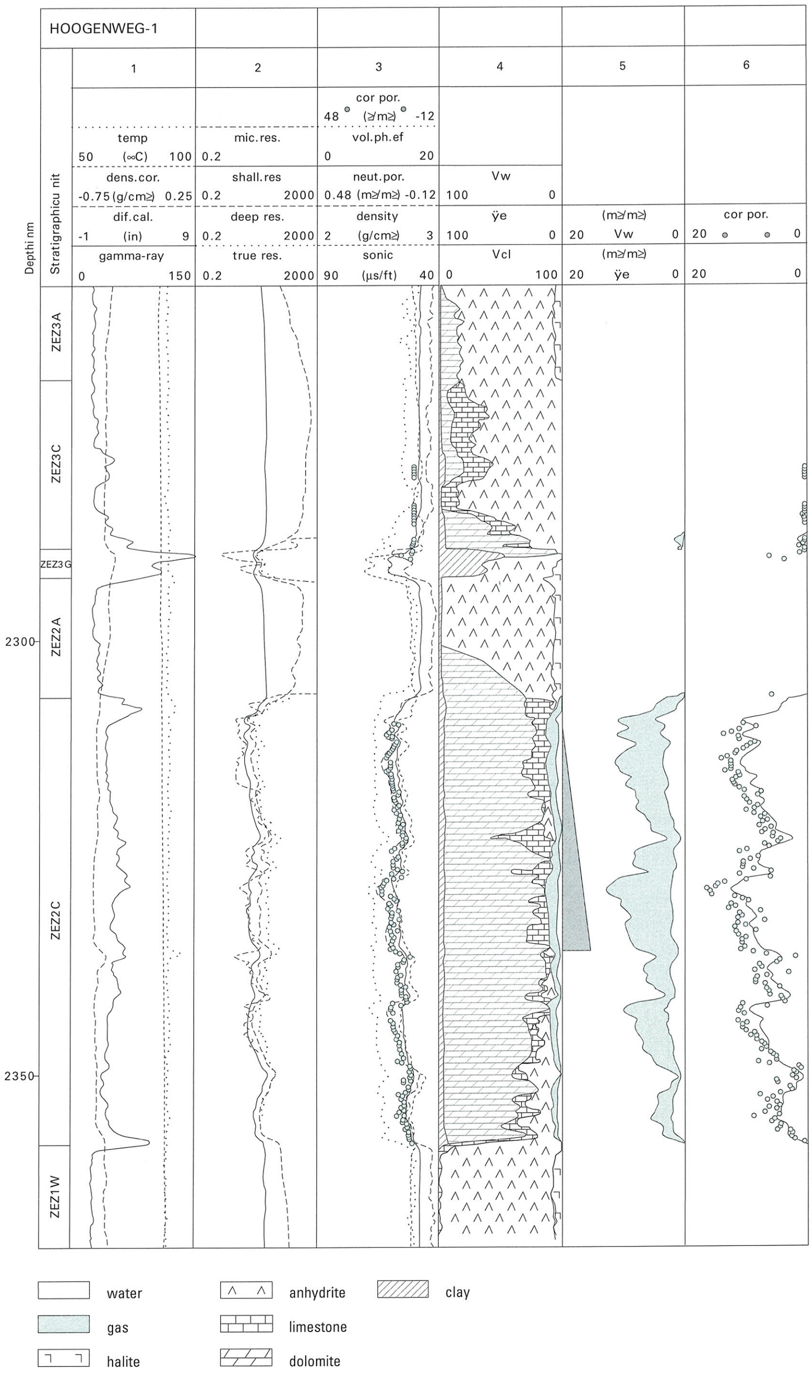


Figure 7.4 Petrophysical evaluation of the sequence of the Z2 and Z3 Carbonate in the Hoogenweg-1 well. The clay content was determined with the use of gamma-ray logs. The effective porosity and the levels of dolomite, limestone, anhydrite, halite were obtained with the use of ELAN.

Column 1 illustrates the gamma-ray log.

Column 2 shows the resistances for different penetrations depths.

Column 3 shows, amongst other data, the porosity logs neutron, density and sonic.

Column 4 gives the ELAN volumes.

Column 5: the effective porosity Øe (left curve) and pore volume water Vw (right curve) all given in percentages.
The Indonesia formula, was applied to determine the water saturation (Fertl, 1987). Furthermore, the tested interval (appendix H) is indicated here by a trapezium sign.

Column 6: the effective porosity compared with the core porosity. In the left-hand column, the boundaries of the formation are indicated. The depths are the true depths.

climate and the periodic influx of sea water. The cycles of the bottommost three formations were initiated by a repetitive succession of transgressions and regressions (Ziegler, 1990). After the third transgression, the conditions in the basin became permanently hypersaline and brief climate changes played an important role in the development of the cycles (Geluk et al., 1997; Wagner, 1994). A complete marine evaporate cycle comprises a claystone - carbonate - anhydrite - rock salt - potassium-magnesium salts - rock salt - anhydrite sequence. The younger, continental, cycles consist predominantly of claystone and rock salt.

The succession of the Zechstein Group begins with the Coppershale, which was deposited in euxinic conditions after the initial transgression (Taylor, 1998). The Z1 Carbonate was deposited in a shallow open-marine setting. Subsequently, hypersaline conditions prevailed owing to a restriction in the circulation in the basin. Sulphates were the first to precipitate in the basin. Tectonic activity was responsible for a differentiation in the palaeogeography within the area. The great thicknesses of the Z1 Anhydrite on the Exloo and Kloosterhaar Anhydrite Platform were caused by a high sedimentation rate consequent to a shallow water depth (Van der Baan, 1990). Elsewhere in the map sheet area, the depth of water was much greater and a highly condensed succession formed. The similarity between the occurrence of the Lower Rotliegend Group and the location of the Exloo Anhydrite Platform indicates a structurally determined location. Z1 Salt was only deposited in the Central Netherlands Basin, as well as, locally, in the southern part of the area (fig. 7.2a).

After the second transgression, the Z2 Carbonate was deposited. The facies model in the map sheet area encompasses a basin, a slope and a carbonate platform (Maureau & Van Wijhe, 1979; Clark, 1986; Van der Baan, 1990; Van de Sande et al., 1996; Geluk, 2000). The organic-rich dolomite in the middle and north of the map sheet area is typical of basin facies. Thick successions of massive carbonates and dolomites with slumps and turbidites are characteristic of the slope facies. The platform facies, in the south and southeast of the map sheet area, are characterised by oolites, pisolites, stromatolites, bioclasts, anhydrite nodules and limestone encrustation. They are indicative of deposition in an area with shallow water where both high and low energetic settings occurred as well as low stand and subaerial exposure.

After the carbonate deposition under normal-saline conditions, evaporites once again precipitated. The thickness development of the Basal Anhydrite took place along the margins of the Z2 Carbonate Platforms. Subsequently, the brine in the basin condensed further and thick sequences of halite remained. In this sequence, a few cycles can also be identified indicating the periodic influx of sea water and fluctuations in the concentration of the brine in the basin (Geluk, 1995). Towards the end of the deposition of the Z2 Salt, the concentration of the brine increased further and potassium-magnesium salt layers were deposited. The great regional distribution of these salts indicates that the basin did not dry out completely.

With the transgression of the Z3 (Leine) Formation, a thin succession of claystones was deposited throughout the area. In the area between Annerveen and Assen, and in the southwest of the map sheet area, two carbonate platforms developed, composed of fine-grained dolomites with large bioclastic components. The Z3 Carbonate in the south and the north of the map sheet area was deposited in a shallow-marine setting. During deposition of the Main Anhydrite Member, platforms occurred in large parts of the map sheet area where the anhydrite was able to achieve considerable thicknesses.

The Z3 Salt was deposited in the greater part of the map sheet area. During deposition of the Z3 Salt, the map sheet area constituted an isolated subbasin that completely dried out. As a result, this area was characterised by deposition of the well-soluble magnesium salts (such as bischofite), not documented in other parts of the Southern Permian Basin.

Following the transgression at the beginning of the Z4 cycle, the Red Salt Clay and Pegmatite Anhydrite Members were deposited. The conditions in the basin had by now become permanently hypersaline. Initially, deposition took place in marine conditions, but during the sedimentation, conditions became increasingly more playa-like. The area of salt precipitation became steadily smaller.

Deposition of the Z5 (Ohre) Formation took place on a playa-like plain on the margin of the Southern Permian Basin in regressive conditions. During the Z5 cycle, halite was only deposited in the north of the map sheet area, thus further diminishing the differences in relief.

The deposits of the Zechstein Upper Claystone Formation rest upon the Z4 (Aller) or the Z5 (Ohre) Formation, separated by a hiatus.

7.3 Petrophysical evaluation

Ten wells of the Z2 and Z3 Carbonate have been evaluated. The majority of these wells lie in the southern part of the map sheet area, where most of the reservoirs occur. The Z3 Carbonate was evaluated in five wells in the map sheet area. To illustrate a log-evaluation of the reservoir sequence of the Z2 and Z3 Carbonate, figure 7.4 shows the results in the case of the Hoogenweg-1 well.

Core analysis data are available from 7 of the 10 selected wells in the map sheet area (Coevorden-28, Dalen-1, Emmer-Compascuum-1, Emmen-13, Hoogenweg-1, Ommen-3 and Radewijk-1). The porosities and permeabilities measured from core samples are generally low (0.5-5.6% and 0.3-1.2 mD for the Z3 Carbonate; 0.3-9.3% and 0.3-1.8 mD for the Z2 Carbonate). Appendix G gives the results of the reservoir calculations for the Zechstein carbonates. The cut-off value of the effective porosity is based on the value of 1%.

The sequences of the Z2 and Z3 Carbonates that have been evaluated consisted mainly of dolomitised platform and slope deposits. The porosity is low and permeability is based on the presence of small fractures.

The Z2 Carbonate within the map sheet area is characterised by a strong variation in the lithological column. In wells in the southern part of the area, on the platform, the reservoir consists mainly of dolomite (Emmer-Compascuum-1, Hoogenweg-1, Dalen-1, Ommen-3, Emmen-13, Kloosterhaar-1), while in the north, in the basin, the unit mainly comprises limestone (Drouwenerveen-Zuideind-1, upper part of Coevorden-28). In the transition zone between the platform and the basin, an alternation of dolomite and limestone zones is found (Eleveld-101). The unit contains a considerable amount of anhydrite in the Radewijk-1 well; this also applies to the topmost part of the member in Dalen-1 well and in the bottommost part in Coevorden-28. In both of the last-mentioned wells, the porosity is low and also displays considerable variation across the reservoir sequence.

8 Lower and Upper Germanic Trias Groups

8.1 General

The Triassic deposits, of youngest Late Permian to Norian age, consist predominantly of red and green coloured clastics and grey coloured carbonates, marls and evaporites. The deposits are subdivided into the Lower and Upper Germanic Trias Groups.

With the exception of the Dalfsen High and above salt structures, the Triassic deposits are found throughout the map sheet area. The greatest thickness, over 2200 m, is reached in the Ems Low (Map 7). Prominent thickness differences are associated with the Holsloot Fault Zone and the Ems Low boundary fault. On the Friesland Platform, the thickness is strongly reduced owing to subsequent erosion. The deposits rest conformably on the Zechstein Group and are unconformably overlain by the Altena, the Niedersachsen or the Rijnland Group, or by the North Sea Supergroup (Maps 18, 19 & 20).

The depth of the base of the Triassic ranges from less than 1300 m on the Friesland Platform to over 4200 m in the Lower Saxony Basin. The structure of the base of the Triassic is dominated by a number of ENE-WSW trending synforms and antiforms (Map 6). In comparrison with the base of the Zechstein and Altena Groups, the base of the Triassic deposits is less severely faulted (compare Maps 3, 6 and 8). The lithostratigraphic succession of the Triassic is illustrated by two stratigraphic sections (fig. 8.1 & 8.3).

8.2 Lower Germanic Trias Group

8.2.1 Stratigraphy

Within this group in the map sheet area, four formations can be distinguished, the Lower Buntsandstein, the Volpriehausen, the Detfurth and the Hardegsen Formations. The first-mentioned formation is composed predominantly of claystones and siltstones, the other formations of an alternation of sandstones and claystones. The last-mentioned formations are referred to in combination as the Main Buntsandstein Subgroup (fig. 8.1). Within the group, minor unconformities occur at the base of the Volpriehausen and Detfurth Formations, which may well have caused some tens of metres of erosion locally (Geluk & Röhling, 1997, 1999).

The Lower Germanic Trias Group, of Late Permian to Scythian age, rests conformably on the Zechstein Group, and is unconformably overlain by the Upper Germanic Trias (fig. 8.3), the Niedersachsen or the Rijnland Group, or by the North Sea Supergroup (Maps 18, 19 & 20).

8.2.2 Lower Buntsandstein Formation

This formation is composed of the Main Claystone and the Rogenstein Members (fig. 8.1). The formation is overlain by the Main Buntsandstein Subgroup via a sharply defined boundary marking a minor unconformity, or unconformably by the Upper Germanic Trias, the Niedersachsen or the Rijnland Group, or by the North Sea Supergroup. The formation has a highly uniform thickness and lithology and its transparent character makes it clearly identifiable on seismic sections. The thickness increases in a northeasterly direction to approximately 350 m (fig. 8.2a).

The *Main Claystone* is composed of a cyclical succession of 20 to 35 m-thick, fining-upwards clay-siltstone sequences, with thin fine-grained sandstone beds at the base. Towards the south of the map sheet area, these sandstone beds increase in thickness. The cyclical repetition is well correlatable on a regional scale in the northern Netherlands and western Germany and gives a highly uniform picture

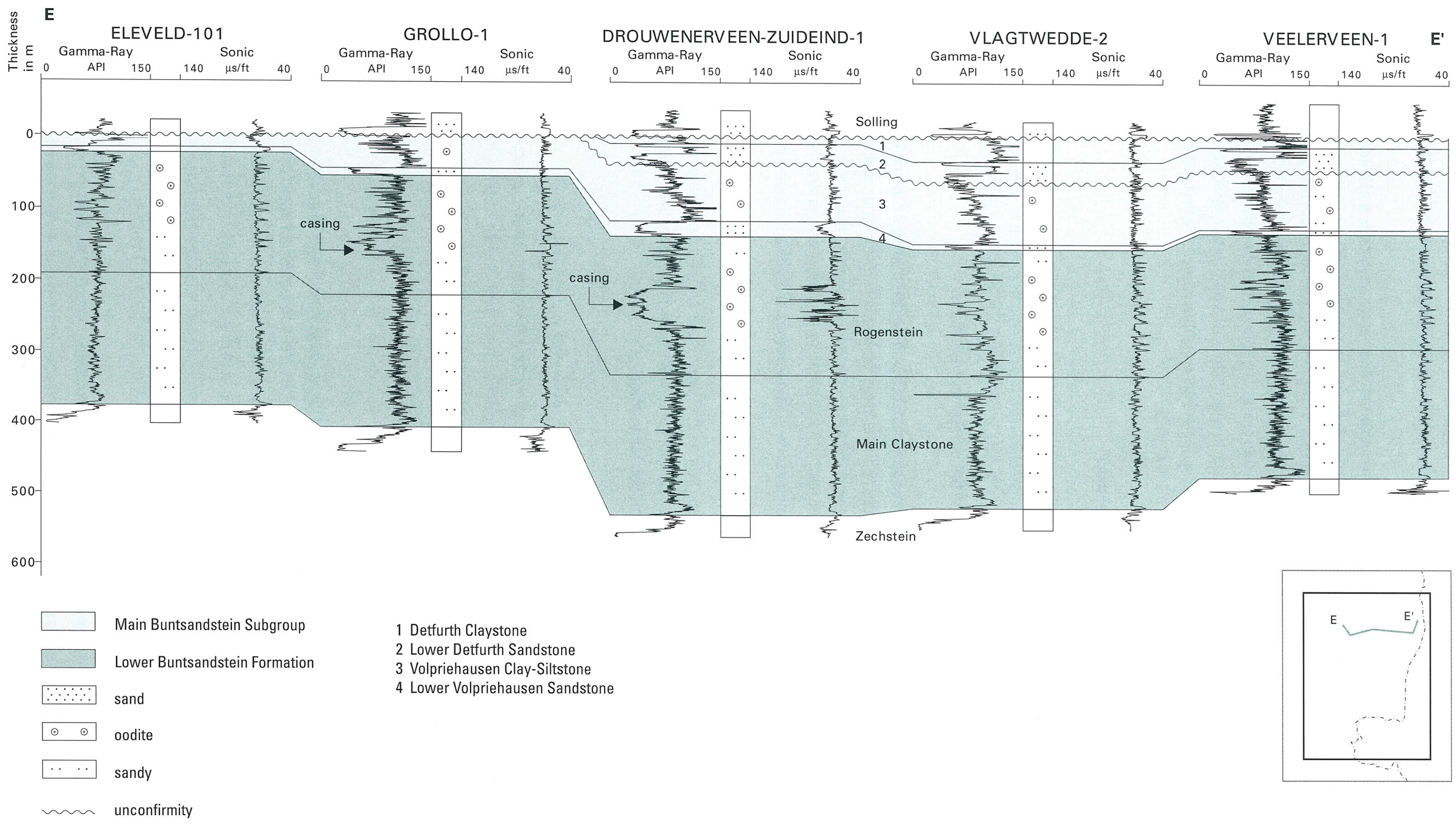


Figure 8.1 Stratigraphic section E-E' of the Lower Germanic Trias Group between the Eleveld-101, Grollo-1, Drouwenerveen-Zuideind-1, Vlagtwedde-2 and Veelerveen-1 wells. This section displays the thickening of the Main Buntsandstein towards the east, and the unconformable Solling Formation overburden. The reference level is formed by the base of the Solling Formation.

(Geluk & Röhling, 1997, 1999). The thickness of the complete member is 150 to 200 m.

The *Rogenstein* consists of red and green coloured fine-sandy claystones and siltstones with abundant mica and oolite beds. The member also consists of a cyclical succession of coarser and finer deposits but, in contrast to the Main Claystone, displays frequent occurrences of oolites, giving the sequence its characteristic appearance on well logs. The oolite beds are characterised by a low gamma-ray value and high acoustic velocity (fig. 8.1). Desiccation cracks are abundant in the fine-grained deposits. Approximately 75 m above the base, four to six characteristic beds occur, which can be identified throughout the area. In the De Wijk field, the oolites constitute one of the productive units (Bruijn, 1996; Gdula, 1983). The member is 150 to 200 m thick.

8.2.3 Main Buntsandstein Subgroup

This subgroup consists of an alternation of claystone, siltstone and sandstone. The subgroup thickens in an easterly direction from approximately 50 m in the extreme northwest to over 300 m immediately to the east of the map sheet area (fig. 8.2b). Within the subgroup, three formations can be distinguished, the Volpriehausen, the Detfurth and the Hardegsen Formations

The difference in the thickness of this subgroup is primarily determined by the degree of erosion prior to deposition of the Solling Formation, and, to a lesser degree, by erosion prior to deposition of the Detfurth Formation. In the Ems Low, in the east of the map sheet area, this erosion was the slightest and all the formations are present; in the west, the erosion was the most pronounced and only a part of the Volpriehausen Formation has been preserved. All the deposits of the subgroup have been eroded locally (fig. 8.2b).

The Main Buntsandstein Subgroup rests on the Lower Buntsandstein Formation separated by a sharply defined boundary marking a minor unconformity, and is unconformably overlain by the Upper Germanic Trias Group or the North Sea Supergroup.

8.2.3.1 Volpriehausen Formation

The Volpriehausen Formation is subdivided into the Lower Volpriehausen Sandstone and Volpriehausen Clay-Siltstone Members. The formation rests on the Lower Buntsandstein Formation separated by a hiatus, and in the northeast is unconformably overlain by the Detfurth Formation and in other parts of the map sheet area by the Solling Formation. The formation reaches its greatest thickness, over 130 m, in the Ems Low, in the east of the map sheet area; towards the west of the map sheet area, the thickness has been reduced by erosion.

The *Lower Volpriehausen Sandstone* rests on the underlying formation separated by a sharply defined boundary, and is overlain by the Volpriehausen Clay-Siltstone, also separated by a sharply defined boundary. The sandstone is in general fine-grained and calcareous. The sequence thickness ranges from under 10 m in the west to, locally, approximately 35 m in the Ems Low. In the southeast of the map sheet area, the base of the member contains an extra sandstone, also known in Germany as the Quickborn sandstone (Geluk & Röhling, 1999). This sandstone is only found in a limited area (fig. 8.2c) and is characterised by clayclasts and a high content of carbonatic material.

The *Volpriehausen Clay-Siltstone* consists of a cyclically composed sequence of red, fine-sandy clay-siltstone consisting of red to green fine-grained sandstone beds. The sandstone beds may contain oolites. The unit rests with a sharply defined boundary on the Lower Volpriehausen Sandstone and is

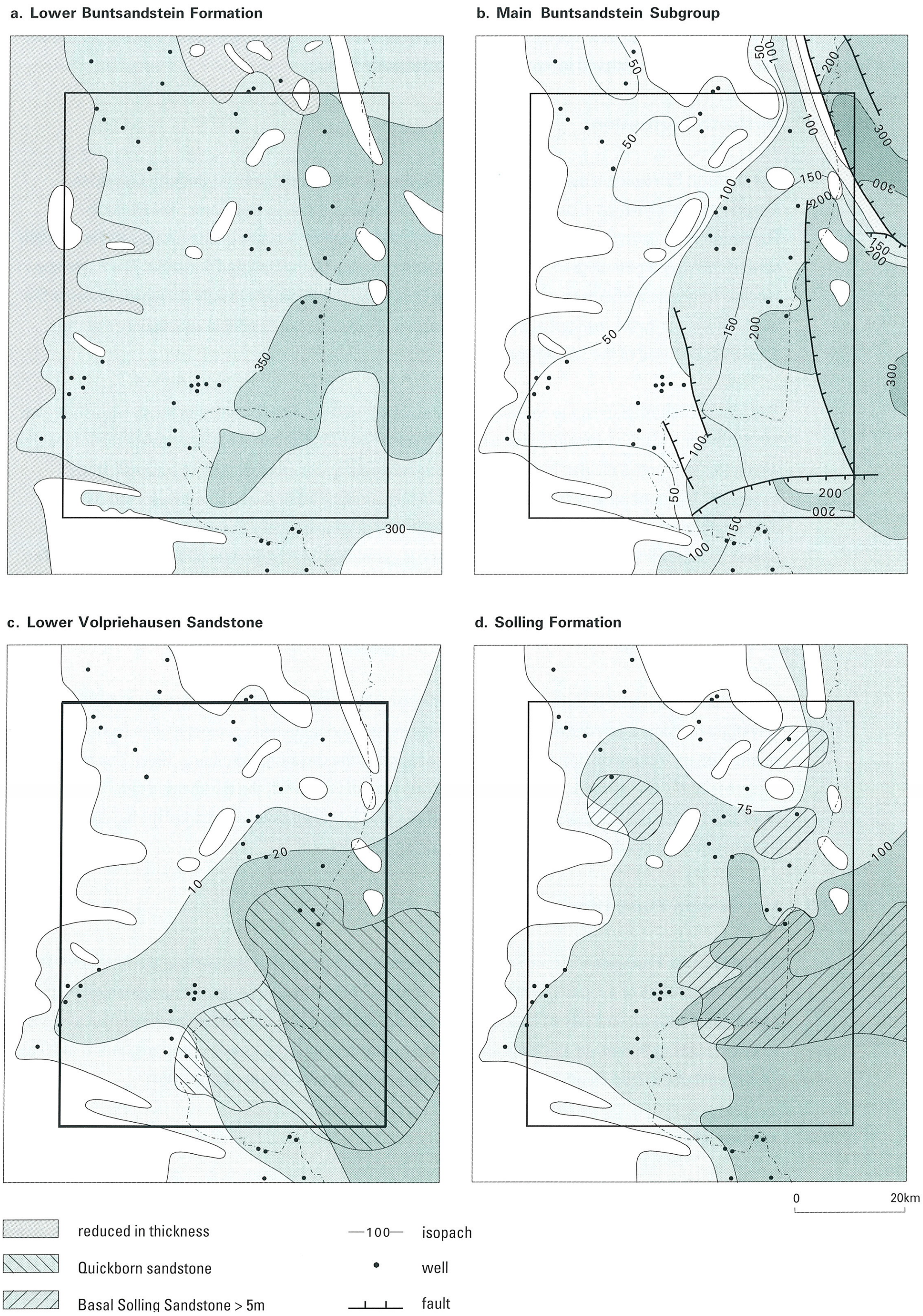


Figure 8.2 a. Thickness map of the Lower Buntsandstein Formation; b. Thickness map of the Main Buntsandstein Subgroup. c. Thickness map of the Lower Volpriehausen Sandstone; d. Thickness map of the Solling Formation. Data for the German part have been derived from Baldschuhn et al. (1999).

unconformably overlain by the Lower Detfurth Sandstone or by the Solling Formation. The most complete succession, over 120 m, has been preserved in the Ems Low; towards the east and south, the thickness has been reduced by erosion to approximately 50 m.

8.2.3.2 Detfurth Formation

The Detfurth Formation is subdivided into the Lower Detfurth Sandstone and Detfurth Claystone Members. The formation is present in the east and middle of the map sheet area. The Detfurth Formation rests upon the Volpriehausen Formation separated by a minor unconformity, and is overlain conformably by the Hardegsen Formation or unconformably by the Solling Formation. The formation reaches its greatest thickness, over 90 m, in the Ems Low. The thickness rapidly decreases towards the west. This is partly the result of a primary decrease in thickness, but mainly in consequence of the erosion at the base of the Solling Formation.

The *Lower Detfurth Sandstone* consists of a complex of medium-fine to coarse-grained, reddish-brown sandstone and also red coloured clay-siltstone layers. The unit displays a highly consistent composition within the area and is divided into two sandstone intervals by the intercalation of a clay-siltstone sequence. The bottommost sandstone interval (approximately 20 m thick), comprises a red coloured clay-siltstone sequence, 5 to 7 m thick. The sandstones display a blocky character on well logs, or an upwardly increasing clay content. The sandstone is cemented with carbonate, anhydrite or quartz. The 10 m clay-siltstone sequence between both sandstone intervals is reddish-brown, and contains a few thin carbonate layers. The topmost sandstone interval, 10 m thick, generally exhibits a block-like character on well logs.

The *Detfurth Claystone* is composed of fine-sandy or silty, predominantly reddish-brown claystone. The claystone contains a few beds of fine to medium-coarse sandstone beds cemented with carbonate or quartz cement. Abundant desiccation cracks are found in the claystone (Wolburg, 1961). The maximum thickness of the unit exceeds 35 m in the Ems Low; towards the west, the thickness is reduced owing to truncation of the base of the Solling Formation. The unit forms an excellent marker for log correlations on account of its characteristic, high gamma-ray log reading.

8.2.3.3 Hardegsen Formation

Deposits of the Hardegsen Formation have only been encountered in a few wells in the Ems Low. This formation consists of a rapid alternation of thin layers of medium-coarse sandstone cemented with carbonate or quartz, and silty or fine-sandy claystone. The deposits are reddish-brown and locally grey in colour. Owing to erosion, the thickness of the formation in the Ems Low is only a maximum of 25 m. To the east of the map sheet area, the thickness increases to over 200 m (Boigk, 1961).

8.3 Upper Germanic Trias Group

8.3.1 Stratigraphy

The Upper Germanic Trias Group, of Late Scythian to Norian age, is composed of four formations, namely the Solling, the Röt, the Muschelkalk and the Keuper Formations. The Solling and the Röt Formations are known in combination informally as the Upper Buntsandstein. The group is present virtually throughout the map sheet area, with the exception of the northernmost and westernmost strip (fig. 8.2d, 8.4a-d). The group rests unconformably on the Lower Germanic Trias Group and is overlain,

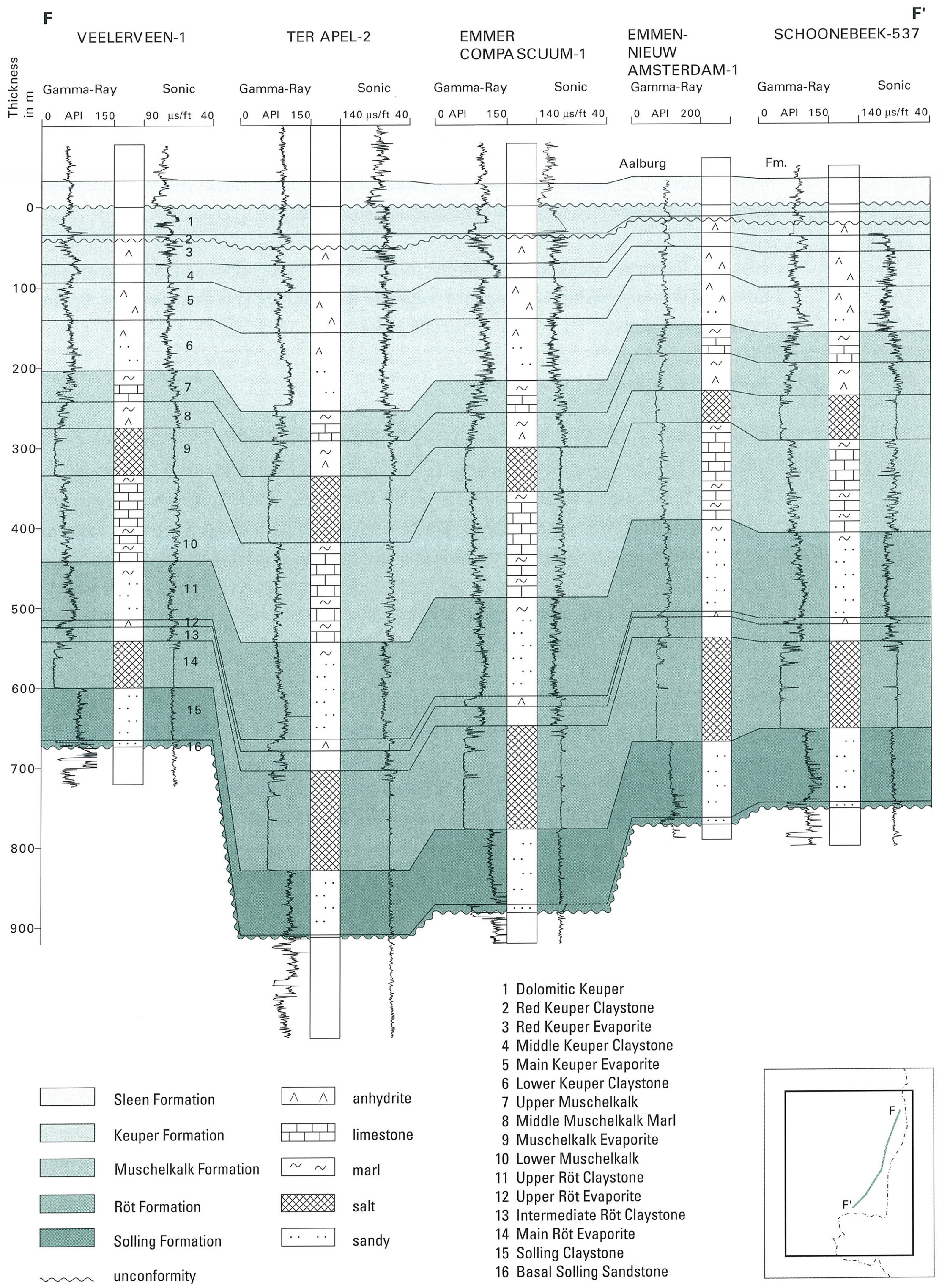


Figure 8.3 Stratigraphic section F-F' of the Upper Germanic Trias Group between the Veelerveen-1, Ter Apel-2, Emmercompascuum-1, Emmen-Nieuw Amsterdam-1 and Schoonebeek-537 wells. The reference level is the base of the Altena Formation.

conformably or unconformably, by the Altena, the Niedersachsen and the Rijnland Groups (Maps 18, 19 & 20).

The northernmost outer limit cooincides with the southern margin of the Groningen High. The greatest thickness of the Upper Germanic Trias Group, over 900 m, is reached in the Ems Low. Locally, the group may be absent in consequence of salt movements or tectonic uplift. The decrease in thickness to the north/northwest and south of the Lower Saxony Basin is largely determined by the deeper truncation caused by the erosion during the Late Kimmerian tectonic phase.

The Upper Germanic Trias Group rests unconformably on the deposits of the Lower Germanic Trias Group and is unconformably overlain by the sediments of the Altena Group or, in more westerly areas, by the Rijnland Group.

8.3.2 Solling Formation

The Solling Formation, of Late Scythian age, occurs within the areal extent of the Upper Germanic Trias Group. The formation is subdivided into the Basal Solling Sandstone and the Solling Claystone Members. The formation rests unconformably on the Main Buntsandstein Subgroup or, locally, on the Lower Buntsandstein Formation. Proceeding in an easterly direction, the Solling Formation rests upon progressively younger formations of the Main Buntsandstein Subgroup. The formation is overlain conformably by the Röt Formation or unconformably by the Rijnland Group. The formation reaches a thickness of over 110 m in the southeast of Drenthe and towards the north and west decreases to 60 m in the vicinity of the Netherlands Swell (fig.8.2d).

The *Basal Solling Sandstone* consists of a succession of one or more fine-grained sandstone layers and thin claystone layers. The sandstones have a blocky appearance on the gamma-ray log. With the exception of a few areas in the north and south, the Basal Solling Sandstone is always encountered in the formation. The thickness of the sandstone ranges from a few metres to 15 m. The greatest thickness is achieved in the southeast of the map sheet area. This occurrence links up with an area in Germany which also has thick, coarse-grained sands at the base of the Solling Formation, in this case referred to as *Döthlingen-Sandstein* (Baldschuhn et al., 1996, 1999; Beutler et al. 1992).

The *Solling Claystone* represents the largest part of the formation and consists of reddish-brown, sometimes green-mottled claystone. The lower parts of the member contain grey layers, which are characterised by a high gamma ray log reading. In the middle part of the member, a few silty and sometimes sandy layers are found. The claystone also contains anhydrite concretions. The Solling Claystone reaches a maximum thickness of just over 90 m.

8.3.3 Röt Formation

The Röt Formation, of Anisian age, is subdivided into the Main Röt Evaporite, the Intermediate Röt Claystone, the Upper Röt Evaporite and the Upper Röt Claystone Members.

The Röt Formation occurs within virtually the entire areal extent of the Upper Germanic Trias Group. The greatest thickness, over 250 m, is reached in the southeastern and southern part of the map sheet area (fig. 8.4 a). The thickness decreases towards the west and the northwest and southwest.

The *Main Röt Evaporite* comprises predominantly white transparent, sometimes orange-brown halite, alternated by thin anhydrite-bearing claystone layers.

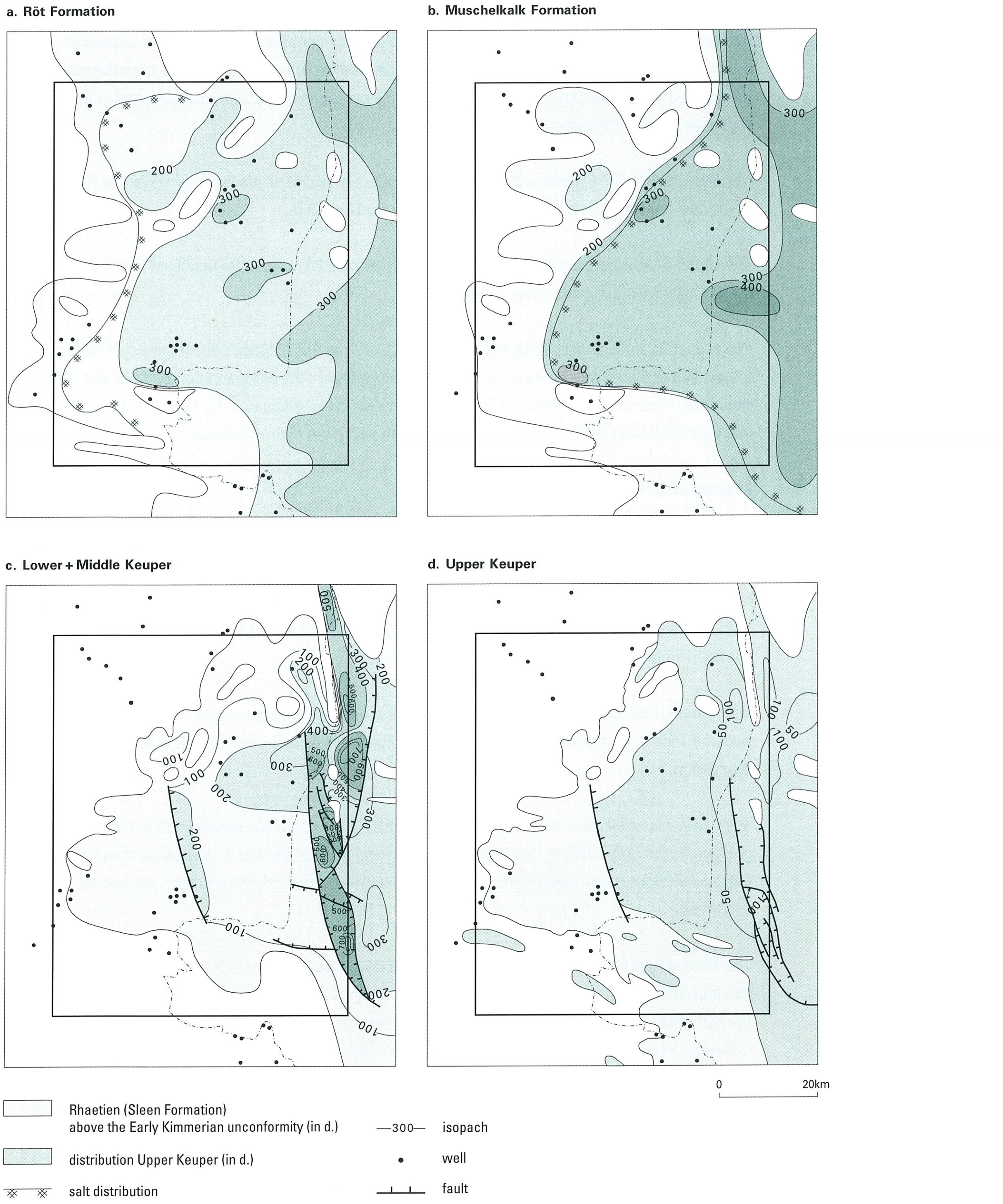


Figure 8.4 a. Distribution and thickness of the Röt Formation; b. Distribution and thickness of the Muschelkalk Formation; c. Distribution and thickness of the Lower Keuper Claystone, Main Keuper Evaporite, Middle Keuper Claystone and Red Keuper Evaporite members in the map sheet area. Data for the German part have been simplified and derived from Baldschuhn et al. (1998). d. Distribution and thickness of the Red Keuper Claystone, Dolomitic Keuper and Upper Keuper Claystone members, combined with the informal Upper Keuper unit. Data for the German part have been derived from Baldschuhn et al. (1998).

On account of this alternation, four cycles can be identified in this member, designated locally by the letters a-d (NITG-TNO, 1998). The topmost part (up to 15 m) consists of anhydrite alternated with claystone. The greatest thickness, over 180 m, is achieved in the eastern part of the map sheet area. Halite is found virtually throughout the area, with the exception of the extreme south and in the northwest, where the unit is composed of anhydrite (fig.8.4a).

The *Intermediate Röt Claystone* is composed of reddish-brown to, in places, grey claystone with the occasional anhydrite layer. The thickness ranges from 10 to 30 m.

The *Upper Röt Evaporite*, which is generally no thicker than 20 m, consists mainly of anhydrite (fig. 8.3). In the Ems Low, a thin halite layer is found.

The evaporitic series is topped by the *Upper Röt Claystone*. This sequence is composed of reddish-brown, sometimes grey, somewhat silty clay and claystone. In the basal and the topmost part of the sequence, a few anhydritic layers occur. The thickness increases towards the Ems Low, to reach a maximum thickness of over 125 metres in the southeast of the map sheet area.

8.3.4 Muschelkalk Formation

The Muschelkalk Formation, deposited during the Late Anisian to Late Ladinian, rests conformably upon the Röt Formation and is conformably overlain by the Keuper Formation or the Altena Group. The formation is composed of the Lower Muschelkalk, the Muschelkalk Evaporite, the Middle Muschelkalk Marl and the Upper Muschelkalk Members. The Muschelkalk Evaporite and Middle Muschelkalk Marl are known in combination informally as *Middle Muschelkalk*.

The formation occurs virtually throughout the map sheet area, with the exception of the westernmost part and, locally, in the north and the south (fig. 8.4b). In the east, the formation achieves thicknesses of over 300 m.

The *Lower Muschelkalk* is composed of an alternation of greyish-white limestone/dolomite beds and grey marls, the proportion of dolomite beds decreasing towards the top. In a large part of the areal extent, the thickness exceeds140 m. The thickness decreases towards the west and the northwest and southwest.

The *Muschelkalk Evaporite* consists from bottom to top of a succession of halite alternating with a few thin anhydrite and claystone layers (fig. 8.3). The member reaches its greatest thickness, over 100 m, in the part of the map sheet area situated furthest to the east. Towards the west, north and southwest, the thickness decreases and the unit is composed of only anhydrite, with a thickness ranging from 25 to 30 m.

The evaporites are overlain by the 20 to 30 m-thick *Middle Muschelkalk Marl*, consisting of light-grey, sometimes greenish to brownish-grey marls and claystone with a few andydrite beds on the base. Characteristic of the unit is the upwardly increasing gamma ray and decreasing acoustic velocity (fig. 8.3).

The topmost calcareous unit, the *Upper Muschelkalk*, is composed of an alternation of grey and greenish-grey dolomite, limestone and marl layers. The proportion of dolomite beds decreases upwardly. The base is formed by a solid dolomite bed allowing extremely good correlation, the so-called *Trochitenkalk*. The thickness of the entire unit ranges from 25 to 60 metres without a clearly observable trend.

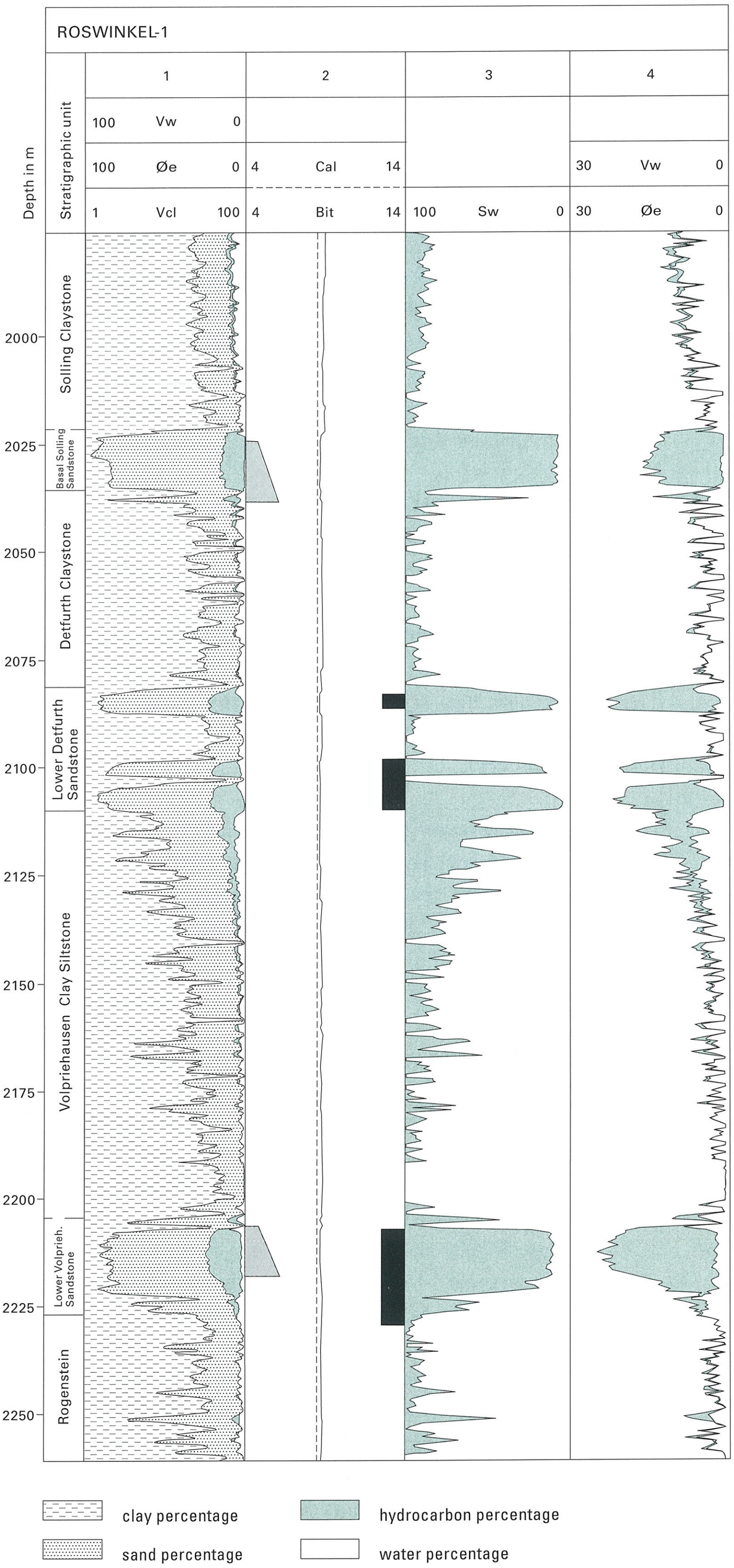
Figure 8.5 Petrophysical evaluation of the sandstones of the Lower and Upper Germanic Trias Groups in the Roswinkel-1 well.

Column 1: clay content V_{cl}, effective porosity $Ø_e$ and pore volume water V_w, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained by the use of a shaly sand model (density log/neutron log), in which the calculated log porosity was corrected for the clay and the hydrocarbons present.

Column 2: drill hole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the tested intervals (appendix J) are indicated by trapezia signs, and the cored interval by a black bar.

Column 3: water saturation S_w in percentages. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987).

Column 4: effective porosity $Ø_e$ (left curve) and the volume of water in the pores V_w (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the true depths.



8.3.5 Keuper Formation

The Keuper Formation, of Late Ladinian to Norian age, consists of an alternation of claystone and evaporite sequences. The formation is subdivided into the Lower Keuper Claystone, the Main Keuper Evaporite, the Middle Keuper Claystone, the Red Keuper Evaporite, the Red Keuper Claystone, the Dolomitic Keuper and the Upper Keuper Claystone Members.

The areal extent is restricted to the Lower Saxony Basin and the thickness increases towards the east and the southeast (fig.8.4c,d). The greatest thickness, over 1000 m, is reached in a N-S trending complex graben in the east of the map sheet area (fig.8.4c). The formation rests upon the deposits of the Muschelkalk Formation, separated by a small hiatus. In the Ems Low, the formation is overlain by the Altena Group separated by a small hiatus, and outside this area, by the last-mentioned group, unconformably. In the south and west of the map sheet area, the formation is overlain unconformably by the Rijnland Group.

The *Lower Keuper Claystone* consists of greenish-grey and reddish-brown, dolomitic claystones with anhydrite in small beds and nodules. In general, the thickness of the unit ranges from 30 to 100 m; in the Ems Low, however, the thickness is over 170 m locally.

In the eastern part of the map sheet area, the *Main Keuper Evaporite* rests upon the basal claystone sequence. This unit consists of an alternation of anhydrite and anhydritic claystone. The thickness of this unit ranges from 30 to 65 m. In the extreme northeast and to the east of the map sheet area, halite layers are found in this unit, which reaches a thickness of over 550 m in fault-bounded depressions (Frisch & Kockel, 1997).

The *Middle Keuper Claystone* is between 10 to 30 m thick in the greater part of the area. The unit comprises claystone with the occasional anhydrite layer. The claystone has a block-like character on the gamma ray log. The unit contains thin sandstone beds. In the Ems Low, the unit achieves thicknesses of 80 to over 150 m. To the south of the Groningen High, this unit rests unconformably upon the Lower Keuper Claystone (Oude Pekela-1 well); an identical observation has been made in the adjacent area in Germany (Wolburg, 1969).

The *Red Keuper Evaporite* comprises an alternation of white to pink anhydrite and grey to brown anhydritic claystone. An aspect typifying this unit is the presence of several thin anhydrite layers. The thickness generally varies from 10 to 30 m, reaching over 60 m in the northeast.

This evaporitic unit is overlain by the *Red Keuper Claystone*, whose thickness ranges from between 2 to 20 m. The thickness increases towards the south and west. In addition to red-coloured claystone, green claystone is also found. This member is of great importance in carrying out regional correlations, owing to the presence of the Early Kimmerian Unconformity at the base. The greatest thickness, over 50 m, is achieved in the Ems Low, immediately to the east of the map sheet area.

The *Dolomitic Keuper* is composed of an alternation of claystone with several anhydrite and dolomite beds. The member is characterised by a conspicuous light colour. The unit has only been found in the eastern part of the map sheet area. The thickness decreases towards the southwest. The maximum thickness is 50 m in the east of the map sheet area. In Germany, this unit, in combination with the Red Keuper Claystone, is known as the *Steinmergelkeuper*.

The *Upper Keuper Claystone* has only been encountered in the eastern part of the map sheet area. The thickness achieved here is the maximum of 20 m and a member mainly comprises grey silty claystones and marls.

The Red Keuper Claystone, Dolomitic Keuper and the Upper Keuper Claystone are differentiated in combination as the informal Upper Keuper. The thickness of these members is illustrated in figure 8.4b.

8.4 Sedimentary development and palaeogeography

The incipient influx of clastics from the south at the end of the Zechstein was prolonged in the Triassic. The Lower Germanic Trias Group was laid down in a large continental basin, which was in essence the same as during deposition of the Zechstein. During the Triassic, initially continental depositional conditions prevailed, which acquired an increasingly marine character owing to a gradual sea-level rise. The highstand reached its maximum during deposition of the Muschelkalk Formation. Tectonic movements occurred during two phases: the Hardegsen phase, which gave rise to a hiatus between the Lower and the Upper Germanic Trias Groups (fig. 8.1) and the Early Kimmerian phase, giving rise to a hiatus within the Upper Germanic Trias Group or between this group and the Altena Group.

The Lower Buntsandstein Formation consists predominantly of lacustrine deposits with a brackish water influence. The cyclical character displayed by these deposits is ascribed to climatic cycles, the so-called Milankovitch cycles, with a periodicity of 100,000 years (Geluk & Röhling, 1997, 1999). The oolites in the topmost part of the Lower Buntsandstein Formation were formed in brackish water in a high-energetic setting, during periods of low clastic influx (Peryt, 1975). The red colour of the sediments as well as the desiccation cracks reflect periods when the lake dried out.

During deposition of the Main Buntsandstein Subgroup, fluvial systems prograded episodically from the south to cover the entire map sheet area. The deposition of sands (Lower Volpriehausen Sandstone, Lower Detfurth Sandstone) thus alternated with that of fine-grained lacustrine deposits (Volpriehausen Clay-Siltstone, Detfurth Claystone). At the base of these sandstones, minor unconformities have been revealed; before the deposition of the Detfurth Formation in particular, relatively pronounced erosion occurred, which resulted in the absence of the top part of the Volpriehausen Clay-Siltstone (Geluk & Röhling, 1997, 1999).

The unconformity at the base of the Upper Germanic Trias Group (Solling Formation) is prominently present in the map sheet area. In the west, on the Netherlands Swell, the group overlies the oldest deposits of the Main Buntsandstein Subgroup, and in the Ems Low, the youngest deposits (fig. 8.2, 14.4). This group displays an alternation from a continental to a more marine depositional environment.

The Solling Formation reflects a transgression from an easterly direction. Closing of the connection with the sea and evaporation of the water present in the basin resulted in the deposition of the salt and anhydrite of the Main and Upper Röt Evaporites. These evaporites were followed by a sequence of claystones. The top part of the Röt Formation reflects the persevering transgression, with a gradual return to normal-marine conditions in the basin, demonstrated by the increase in the number of interbedded limestone beds. As a result of this transgression, the sediment source area was increasingly submerged by the sea, and the clastic sediment deposition changed over to a limestone-dominated succession of the Muschelkalk Formation. The Lower Muschelkalk was deposited in a marine to supratidal setting, while the renewed closing of the connection between the Northwest European Basin and the Tethys facilitated deposition of the Muschelkalk Evaporite and the Middle Muschelkalk Marl. Subsequently, the Upper Muschelkalk was deposited, again during normal-marine conditions.

The Keuper Formation was deposited in shallow-marine, marginal marine to evaporitic depostional conditions. During deposition of this formation, strong tectonic movements took place, which had a great influence on the facies and thickness pattern of the formation. In grabens in the northeast and immediately to the east of the map sheet area, thick salt beds were deposited, whereas beyond these grabens, a highly condensed succession of anhydritic claystones is present. The latter is characteristic of the greater part of the map sheet area.

8.5 Petrophysical evaluation

The sandstones of the Lower Germanic Trias Group form a major target for exploration in the map sheet area. During the course of the last 30 years, several gas fields in the Triassic deposits have been demonstrated both here and immediately outside the area (fig. 2.2d).

The deposits of five wells in the map sheet area have been petrophysically evaluated (appendix I). These wells are all situated in the Ems Low. In two of the wells, the sandstones of the Lower Germanic Trias Group have been found to be gas-bearing (appendix J). To illustrate a log-evaluation of the reservoir sequence of the Lower and Upper Germanic Trias Group, the Roswinkel-1 well is given (fig. 8.5).

Out of 5 selected wells in the map sheet area, core analysis data are available from only one (Roswinkel-1). Average porosities measured from core data for the Lower Volpriehausen Sandstone lie at 22% (9-28%), for an average permeability of 600 mD (12-1270 mD). In the case of the Lower Detfurth Sandstone, the average values are at 18.7% and 583 mD. The Basal Solling Sandstone in this well was strongly cemented with salt and dolomite.

The sandstones of the Upper Buntsandstein Group and the Basal Solling Sandstone have a roughly similar porosity; they all fall more or less within the range of 10 to 20%. Nonetheless, the individual sandstone sequences display notable porosity differences. Besides considerable thickness variations, the Basal Solling Sandstone also displays strong fluctuations in the average porosity, from 9.5 to 17.4%. The Lower Volpriehausen Sandstone also varies markedly in thickness, between 6 and 25 m, while the divergence in porosity is only between 15 and 21%. Besides the most constant thickness, the Lower Detfurth Sandstone shows the highest porosities, from an average of 15.8 to 24.2%. These high values are found exclusively in the bottommost sandstone sequence.

Besides the sandstones of the Lower and Upper Germanic Trias Groups, a number of other reservoir rocks also occur, with a restricted areal extent. These are the Rogenstein (Lower Buntsandstein Formation) and the Lower Muschelkalk. These units have not been evaluated owing to the local character of these reservoirs. The Rogenstein is found as reservoir rock in the De Wijk field; the best reservoirs occur in the oolite beds (max. 30% porosity and 1 Darcy permeability) and thin sandstone beds (max. 25% and 10-100 mD) at places where these rocks are situated immediately under the Late Kimmerian unconformity (Gdula, 1983). The favourable reservoir characteristics are ascribed to secondary leaching of the cement. The Lower Muschelkalk also has local reservoir characteristics, which also applies to occurrences just below the late Kimmerian unconformity. The porosity of this unit is high but the permeability is only a maximum of 26 mD (Gdula, 1983). The Lower Muschelkalk has been found to be gas-bearing in the De Wijk and the Coevorden fields.

9 Altena Group

9.1 Stratigraphy

The Altena Group, of youngest Late Triassic to Middle Jurassic age, consists predominantly of dark coloured claystones, which were deposited in a marine environment. The group is subdivided into the Sleen, the Aalburg, the Posidonia Shale and the Werkendam Formations.

Within the map sheet area, the Altena Group rests on the Upper Germanic Trias Group, separated by the Early Kimmerian unconformity in the southwestern part (fig. 8.4d). In the northern and eastern part of the map sheet area, the formation rests conformably or via a minor hiatus on the aforementioned group. The occurrence of the group is restricted to the Lower Saxony Basin (Map 8). The group achieves its greatest thickness, 1100 m, in the Ems Low. In a number of grabens in the Lower Saxony Basin, the Altena Group reaches a thickness of over 700 m (Map 9). The deposits are covered by the Niedersachsen Group and the Rijnland Group, separated by the Late Kimmerian unconformity (Maps 18 & 19). The depth of the base of the deposits ranges from 1500 m in the southwest to over 2700 m in the Lower Saxony Basin. The depth map of the base of the group is characterised by an ENE-WSW trending pattern of synforms and antiforms (Map 8).

The composition of the group is illustrated by the Vlagtwedde-2 well (fig. 9.1).

9.1.1 Sleen Formation

The Sleen Formation, deposited during the Rhaetian (Late Triassic), occurs within the entire areal extent of the Altena Group. In the Ems Low in the adjacent part of Germany, the formation may achieve thicknesses of over 100 m (Baldschuhn et al., 1999). The formation consists of grey and brown, fossil-rich claystone with locally one or more sandy sequences in the middle part. The claystone also contains pyrite concretions.

The formation is clearly identifiable by the relatively high values on the gamma-ray log and by the low acoustic velocity (fig. 9.1). In the north and east of the areal extent, the Sleen Formation rests on the Keuper Formation conformably or via a small hiatus. In the southern and western part of the map sheet area, the Sleen Formation rests unconformably on the Keuper or the Muschelkalk Formation.

9.1.2 Aalburg Formation

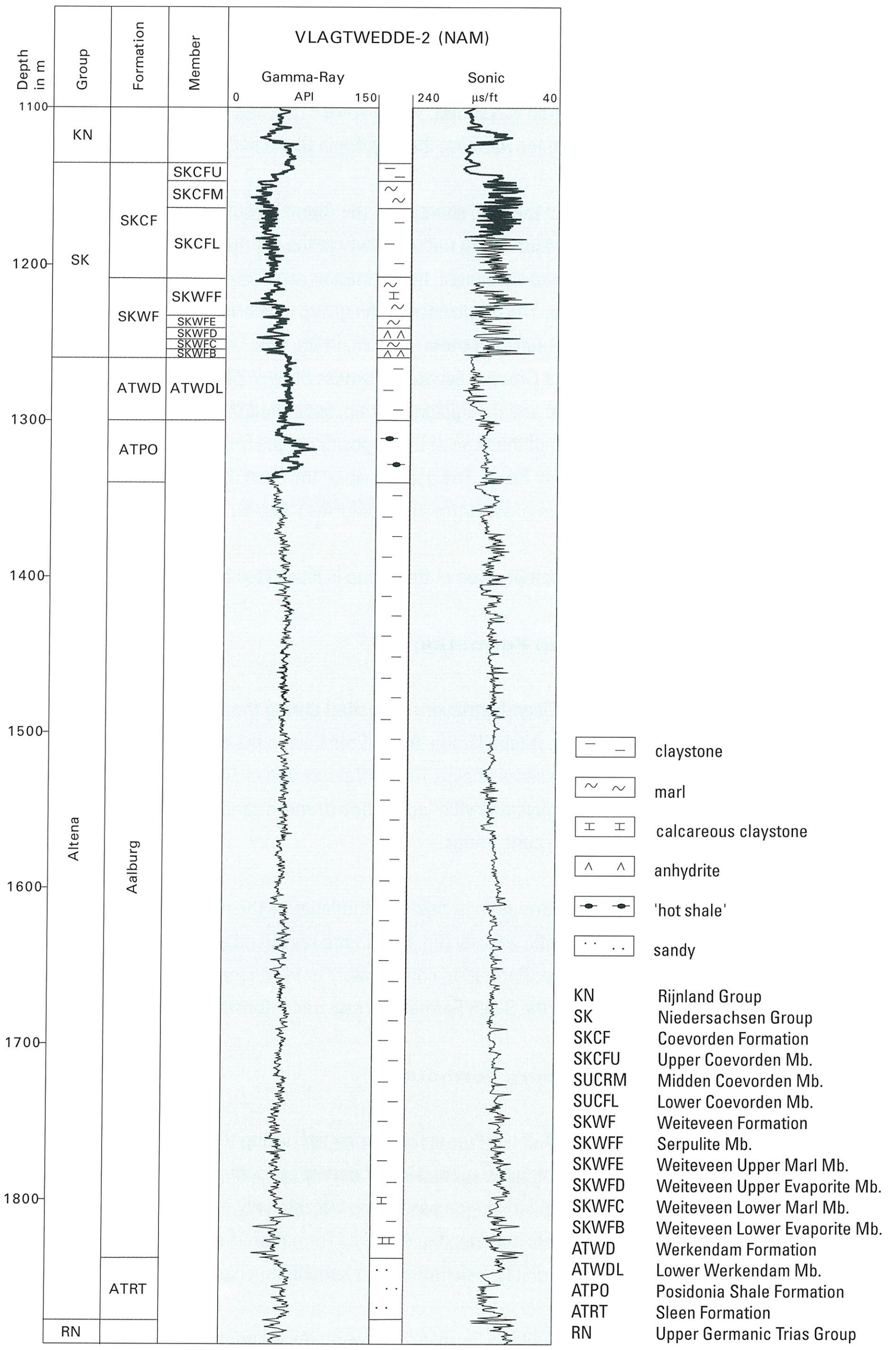
The Aalburg Formation, deposited during the Hettangian to Pliensbachian age, comprises a monotonous succession of dark-grey, pyrite-bearing claystone, which is alternated by limestone layers, particularly in the basal part. Occasionally, thin, silty to sandy layers occur, as well as layers rich in organic material (fig. 9.1). The formation is extremely fossil-rich; findings include fragments of ammonites, belemnites and lamellibranchiates as well as plant remains.

The Aalburg Formation is found throughout the areal extent of the Altena Group (Map 9; fig. 9.2). The formation is a maximum of 500 m thick in the northeast of the map sheet area where the Posidonia Shale Formation rests conformably on the Aalburg Formation.

9.1.3 Posidonia Shale Formation

The Posidonia Shale Formation, of Toarcian age, occurs only in the northeast and in the south of the map sheet area. In addition, there are abundant occurrences of the formation in the Lower Saxony Basin (fig. 9.2), where it overlies the deposits of the Aalburg Formation conformably. The thickness ranges

Figure 9.1 Stratigraphic diagram and log characteristics of the Altena Group in the Vlagtwedde-2 well.



from 20 to 40 m. The formation comprises bituminous, dark-grey claystone with pyrite concretions and plant remains. Furthermore, fish relics have also been observed. The formation constitutes a major oil-source rock in this region (Binot et al., 1991).

9.1.4 Werkendam Formation

Within the map sheet area, the basal part of the formation, the *Lower Werkendam Claystone Member*, has been preserved locally. The member was deposited during the Aalenian and the Bajocian (Middle Jurassic) and is 20 to 150 m thick. In the adjacent part of Germany, the formation has a wide areal extent in the subsurface (Meyer, 1969). The formation is overlain unconformably by the Niedersachsen Group.

The Lower Werkendam Claystone is composed predominantly of dark-grey claystone, which may be brown or green-coloured. In the most basal part of the member, the occasional bituminous layer is found. The claystone contains brown sferulites (siderite), pyrite concretions, lignite, fish remains and crinoid stalks.

Figure 9.2 Extent of the various formations within the Altena Group. The younger deposits of this group (Posidonia Shale and Werkendam Formations) are only found locally within the map sheet area, but occur on a wider scale to the east of the map sheet area. Data for the German section have been derived from Baldschuhn et al. (1991), Lokhorst (1998) and Meyer (1969).

9.2 Sedimentary development and palaeogeography

The Altena Group was deposited following a distinctive transgression during the youngest Triassic, favouring an open-marine depositional environment which extended over a large part of North Western Europe. The clays and silts of the Sleen Formation reflect brackish-water, marginal-marine to shallow-marine conditions. This was superseded by basin deepening accompanied by deposition of a thick succession of clay of the Aalburg Formation under deep-marine conditions. The monotonous, fine-grained character of the unit reveals that in the vicinity of the map sheet area, all the highs were submerged by the sea. The thin organic-rich layers indicate stagnation of the basin-floor circulation. The greatest subsidence was initiated in the east of the map sheet area. The Posidonia Shale Formation marks a major period of euxinic sedimentation. These depositional conditions were presumably caused by stratification of a warm, salt-water body from the Tethys Sea coming into contact with cold Arctic sea water in present Western Europe, during which the anoxic conditions in the deepest layer prevailed. All the organic material was preserved in the bituminous deposits (Ziegler, 1990). Open-marine conditions were again re-established during deposition of the Werkendam Formation which, in response to tectonic movements and subsequent erosion, is found only very locally.

10 Niedersachsen Group

10.1 Stratigraphy

The Niedersachsen Group, of Late Jurassic and earliest Cretaceous age (Middle Kimmeridgian to Ryazanian, or possibly earliest Valanginian), is composed of marl, claystone, evaporites and limestone. The group is subdivided into the Coevorden and the Weiteveen Formations.

The distribution of the Niedersachsen Group is mainly confined to the Lower Saxony Basin. The depth of the base ranges from over 1000 m in the southeast of the area to 2300 m in the central part (Map 10). The greatest thickness, over 650 m, is achieved in the southeasternmost part of the map sheet area (Map 11). The group is absent primarily on the Emmen-Fehndorf High, which formed an island in the Lower Saxony Basin. With in this basin, dring the deposition of the Niedersachsen Group, tectonics caused a system of E-W-oriented troughs and highs, which were to play a major part in determining the deposition of this group and the overlying Rijnland Group (Maps 10-14). The composition of the group is illustrated by the Vlagtwedde-2 well (fig. 9.1).

The Niedersachsen Group rests unconformably on the Altena Group or, locally, on the Upper Germanic Trias Group (Map 18). The group is overlain unconformably by the Rijnland Group in practically all parts of the map sheet area. Occasionally, the group is overlain by the Chalk Group, in response to fault and salt tectonism (for the vicinity of the Hoogeveen saltdome, see fig. 14.10).

In the area to the north of the Niedersachsen Basin, deposits of the Schieland Group occur locally on the Groningen High. These deposits are distinguished by the sandy character and the presence of coal seams of the Niedersachsen Group. For a description of these deposits, reference should be made to the adjacent map sheet situated to the north (Rijks Geologische Dienst, 1995).

At the southern margin olf the Lower Saxony Basin, the group was encountered in three wells, but was not seismically mappable (Map 10). This is expected also to be case at many more localities. These occurrences are expected to be patches of the group and not one continuous area.

10.1.1 Weiteveen Formation

This formation is found in the Niedersachsen Basin. The greatest thickness, over 350 m, is achieved in the extreme southeast. In the adjacent part of Germany, the formation may reach thicknesses of over 2000 m in the Georgsdorf Trough (Bischoff & Wolburg, 1963; Meyer, 1969). In the majority of the area of distribution, the thickness is less than 200 m. Above salt structures, the thickness is drastically reduced or the formation is completely absent (Map 11).

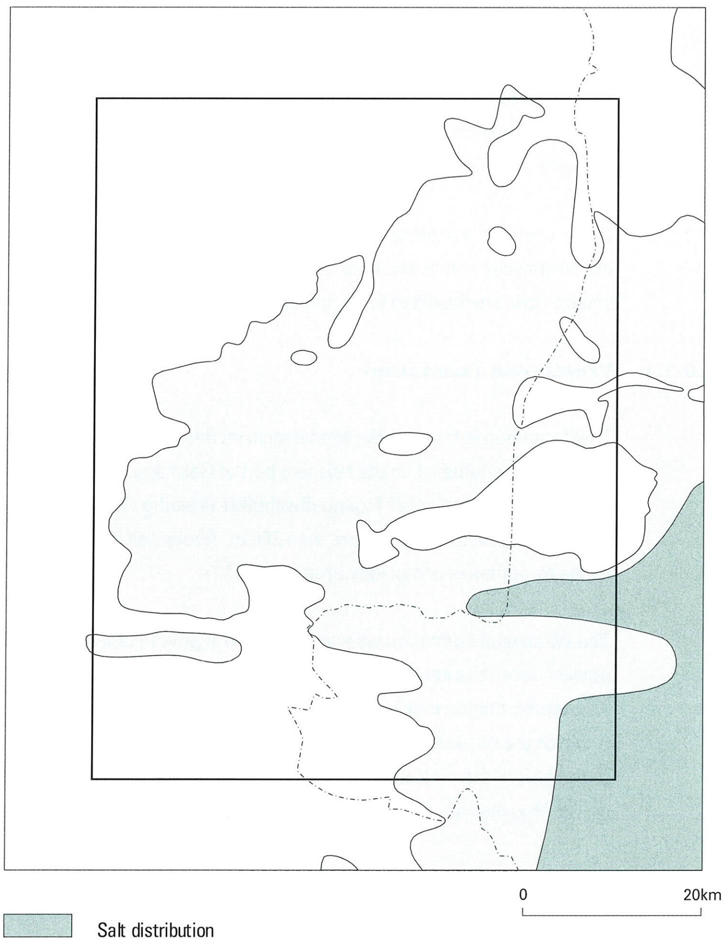
The Weiteveen Formation was deposited during the Middle Kimmeridgian to Late Portlandian or possibly even the earliest part of the Ryazanian. In most cases, the Weiteveen Formation rests upon the Aalburg Formation making an unconformable contact, and locally may also rest upon the Posidonia Shale or the Werkendam Formation, for example in the northeast close to the Dutch-German border and to the east of the map sheet area, in Germany. In the southwest, the Weiteveen Formation rests locally on the Muschelkalk or the Keuper Formation (Map 18).

Within the Weiteveen Formation, the Weiteveen Basal Clastic, the Weiteveen Lower Evaporite, the Weiteveen Lower Marl, the Weiteveen Upper Evaporite, the Weiteveen Upper Marl and the Serpulite Members can be distinguished. The lithological composition of the formation exhibits pronounced lateral variations. In the southeast, there are intercalations of evaporites which diminish in a northwesterly and westerly direction, making way for limestone intercalations. Here, the formation cannot always be unequivocally distinguished from calcareous deposits of the Triassic (Dolomitic Keuper Member) or the Aalburg Formation. In the Weiteveen Formation, six members can be differentiated; this subdivision is consistent with the subdivision of the Malm sediments described by Bischoff & Wolburg (1963) and Gramann et al. (1997) with respect to the adjacent part of Germany.

The *Weiteveen Basal Clastics* consists of variegated conglomerate, sandstone and claystone. The conglomerates exhibit a pronounced variation in composition, pointing to a local provenance. This member yields a large number of plant and wood remains. The member only occurs to the south of the Emmen-Fehndorf High, where the thickness is 5 to 20 m (Ruinen-1, Schoonebeek-197).

To the north of the Emmen-Fehndorf High, the *Weiteveen Lower Evaporite* is at the base of the formation (fig. 9.1). This member consists of an alternation of dolomitic or anhydritical claystone, anhydrite, halite and limestone. The uppermost part of the unit is generally more argillaceously developed than the basal part. The thickness of the unit increases from 25 to 100 m in the southeast of Drenthe. In a northeasterly direction, the thickness decreases to 5-10 m.

Fig. 10.1 Extent of the Niedersachsen Group. The map sheet area is situated on the western margin of the Lower Saxony Basin, where a salt basin was located. Data for the German section have been derived from Baldschuhn et al. (1991, 1999) and Schott (1950).



In the southeasternmost part of Drenthe, the evaporitic deposits prevail in this member. In a northerly and westerly direction, the proportion of evaporites decreases in favour of the carbonates. Halite deposits are only encountered in wells in the extreme southeast and in the adjacent part of Germany (Schott, 1950). Above salt structures, the proportion of anhydrite decreases. In a northerly and westerly direction, the member passes laterally into the Main Weiteveen Member.

The *Weiteveen Lower Marl* consists of bluish-grey marl, which may sometimes be anhydritical. This member is only found in the southeastern part of the map sheet area. In a northerly and westerly direction, the marl passes laterrally into the Main Weiteveen Member. The thickness ranges from 20 to 40 m. Above salt structures, the unit may be completely absent.

The *Weiteveen Upper Evaporite* only occurs in the southeastern part of the map sheet area, to the south of the Emmen salt ridge. This sequence comprises an alternation of anhydrite, limestone, claystone and marl. In the south, along the border with Germany, halite intercalations are also found (fig.10.1). In a northerly and westerly direction, the anhydrite disappears and this member passes into the Main Weiteveen Member. The thickness is generally above 20 m, increasing to over 70 m in the extreme southeast of the map sheet area.

The uppermost evaporitic unit is covered by the *Weiteveen Upper Marl*, which comprises marl and claystone with an occasional limestone or anhydrite bed. The thickness ranges from 10 to 40 m.

The entire evaporite-marl succession passes laterally into the *Main Weiteveen Member*. This unit comprises an alternation of marl, claystone and limestone as well as minor anhydrite intercalations. This sequence increases in thickness in a southerly direction from 10 to 90 m. In the southeast, the member passes into the aforementioned evaporite-marl succession.

The Weiteveen Upper Marl or the Main Weiteveen Member is overlain by the *Serpulite Member*. This succession consists of an alternation of bluish-grey marls, claystone and limestone. Anhydrite beds and nodules are frequently found in the southeastern part of the map sheet area. The limestones are composed of small fragments of pelecypoda and serpulid tube worms and ostracods. The maximum thickness of the member, 50 to 100 m, is achieved in the southeast of the map sheet area. Elsewhere, the thickness is 10 to 40 m. Above salt structures, the member is highly condensed or even completely absent. On the margin of the basin where both the Weiteveen and the Coevorden Formations are calcareously developed, the Serpulite Member cannot always be clearly identified.

10.1.2 Coevorden Formation

The areal extent of the Coevorden Formation, deposited during the Ryazanian to possibly earliest Valanginian, virtually coincides with that of the underlying Weiteveen Formation. The boundary between both formations is conformable or without any apparent hiatus. The greatest thickness, nearly 300 m, is reached in the southeast of the map sheet area. However, the thickness increases beyond the extent of the map sheet area, to over 700 m in the Schoonebeek-Meppen Trough (Schott et al., 1967a,b; Meyer, 1969). Within the major part of the area of distribution, the formation yields a thickness of 50 to 100 m. Above salt structures, the thickness is drastically reduced or is completely absent in the formation.

Within the Coevorden Formation, three members can be distinguished, the Lower Coevorden, Middle Coevorden and Upper Coevorden Members.

The *Lower Coevorden* consists predominantly of an alternation of grey claystone and marl with the occasional limestone bed in the basal part. Towards the margin of the basin, the number of limestone intercalations increases, with the result that the distinction from the underlying and overlying sequences becomes less clear. The greatest thickness, over 50 m, is reached in the southeast of the map sheet area and immediately to the north of the Emmen-Fehndorf High. Salt tectonics caused local variations in thickness; the member is absent above a number of salt structures.

The *Middle Coevorden* comprises a fossil-rich alternation of grey marl, limestone and claystone. On the margin of the basin, the member displays a silty to sandy development. The thickness is a maximum of 50 to 85 m in the southeast of the map sheet area, elsewhere ranging from 10 to 35 m.

In a few areas isolated from each other in the south and east of the map sheet area, the *Upper Coevorden* rests conformably upon the Middle Coevorden. The unit is composed of brownish-grey claystone and marl which occasionally exhibit a silty to sandy development. In a few intervals, the claystone (known in Germany as Papierschiefer) is laminated and strongly bituminous. These deposits form a major oil-source rock, generating the oil of, for example, the Schoonebeek field (Binot et al., 1991). The thickness ranges from 10 to 25 m, with the exception of the extreme southeast, where thicknesses of 50 to 100 m are reached.

10.2 Sedimentary development and palaeogeography

The Niedersachsen Group was laid down in the Lower Saxony Basin. As this basin originally had no uninterruped connection with the open sea, sediments were consequently deposited in a fresh, brackish water to hypersaline setting. During deposition of the group, the Lower Saxony Basin gradually became less isolated from the open sea, which is revealed by the changeover from the evaporitic setting of the Weiteveen Formation to the lacustrine and sometimes marginal marine setting of the Coevorden Formation (Wolburg, 1949; Herngreen et al., 1980).

The deposits of the Weiteveen Formation in the map sheet area reflect the enlargement of the Lower Saxony Basin to the west. This formation was deposited in arid climate conditions (Herngreen et al., 1980). The oldest sediments, the Weiteveen Basal Clastics, were only deposited in the adjacent part of Germany and to the south of the Emmen Fehndorf High and consist of fine-grained lacustrine sediments, with local intercalations of fluvial sand and gravel deposits. Subsequently, alternating hypersaline and lacustrine conditions again predominated and deposition of fine-clastic sediments and evaporites took place, during which the sedimentation area spread further to the west. However, the fine-grained and evaporitic character of the sediments indicate that the highs to the west of the Lower Saxony Basin supplied practically no sediments and were located at around water level.

Deposition of the Coevorden Formation occurred on the western margin of a fresh to brackish water basin. The boundary between the Coevorden and the Weiteveen Formation appears to reflect a major climate changeover to a humid climate (Herngreen et al., 1980). During the deposition of the Middle and Upper Coevorden in particular, a few marine incursions occurred from a northerly direction (Central North Sea Graben, Vlieland Basin). This connection is thought to have been related to the Hantum Fault Zone. The sediments are mainly fine-clastics, laid down from suspension, while the carbonates are considered to have been storm layers or hard grounds. The thin beds, rich in organic material, reflect euxinic periods in the basin (Van Adrichem Boogaert & Kouwe, 1993-1997).

11 Rijnland Group

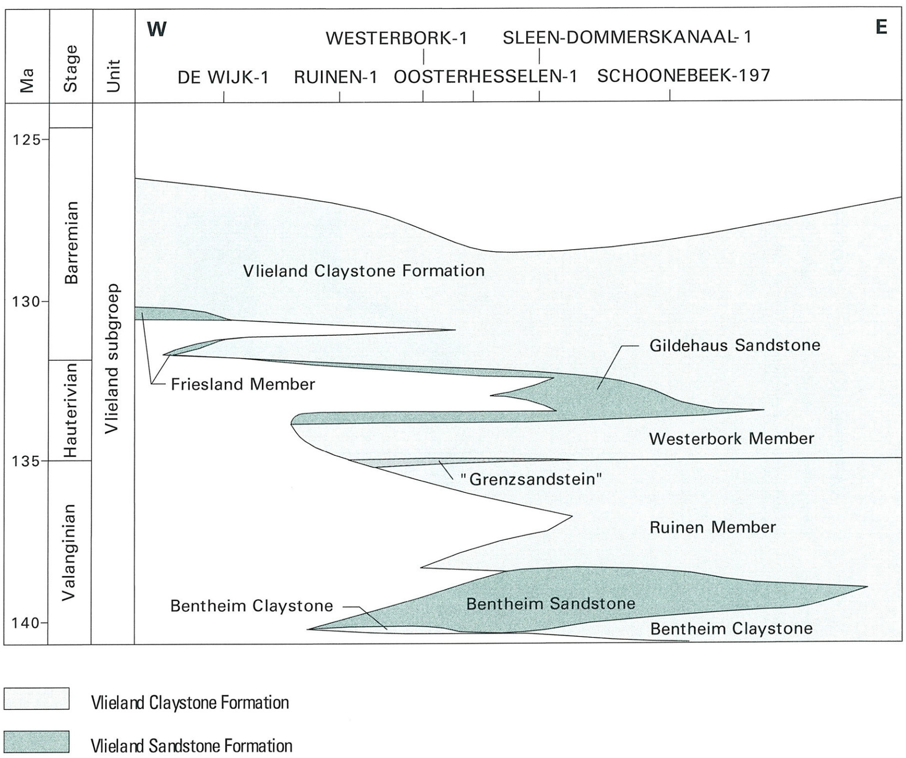
11.1 Stratigraphy

The Rijnland Group consists predominantly of marine sandstones, claystones and marls. The group is subdivided into the Vlieland Sandstone, the Vlieland Claystone and the Holland Formations. The Rijnland Group was deposited during the Valanginian up to the Albian. The Vlieland Sandstone and the Vlieland Claystone Formation together form the informal Vlieland subgroup (fig. 11.1).

In the eastern and central part of the map sheet area, the Rijnland Group rests conformably upon the Niedersachsen or the Altena Group (Map 19; RGD, 1994e). On the margin of the Lower Saxony Basin, a hiatus occurs between the Niedersachsen Group and the Rijnland Group, which may well span the entire Valanginian and Hauterivian. Outside the basin and locally above salt structures, the Rijnland Group rests unconformably upon the Limburg, the Zechstein, the Lower or Upper Germanic Trias or the Altena Group (Map 19). The base of the group, the Late Kimmerian II unconformity, is diachronous and varies in age from Valanginian in the centre of the Lower Saxony Basin to Albian on the Friesland Platform. The group is overlain by the Chalk Group.

The Rijnland Group deposits are found throughout the map sheet area except above a few salt structures (Map 12 & 13). The depth ranges from a few hundred metres above salt structures to over 2000 m on the Friesland Platform in the south of thix area and locally in the surroundings of Assen (Map 12). In the map sheet area, the thickness ranges from less than 200 m on the Friesland Platform and Groningen High to 600 m locally in the Lower Saxony Basin. Further into the basin in an easterly direction, the thickness increases in a southeasterly direction to practically 2000 m (Meyer, 1969; Schott et al. 1967a,b).

Figure 11.1 Litho-chronostratigraphic overview of the Rijnland Group in the Lower Saxony Basin.



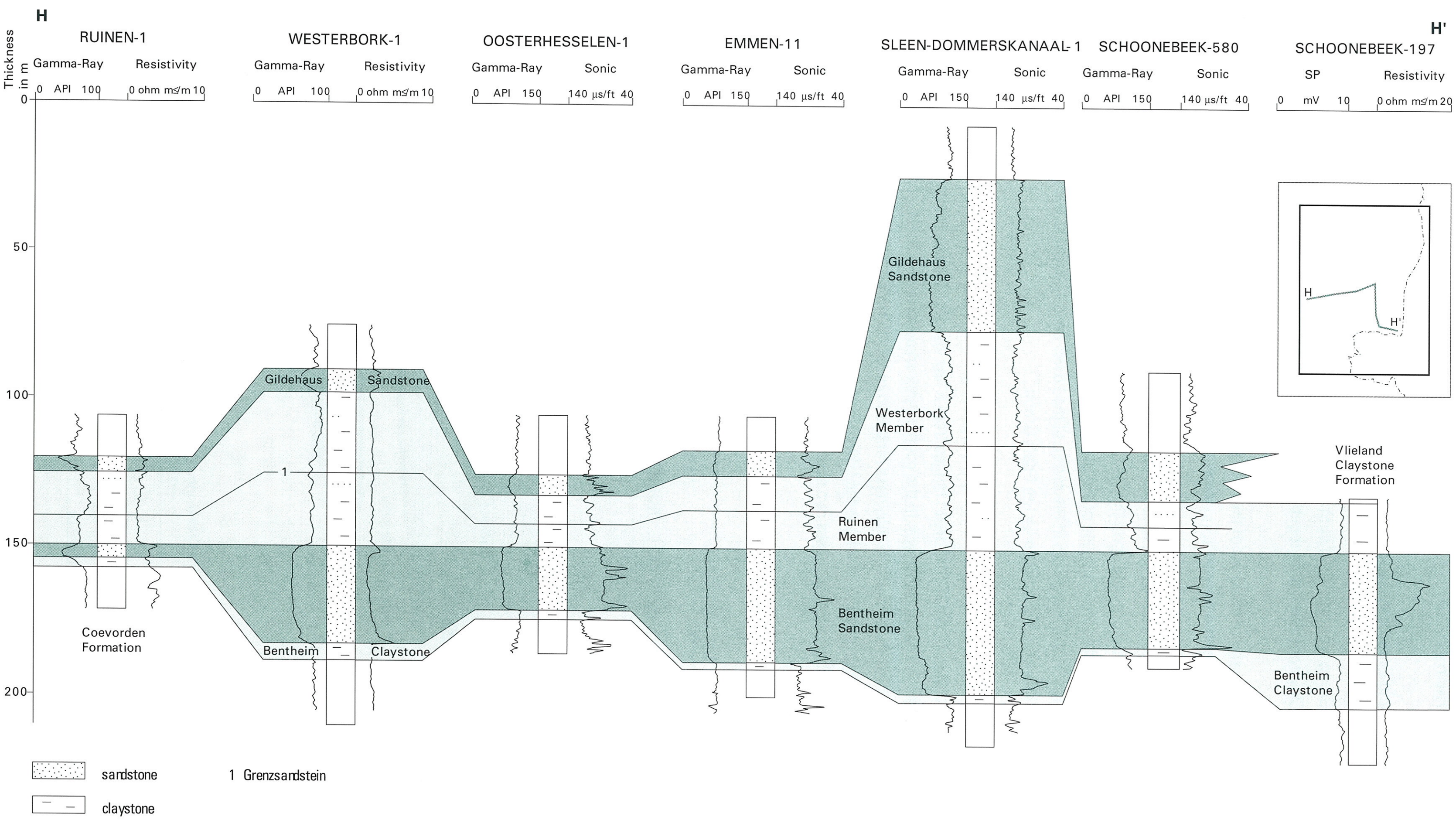


Figure 11.2 Stratigraphic section H-H' of the Rijnland Group between the Ruinen-1, Westerbork-1, Oosterhesselen-1, Emmen-11, Sleen-Dommerskanaal-1, Schoonebeek-580 and Schoonebeek-197 wells. This section shows considerable differences in thickness, as a result of synsedimentary fault movement. The reference level is the top of the Bentheim Sandstone.

The composition of the Rijnland Group is illustrated by a number of sections (fig. 11.2 & 11.3).

11.1.1 Vlieland subgroup

The Vlieland subgroup occurs throughout the area, with the exception of the Emmen-Fehndorf High, the southwest of the map sheet area and above salt structures (fig. 11.4a). In the Lower Saxony Basin, the subgroup rests conformably upon the Niedersachsen Group or unconformably upon the Altena Group. Beyond the limits of this basin, the subgroup rests conformably on deposits of the Altena, the Lower or Upper Germanic Trias, the Zechstein or the Limburg Group (Map 19).

The subgroup comprises the Vlieland Sandstone and the Vlieland Claystone Formations; these formations are each other's lateral equivalents. The subgroup exhibits several hiatuses (fig.11.1) which may be pronounced, in particular close to the former basin margin and the Emmen-Fehndorf High. Based on biostratigraphic research, the hiatuses are concentrated on the transition from the Hauterivian to the Barremian; in addition there are strong indications of a hiatus on the transition from the Valanginian to the Hauterivian (RGD, 1990, 1994a,b,c,d). In view of the exceptionally minimal thicknesses locally, there is a probably a condensed succession present.

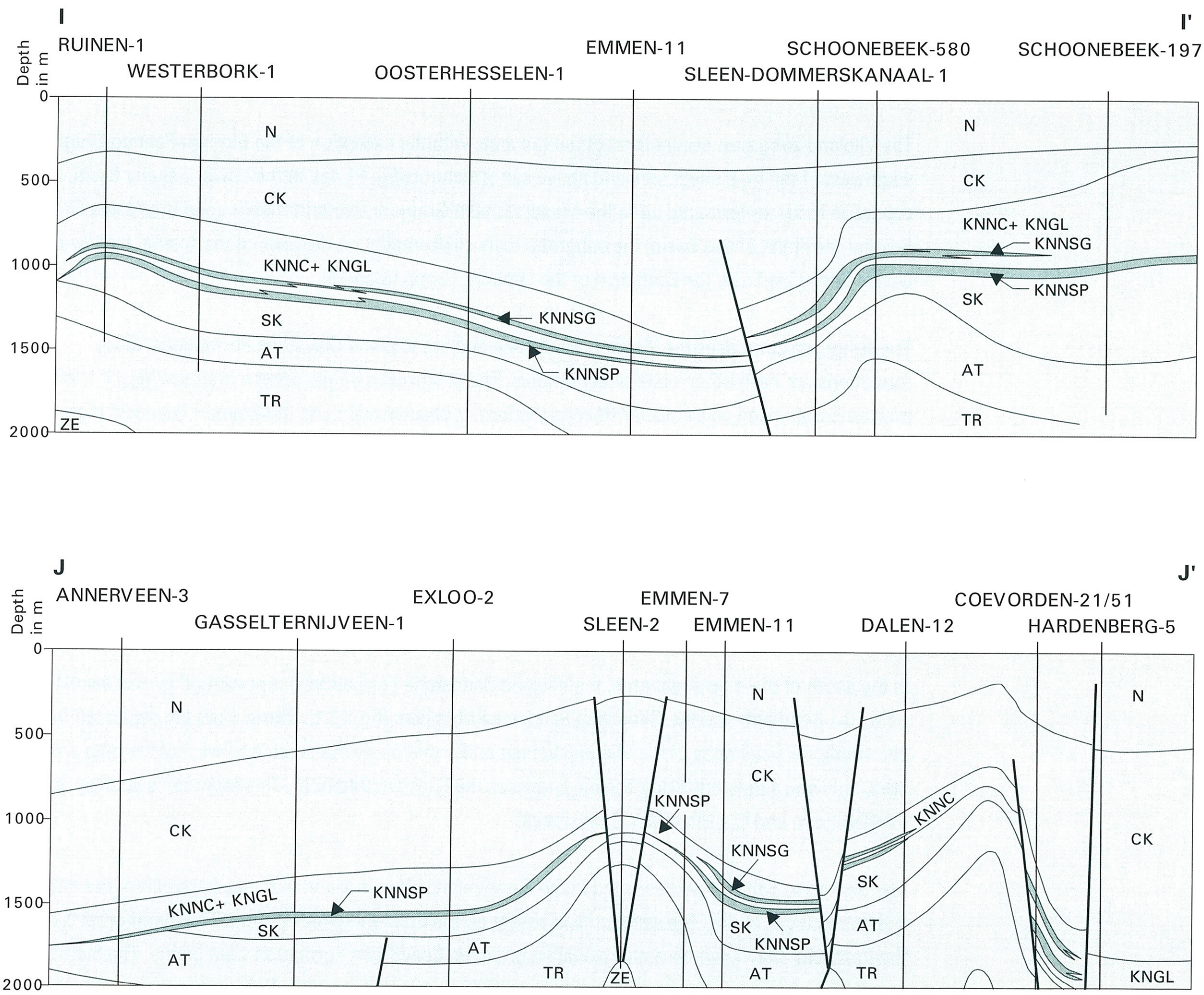
11.1.1.1 Vlieland Sandstone Formation

In the south of the map sheet area, the Vlieland Sandstone Formation is represented by two sandstone units, the Bentheim and the Gildehaus Sandstone Members (fig. 11.1). These units are separated from each other by claystones of the Vlieland Claystone Formation. In the south and west of the map sheet area, only one sandstone body occurs, known as the Friesland Member. This member is younger than the Bentheim and the Gildehaus Sandstones.

The *Bentheim Sandstone*, deposited in the Early Valanginian, is found in the eastern part of the map sheet area (figs. 11.4b). The sandstone is absent on the Emmen-Fehndorf High. The member rests on the Bentheim Claystone via a sharp contact or on the Coevorden Formation via a hiatus. The member is composed of grey sandstone with lamellibranchiates and plant remains. Sometimes the sandstone is variegated as a result of the presence of reddish-brown rock fragments. The grain size ranges from fine to medium-coarse-grained sand. A few clay intercalations are found, as well as siderite-cemented horizons. The sandstone yields glauconite, pyrite and siderite. The greatest thicknesses in the unit occur in the southeast of the area, where the unit reaches a thickness of over 60 m (fig. 11.4b).

In the Schoonebeek field, three sandstone sequences have been identified, separated from each other by thin claystone layers. In this field, the thickness of the sandstone increases towards the east from approximately 10 to over 50 m. This variation is attributed to the fact that in the western part of the field, only the bottommost sequence has been preserved under the Holland Formation, whereas in an easterly direction, the middle and uppermost sandstone sequences have also been preserved (fig. 11.5).

The *Gildehaus Sandstone*, deposited during the Hauterivian (RGD, 1994a,c), rests conformably or via a hiatus on the Westerbork Member. On the Emmen-Fehndorf High, locally, the sandstone rests unconformably on the Coevorden Formation. The Gildehaus Sandstone consists of coarse to fine sandstone, sometimes with a gravel-sized fraction. Occasionally, the carbonate content has increased to the extent that a calcarenite may be said to be present. The sandstone yields clay flakes and coal fragments. Glauconite and iron oolites are also found. The sandstone only occurs in the southern part of the map sheet area, at thicknesses of 4 to 50 m (fig. 11.4c). To the south of the map sheet area, the sandstone reaches a thickness of over 200 m (Meyer, 1969). In an easterly direction, the sandstone



N North Sea Supergroup
CK Chalk Group
KNGL Holland Formation
KNNC Vlieland Claystone Formation
KNNSG Gildehaus Sandstone
KNNSP Bentheim Sandstone
SK Niedersachsen Group
AT Altena Group
TR Upper and Lower Germanic Trias Groups
ZE Zechstein Group

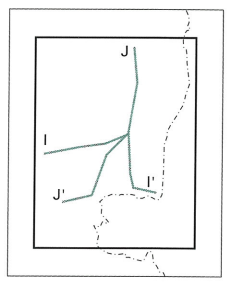


Figure 11.3 Geological section I-I' and J-J' showing the distribution of the Vlieland Sandstone Formation in the Lower Saxony Basin. Thicker sandstones have been encountered between the salt structures, and are thinner or were not deposited immediately above the salt structures (Sleen-2 in section J-J').

rapidly decreases in thickness and passes laterally into the Vlieland Claystone Formation.

The *Friesland Member* is encountered in the southwest and extreme north of the map sheet area, as well as the westerly adjacent map sheet. This member, over 20 m thick, comprises fine to coarse sandstone and conglomerate. The great variation in age, from Hauterivian in the northern part and the southwest (RGD, 1995a, b, c) to Middle Barremian in Map Sheet V situated to the west (Rijks Geologische Dienst, 1993a) suggests that the Friesland Member does not consist of a single sandstone, but of a complex of sandstone intercalations delineating the the expansion of the sedimentation area in a westerly direction (Rijkers & Geluk, 1996).

11.1.1.2 Vlieland Claystone Formation

Within the area where the Vlieland Claystone Formation and the Vlieland Sandstone Formation interfinger, from old to young the Bentheim Claystone, the Ruinen and the Westerbork Members are distinguished (fig. 11.1). Where the Vlieland subgroup comprises only one basal sandstone or is devoid of sandstones, the Vlieland Claystone Formation is not subdivided into members or is given the informal name Schoonebeek member. In the map sheet area the formation, of Valanginian to Barremian age, achieves its greatest thickness, over 200 m, in the southeast. In the centre of the Lower Saxony Basin, the formation reaches a thickness of over 1200 m (Meyer, 1969; Schott et al., 1967a,b). The formation rests conformably or via a hiatus on the Vlieland Sandstone Formation, or unconformably on older units. The formation is overlain conformably by the Holland Formation.

The *Bentheim Claystone*, deposited during the Early Valanginian, consists of a marly, silty to sandy claystone, grey in colour. These sedimentary rocks contain a few ammonite and shell fragments, organic remains and pyrite. Although the thickness generally does not exceed a few metres, thicknesses of 10 to 20 m are achieved locally.

The *Ruinen Member*, of Late Valanginian age, consists of a dark grey, fossiliferous, calcareous claystone as well as siderite horizons. The member overlies the Bentheim Sandstone and is 10-20 m thick. A thin sandstone, the *Grenzsandstein*, separates the Ruinen from the overlying Westerbork Member (figs. 11.1, 11.2).

The *Westerbork Member*, probably of Early Hauterivian age, is composed of dark grey silt to gravelly claystone and marl, in which scattered occurrences of iron oolites occur. Fish and coal remains and lamellibranchiates are found in the sediment. The thickness of the member ranges from 5 to 70 m.

11.1.2 Holland Formation

The Holland Formation consists predominantly of grey and reddish-brown marl and claystone deposited during the youngest part of the Early Cretaceous (Aptian to Early Cenomanian; Frieg & Kemper, 1989). A number of intraformational hiatuses are present in the unit. The formation achieves its greatest thickness, over 200 m, in the southeast of the map sheet area (fig. 11.4d). In a northwesterly direction, the thickness decreases to less than 50 m. Towards the centre of the Lower Saxony Basin, the thickness increases to over 500 m ('t Hart, 1969; Meyer, 1969).

The Holland Formation rests on the Vlieland subgroup, separated unconformably or via a hiatus. On the margins of the basin and locally on the Emmen-Fehndorf High, the Holland Formation rests upon the Coevorden, the Weiteveen or the Aalburg Formation. Outside the basin, the Holland Formation rests upon the Upper or Lower Germanic Trias, the Zechstein, the Upper Rotliegend or the Limburg Group.

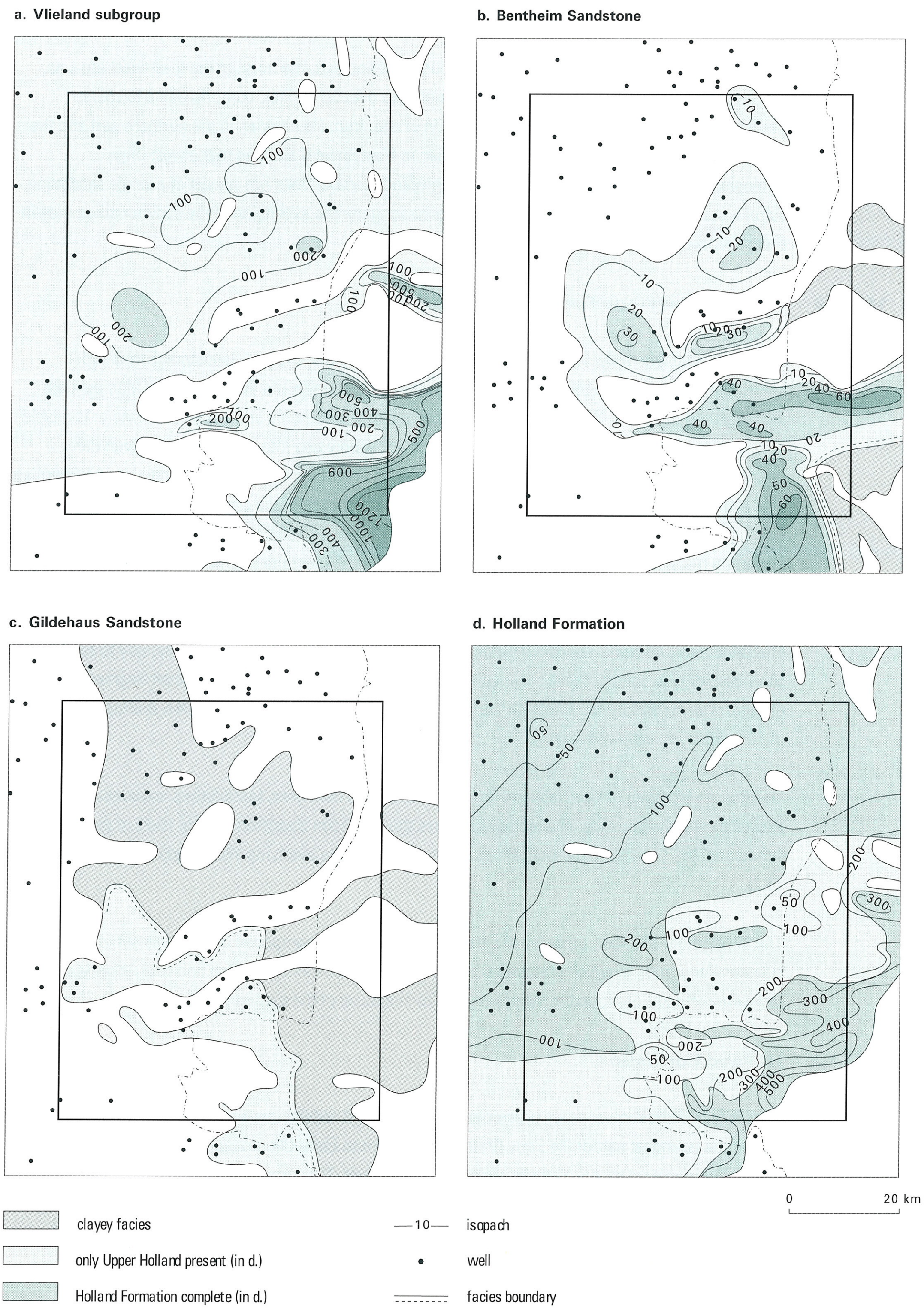


Figure 11.4 a. Thickness of the Vlieland subgroup; b. Thickness of the Bentheim Sandstone; c. Thickness of the Gildehaus Sandstone; d. Thickness of the Holland Formation. Data from the adjacent area of Germany have been taken from Meyer (1969) and Schott et al. (1967a,b).

The Texel Formation overlies the Holland Formation conformably or separated by a hiatus. A tripartition in the formation can be made, based on variations in the carbonate and clay content; these are, in succession, the Lower Holland Marl, the Middle Holland Claystone and the Upper Holland Marl Members.

The *Lower Holland Marl* consists of grey and reddish-brown marl. At the base, intercalations of laminated bituminous claystone layers are sometimes found, with pyrite particles (*Fischschiefer*: RGD, 1994c). This unit was formed in the Early Aptian and the earliest part of the Late Aptian. The Lower Holland Marl rests upon deposits of the Vlieland subgroup, unconformably or separated by a hiatus. The thickness of the member ranges from 10 to 30 m, with the greatest thicknesses apparently related to salt structures. The thickness of the unit decreases in a northwesterly direction.

The *Middle Holland Claystone*, of Late Aptian to Early Albian age, is composed of grey and reddish-brown calcareous claystone, which, in the southeast of Drenthe, exhibits a sandy setting at the base ('t Hart, 1969). The member rests upon the Lower Holland Marl, in general conformably or separated by a hiatus. Above highs in the southeast of Drenthe, the sequence rests unconformably on the Coevorden, Weiteveen or Aalburg Formation and in the south of the map sheet area, sometimes on even older formations of the Upper Germanic Trias Group (Röt or Solling Formation). The member is encountered in all parts of the map sheet area, except above a few salt structures and in the extreme south. The thickness is generally no more than 25 m. In the extreme southeast of Drenthe, thicknesses of 50 to 100 m are reached.

The topmost unit, the *Upper Holland Marl*, comprises a succession of light-grey and reddish-brown marls, which upwardly increase in carbonate content. The Upper Holland Marl generally rests conformably upon the Middle Holland Claystone and is overlain by the Texel Formation. The member occurs virtually over the entire areal extent of the Rijnland Group. The thickness is 50 to 70 m in the

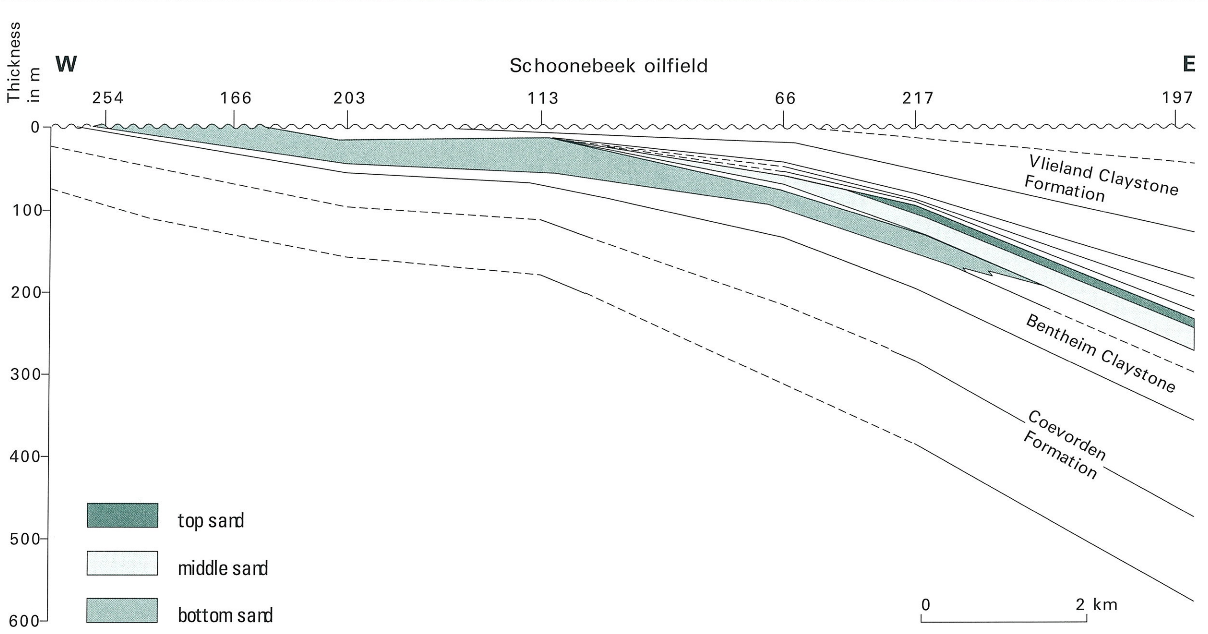


Figure 11.5 E-W correlation through the Schoonebeek field, showing the three units of the Bentheim Sandstone. The reference level is the base of the Middle Holland Claystone.

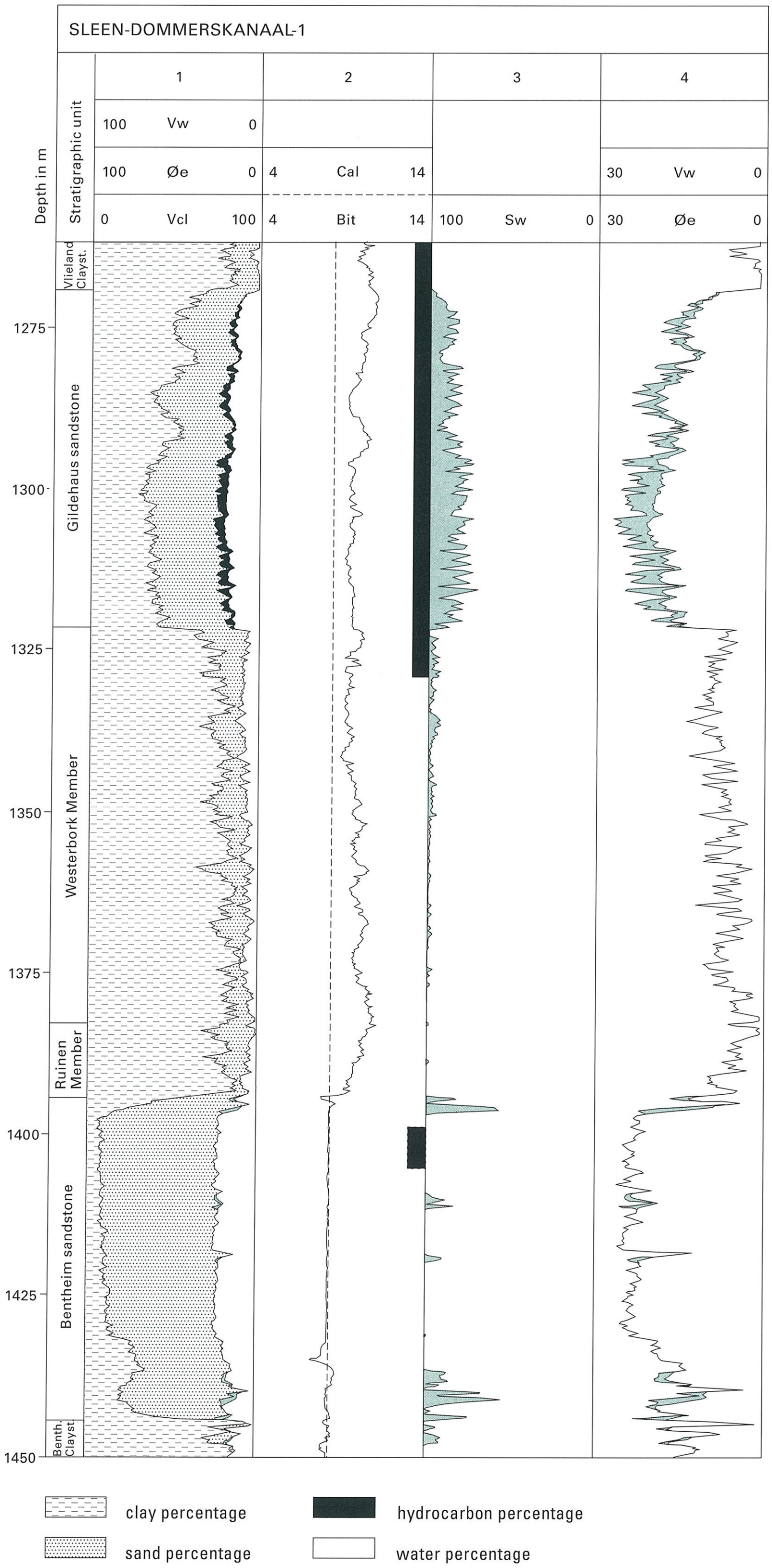


Figure 11.6 Petrophysical evaluation of the sandstones of the Rijnland Group in the Sleen-Dommerskanaal-1 well.

Column 1: clay content V_{cl}, effective porosity $Ø_e$ and pore volume water V_w, all given in percentages. The clay content was determined with the use of Gamma-Ray logs. The effective porosity was obtained by the use of a shaly sand model (density log/neutron log), in which the calculated log porosity was corrected for the clay and the hydrocarbons present.

Column 2: drill hole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the cored intervals are indicated by a black bar.

Column 3: water saturation S_w in percentages. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987).

Column 4: effective porosity $Ø_e$ (left curve) and the pore volume water V_w (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the true depths.

northern part of the map sheet area and increases to over 150 m in the south. Where the Middle Holland Claystone is absent, the unit rests unconformably on older formations. Within the marl, shell fragments are present. The member was deposited in the Early to Late Albian, probably continuing into the Early Cenomanian in the Lower Saxony Basin (Frieg & Kemper, 1989).

11.2 Sedimentary development and palaeogeography

The onset of deposition of the Vlieland subgroup is marked by a major transgression, which terminated the lacustrine conditions of the Coevorden Formation and preluded a long period of marine sedimentation. The deposition of the Rijnland Group was determined by the subsidence of the Lower Saxony Basin (fig. 3.1). The highs surrounding this basin supplied sediment during the deposition of the Vlieland subgroup and were subsequently flooded during the deposition of the Holland Formation.

Along the former basin margins in the southern part of the map sheet area, deposition of the Vlieland subgroup was predominantly characterised by the accumulation of sands, while in an easterly direction, towards the basin centre, these sands rapidly became thinner (fig. 11.4b,c) and the clay and silt deposits became markedly thicker. Along the margins of these basins, deposition of sand or clay was determined by the relative sea-level: highstands gave rise to clay or silt deposition (Bentheim Claystone, Ruinen and Westerbork Members), and at a relatively lowstand, sands were accumulated (Bentheim Sandstone and Gildehaus Sandstone Members), distinguishable by great differences in depositional environment.

The Bentheim Sandstone was deposited as a coastal barrier complex subjected to strong longitudinal and tidal currents along the margins of the Lower Saxony Basin (Kemper, 1976, 1992). These strong currents prohibited clay settling and facilitated the good sorting of the sandstone. A relief of troughs and highs determined the thickness development of this sandstone to a considerable extent. After deposition of the Bentheim Sandstone, a relative sea-level rise favoured an enlargement of the basin facies, initiating deposition of the Ruinen and Westerbork Members.

The Gildehaus Sandstone was deposited in a period during which the current was considerably weaker. Kemper (1992) suggests that a more humid climatic environment led to an increased influx of erosional products from the highs into the basins. Owing to the weaker current, the Gildehaus Sandstone contains more clay than the Bentheim Sandstone.

Subsequent to the deposition of the Gildehaus Sandstone, a sea-level rise again induced deposition of predominantly fine-grained material; only in the immediate proximity of the highs did sand deposition persist and expansion of the area of sedimentation over the highs was less pronounced. Alternatively, the deposits on the highs were again subjected to erosion at a later stage.

The Holland Formation in the basins reflects the deposition of argillaceous marls and clays (Lower Holland Marl and Middle Holland Claystone), while in the southeast, sands and conglomerates, the products of local erosion, were also accumulated. This was superseded by a prominent sea-level rise, the Albian transgression, identified throughout Western Europe (Crittenden, 1987). During this transgression all the highs in and around the map sheet area were flooded, thus terminating the influx of clastic material, illustrated by the increase in carbonate content of the Upper Holland Marl.

11.3 Petrophysical evaluation

A petrophysical evaluation was carried out on the deposits of this group in nine boreholes in the map sheet area and the immediate surroundings (Appendix K). In two boreholes, the sandstones of the Rijnland Group were found to be gas or oil-bearing (appendix L). In the petrophysical evaluation, use was made of the shaly sand model with the density log (and neutron log) as porosity log or logs. The gamma-ray log serves as clay indicator. To illustrate a log evaluation of the Rijnland Group, figure 11.6 shows the results in the case of the Sleen-Dommerskanaal-1 well. The reservoir of the Rijnland Group consists of an alternation of sands and shales.

Out of the nine selected wells in the map sheet area, core analysis data are available from only one (Sleen-Dommerskanaal-1). Average porosities measured from drill-core samples range from 12-33%, the permeabilities from 135-525 mD.

Appendix K gives the results of the reservoir calculations for the Rijnland Group. The cut-off value of the effective porosity is based on the value of 8%. This value is based on core analysis results based on a permeability cut-off of 0.1 mD. For the cut-off of the clay content, the value of 50% has been selected.

12 Chalk Group

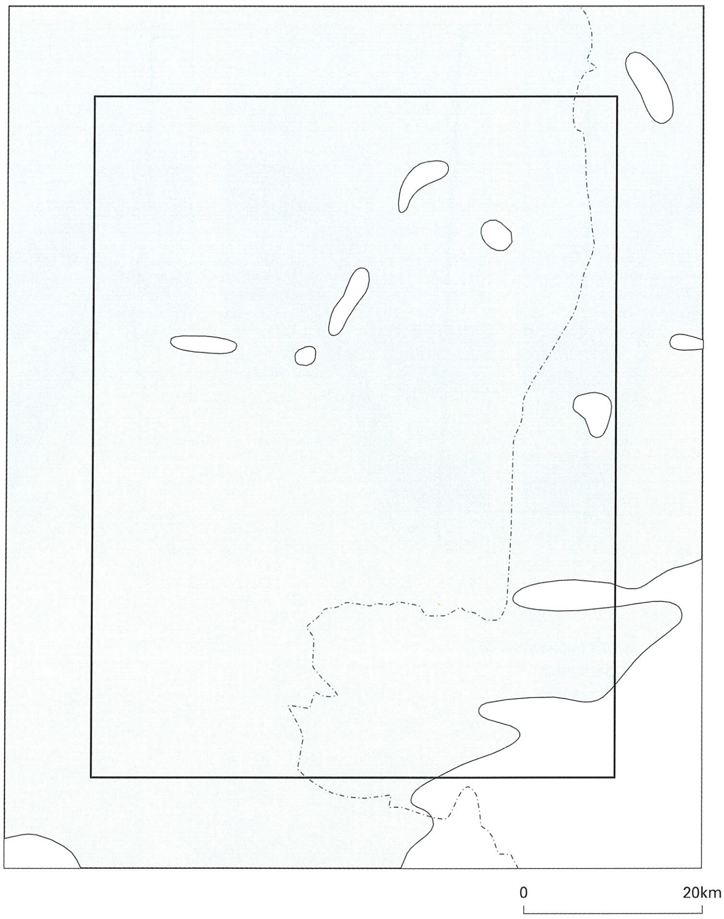
12.1 Stratigraphy

The Chalk Group, Cenomanian up to Maastrichtian in age within the map sheet area, is composed of a succession of well-cemented, light coloured, fine-grained pelagic chalk and marly limestones. A characteristic feature of these sediments is that the main constituents are calcareous skeletons of planktic and benthic organisms with very little influx of terrigeneous material. The thickness of the group within the map sheet area ranges mostly from 500 to 1000 m. The greatest thickness, over 1300 m, is achieved in the south of the area on the Friesland Platform, and around salt and inversion structures in the eastern part (Map 15).

The Chalk Group is found throughout the map sheet area, except above a few salt structures (Map 14; fig. 12.1). The depth of the base of the group ranges from a few hundred metres above a number of salt structures to over 1900 m in the vicinity of Assen.

The Chalk Group is subdivided into the Texel and the Ommelanden Formations and rests conformably or separated by a hiatus on the Holland Formation and, as a result of salt movement, locally on the Zechstein or the Lower or Upper Germanic Trias Group. The Chalk Group is overlain unconformably by the North Sea Supergroup. The succession of the group is illustrated in a stratigraphic section (fig. 12.2).

Figure 12.1 Extent of the Chalk Group in the map sheet area. Data for the German section have been derived from Baldschuhn et al. (1996).



12.1.1 Texel Formation

The Texel Formation, Cenomanian in age, is found throughout the areal extent of the Chalk Group. The Texel Marlstone and the Plenus Marl Members can be identified in the formation. The thickness of the formation is 50 m on the Groningen High and the Friesland Platform. In the Lower Saxony Basin, the formation reaches a thickness of 100 to 150 m.

The *Texel Marlstone*, of Cenomanian age, consists of alternating white marls and limestone beds in the bottommost 10-20 m, with limestone beds above. In the basal part, the marls may exhibit a silty to sandy development and contain *Inoceramus* fragments. Stylolites have developed in the limestone.

The *Plenus Marl*, latest Cenomanian in age, consists of a calcareous, bituminous, dark-coloured laminated claystone, with a very characteristic well-log reading. The sequence is generally 1 to 5 m thick. Fish and coal remains are found in the sequence. On the Emmen-Fehndorf High, as well as in a few wells around the high, the member is absent.

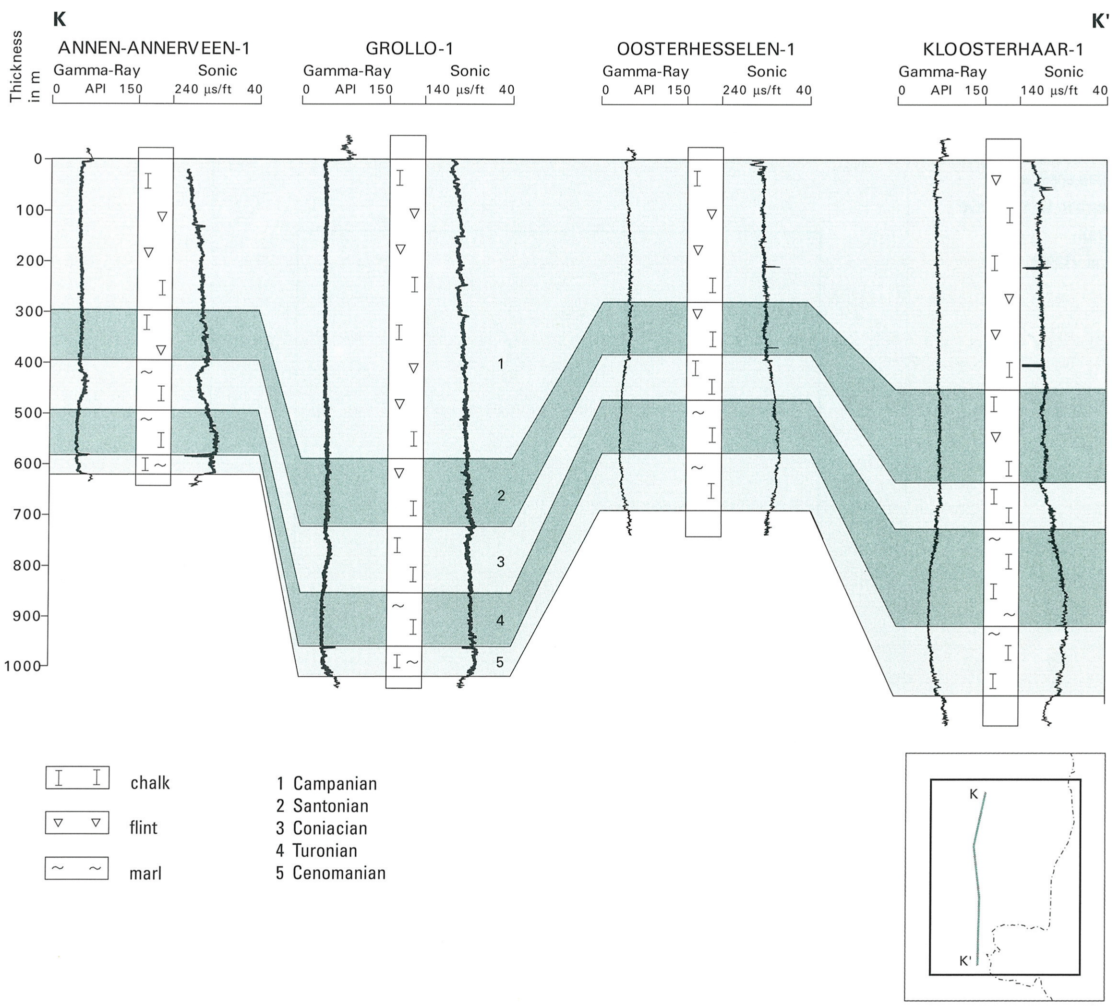


Figure 12.2 Correlation section K-K' of the Chalk Group between the Annen-Annerveen-1, Grollo-1, Oosterhesselen-1 and Kloosterhaar-1 wells.

12.1.2 Ommelanden Formation

The Ommelanden Formation, deposited during the Turonian to the Maastrichtian, is found virtually throughout the map sheet area. The formation is not subdivided into members. However, log correlation and seismic interpretation enabled identification of the different Cretaceous stages, based on the classification in northwest Germany established by Baldschuhn & Jaritz (1977), supported by micropalaeontological datings (RGD, 1995d).

The formation consists predominantly of white chalk, limestone and grey marl. The pure limestone occurs in the bottommost part of the formation (Turonian), while the middle part of the formation has more of a marly character (Coniacian and Santonian). The fine carbonate matrix comprises remains of planktic and benthic macrofossils. Fragments of microfossils, such as lamellibranchiates, brachiopodes and echinoderms, also occur. A few horizons contain chert nodules and pyrite.

The Ommelanden Formation generally rests conformably on the Texel Formation and is unconformably overlain by deposits of the North Sea Supergroup. The thickness ranges from approximately 100 to 900 m. The greatest thickness is achieved in the extreme south of the map sheet area on the Tubbergen High.

The stratigraphic correlation diagram (fig. 12.2) shows that in the direction of the Lower Saxony Basin, the bottommost units in particular of the Ommelanden Formation increase in thickness, while the thickness of the Campanian deposits decreases in the same direction. Despite the fact that the total thickness of the formation remains roughly the same, the internal succession displays a pronounced lateral variation from place to place, partly attributable to the occurrence of subaqueous avalances and erosion during the basin inversion (fig. 14.5).

12.2 Sedimentary development and palaeogeography

The eustatic sea-level rise which had already commenced during deposition of the Rijnland Group developed into a global transgression during the deposition of the Chalk Group. The coastline migrated further to the south, away from the map sheet area. This resulted in an increase in the carbonate content in the Texel Formation towards the top of the formation. The Plenus Marl, at the top of this formation, reflects a period during which anoxic conditions in the basins prevailed regionally.

The Ommelanden Formation was deposited under low energetic conditions on a shallow carbonate platform. Sea-level fluctuations and inversion tectonics resulted in variations in the ratio of marl and clay. These inversions during the Sub-Hercynian phase (Santonian) and erosion during the Early Palaeocene are responsible for the current thickness of the group. The inversion phase was also characterised by slumping and redeposition of units of the Ommelanden Formation (fig. 14.5). This inversion led to the pronounced subsidence of the former highs surrounding the Lower Saxony Basin.

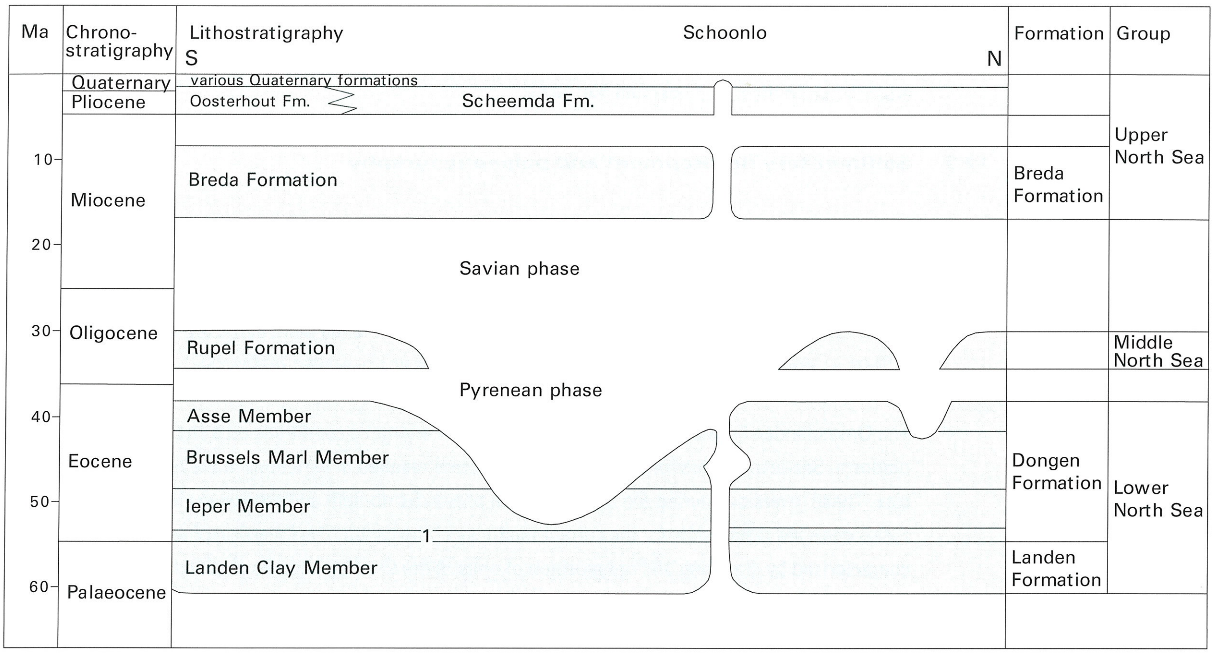
13 North Sea Supergroup

13.1 Stratigraphy

The North Sea Supergroup is predominantly composed of clays and sands deposited in a shallow-marine and continental environment. The supergroup is subdivided into the Lower North Sea, the Middle North Sea and the Upper North Sea Groups. The groups are separated from each other by the Pyrenean phase (Late Eocene/Early Oligocene) and the Savian phase (Late Oligocene/Early-Miocene). The North Sea Supergroup unconformably overlies the deposits of the Chalk Group and, locally, the caprock of saltdomes (Map 20).

The North Sea Supergroup is present throughout the map sheet area (Maps 16 & 17). The thickness was influenced by halokinetic movements of the Zechstein salt and ranges from 1000 m in the northwest to over 120 m above the Schoonlo and Zuidwending salt structures. Above many salt structures, the Lower and Middle North Sea Group was partially or completely eroded during the Late Eocene and the Oligocene. A number of salt structures display subrecent activity, related to the movements along the Coevorden, Dalen and Hantum Fault Zones (Map 17).

This chapter gives an explanation of the composition and structure of the North Sea Supergroup by means of a chronostratigraphic overview (fig. 13.1) and two sections through the map sheet area (fig. 13.2). The Quaternary sediments are not described here, but are referred to in geological maps (Rijks Geologische Dienst 1979, 1990) and publications (Rappol, 1992; Zagwijn, 1989).



1 Basal Dongen Tuffite

Figure 13.1 Lithostratigraphic overview of the Tertiary and Quaternary deposits in the map sheet area.

13.1.1 Lower North Sea Group

The Lower North Sea Group, deposited during the Late Palaeocene and the Eocene, is present throughout the map sheet area, except immediately above a number of saltdomes (Zuidwending, Schoonlo). The group rests unconformably on the Chalk or the Zechstein Group (fig. 13.2) and is overlain by the Middle or Upper North Sea Group, also unconformably. The Lower North Sea Group comprises the Landen and Dongen Formations (fig. 13.1).

13.1.1.1 Landen Formation

The Landen Formation consists of sand and clay and is present virtually throughout the map sheet area. The formation is absent immediately above a number of salt structures owing to erosion or non-deposition. The formation consists entirely of the *Landen Clay.* This member, of Late Palaeocene age, is a 10-40 m. thick dark greenish-grey clay succession, containing glauconite, mica and pyrite. The argillaceous sediments have been cemented with carbonate in places.

13.1.1.2 Dongen Formation

The Dongen Formation is composed of the Basal Dongen Tuffite, the Ieper, the Brussels Marl and the Asse Members. The thickness of the formation in the map sheet area is related to halokinetic movements and erosion during the Pyrenean and Savian phases and achieves a thickness of over 450 m in the north (fig. 13.2). The Dongen Formation rests conformably upon the Landen Formation and is unconformably overlain by deposits of the Middle North Sea Group.

The *Basal Dongen Tuffite,* of Early Eocene age and from 10 to 30 m thick, is composed of greenish-grey, glauconitic-bearing sandy clays and dark tuffaceous intercalations. The middle part contains dark grey to bluish-grey tephra with thin claystone layers.

The *Ieper Member,* of Early Eocene age, consists of brownish-grey and reddish-brown clay at the base and sandy clay at the top and, locally, may contain pyrite, shells, coalified plant remains and benthic foraminifera. The fat clays contain sandy and silty horizons. The topmost part of the Ieper Member comprises greenish-grey, glauconitic and marly sand intercalations. Sand nests in the member indicate bioturbation. The thickness of the member ranges from 120 m to 250 m.

The *Brussels Marl* is composed of very fine-grained, micaceous sands and contains abundant shell and echinoderm fragments and glauconite. Upwardly, the carbonate content increases and the glauconite content decreases. The thickness increases rapidly from a few tens of metres in the south to an average of 120 m in the north of the map sheet area.

The *Asse Member,* of Late Eocene age, is a highly plastic and greenish-grey to bluish-grey calcareous clay. The clay yields abundant occurrences of pyrite and glauconite. The entire sequence comprises sand nests induced by bioturbation. The thickness of the Asse Member ranges from 30 to 110 m. Erosion resulting from regional uplift in the south and salt movement in the north are responsible for the thickness differences in the member. Erosion in the former Lower Saxony Basin accounts for absence of the member, except in a number of depletion areas associated with salt structures. The central part of the map sheet area reveals an anticlinal structure of Early Tertiary age, at places where the top of the Dongen Formation was eroded. The area that underwent the greatest erosion can be seen in the map showing the extent of the Asse Clay (fig. 13.3).

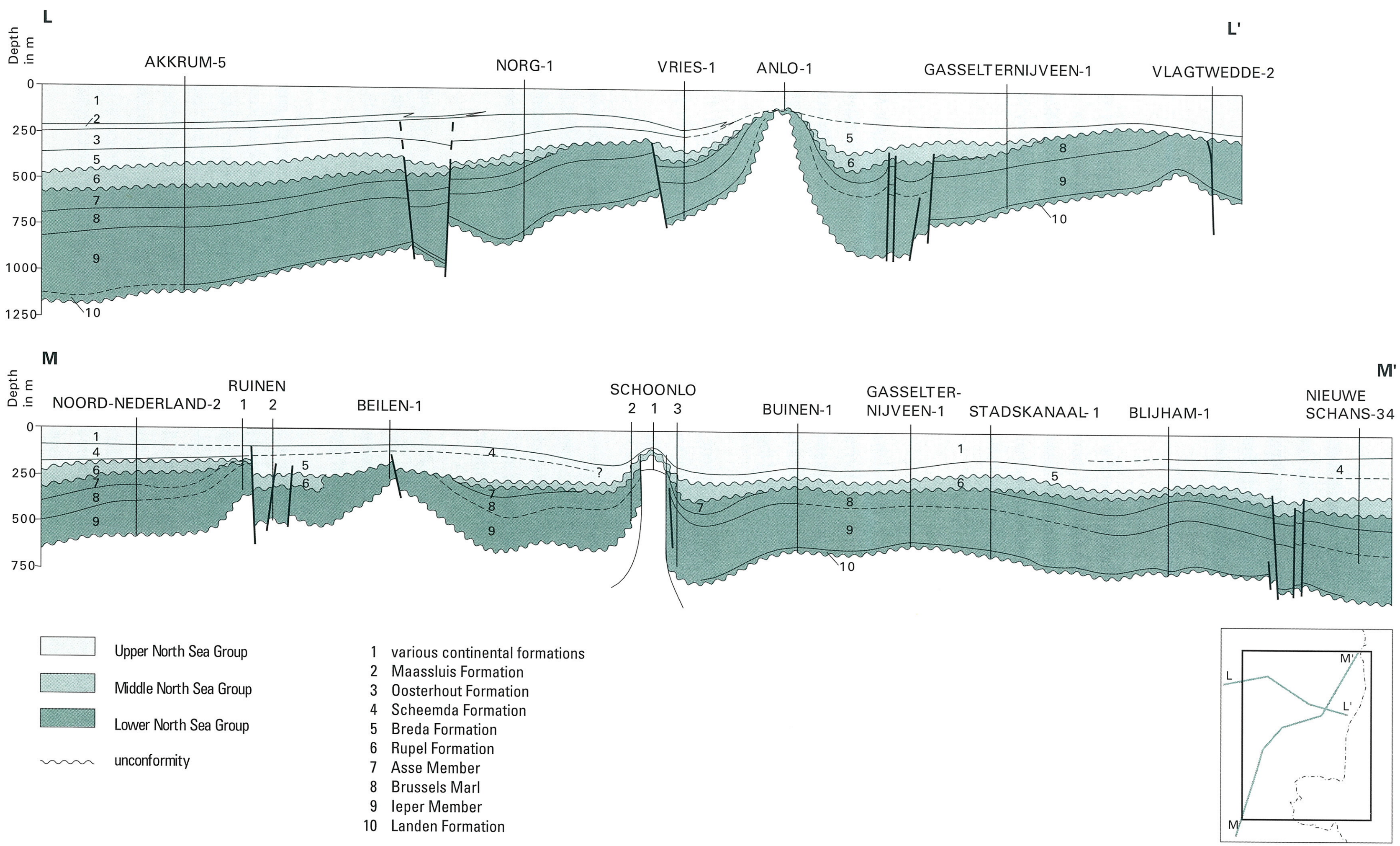


Figure 13.2 Sections L-L' and M-M' through the Cenozoic deposits of the map sheet area (Rijks Geologische Dienst 1983, 1984).

13.1.2 Middle North Sea Group

The Middle North Sea Group, deposited during the Early and Middle Oligocene, rests unconformably on the Lower North Sea group and is overlain, also unconformably, by the Upper North Sea Group. In the map sheet area, the group consists entirely of the Rupel Formation. The thickness ranges from 180 m in the south to 50 m in the north. The Middle North Sea Group is present virtually throughout the map sheet area, with the exception of the Veendam, Hoogezand, Zuidwending, Winschoten, Onstwedde, Schoonlo, Gasselte-Drouwen and Hooghalen salt structures (fig. 13.4; see fig. 14.10 for the location of the salt structures).

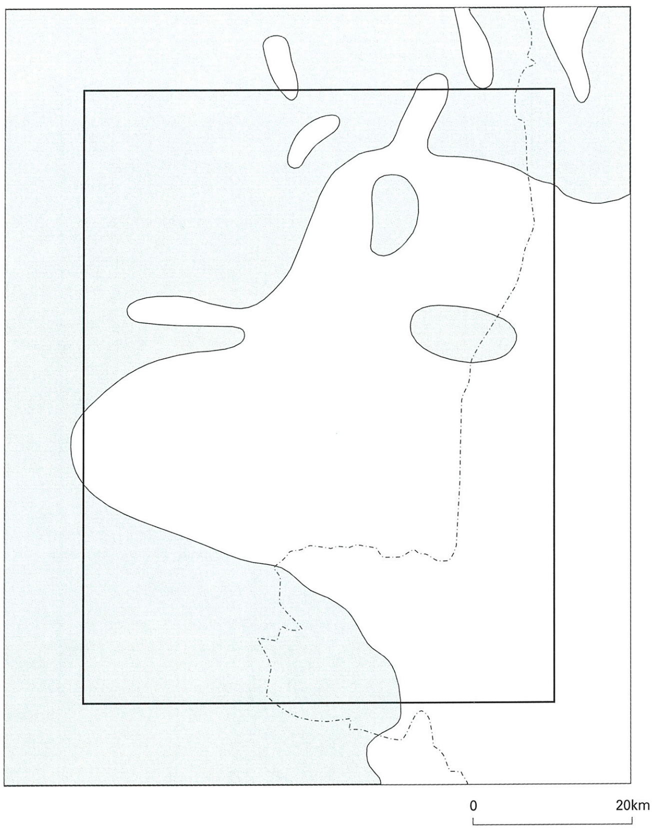
13.1.2.1 Rupel Formation

The Rupel Formation, of Early and Middle Oligocene age, comprises the Vessem and Rupel Clay Members. The *Vessem Member* consists of 5 to 30 m glauconite and pyrite-bearing sands and is only found in the southern part of the map sheet area. The *Rupel Clay* consists of stiff, fat, pyrite-bearing, greenish-grey clay and was deposited in thicknesses of 20 to 80 m in the map sheet area.

13.1.3 Upper North Sea Group

The Upper North Sea Group is subdivided into the Breda, Oosterhout, Scheemda Formations and the Quaternary deposits. The group rests unconformably upon the Middle North Sea Group and unconformably overlies a number of salt structures. The sediments of this group are of Miocene,

Figure 13.3 Extent of the Asse Member, indicating the area of the Pyrenean uplift and erosion. This area largely coincides with the Lower Saxony Basin (Rijks Geologische Dienst 1983, 1984).



Pliocene and Quaternary age. In the southeast of Drenthe, a minimal thickness of 100 m is achieved, increasing to over 400 m in the northwest. In the southern part of the map sheet area, thicknesses, over 300 m, appear in the Coevorden and Dalen Grabens. The depth of the base of the Upper North Sea Group, which is virtually identical to the thickness map, is shown on Map 17.

13.1.3.1 Breda Formation

The Breda Formation, deposited during the Miocene, consists of glauconitic, greenish-black clays and sands, with a high gamma-ray log reading. Upwardly, the formation demonstrates grain-size increase while the glauconite content decreases. The formation is over 100 m thick in the north of the map sheet area.

13.1.3.2 Oosterhout Formation

The Oosterhout Formation, of Pliocene age, is only found in the southwest of the map sheet area and consists of an alternation of shell-rich argillaceous sands and sandy clays. The bottommost and topmost part of the formation in particular exhibit a sandy development. The formation is approximately 75 m thick.

13.1.3.3 Scheemda Formation

The Scheemda Formation, of Pliocene age, comprises a sequence of sands and clays, predominantly

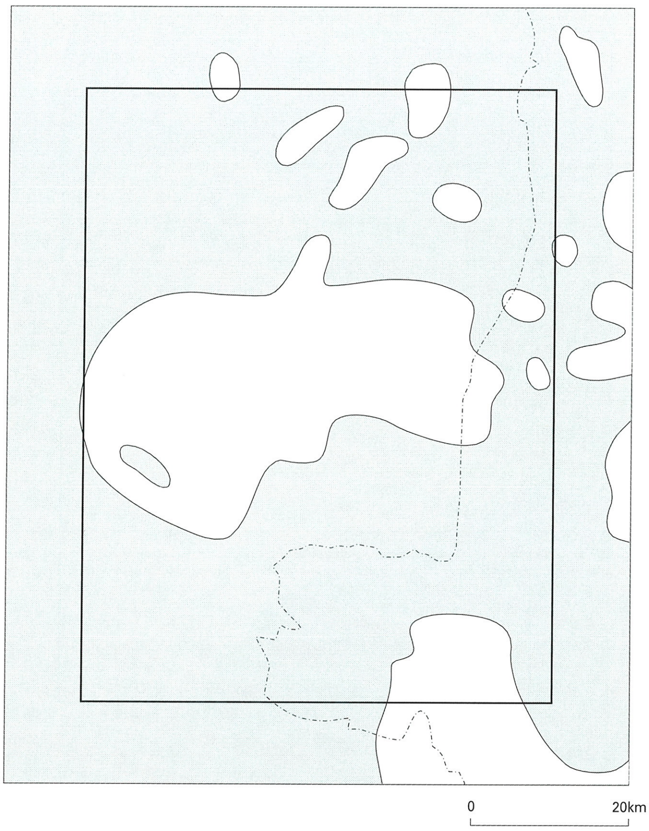


Figure 13.4 Extent of the Middle North Sea Group (Rupel Clay Member), indicating the area of the Savian uplift and erosion (Rijks Geologische Dienst 1983, 1984).

fluvially deposited and partly on coastal-plains. The sediment contains wood remains, peat flakes, clay fragments and fine gravel. The formation is a lateral equivalent of the Oosterhout Formation, into which it passes in the north and east of the map sheet area.

The youngest formations of Quaternary age are composed of sandy gravel beds, sands (occasionally calcareous), clays, loam (occasionally argillaceous) and peat. The maximum thickness of the Quaternary formation is over 220 m in the northwest and less than 80 m above a few salt structures.

13.2 Sedimentary development and palaeogeography

The Cenozoic history is closely associated with the evolution of the North Sea, which nowadays still covers a part of the North Sea Basin. The present map sheet area, which lay on the margin of the North Sea Basin, was subject to sea-level changes, consequently initiating deposition of an alternation of marine, shallow-marine and continental sediments. During the Cenozoic, the area was strongly affected by tectonic movements in the Lower Saxony Basin.

After a period of uplift and erosion (Laramide phase), sedimentation resumed with the Landen and Dongen Formations. Deposition of sands and clays regularly alternated in a shallow-marine setting. During the Tertiary, the basin subsidence and the rate of sedimentation in general maintained each other in a state of equilibrium, although sea-level fluctuations were responsible for several large hiatuses. (Zagwijn, 1989).

The sediments of the North Sea Supergroup were deposited predominantly in shallow-marine conditions. During this period, the coastline was situated far to the south of the map sheet area. During the deposition of the youngest sediments of the group, the Scheemda Formation and the other Quaternary formations, continental depositional conditions extended over the area.

13.3 Petrophysical data

Deposits of the North Sea Supergroup have not been petrophysically evaluated, as hydrocarbons are generally not encountered. However, an exception to this is the Basal Dongen Tuffite in the De Wijk field, where this unit forms one of the reservoirs. Despite the fine-grained character of the deposits, the unit has a porosity of approximately 30% and a permeability of between 10 and 100 mD (Gdula, 1983). These favourable characteristics are attributed by the last-mentioned author to the the good sorting of the sediments and the absence of diagenesis.

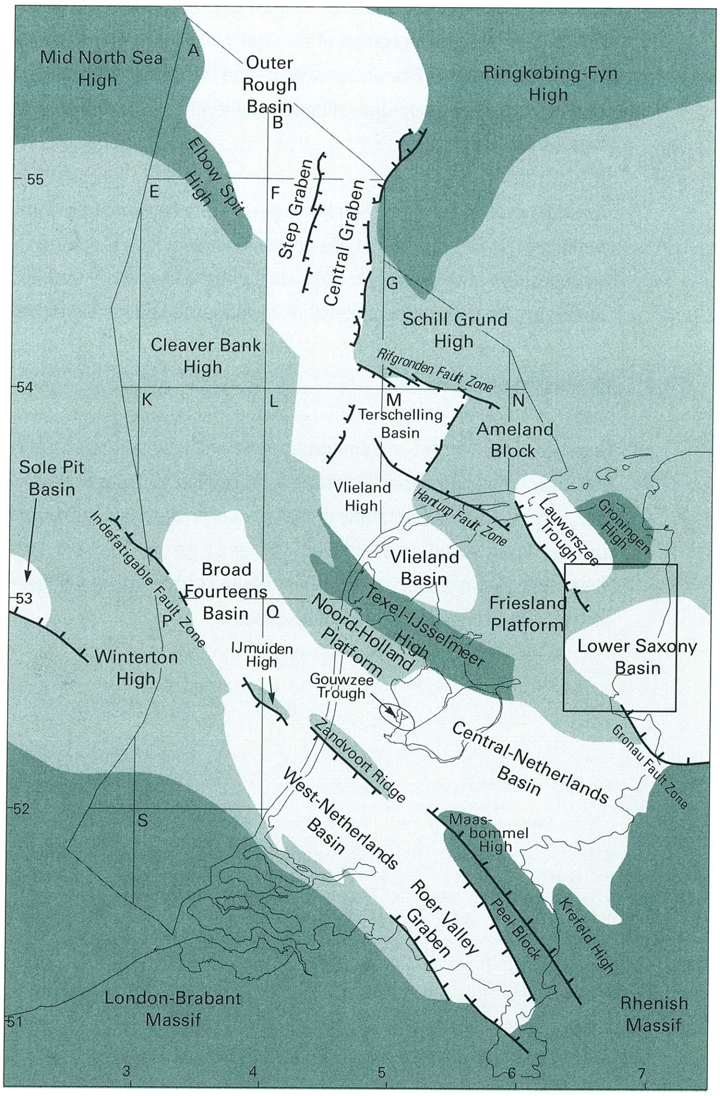
14 Geological history

14.1 Introduction

This chapter gives an overview of the geological history of the map sheet area from the Carboniferous to the Quaternary. For the older history, reference should be made to the summary publications by Franke (1990) and Ziegler (1988, 1989, 1990). The Quaternary is described in detail in the geological maps (Rijks Geologische Dienst, 1979, 1990) and publications (Rappol, 1992; Zagwijn, 1989).

The geological history of each subsequent period is illustrated by the various tectonic phases (fig. 1.5). During the Late Carboniferous these were the phases of the Variscan Orogeny, related to the forming of the Variscan mountains in Central Europe. The Early Triassic to earliest Cretaceous period was marked by a number of extensional tectonic phases, which were responsible for the formation of the major structural units in the map sheet area. During the Sub-Hercynian phase in the Late Cretaceous, a compressive stress field was responsible for a brief change (inversion) in the direction of movement of the major structural elements. The phases during the Tertiary were associated with the Alpine Orogeny.

Figure 14.1 Overview of the principal structural elements in The Netherlands during the Mesozoicum (after Van Adrichem Boogaert & Kouwe, 1993-1997). The position of the map sheet area, on the western margin of the Lower Saxony Basin, has been outlined.



Compressive deformation can be ascribed to the collision between Africa and Europe to the south and the opening of the Atlantic Ocean to the northwest of the map sheet area. The tectonic phases, together with the climate and the sea level, were the determining elements in the development of the area.

The specific development of the map sheet area has been examined in a regional context (fig. 14.1). The major tectonic structures discussed in this chapter are illustrated in figure 3.1.

14.2 Basin development, sedimentation and tectonics

14.2.1 Late Carboniferous

The Variscan Orogeny left a profound mark on the geological history of the Late Carboniferous. The evolution of the Variscan mountains to the south and southeast of the present Netherlands also made a major impact on the geohistory of the map sheet area. The Variscan Orogeny marks the closure of the Proto-Tethys and the formation of the supercontinent Pangaea (Ziegler, 1990). Two compressive deformation phases are identified: the Sudetic and the Asturian tectonic phases, during which a roughly E-W oriented mountain chain was formed in Europe, with the deformation front migrating increasingly further to the north (Lorenz & Nicholls, 1976).

In response to the compression and the isostatic load of the Variscan mountains, a foreland basin was formed to the north of this fold belt (fig. 4.4), following drastic subsidence from the beginning of the Late Carboniferous. This basin became the depocentre of vast quantities of erosional products from the mountain chain. The depositional setting during the Late Carboniferous displays a clear tendency of regression, ranging from strongly marine-influenced delta and pro-delta deposits during the Namurian to paralic and subsequently fluvial deposits during the Westphalian. During the latest Westphalian A and the Westphalian B, the fluvial influence on the sedimentation became more pronounced and large-scale peat formation occurred in marshes in between the rivers; these deposits, the Maurits Formation, form a major source rock for Dutch natural gas. Episodically, brief transgressions occurred, persisting into the Westphalian C. These transgressions, attributed to glacio-eustatic sea-level changes (Ross & Ross, 1987), invaded vast areas, facilitated by the flat relief of the basin. During the Westphalian C and D the climate became drier owing to the gradual northward drift of the area away from the equator (Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996; Ziegler, 1990), in combination with the formation of the Variscan mountain chain to the south of the area which formed a barrier for the humid air from the south.

From the Early Westphalian C onwards, sedimentation increasingly concentrated in the Ems Low in the east of the map sheet area (Füchtbauer et al., 1991). Under the influence of the compressive stress regime, a number of NW-SE faults zones were reactivated. Although the present areal extent of the Westphalian D and Stephanian is confined to the Ems Low (fig. 4.1), it may be assumed that sedimentation during this period also occurred outside the Ems Low. However, the sediments were thinner here and were subject to erosion during the Early Permian. The unconformable contact between Stephanian and older Westphalian deposits is an indication of the Asturian tectonic phase.

The Asturian phase in effect brought an end to the Variscan Orogeny. The tectonic movements during the Permian are of wrench and extensional nature, heralding the disintegration of Pangaea and the opening of the Atlantic Ocean during the Late Triassic to earliest Cretaceous. These wrench and extensional tectonics during the Early Permian resulted in major subsidence in the Ems Low and pronounced uplift and erosion on the Friesland Platform and the Groningen High. Here, deposits of the Westphalian B outcrop nowadays (fig.4.1) and over 1500 m of the Limburg Group has been eroded.

The reconstructed erosion in the Ems Low is presumed to have been less than 300 m.

14.2.2 Permian

During the Early Permian, the map sheet area underwent E-W oriented extensional stresses, triggering the formation of profound faults, in response to which volcanic activity was initiated in the east of the map sheet area and the adjacent part of Germany. In the Ems Low, lava flows and lacustrine sediments alternated in the Lower Rotliegend Group (Map 1). The extrusion of volcanic rocks appears to be related to the interference of N-S with E-W trending fault systems. Extensional forces here formed a small pull-apart basin, in which lava flows and sediments accumulated. Deposition of these sediments was followed by a long period of erosion and non-deposition.

At the end of the Early Permian, a combination of extensional stresses and cooling of these volcanic rocks led to the development of a vast intracratonic continental basin: the Southern Permian Basin, in which the erosional products originating from the Variscan mountains were deposited in a terrestrial environment. The oldest sediments in this basin have been identified in Northeast Germany, from where the sedimentation area extended to the west and south (Plein, 1995).

The greater part of the map sheet area had for a long time been outside the area of sedimentation. The Ems Low, subject to volcanic activity in the Early Permian, was the last to be covered by sediment (fig. 5.1). Not until the Late Permian did the northern part of the map sheet area form part of the

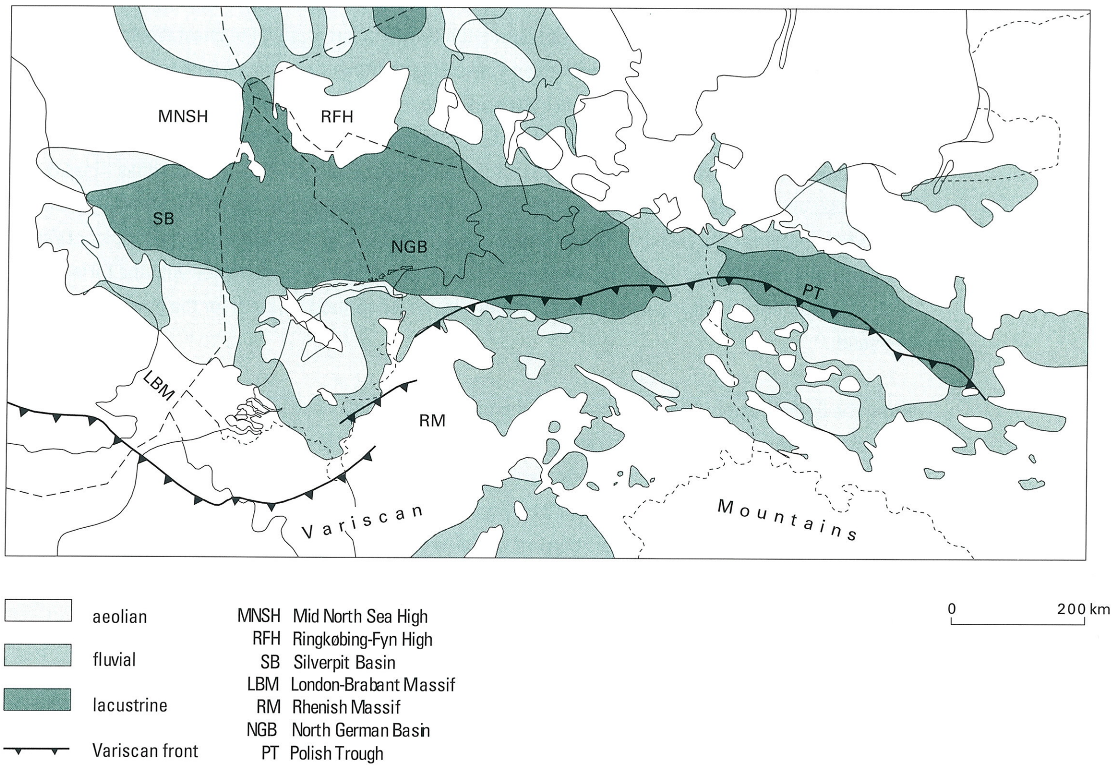


Figure 14.2 Palaeogeography of Northwest Europe at the beginning of the Late Permian (Upper Rotliegend Group; after Lokhorst, 1998; Sørensen & Martinsen, 1987).

Southern Permian Basin (fig. 14.2). Aeolian and fluvial sands and conglomerates of the Upper Rotliegend Group were deposited in arid climate conditions. In a northwesterly direction, the ratio of the fluvial sediments decreases in favour of aeolian and lacustrine sediments. During more humid periods, lacustrine conditions extended across the northern part of the area (Ten Boer Member). As the rate of sediment accumulation in the Southern Permian Basin did not keep pace with subsidence of the area, the basin subsequently became situated below the palaeo sea-level (Glennie, 1983).

Graben formation in the North Atlantic/Arctic region combined with a eustatic sea-level rise initiated the forming of an open passage between the Barentsz Sea in the north and the Southern Permian Basin (Ziegler, 1990). In response to this, a very rapid transgression occurred in the basin, which had already subsided below the palaeo sea-level (Glennie, 1983). This initiated the forming of a large inland sea, in which cycles of carbonates and evaporites were deposited, as a result of a combination of the arid climate on the one hand and an alternating influx of sea water on the other. Major transgressions mark the bases of the different cycles (Taylor, 1998).

The deposition of the Z1 (Werra) Formation was accompanied by transtensional movements, the Tubantian I phase (Geluk, 1999a). These movements triggered a reactivation of older fault zones and made a major impact on the palaeogeography of the Zechstein Group. In the south and east of the map sheet area, an anhydrite platform was formed, which subsequently constituted a barrier, initiating the formation of a subbasin to its south (NITG-TNO, 1998). The presence of this anhydrite platform is related to the Lower Permian volcanic deposits (compare figs. 5.1 and 7.2a).

Loading caused by rapidly accumulated anhydrite on a differentiated substrate gave rise to intensification of the differences in relief already present. This produced considerable differences in thickness in the Z1 (Werra) Formation (Geluk, 1999a). The differential movements during the Tubantian I phase ceased during the deposition of the Z1 (Werra) Formation; the younger deposits of the Zechstein Group cover the relief like a blanket (Geluk, 1999a; Geluk et al., 1997).

During the deposition of the Z2 (Stassfurt) to Z4 (Aller) Formation, the area was situated on the southern margin of the main basin, as a result of which salt was deposited in each of these formations. During the initial transgressions at the beginning of the cycles, normal marine conditions prevailed, favouring the deposition of carbonates. These carbonates formed major reservoir rocks in the map sheet area. The Z2 Carbonate was deposited, mainly in large thicknesses, along the flanks of the Z1 anhydrite platform (fig.7.2b). On the former anhydrite platform, shallow-water and high-energetic depositional conditions prevailed. To the north of the platform, in the basin, a strongly condensed succession of fine-grained, organic-rich deep-water carbonates was deposited. The greatest sediment thicknesses occurred on the slope between the platform and the basin, which is largely built up of redeposited platform material.

The influx of sea water into the basin was again restricted and was followed by deposition of anhydrite and rock salt. Particularly during the deposition of the Z2 Salt, great thicknesses of rock salt were deposited in the map sheet area, up to approximately 700 m. The majority of the relief still present during the Z2 Carbonate was levelled out. The cyclicity in the Z2 Salt is ascribed to fluctuations in the influx of sea water (Geluk, 1995). The deposition of potassium-magnesium salts after the deposition of the Z2 cycle took place during a period of the greatest precipitation of the brine present.

After the deposition of the Z2 Salt, the differences in relief in the basin had largely disappeared.
The southern part of the Groningen High was somewhat shallower and favoured the formation of shallow-water carbonates. The Friesland Platform also constituted a shallow-water setting, where a thick sequence of anhydrite was laid down. The deposition of the Z3 Salt Member was followed by large-

scale drying up of the basin. In isolated depocentres, potassium-magnesium salts, varying in chemical composition, were deposited. The map sheet area is notable in the presence of bischofite, one of the most soluble salts on earth (Coelewij et al., 1978; Geluk, 1995). This indicates complete drying out of the basin at the end of the deposition of the Z3 Salt.

The youngest cycles of the Zechstein exhibit a filling up of the Southern Permian Basin; the brine present in the basin continued to be hypersaline. In the Z4 (Aller) and Z5 (Ohre) Formations, carbonate was no longer deposited, but claystone and salt were the main sediments to be laid down. Preceding the deposition of the Zechstein Upper Claystone Formation, tectonic movements took place in the map sheet area initiating uplift of the Friesland Platform and the Groningen High. These events, the Tubantia II phase, constituted a period of extensional tectonics (Geluk, 1999a). After these movements, the Zechstein Upper Claystone Formation was deposited on older sediments of the Zechstein Group like a blanket and the extent of the Z5 (Ohre) Formation became restricted (fig. 7.4d).

14.2.3 Triassic

The Triassic was characterised initially by highly uniform basin subsidence. The Southern Permian Basin persisted and is therefore often referred to as the Permo-Triassic Basin. As a result of two phases of extensional tectonics, the basin was modified during the Triassic and transected by several NNE-SSW trending elements, including the Ems Low, the Glückstadt Graben, the Horn Graben and the Central North Sea Graben (Ziegler, 1990). The clastics transported during the Triassic originated from the

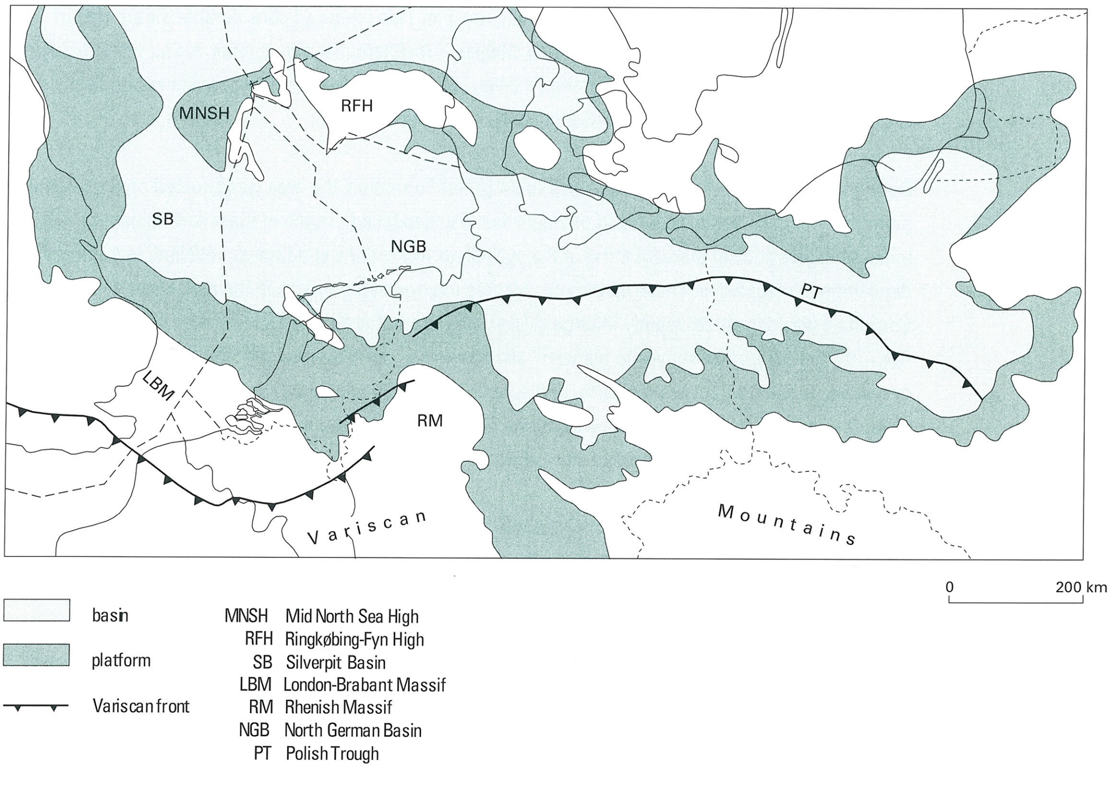


Figure 14.3 Palaeogeography of Northwest Europe during the Late Permian (Z2 Carbonate; Lokhorst, 1998).

Variscan mountains situated in the south. During the Late Triassic, the material transported came predominantly from the Fennoscandian Shield (Ziegler, 1990).

Sedimentation in the map sheet area initially occurred in a lacustrine to playa environment. Uplift of the source areas, in combination with fluctuations in the water table in the basin, favoured the episodic progradation of fluvial systems in the basin and the formation of sand dunes, initiating a cyclical succession of sand and clay/silt (Geluk & Röhling, 1997). During the Early Triassic, several Variscan tectonic elements were reactivated during the Hardegsen phase. To the west and the north of the map sheet area, a high emerged, the Netherlands Swell. Here, erosion exceeded 300 m, while in the Ems Low, a mere 100 m or so was removed by erosion. Owing to these movements, none or only the lowermost deposits of the Main Buntsandstein Subgroup have been preserved on the high (fig. 14.4).

The movements of the Hardegsen phase comprise three, brief pulses of extensional movements, separated by longer periods of regional subsidence. During these pulses, the Netherlands Swell became increasingly accentuated. Between these intervening periods of subsidence, the differences in sediment accumulation between the Netherlands Swell and the Ems Low were minimal. The present differences in thickness (fig. 8.2b) are principally the result of erosion and, to a lesser extent, depositional differences (Geluk & Röhling, 1997). The thickness of the Lower Detfurth Sandstone reveals that the Netherlands Swell formed a clear palaeo-relief where only thin sand layers were deposited. During the uplift and erosion, a number of NW-SE oriented faults were reactivated, in which locally intensive erosion occurred and virtually the entire Lower Buntsandstein Formation disappeared as a result of erosion. The Hardegsen phase was also characterised by the initial movement of the Zechstein salt in the map sheet area, particularly in the NE of the area.

The Hardegsen phase was followed by a period during which the Ems Low continued to display more pronounced subsidence (Geluk et al., 1996). The lacustrine deposits of the Solling Formation covered the entire area like a blanket. During the Middle Triassic, the Permo-Triassic Basin achieved a connection with the open ocean (Ziegler, 1990), and a gradual transgression took place in the Permo-Triassic Basin from an easterly direction. This transgression stagnated a number of times, culminating in the deposition of evaporites, particularly in the east of the map sheet area (Main Röt Evaporite, Upper Röt Evaporite and Muschelkalk Evaporite Members). During the Late Anisian, a marine environment was established in the area. Within a wide range of the map sheet area, the highs were flooded by the sea and the decrease in supply of clastic material favoured the deposition of carbonates, marls and evaporites from the Late Anisian to Ladinian (Muschelkalk Formation).

During the Middle Triassic to Early Cretaceous, tectonic instability increased drastically, as a result of the break up of Pangaea (Ziegler, 1990). This instability was expressed in a number of tectonic pulses during the Middle and Late Triassic, the most intense movements in the Triassic occurring during the Carnian (Late Triassic).These periods are known as the Kimmerian phases, dominating the structural evolution of Northwest Europe. For practical reasons, they are related to the pronounced hiatuses in the stratigraphic succession.

The first pulse, the Early Kimmerian tectonic phase, initiated pronounced differentiation in the area. In the NE of the map sheet area, a N-S oriented complex graben system was formed, accommodating much of the extension (see fig. 8.4c). This graben is considered to be a modification of the Ems Low dating from the Carboniferous and Early Permian. During the Late Triassic, movements also took place along the Holsloot Fault Zone (fig. 14.5). The movements in the graben commenced during the Hardegsen phase. Initially, they were characterised by uplift and erosion, later by profound subsidence.

These grabens provide a good example of the rift-raft structures described in the literature, in which the Triassic is pulled apart in large blocks (Best, 1996; Thieme & Rockenbauch, 1999). During the Late Anisian and the Carnian, the most pronounced subsidence occurred, with intermittent activity, along the faults. (Frisch & Kockel, 1997; Geluk, 1999b). During the Carnian, thick bodies of rock salt were deposited in the graben, with virtually no salt deposition occurring outside the graben. The thickness of the Keuper Formation in the Ems Low may total 1000 m, in contrast to a bare 200 m in the graben connected to the Holsloot Fault Zone. Simultaneously with the major subsidence, erosion occurred in the areas situated outside the graben, during which the degree of erosion increases from the graben in a southwesterly direction.

During the Norian, the tectonic activity drastically reduced, which is apparent from the greatly reduced differences in thickness between the graben and the areas to its west. The Red Keuper Claystone marks the Early Kimmerian unconformity. The westernmost and southernmost part of the map sheet area were elevated areas for a more prolonged period, which can be inferred from the Rhaetian transgression on the Early Kimmerian unconformity in (fig. 8.4d). The Holsloot Fault Zone is presumed to have played a major role. The youngest Triassic (Rhaetian) marked the onset of regional subsidence in the area and the differential fault movements diminished.

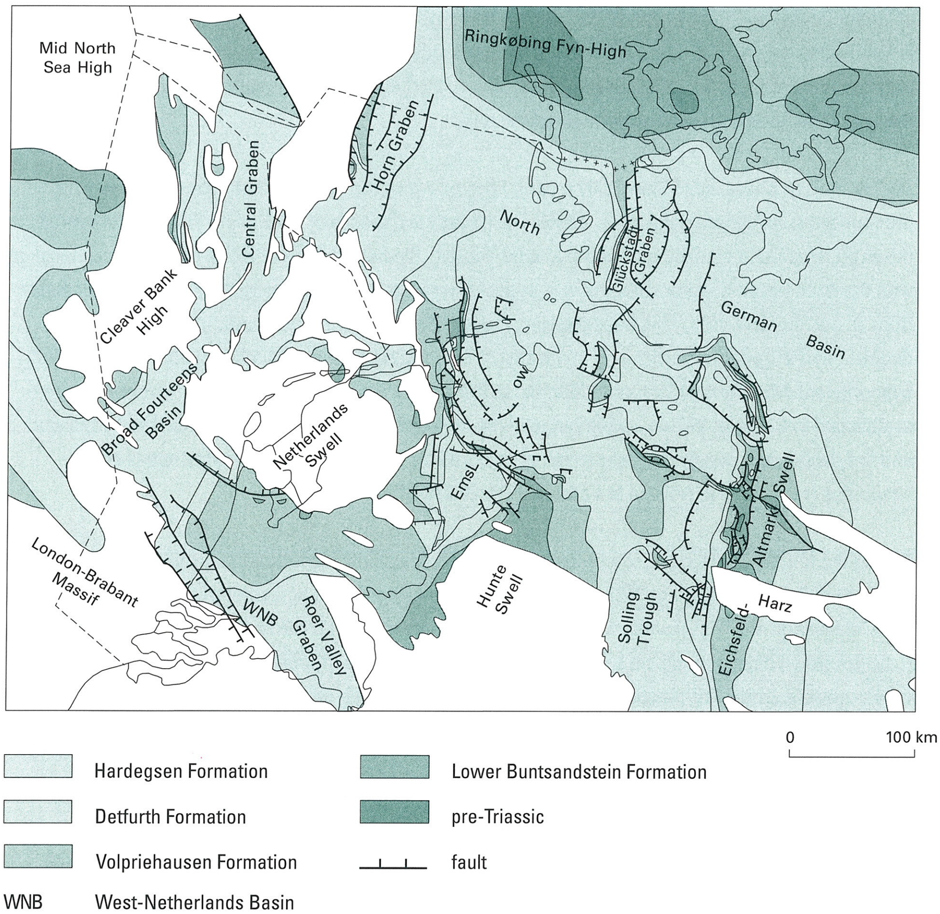


Figure 14.4 Subcrop map below the Hardegsen unconformity (after Geluk & Röhling, 1999).

14.2.4 Jurassic

In combination with a sea-level rise, the regional subsidence beginning in the Rhaetian initiated the deposition of fine-grained marine sediments. The deposits of the Early and Middle Jurassic are found nowadays in separate basins, despite having originally been deposited in a single, continuous, vast area extending across a large parts of Northwest Europe. This is apparent from the uniform composition and the fine-grained character of the deposits. At the end of the Early Jurassic (Toarcian), a period of stagnation set in in the marine basins initiating deposition of organic-rich sediments (Posidonia Shale Formation) in large parts of this area. In the east of the map sheet area these deposits have been preserved locally (fig. 9.2).

The prolongation of differential fault movements during the Early Jurassic is indicated by the thickness pattern of the deposits of the Aalburg Formation. The E-W orientation of the fault structures differed from that during the Late Triassic. During the Bajocian Bathonian, the sea basin became shallower and smaller, presumably in conjunction with the uplift of the Central North Sea (Ziegler, 1990). This uplift, the Mid-Kimmerian phase, also affected the north of the map sheet area. The Friesland Platform and the Groningen High formed part of a large area of uplift, which also spanned the central North Sea and

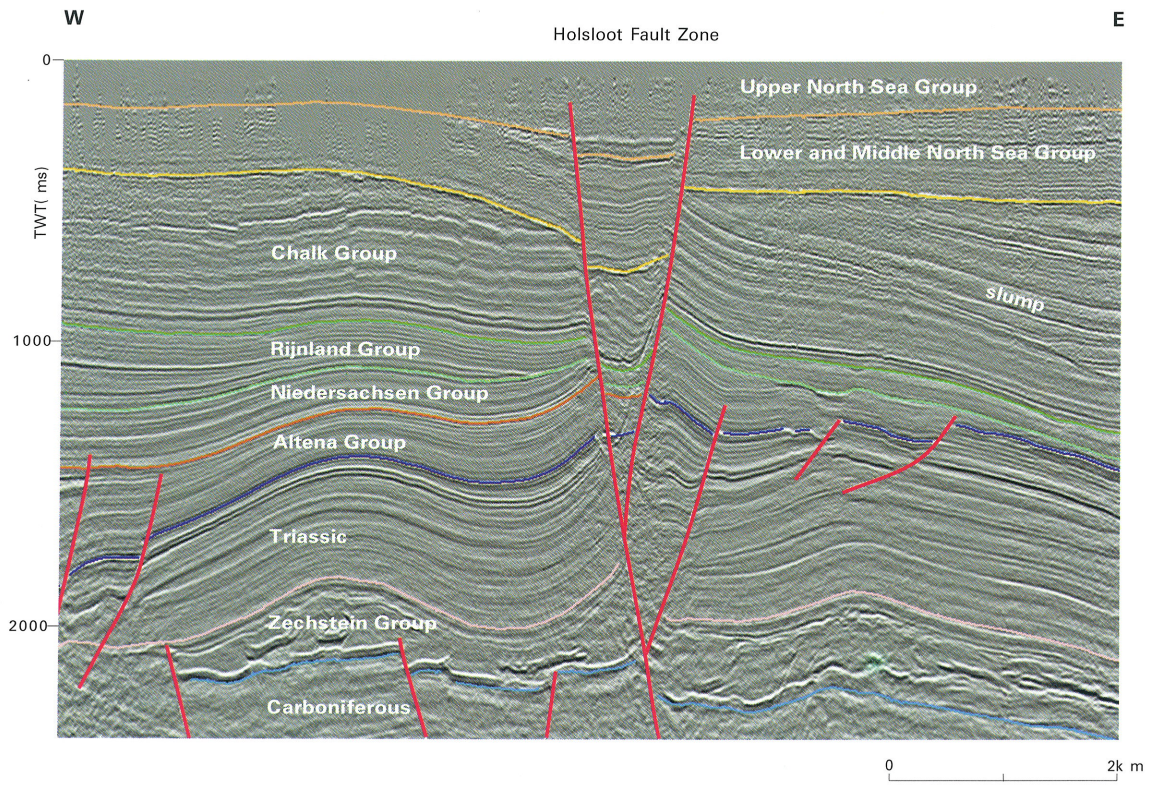


Figure 14.5 Seismic section through the Holsloot Fault Zone. This Tertiary fault structure was active during the Late Triassic, which is clearly visible from the prominent differences in thickness. In the Upper Cretaceous, slumping could be observed. 3D survey Hoogenweg, line 6080.

northern parts of Germany (Ziegler, 1990). This uplift phase triggered a sand influx from the north in the Lower Saxony Basin, in particular to the east of the map sheet area.

The Late Jurassic is a period characterised by a number of major tectonic events, the Late Kimmerian phase, with a primary pulse occurring at the beginning of the Late Jurassic, and a second at the boundary of the Ryazanian-Valanginian. The ENE-WSW trending extensional stresses resulted in the formation of a number of rift basins in Northwest Europe, such as the Central North Sea Graben, the West and Central Netherlands Basin and the Lower Saxony Basin. The Oxfordian and Kimmeridgian marked a period of very pronounced subsidence in the Lower Saxony Basin (Baldschuhn et al., 1991; Betz et al., 1987; Gramann et al., 1997). The subsidence was concentrated in a number of fault-related troughs, only the shallower prolongations of which are found in the map sheet area. These troughs were separated by highs, such as the Emmen-Fehndorf High (fig. 3.1).

The Lower Saxony Basin was directly connected to the Central Netherlands Basin, which is demonstrated by the similarities in the sedimentary succession in both composition and age (NITG-TNO, 1998; Rijks Geologische Dienst, 1993a). This connection was subsequently removed by pre-Valanginian erosion. During the Late Jurassic, the Lower Saxony Basin was isolated from other marine basins, one consequence of which was the deposition of an evaporitic succession.

During the youngest part of the Portlandian, the differential movements diminished and the area of sedimentation extended further over the salt structures and the highs flanking the basin (Serpulite Member). The highs are also thought to have been largely covered by a thin succession of sediment.

14.2.5 Cretaceous

The Cretaceous was marked by a gradual sea-level rise, which was to reach its maximum high stand in the Late Cretaceous (Hancock & Scholle, 1975). By the end of the Early Cretaceous, the sedimentation had extended over the entire map sheet area. The Cretaceous transgression is thought to have been a response to the increased rates in sea-floor spreading and the associated enlargement in volume of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979). The subsidence continued into the Turonian, after which the Late Cretaceous inversion movements associated with the Sub-Hercynian phase initiated uplift of the basin areas and a subsidence of the former highs.

Initially, lacustrine sediments were deposited in the map sheet area (Coevorden Formation). During the Ryazanian, the basin subsidence was regionally confined and the area of sedimentation with respect to the Late Jurassic extended even further over the former basin margins. Brackish water influx in the lacustrine Lower Saxony Basin (Wolburg, 1949) indicate a connection with the Vlieland Basin or the Terschelling Basin for short periods. Between these areas, no Upper Jurassic deposits have been preserved. Differential movements of the Hantum Fault are presumed to have contributed to this connection. Another interpretation is that the influx was effected by the so-called Vlieland Sandstone corridor, to the west of the map sheet area (Rijkers & Geluk, 1996). During the earliest Valanginian, the Lower Saxony Basin and the Central Netherlands Basin became connected to the afore-mentioned marine basins in response to a sea-level rise.

The second pulse of the Late Kimmerian phase, during the Ryazanian-Valanginian, favoured an accentuation of the relief around the basins. The Tubbergen High, Dalfsen High and the Friesland Platform were subjected to strong uplift, and profound erosion took place here (Map 19). The large quantity of erosional material accumulated as sand around these highs in a shallow-marine setting

(Bentheim Sandstone, Gildehaus Sandstone). The finer components were deposited in the central parts of the basins.

During the Hauterivian and Barremian, the area of sedimentation extended further over the adjacent highs. The thickness development of the deposits indicate that the Lower Saxony Basin continue to subside prominently (fig. 11.4a-c). During the Aptian a brief regression took place, coinciding with the Austrian tectonic phase (Ziegler, 1990). These movements favoured the reactivation of highs in the south of the area and caused a hiatus in the sedimentary succession. This is particularly apparent above the Schoonebeek oil field (fig. 11.5).

The movements of the Austrian tectonic phase were followed by the onset of regional subsidence of the entire area. During the Late Aptian and particularly the Albian, all the highs in and around the map sheet area were flooded by the sea. This Albian transgression has been identified throughout Northwest Europe (Crittenden, 1987). The sea-level rise continued during the Turonian, as a result of which the marine area in Northwest Europe enlarged prominently and the influx of clastic material correspondingly decreased. Clays and marls of the Aptian and Albian were succeeded by thick

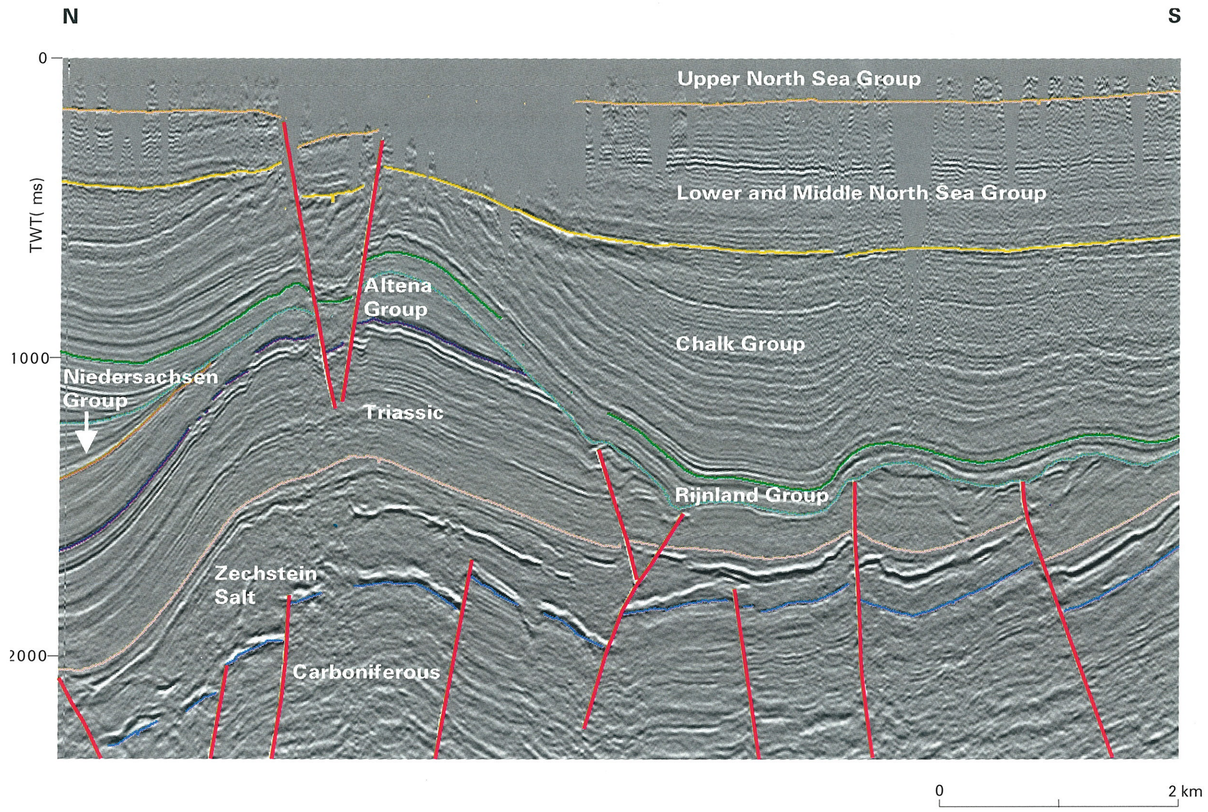


Figure 14.6 Example of an inversion structure. The thinning of the Upper Cretaceous (Chalk Group) is complementary to the thickness of the Triassic to Lower Cretaceous sediments. Extension during the Late Tertiary initiated the formation of the graben in the flank of the inversion anticline. This profile also clearly depicts the decoupling of the faults above and below the salt. 3D survey Hoogenweg, line 8400.

successions of marl and limestone during the Cenomanian and Turonian. The greatest subsidence continued to be concentrated in the Lower Saxony Basin, but the differences in subsidence drastically diminished and active faulting is thought to have virtually ceased (Baldschuhn et al., 1991).

This period of regional subsidence came to an end during the Coniacian, as a result of major plate reorganisation, induced by an extensional stress regime and graben formation preceding the sea-floor spreading in the Arctic and North Atlantic Ocean (Coward, 1991), the collision of Africa and Europe (Ziegler, 1987) and a number of local factors (Baldschuhn et al., 1991). This initiated a compressive tectonic regime, culminating in a reverse direction of movement along faults during the Coniacian to Early Campanian period. The inversion initiated uplift of the former Upper Jurassic/Lower Cretaceous basins and pronounced subsidence of the former highs (Baldschuhn et al., 1991; Tantow, 1992). These original highs subsequently formed the marginal troughs of the elevated areas and the degree of subsidence is related to the extent of uplift of the adjacent basins (Voigt, 1963). To the east of the map sheet area, in the Lower Saxony Basin, practically the entire succession of the Cretaceous was eroded as a result of the inversion. Here, the inversion was accompanied by the intrusion of magma, resulting in the formation of the Vlotho and Bramsche Massifs (Teichmüller et al., 1984). In the map sheet area itself, the inversion was notably less intense and preluded the uplift of a number of former areas of subsidence, such as the Schoonebeek structure in the south and a phase of an accelerated ascent of salt structures accompanied by the lateral intrusion of salt (see section 14.4). Figure14.6 gives an example of the inversion.

The inversion movements had terminated by the beginning of the Campanian; regional basin subsidence subsequently resumed and the sedimentation of the Chalk Group extended over the inverted basins.

14.2.6 Cenozoic

The Tertiary and Quaternary evolution is determined by the development of the North Sea Basin, which has governed the sedimentation pattern up to the present time. During the Tertiary and the Quaternary, a rising sea-level combined with continuing regional subsidence in the central part of the North Sea resulted in the deposition of over 3500 m of sediment (Ziegler, 1990). However, the subsidence was considerably less in the map sheet area and particularly in its southeastern part (Maps 16 & 17).

A regression during the Early Palaeocene in combination with the aftereffect of the inverted Lower Saxony Basin triggered uplift and erosion, during which the youngest, post-inversion deposits of the Chalk Group were eroded in a wide area around this basin. This uplifted phase is known as the Laramide phase.

During the Tertiary, the sedimentation was largely governed by sea-level changes and by a number of Alpine Orogeny-related tectonic phases, such as the Pyrenean (transition Eocene-Oligocene) and the Savian (transition Oligocene-Miocene). The depositional succession of the North Sea Supergroup consequently displays hiatuses and erosion. The uplifted area comprised the Lower Saxony Basin and its margins. Although most of the formations were in fact deposited within the map sheet area, they were subsequently removed by erosion, which may be concluded from the facies of the deposits and isolated occurrences in relation to deposits outside the map sheet area.

During the Tertiary, further active faulting occurred in a few places only, and relates principally to movements related to the Late Kimmerian fault zones, such as the Hantum Fault Zone, the Dalen Graben and the Holsloot Fault Zone (fig. 3.1; Maps 16 &17).

During the Pliocene, the sea began to withdraw from the map sheet area, commencing with the north part of the area. During the Quaternary, terrestrial conditions prevailed and the present topography was formed by a number of glacials and interglacials.

14.3 Geochemical evaluation and burial history

14.3.1 Introduction

As a contribution to the mapping activities, a geochemical evaluation and a modelling study have been carried out on the generation of hydrocarbons. The modelling study is based on a combination of geological, geochemical and petrophysical data.

The most important source rock for hydrocarbons in the map sheet area is the coal of the Limburg Group (Upper Carboniferous). The coal was formed from terrestrial plant material (kerogen type III). From this coal, gas was predominantly generated during the course of geological history. The gas was captured in reservoirs which have been encountered in several places in the area (see Chapter 2). The coal-bearing within the Limburg Group is confined to the Caumer Subgroup. The coal-bearing in this subgroup, approximately 2000 m thick, differs considerably. In the Baarlo and the Ruurlo Formations, the coal-bearing is 1 to 2%, whereas in the uppermost part, the Maurits Formation, it is approximately 3.5%.

In addition to the coal seams, the map sheet area also contains other potential oil or gas-source rocks. These are the hot shales of the Geverik Member, the lacustrine source rocks in the Limburg Group and the basin facies of the Z2 Carbonate. Apart from these Palaeozoic source rocks, the map sheet area also contains source rocks of Mesozoic age. These are the organic-rich marine Posidonia Shale Formation in the Altena Group (kerogen type I) and lacustrine source rocks in the Coevorden Formation. These source rocks predominantly generated oil, particularly the oil in the Schoonebeek field.

By far the majority of the hydrocarbons in this area are derived from the Limburg Group. Owing to the absence of information on the Geverik Member, only the hydrocarbon generation of the Caumer Subgroup has been modelled.

One of the methods of reconstructing the burial history of an area is by comparing measured coalification of organic material in sediments with theoretically calculated coalification values. This procedure is based on the nature of organic material that, with increasing temperatures (and therefore an increasing burial depth), the physical and chemical composition changes. The degree of coalification is dependent on the temperature, the duration of the temperature absorption and the nature of the organic material itself. The changes in the organic material are described by Arrhenius's Law. They are, moreover, related to the reflectance of the organic material, which enables the theoretical reflection value to be calculated. The empirical reflection value is measured under standard conditions. In the case of organic constituents of coal, the reflectance ranges from 0.2%Rr (peat), via 0.6%Rr (brown coal), to over 2%Rr (anthracite).

In order to gauge the burial history in the geological modelling studies, various types of parameters were entered, indirectly related to Arrhenius's Law. The stratigraphic and geochronological input describes the rate of sedimentation and in this way determines the effects of time. The lithological data provide the preconditions for compaction, conductivity and heat capacity. In this way, in combination with the surface temperature, the vertical heat flow and the prevailing temperature can be calculated. The type of organic material is determined microscopically and chemically. This provides information on the activation energies of the organic bonds and therefore on type and quantity of hydrocarbons generated.

Burial-graphs were compiled for15 wells in the area, in accordance with the geo-history analysis described. Owing to the substantial uplift and erosion in the area, uncertainty increases proportionally with the age. With the aid of the GENEX software package, the theoretical coalification was subsequently determined from assumptions on the palaeo heat flow. The theoretically calculated coalification was subsequently tested against actual coalification data found, enabling the number of possible burial-depth curves to be restricted to a few realistic models. The reconstruction of oil and gas generation is founded on a large number of input data, each with their own uncertainties. Suppositions are made regarding the degree of erosion, the depth of the basement, the lithological characteristics, the palaeo-heat flow, permeability and compaction. The reconstruction of the quantities of hydrocarbons generated is influenced in particular by the suppositions made regarding palaeo-heat flow, the degree of erosion and the kinetic concept assumed.

The reconstruction of the palaeo burial history of the map sheet area is complex, on account of the many deformation phases and consequent erosion. The reconstruction of the area assumes a more-or-less uniform thickness of the coal-bearing layers of the Caumer Subgroup. During the deposition of the Dinkel and Hunze Subgroups, in the area to the east (Ems Low), major subsidence occurred. In the analysis of each well, the reconstruction of the burial history has been carried out in the greatest possible detail. For the palaeo-heat flow within the map sheet area, this study assumes a constant heat flow.

A study was made of the organic constituents of the rocks of the Limburg Group and the Coppershale from 13 wells within the map sheet area in order to test the burial model. The Altena Group was not available. The degree of coalification was determined from various parameters such as vitrinite reflections (%Rr), RockEval Tmax and other geochemical indices.

14.3.2 Results

This geographical distribution of the wells studied enables a reconstruction to be made of the entire map sheet area. Of the 15 wells investigated, reliable coalification data were obtained from 13 of them. In two wells, the organic material content was too low. These data, and a comparison with data derived from Koch et al., (1997), enable a good understanding to be achieved of the coalification of the top of the Limburg Group, displaying the highest figures in the Lower Saxony Basin and lower coalification in the area of the Friesland platform (fig. 14.7a).

The burial depth history of the area is illustrated by the Annerveen-Wildervank-1 wells on the flank of the Groningen High (fig. 14.8) and the Dalen-7 well in the Lower Saxony Basin (fig. 14.9). Both wells display striking differences in the quantity and time span of the generated hydrocarbons. In the Dalen-7 well, gas generation already begins directly below the top of the Limburg Group and a large part of the organic material was converted into hydrocarbons in the course of geological history. In the Annerveen-Wildervank-1 well, the topmost part of the Limburg Group lies within the oil window and significant gas generation does not begin until 500 m below the top of the Limburg Group (fig. 14.8a).

The initial coalification stage already occurred at the end of the Carboniferous, as revealed by both wells. However, the quantity of hydrocarbons generated was insufficient to result in expulsion of hydrocarbons. Hydrocarbon generation ended with uplift during the Early Permian. The second phase of coalification and related hydrocarbon generation phase took place during the Triassic-Jurassic interval.

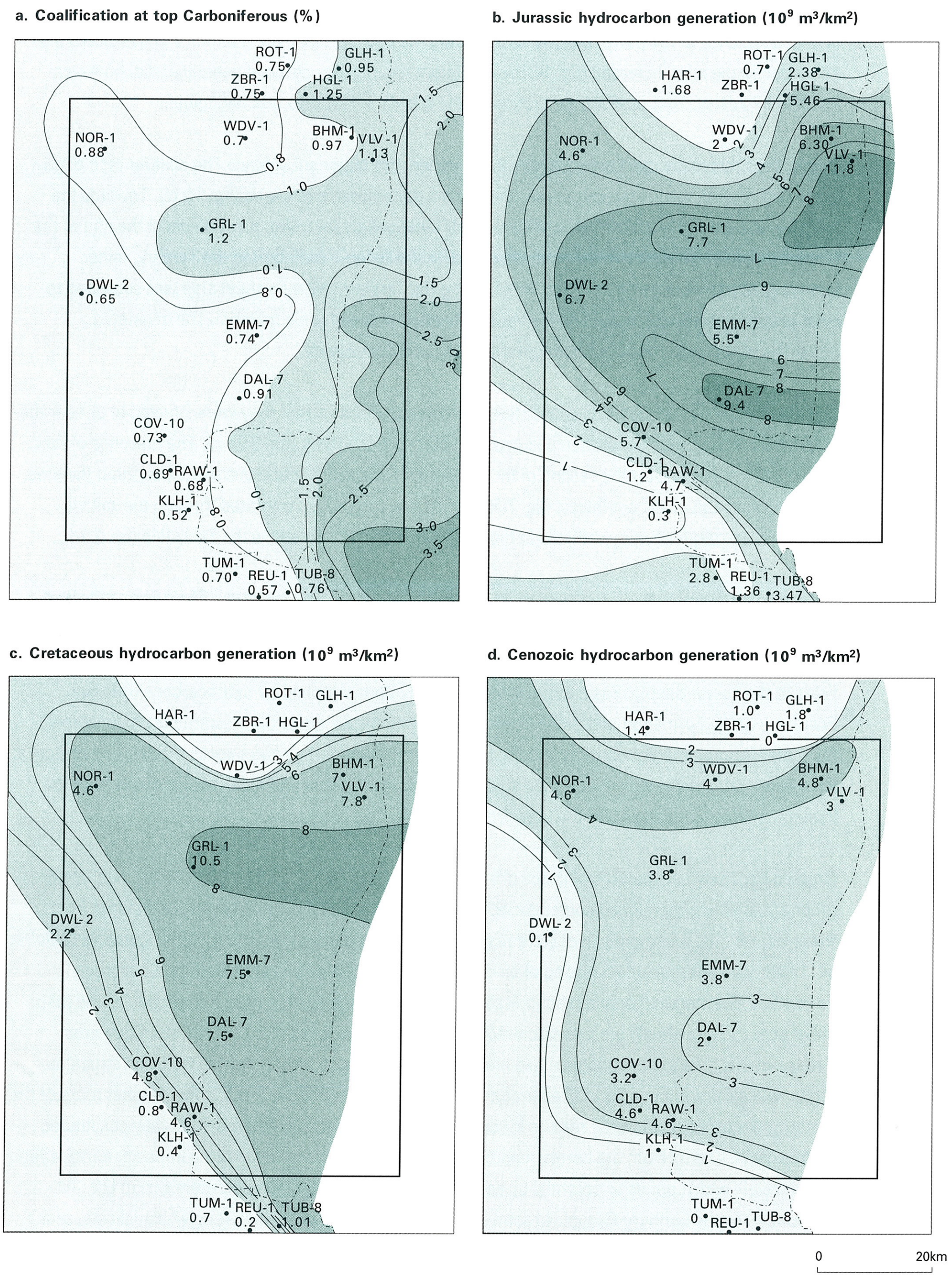


Figure 14.7 a. Contour map of the degree of coalification for top Carboniferous. This contour map has been based on the wells shown. The coalification pattern for the adjacent German part has been derived from Koch et al. (1997).
b. Contour map of the hydrocarbon generation during the Jurassic (in $10^9 m^3/km^2$). The largest quantities were generated in the Lower Saxony Basin; on the surrounding highs, generation manifestly decreased.
c. Contour map of the hydrocarbon generation during the Cretaceous (in $10^9 m^3/km^2$) in the map sheet area. The largest quantities were generated in the Lower Saxony Basin.
d. Contour map of the hydrocarbon generation during the Cenozoic (in $10^9 m^3/km^2$) in the map sheet area. The largest quantities were generated in the Lauwerszee Trough to the south of the Groningen High.

The main generation on the western margin of the Ems Low occurred during the Early Jurassic. In view of the subsidence of the Lower Saxony Basin during the Late Jurassic, the quantities of hydrocarbons generated in the area increased (fig. 14.7b). The quantities of hydrocarbons generated did, however, result in expulsion. Hydrocarbon generation on the Friesland Platform was negligible.

During the Cretaceous, the Lower Saxony Basin underwent major subsidence The contour map of gas generation during the Cretaceous shows the highest generation in this area (fig. 14.7c). Towards the margins, gas generation diminishes. With the uplift induced by inversion movements at the end of the Cretaceous, gas generation in the area decreased. In the Dalen-7 well, during the Tertiary, minor quantities of gas were generated (fig. 14.9). During the Tertiary, the map sheet area was subjected to even greater subsidence, triggering further coalification of the organic material. The generated quantities of gas were less than during the Jurassic and Cretaceous.

The distribution of the gas fields encountered in the area indicates that they were situated in or near the area where the greatest generation had occurred during the Tertiary (fig. 2.2a-d). The presence of rock salt was of importance for the sealing of the reservoirs. Rock salt is found virtually throughout the area, with the exception of the southwest (fig. 7.3b-d). In a few places, gas migrated through the salt via faults, and consequently accumulated in the reservoir rocks located above the Zechstein (fig. 2.2d).

Regarding oil occurrences in the area, rocks of the Z2 Carbonate, the Posidonia Shale Formation and Coevorden Formation are assumed to have constituted oil-source rocks. In the Coevorden Formation, a bituminous facies is found in the Upper Coevorden. Research by Binot et al. (1991) has revealed that oil fields in the Lower Saxony Basin in Germany have only been supplied by hydrocarbons from the Posidonia Shale Formation and/or the Coevorden Formation. As far as the western part is concerned, they infer from biomarker-patterns and the spatial distribution of the source rocks that the Coevorden Formation, principally, was in effect the source rock for oil. In some oil fields, mixing of oils from the Posidonia Shale Formation and the Coevorden Formation occurred (Binot et al., 1991).

Organic-geochemical analyses of Dutch oils in the map sheet area allow no clear allocation to one or other of the above-mentioned source rocks, owing to the scarcity of available sample material from these formations. A comparison of sterane patterns with the patterns described in the literature (Binot et al., 1991) does not preclude a mixing of oil of the Posidonia Shale Formation and the Coevorden Formation. The sterane/hopane ratio indicates that the generated oils in the southern part of the map sheet area (Schoonebeek) are premature. Modelling shows the rocks of the Altena and Coevorden Groups in this area to be immature. This may be attributed to the location of the wells, on structural highs, while the source rocks in deeper parts are within the oil window. Despite the fact that rocks of the Limburg Group are sufficiently mature for oil generation, it is not thought likely that they constituted source rocks. The oil from the northern part (Stadskanaal, Gieterveen) display a composition indicating a mature oil, which points to potential oil accumulation from rocks of the Zechstein Group (Z2 Carbonate) or the Limburg Group. No sample material from the Zechstein Group was available, as a result of which this supposition cannot be confirmed by geochemical oil-source rock correlation.

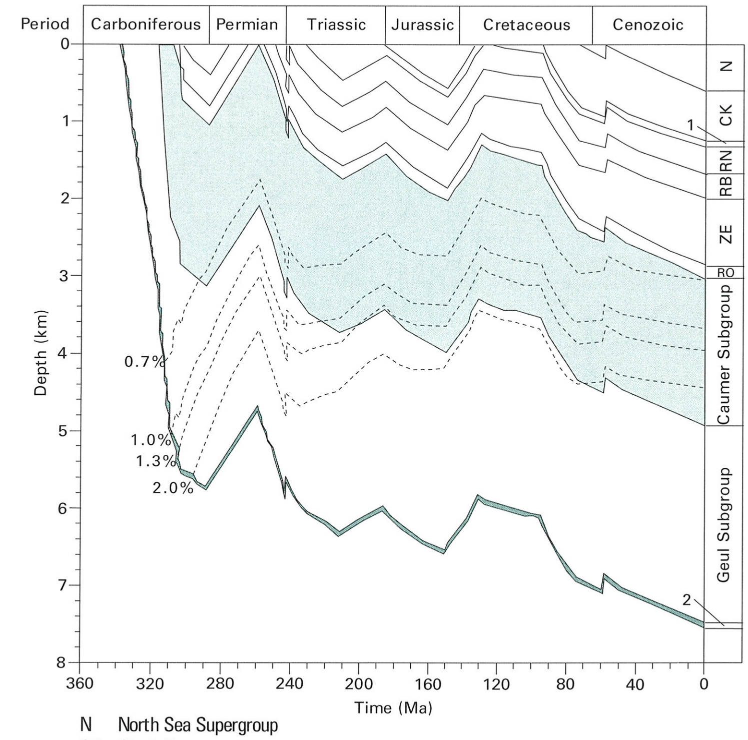
14.4 Salt movement

14.4.1 Introduction

The plastic properties of salt had a major influence on the structural geological development of the map sheet area. Salt has an absorbing effect on the geological structure, as the faults present under the salt are accommodated through the plastic properties of salt. The effect is a decoupling of the fault tectonics

Figure 14.8 a. Burial history diagram of the Annerveen-Wildervank-1 well on the southern margin of the Groningen High. The dotted lines indicate the coalification (%Rr). Gas was generated from coal seams of the Caumer Subgroup lying in the gas window (%Rr van 0.8 tot 2.0).
b. Hydrocarbon generation as a function of time in the Annerveen-Wildervank-1 well. The largest quantities were generated predominantly during the Cretaceous and the Cenozoic.

a



N North Sea Supergroup
CK Chalk Group
1 Rijnland Group
RN Upper Germanic Trias Group
RB Lower Germanic Trias Group
ZE Zechstein Group
RO Upper Rotliegend Group
2 Geverik Member

b

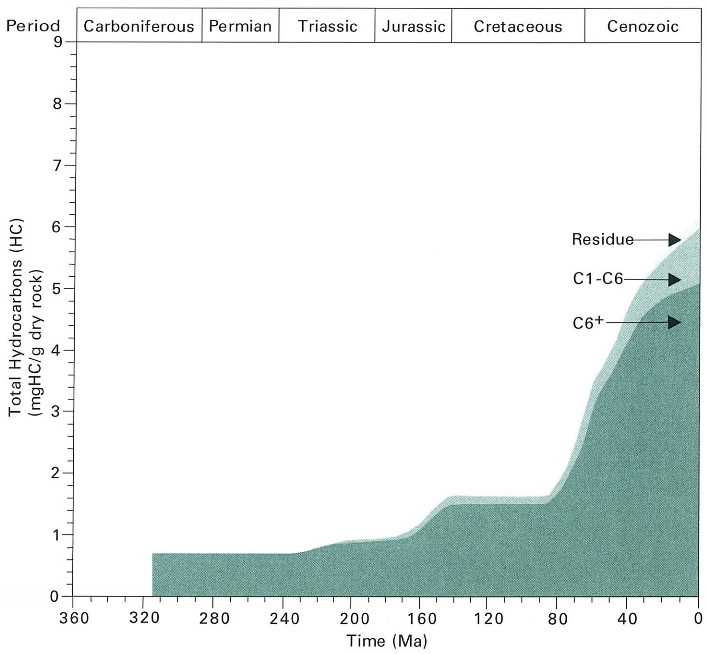
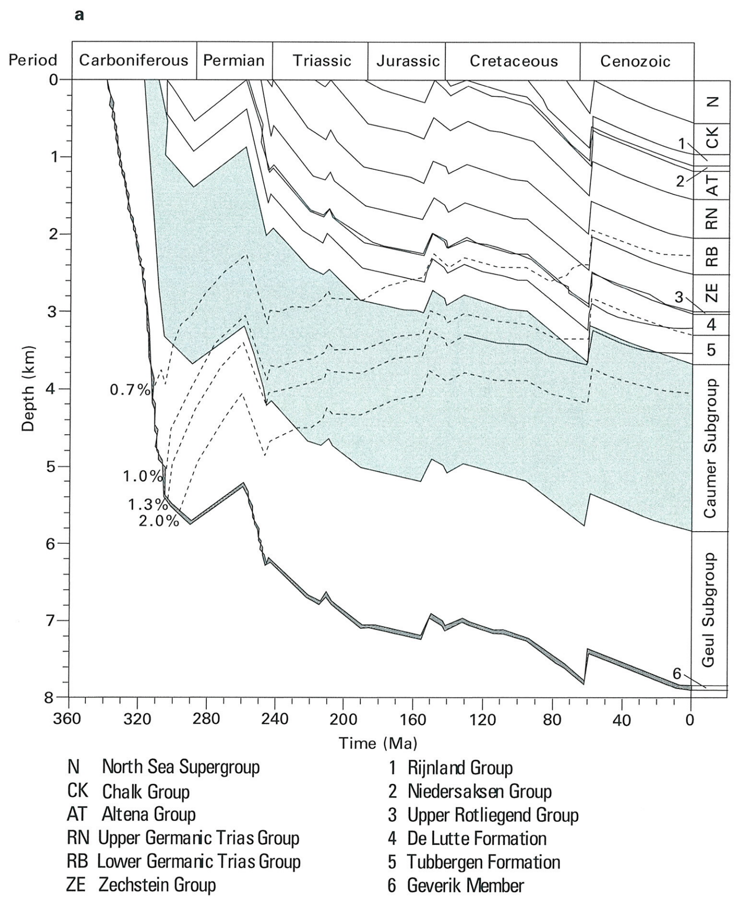
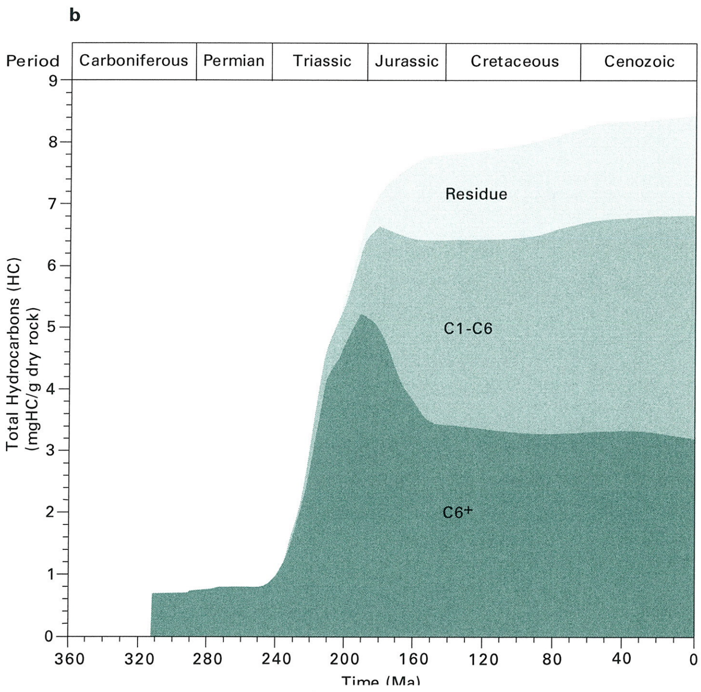


Figure 14.9 a. Burial history diagram of the Dalen-7 well in the southern part of the Lower Saxony Basin. The dotted lines indicate the coalification (%Rr). Gas was generated from coal seams of the Caumer Subgroup lying in the gas window (%Rr van 0.8 tot 2.0).
b. Hydrocarbon generation as a function of time in the Dalen-7 well. Gas generation here took place from the Triassic onwards.



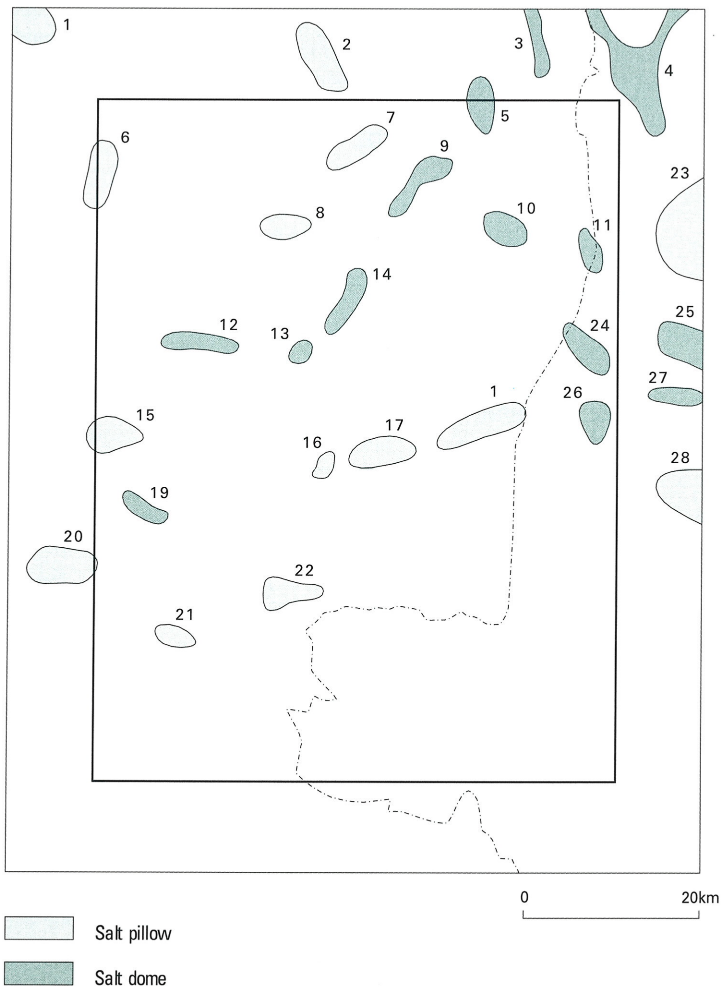


below and above the salt (compare the fault pattern in Maps 3, 6 and 8). This comparison reveals that not only the Zechstein Salt was the cause of such decoupling, but in addition the salts in the Triassic.

Furthermore, the plastic properties of salt and the density contrast between the light salt and the heavier overburden had a major impact on sedimentation. In the map sheet area as in many other places in the Southern Permian Basin, the salt accumulated in a number of salt structures. This caused the salt to migrate into a number of structures in a lateral and vertical direction, and the top of the salt forms a significant topography (Map 4). 28 salt structures can be differentiated, a number of which are located on German territory (fig. 14.10, table 14.1). A distinction is made between salt domes, where the salt has pierced the overburden and is enveloped by much younger sediments, and salt pillows, where the salt forms a pillow-shaped thickening without piercing of the overburden. In addition, a special type of salt structure can be distinguished in the map sheet area, the so-called salt intrusion (section 14.4.3).

Salt structures are of importance from a number of different perspectives. On the one hand, swelling movement of salt induces minerals or natural resources to be pushed up to the near surface; on the other hand, the movement influences the depth and the thickness of sediment sequences. In areas where salt depletion occurs, it facilitates accommodation space for sedimentation; in areas where salt

Figure 14.10 Location of the salt structures in the map sheet area. For an overview of the names and the characteristics of the structures, reference should be made to table 14.1.



intruded, uplift and erosion are the result. In this sense, salt also has a considerable effect on the flow pattern of liquids (water, oil) and gases in a given area.

Table 14.1 Overview of salt structures with their characteristics.
The numbering of the salt structures refers to figure 14.10. The type of salt structure is indicated by P: pillow or D: diapir (dome). The thickness of the caprock is determined from boreholes. Data of German structures are derived from Jaritz (1973). Depth in m below Mean Sea Level (NAP), thickness caprock in m.

Nr.	*Name*	*Type*	*Depth*	*Caprock*	*Overburden*
1.	Gerkesklooster	P	950		Triassic
2.	Hoogezand	P	950		Triassic
3.	Klein-Ulsda	D	900	yes	Upper Cretaceous
4.	Bunde	D	150	yes	Tertiary
5.	Winschoten	D	400	20	Cretaceous/Tertiary
6.	Norg	P	1400		Triassic
7.	Veendam	P	1200		Triassic
8.	Anloo	P	400		Triassic
9.	Zuidwending	D	110	40-50	Tertiary
10.	Onstwedde	D	250	yes	Tertiary
11.	Boertange	D	550	yes	Upper Cretaceous
12.	Hooghalen	D	250	yes	Tertiary
13.	Schoonlo	D	120	80	Tertiary
14.	Gasselte-Drouwen	D	350	yes	Tertiary
15.	Dwingelo	P	1300		Triassic
16.	Gees	P	1700		Triassic
17.	Emmen West	P	2380		Triassic
18.	Emmen Oost	P	2700		Triassic
19.	Hoogeveen	D	900	yes	Jurassic
20.	De Wijk	P	1400		Triassic
21.	Dedemsvaart	P	1500		Triassic
22.	Coevorden	P	1900		Triassic
23.	Wildes Moor	P	2200		Triassic
24.	Neusustrum	D	300	100	Lower Cretaceous
25.	Wahn	D	300	yes	Upper Jurassic
26.	Oberlanger Tenge	D	200	30	Tertiary
27.	Lathen	D	200	yes	Tertiary
28.	Apeldorn	P	2900		Triassic

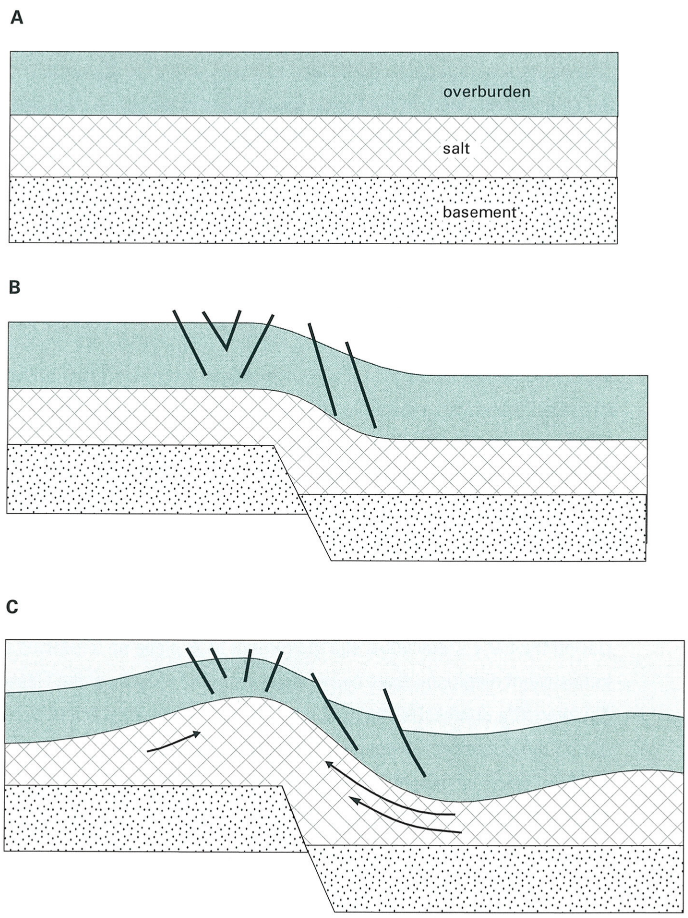
The development of salt structures has been the subject of many publications. The assumption was previously made that the density contrast between the light salt (2.2 gr/cm^3) and the heavier overburden (2.5 gr/cm^3) was suitable for the formation of salt structures (Trusheim, 1963). The current perception, however, is that the formation of salt structures can be attributed to an interaction of tectonic stress and density contrast, where tectonic stress was the primary factor in determining whether a structure would become a pillow or a dome structure (Koyi et al., 1993; Remmelts, 1995; Rijks Geologische Dienst, 1993b). Indirect indications to this effect are given by the fact that salt structures are related to major structural trends, and direct evidence is provided by the mapping of these faults on 3D seismics (compare fig. 14.10 and Map 3).

In the map sheet area, there is a strong connection between the fault tectonism and the salt structures. The orientation of most of the salt structures is E-W or N-S; a comparison between the map of the Zechstein Group with that of the base of the group (Maps 3 & 4) indicates that the majority of the salt structures appear to be fault-induced.

14.4.2 Groups and individual salt structures

The most obvious structures in the map sheet area are formed by a number of culminations with a similar geographical orientation. A distinction can be made between roughly E-W oriented structures (Hooghalen, Gees-Emmen), NE-SW oriented structures (Gasselte-Drouwen, Zuidwending, Veendam) and NNW-SSE oriented structures (Klein-Ulsda, Bunde). In addition, there are a number of individual, more or less circular structures (Schoonlo, Onstwedde, Boertange). Circular structures appear to be related to an interference of fault trends (Remmelts, 1995, Rijks Geologische Dienst, 1995). In the Zuidwending structure, an interference of two different trends can be observed in the change of direction from SW-NE to E-W.

Figure 14.11 Schematic line drawing showing the development of a salt structure in relation to active basement faulting.
A: the primary situation;
B: the formation of the fault in the basement;
C: the response of the rock salt, which accumulates on the high block.



The salt movement can be dated from the infillings of the rim synclines. In the Lower Saxony Basin, this does not generally present a problem, but on the margins of this basin, where large hiatuses in the rock successions may occur, the time span of the salt movement cannot be unequivocally dated. This applies particularly to the Hoogezand, Anloo, Dwingelo and De Wijk structures. Data on these salt pillows are insufficient to state anything other than that, in general terms, they originated before the Cretaceous.

The earliest salt movement occurred in the eastern part of the map sheet area, related to fault movements in the Ems Low during the Hardegsen phase, resulting in the Klein-Ulsda, Onstwedde and Boertange structures initially as a salt pillow during the Early Triassic. The same has been observed in the case of a number of structures in Germany (Jaritz, 1973). The Gasselte-Drouwen, Klein-Ulsda and Hoogeveen structures developed into salt diapirs during the Triassic already. This area was characterised by diapirism during the Ladinian to Carnian. which also applies to the Neusustrum, Oberlanger Tenge and Wahn structures in Germany (Jaritz, 1973). The diapirism is related to the Late Triassic subsidence of the Ems Low (fig. 8.4c). During the Late Triassic, the number of salt pillows was augmented by Hooghalen, Schoonlo and presumably the structures on the margin of the Groningen High (Gerkesklooster, Zuidwending, Winschoten, Hoogezand).

During the Early Jurassic, the number of active salt diapirs again increased, with Onstwedde, Boertange and Schoonlo, while Gasselte-Drouwen and Klein-Ulsda continued to be active as diapirs. The Hoogeveen diapir diminished drastically in activity, and on top, during the Early Jurassic, sediment accumulated. The Hooghalen, Hoogezand, Anloo, Dwingelo, Norg, De Wijk and Dedemsvaart salt pillows are also thought to have been formed during the Jurassic. The principal structures active during the Late Jurassic were in the Lower Saxony Basin; diapirism occurred in the vicinity of Klein-Ulsda, Onstwedde, Gasselte-Drouwen and Boertange and in a number of structures in Germany (Jaritz, 1973).

The Early Cretaceous was characterised by pronounced uplift of the Groningen High and the Friesland Platform, associated with the Late Kimmerian phase. These structural units were partly fault-bounded, with salt flow occurring along the faults. Above the salt structures, drastic erosion occurred; the Schoonlo, Hooghalen, Gasselte-Drouwen, Onstwedde and Boertange structures are presumed to have reached the surface. Other structures reached the near surface and the strength of the overburden was seriously affected by erosion. This is the case in a large number of salt pillows. The alteration in the structural framework initiated a change in pattern of salt movement. The salt structures during the Cretaceous and Tertiary were primarily related to the Hantum—Holsloot—Dalen—Reutum fault system (fig. 3.1; Map 16); the salt structures here formed a major part of this system (compare Maps 4 & 16). The salt structures are of particular importance as E-W components of this fault system and part of the NNE direction also appears to have been accommodated along this fault system. The N-S faults display less salt movement.

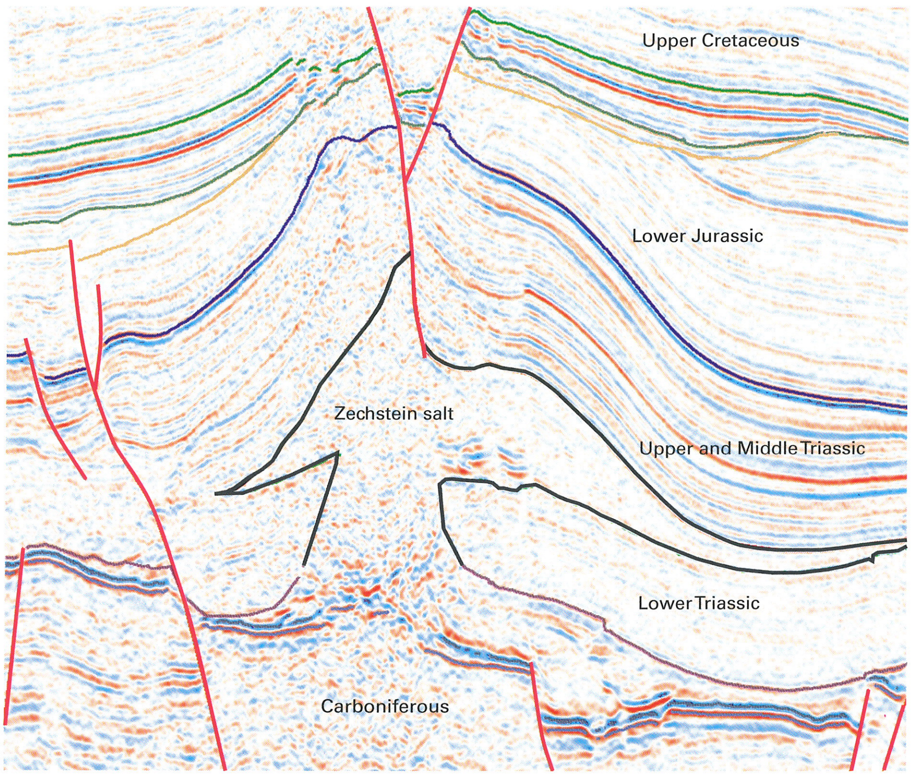
During the Early Cretaceous, salt movement took place on a reduced scale. Secondary rim synclines, indicative of diapirism, have been observed in the vicinity of the Gasselte-Drouwen, Onstwedde and Zuidwending domes. During the Late Cretaceous, salt movement occurred on a wide scale, mainly during the Coniacian-Campanian time interval, indicating a connection with the tectonic activity during the Sub-Hercynian inversion phase. A large number of salt diapirs reveal pronounced activity, including Anloo, Winschoten, Zuidwending, Hooghalen, Schoonlo, Gasselte-Drouwen and Boertange. During the Late Cretaceous, several structures were covered by sediment as in the case of Boertange.

During the Palaeocene-Eocene, the Anloo, Zuidwending, Hooghalen, Schoonlo and Gasselte-Drouwen structures continued to be highly active. Differences in the thickness of sequences are indicative of prominent activity related to the Pyrenean phase, in particular during the Late Eocene-Oligocene. In many salt structures, there appears to have been a change in subsidence pattern compared to the Late Cretaceous. In the Zuidwending structure, the ascent is concentrated mainly in the northern part of the structure, and in the southern part, the caprock is already overlain by Palaeocene sediments. After the Oligocene, there is a clear decrease in activity of the salt structures; with the exception of Anloo salt pillow, all the salt structures in the area were overlain by Late Miocene deposits. After the Miocene, only after-effects occurred, the most intensive movements being in the vicinity of Zuidwending, Gasselte-Drouwen, Onstwedde, Schoonlo and Hooghalen (Map17).

The Anloo structure is an example of a typical non-diapiric structure lying close to the surface. Prior to the Cretaceous, erosion had already cut down into the Röt Formation. During the Cretaceous and the Tertiary, a listric fault formed in the overburden above the salt pillow, causing the southern part of the overburden to slide down. The overburden was thrust upwards passively by the salt. Beneath Quaternary deposits, only the oldest part of the Chalk Group has been encountered in the Anloo-1 well. This, in turn, overlies the Rijnland and the Lower Germanic Trias Group respectively. A special study has been carried out on the internal composition of the salt pillow, using the cycles of the Z2 Salt identifiable on well log data (Geluk, 1995). The salt pillow is internally composed of a number of recumbent flow-faults, with normal and overturned parts of the Z2 Salt. In the topmost part of the salt pillow, there is a normal stratigraphic contact with the Lower Germanic Trias Group.

The Zuidwending structure is a salt dome in the northern part of the area. In this area, the rock salt is exploited by means of solution mining, carried out by Akzo Nobel Salt B.V. Eleven boreholes have been drilled in this structure, characterised by a northern and southern culmination. In a part of these wells, cores have been taken from the Zechstein Salt. These display extremely steep-inclined (70-90°) rocks of

Figure 14.12 Example of a salt wedge intrusion. The Zechstein Salt has penetrated the Röt layer at this point. The prominent thickening of the Middle and Upper Triassic on both sides of the fault above the Zechstein Salt is indicative of the fact that this was a major palaeo normal fault.



the Z2 (Stassfurt) Formation in the central part of the northern culmination of the Zuidwending salt dome (Harsveldt, 1980). Only on the extreme rims of the salt dome have rocks of the Z3 (Leine) Formation been encountered. In this salt dome, the Main Anhydrite has not been encountered in boreholes, but is nevertheless thought to be present in the structure.

In the Veendam salt pillow, thick magnesium salt beds have been penetrated in the Z3 Salt near the top of the pillow (Coelewij et al., 1978). Exploitation of these magnesium salts is carried out by NedMag Industries. In a number of salt pillows in the area, thickened potassium-magnesium salt beds are also thought to be present in the Z3 (Leine) Formation.

14.4.3 Salt intrusion

In addition to traditional salt structures in the sense of salt pillows and domes, salt intrusion, in this instance referred to as salt wedges, are also found in the map sheet area. This type of structure in the adjacent part of Germany has been described by Baldschuhn et al. (1998). Salt intrusion is differentiated from other salt structures in that the salt has intruded laterally into the Triassic salt layers. In the map sheet area, such salt wedge structures are only encountered in the eastern part of the map sheet area. Diagnostic criteria for such structures are in particular the occurrence of divergent reflectors above and below the salt intrusion (fig. 14.12).

In this area, the Zechstein salt has penetrated laterally into the Röt salt layer, causing the development of a mushroom-like structure. The genesis of these structures, also described as squeezed salt domes, is an interaction of extensional and compressional tectonics. During the extensional phases (Triassic-Jurassic), fault movements in the basement induced salt movement, subsequently causing salt to fill the space present in the fault zone. The structure was deformed by compression during the Coniacian-Campanian in the Sub-Hercynian phase, in response to which the salt was pressed laterally into the Triassic deposits.

15 Applied geology and environmental planning

15.1 Introduction

This chapter discusses the opportunities for potential applications afforded by the subsurface of the map sheet area, in contrast to those already being applied. Concessions have been granted for the exploitation of gas, oil and salt (see Chapter 2); underground gas storage is already taking place in The Netherlands as well as immediately over the border in Germany. In this discussion, we will restrict ourselves to technologies already applied elsewhere. Applications in use in the shallow subsurface (underground construction, near-surface exploitation of mineral and natural resources, storage of cold/heat energy) fall outside the scope of the present map sheet.

In a study carried out by the NITG (1997b), the following underground applications were distinguished:
- exploitation of thermal energy
- exploitation of thermal water
- gas storage
- CO_2 storage
- storage of highly toxic waste

This will be discussed in further detail in the following sections.

15.1.1 Exploitation of thermal energy

The exploitation of thermal energy has for some time been regarded as being viable in The Netherlands, although the subject is for the moment restricted to bureau studies. The preconditions for thermal energy exploitation consist of an aquifer containing water of a raised temperature, capable of producing large quantities of water (for example > 5000 m^3/day). A distinction is made between deep and shallow geothermy; in deep geothermy, the temperature necessary for the formation water is approximately 75° C, whereas in the shallow variant, the temperature of the formation water must be 12 to 45° C. As the temperature increases roughly in a linear proportion to the depth, deep geothermy may be carried out at depths greater than 1200 m.

To be suitable for thermal energy exploitation, an aquifer must have high levels of porosity and hydraulic conductivity, and these also present the greatest risk factor. A study of the potential aquifers in the area, often constituting the reservoir rocks for oil and gas, reveals that the majority do not meet the requirements of water yield on account of their poor transmissivity (the product of thickness and hydraulic conductivity). This is true in the case of the sandstones in the Limburg Group and the carbonates of the Zechstein Group.

Good potential deep geothermal conditions are thought to pertain in the Upper Rotliegend Group in the northwest of the map sheet area, and the Main Buntsandstein Subgroup and the Rijnland Group in the Ems Low. The energy content of these aquifers is shown in Table 15.1. These values have been derived from Haenel & Staroste (1988) and NITG (1997a).

Table 15.1 Heat content of a number of aquifers in the map sheet area.

Aquifer	*Heat content*
Bentheim Sandstone	0.4 * 10^{18} J
Main Buntsandstein/Solling	3 * 10^{18} J
Upper Rotliegend Group	5 * 10^{18} J

Good potential shallow geothermal conditions are thought to pertain in the Rijnland Group in the extreme southeast and in the Brussels Marl in the north and west of the map sheet area.

15.1.2 Exploitation of thermal water

Thermal water exploitation calls for specific criteria to be met in relation to the chemical composition and temperature of the formation water. It is important for a prospective thermal bath to adhere to German norms laid down for medicinal water. These have been reproduced in table 15.2. It is generally true that water at a depth greater than a few hundred metres will meet these standards. In addition, the prospective aquifer must have the capacity to produce tens of m^3/day. Theoretically, there is no shortage of aquifers meeting the necessary criteria; the main limiting conditions, however, will be the investments reserved for the development of the thermal spring. In view of the fact that the drilling costs increase in direct proportion to the depth, the aim will obviously be to locate an aquifer as near to the surface as possible. Thermal water exploitation is conducted to the north of the map sheet area, in the Nieuweschans thermal bath, where hot salt water is extracted from the Brussels Marl from a depth of approximately 550 m.

Table 15.2 Requirements for medicinal water

Specifications of the minimum requirements for different types of medicinal water (Heilwasser) as stipulated by the German Bäderverband (30/6/1979). Some of the designations entitled to be used on compliance with a particular specification have been shown in brackets. For the purposes of comparison, the last column gives the composition of the water in the Nieuweschans well in Groningen (Glasbergen, 1982).

	Minimum value		*Nieuweschans well*
Temperature	18° C	(Thermal)	?
Total dissolved constituents	1000 mg/l		?
Sodium	8500 mg/l	(Sole)	45000 mg/l
Iron	20 mg/l		56 mg/l
Sulphur	1 mg/l	(Sulphur)	
Fluoride	1 mg/l		
Iodide	1 mg/l		2.5 mg/l
Carbon dioxide	1000 mg/l		109 mg/l

The greater part of the area theoretically offers potentiality for thermo-medicinal water abstraction. Exceptions to this are the locations immediately above salt domes (Map 4). The depth at which a suitable aquifer occurs differs in each location. As the preconditions for each individual project may differ substantially, the suitability of each location needs to be thoroughly assessed. Within the scope of this publication, it is only possible to summarise the potentially suitable aquifers:

- Brussels Marl
- Gildehaus Sandstone
- Bentheim Sandstone
- Basal Solling Sandstone
- Lower Detfurth Sandstone
- Lower Volpriehausen Sandstone

In most cases, the water will be able to meet the criteria for classification as *Thermal Sole*, particularly the water in the deeper subsurface (>400 m) in the immediate vicinity of salt domes.

15.1.3 Underground storage of gas

In underground gas storage, a distinction is made between the storage of natural gas in aquifers or reservoirs, where volumes of several hundreds of 10^6 Sm^3 or more are stored, and storage in salt caverns, entailing smaller volume storage. Storage in reservoirs or aquifers provides for seasonal fluctuations, while storage in salt caverns allows for short-term fluctuations in gas supply (peak shaver) or as a strategic reserve.

15.1.3.1 Aquifer or reservoir

One of The Netherlands' storage projects (referred to as Underground Gas Storage) is located in the map sheet area. Since 1997, natural gas has been stored in the Norg gas field. Half the capacity in this gas field, with the Slochteren Formation as reservoir rock, had already been exploited. The Norg field is the largest UGS in The Netherlands, with a capacity of $4.6*10^9$ Sm^3. The UGS is carried out by means of 6 wells, with a maximum daily production of $80*10^6$ Sm^3. There are also two UGS facilities in the adjacent part of Germany in, respectively, an aquifer and a former gas field: Kalle ($0.6*10^9$ Sm^3) and Uelsen ($0.9*10^9$ Sm^3). Both UGS facilities are located in the Main Buntsandstein Subgroup (NLfB, 1999).

Besides these UGS projects, which had already been realised, the map sheet area is seen as a likely source of additional forms of storage. These are, on the one hand, existing gas fields or aquifers, where suitability is primarily dictated by economic factors such as total storage volume, volume of working gas and productivity. In theory, the majority of the gas-bearing units in the map sheet area are suitable for this purpose. The Slochteren Sandstone, the sandstones in the Main Buntsandstein Subgroup, the Basal Solling Sandstone and the Lower Cretaceous sands offer the greatest potential owing to their good permeability and shallow depth range. Subsequent selection is made on a basis of economic, logistic and environmental planning factors, stipulated by the potential clients.

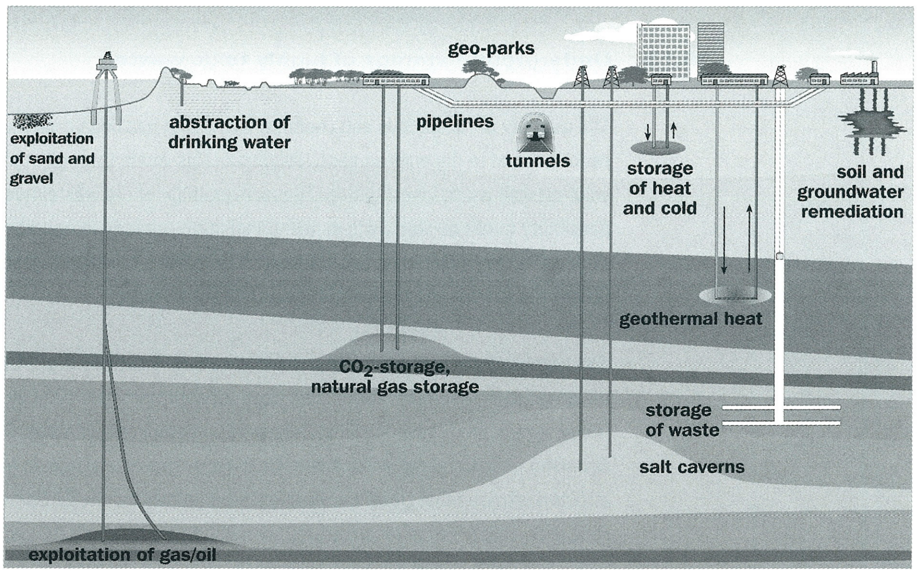


Figure 15.1 Schematic overview of the applications in the subsurface.

15.1.3.2 Salt caverns

In addition to reservoirs or aquifers, gas storage in salt caverns is a further option in the map sheet area. This type of storage is in principle geared to short-term peak demand for natural gas, not exceeding one or two days' duration. In connection with the pressure regime and the rock salt creep, the storage needs to be at a depth of approximately 500 to 1800 m. The best conditions are found in the Zechstein salt, especially in salt domes.

For this type of storage, the following slat domes offer appropriate conditions: Anloo, Zuidwending, Winschoten, Onstwedde, Gasselte-Drouwen, Hooghalen, Schoonlo and Boertange (fig. 14.10; table 14.1). Because leaching of the caverns occurs, this form of gas storage could be carried out in combination with salt exploitation. Storage could also be done on a separate basis, with the possibility of discharge of the diluted brine into the sea, as has already been carried out in Denmark during cavern construction (Quast, 1986). In such instances, statutory and environmental provisions are important factors, besides the economic aspects.

15.1.4 Underground storage of CO_2

Reduction in the discharge of CO_2 is the focus of worldwide attention. This type of gas is regarded as being one of the major greenhouse gases, which may be one of the causes of global warming. One of the possible solutions for the reduction in CO_2 discharge is to store it in aquifers or abandoned gas fields. Storage in depleted gas fields (fig. 2.2) might offer a solution to the problem of surface subsidence. CO_2 could also be instrumental in oil exploitation. The viability of CO_2 storage in the subsurface is still being studied.

The map sheet area is one such area with the potential for CO_2 storage in depleted gas fields or aquifers. In contrast to the storage of gas, the gas field ideally needs to have been fully exhausted before CO_2 storage can take place; if this is not the case, the problems of mixing need to be resolved. The economic viability of gas exploitation with simultaneous CO_2 injection is a subject under discussion. Injection into the present oil fields in the map sheet area could be an option as a stimulus to oil production, but specific research is first needed. Storage in salt caverns is another possibility, but is regarded, as being less suitable in view of the large number of caverns that would be required (NITG 1997b).

15.1.5 Underground storage of highly toxic waste

The quantity of radioactive and chemical waste that has been produced over the last decades forms a serious threat to the environment. Isolation of this waste through storage in the subsurface may form a solution well worth investigating. The recoverability of the waste must, however, be guaranteed. One possibility might be storage in conventional mines already in operation over a long period of time. Within the map sheet area, two formations form potential targets for further examination, the Z2 Salt (Zechstein Group) and the Rupel Clay (Rupel Formation).

Salt domes of the Zechstein Group occur at several locations (fig. 14.10). Assuming that mining in unconsolidated sediments down to a depth of approximately 500-600 m is feasible as far as this aspect is concerned, the following salt structures offer perspectives: Anloo, Hooghalen, Schoonlo, Gasselte-Drouwen, Zuidwending, Winschoten, Onstwedde and Boertange. In terms of internal composition of the structure, Anloo most closely resembles a salt pillow and the Z2 Salt only occurs at depths below 1175 m (Geluk, 1995). The other structures are salt domes, in which the depth of the top ranges from 120 m

(Zuidwending) to 650 m (Boertange). To the extent that information from wells is available, the structures appear to be composed primarily of the Z2 Salt. From the point of view of future safety guarantees, the structures located at deeper levels should be given priority.

The Rupel Clay is only encountered in the northern and western part of the map sheet area at a depth of between 250 and 400 m (fig. 13.4). The thickness of the unit does not in general exceed 100 m.

15.1.6 Salt exploitation

Two concessions have been granted for salt exploitation in the northern part of the area (fig. 2.1). Potentially exploitable salt deposits also occur outside these concession areas. Rock salt exploitation may theoretically also be carried out in all near-surface salt domes, while in a large number of deeper salt pillows, KMg-rich salt layers are encountered, analogous to the situation in the vicinity of Veendam. This is principally the case in the salt pillows in the northern part of the map sheet area.

15.2 Integrated applications

When taking stock of the possibilities for deep applications in the subsurface, the first priority is to establish which of the possible applications are mutually conflicting. Practice has shown that salt and gas exploitation may in principle be conducted at one and the same location, provided the horizon level from which the gas is exploited is not located above the salt occurrence. However, CO_2 storage and gas exploitation in the same unit may not be combined, and neither may gas and thermal energy exploitation.

Table 15.3. Overview of the underground applications.
Applications at a location in the same unit are shown on the horizontal scale, applications at a location in different units, are shown on the vertical scale.

Application	*Gas expl.*	*Oil expl.*	*Salt expl.*	*CO_2 storage*	*Gas storage*	*Waste storage*
Gas exploit.		yes		no	no	no
Oil exploit.	yes			yes	yes[1]	
Salt exploit.	yes[1]			yes[1]	yes[1]	yes[1]
CO_2 storage	no	yes	yes		no	yes[1]
Gas storage	no	no	yes	no		
Waste storage	yes	yes				
Thermal energy	no	no	yes	no	no	

[1]Conditionally

Appendices

Seismic data used

Survey	*Year*	*Owner*	*2D/3D*
Almelo	1985	NAM	3D
Annerveen	1983	NAM	3D
Blijham	1994	NAM	3D
Bonnerveen	1985	NAM	3D
Eext	1992	NAM	3D
Emmen	1983	NAM	3D
Emmen West	1985	NAM	3D
Exloo	1984	NAM	3D
Gasselternijveen/Stadskanaal	1982	NAM	3D
Groningen Westflank dl 2	1986	NAM	3D
Groningen Veld dl 4	1988	NAM	3D
Grootegast 1, 3, 4 en 5	1985-1986	NAM	3D
Hoogenweg-Schoonebeek	1984-1991	NAM	3D
Hijken	1993	NAM	3D
Klazienaveen	1988	NAM	3D
Musschelkanaal	1984	NAM	3D
Nieuwe Pekela	1985	NAM	3D

Overview of wells used

Well nr.	Name	Code	Owner	Final depth	Year
1.	Allardsoog-1	ALO-1	NAM	3180	1984
2.	Annerveen-Anlo-1	ANA-1	NAM	3014	1962
3.	Annen-Anlo-1	ANL-1	NAM	3817	1965
4.	Annerveen-5	ANN-5	NAM	3060	1984
5.	Annerveen-Schuilingsoord-1	ANS-1	NAM	3190	1970
6.	Annerveen-Veendam-1	ANV-1	NAM	3217	1969
7.	Annerveen-Veendam-3	ANV-3	NAM	3200	1983
8.	Appelscha-1	APS-1	NAM	3000	1971
9.	Assen-1	ASN-1	NAM	3750	1982
10.	Beilen-1	BEI-1	NAM	2943	1952
11.	Bergentheim-Hardenberg-1	BHH-1	NAM	2420	1959
12.	Blijham-1	BHM-1	NAM	3502	1972
13.	Blijham-2	BHM-2	NAM	4055	1979
14.	Blijham-3	BHM-3	NAM	3750	1980
15.	De Bente-1	BNT-1	NAM	1350	1975
16.	Bolderij-1	BOL-1	NAM	2993	1972
17.	Boerakker-1	BRA-1	NAM	3262	1984
18.	Beerta-1	BTA-1	NAM	3557	1992
19.	Buinen-1	BUI-1	NAM	4489	1981
20.	Collendoorn-1	CLD-1	NAM	3135	1983
21.	Collendoornerveen-1	CLDV-1	NAM	2995	1990
22.	Coevorden-3	COV-3	NAM	3048	1950
23.	Coevorden-4	COV-4	NAM	3208	1951
24.	Coevorden-6	COV-6	NAM	1214	1954
25.	Coevorden-7	COV-7	NAM	3092	1971
26.	Coevorden-9	COV-9	NAM	3165	1975
27.	Coevorden-10	COV-10	NAM	3241	1975
28.	Coevorden-11	COV-11	NAM	3113	1976
29.	Coevorden-24	COV-24	NAM	3173	1981
30.	Coevorden-28	COV-28	NAM	3919	1983
31.	Coevorden-31	COV-31	NAM	3190	1983
32.	Coevorden-33	COV-33	NAM	3129	1983
33.	Coevorden-38	COV-38	NAM	3094	1985
34.	Coevorden-40	COV-40	NAM	3803	1985
35.	Coevorden-41	COV-41	NAM	3670	1985
36.	Coevorden-42	COV-42	NAM	3402	1985
37.	Coevorden-47	COV-47	NAM	3189	1986
38.	Coevorden-51	COV-51	NAM	3081	1990
39.	Dalen-1	DAL-1	NAM	3425	1972
40.	Dalen-2	DAL-2	NAM	3494	1974
41.	Dalen-6	DAL-6	NAM	3285	1979
42.	Dalen-7	DAL-7	NAM	4020	1980
43.	Dalen-9	DAL-9	NAM	3490	1982
44.	Denekamp-2	DEN-2	NAM	2425	1952
45.	Diever-1	DIV-1	NAM	2260	1961

Overview of wells used

Well nr.	Name	Code	Owner	Final depth	Year
46.	Donkerbroek-1	DKK-1	CHE	1968	1981
47.	Donkerbroek-3	DKK-3	HAR	2770	1991
48.	Drouwenermond-1	DRM-1	NAM	4280	1982
49.	Den Velde-1	DVD-1	NAM	3226	1986
50.	De Venen-1	DVN-1	NAM	3020	1989
51.	Drouwenerveen-Zuideind-1	DVZ-1	NAM	4303	1983
52.	Dwingelo-1	DWL-1	NAM	938	1949
53.	Dwingelo-2	DWL-2	NAM	3792	1955
54.	Eemskanaal-1	EKL-1	NAM	3064	1970
55.	De Eeker-107	EKR-107	NAM	3000	1966
56.	Eleveld-101	ELV-101	NAM	3550	1971
57.	Eleveld-102	ELV-102	NAM	3807	1975
58.	Emmer-Compascuum-1	EMC-1	NAM	4432	1979
59.	Emmen-1	EMM-1	NAM	1412	1948
60.	Emmen-2	EMM-2	NAM	1656	1949
61.	Emmen-4	EMM-4	NAM	1787	1951
62.	Emmen-6	EMM-6	NAM	1379	1954
63.	Emmen-7	EMM-7	NAM	4364	1969
64.	Emmen-8	EMM-8	NAM	4370	1976
65.	Emmen-11	EMM-11	NAM	4567	1979
66.	Emmen-13	EMM-13	NAM	4235	1982
67.	Emmen-14	EMM-14	NAM	4350	1982
68.	Emmen-16	EMM-16	NAM	4213	1982
69.	Emmen-Nieuw Amsterdam-1	ENA-1	NAM	3710	1969
70.	Eexterveen-1	ETV-1	NAM	3315	1978
71.	Exloo-1	EXO-1	NAM	2944	1965
72.	Exloo-2	EXO-2	NAM	4283	1973
73.	Froombosch-1	FRB-1	NAM	2889	1966
74.	Grootegast-1	GGT-1	NAM	3022	1961
75.	Goldhorn-1	GLH-1	NAM	4500	1980
76.	Grolloo-1	GRL-1	NAM	4652	1980
77.	Geesteren-1	GST-1	NAM	2400	1971
78.	Gasselternijveen-1	GSV-1	NAM	4200	1979
79.	Gieterveen-Oost-1	GTV-1	NAM	4028	1981
80.	Haren-1	HAR-1	NAM	3577	1953
81.	Hardenberg-1	HBG-1	NAM	1501	1949
82.	Hardenberg-2	HBG-2	NAM	3536	1967
83.	Hardenberg-3	HBG-3	NAM	2973	1968
84.	Hessum-1	HES-1	CON	2223	1968
85.	Heiligerlee-1	HGL-1	NAM	3100	1982
86.	Hoogenweg-1	HGW-1	NAM	3300	1988
87.	Hijken-1	HIJ-1	PET	1925	1965
88.	Harkstede-1	HRS-1	NAM	3343	1977
89.	Kolham-1	KHM-1	NAM	4050	1989
90.	Kloosterhaar-1	KLH-1	NAM	2670	1981

Overview of wells used

Well nr.	*Name*	*Code*	*Owner*	*Final depth*	*Year*
91.	Kooipolder-1	KPD-1	NAM	2994	1966
92.	Marumerlage-1	MAL-1	NAM	3152	1984
93.	Meeden-1	MDN-1	NAM	3550	1983
94.	Midlaren-1	MLA-1	NAM	3650	1985
95.	Marslanden-1	MSL-1	PLA	2801	1974
96.	Midwolda-1	MWD-1	NAM	2940	1965
97.	Noordbroek-1	NBR-1	NAM	2889	1962
98.	Noord-Nederland-1	NNE-1	BPM	598	1937
99.	Noord-Nederland-2	NNE-2	BPM	589	1938
100.	Noord-Nederland-5	NNE-5	BPM	727	1938
101.	Noord-Nederland-6	NNE-6	BPM	469	1938
102.	Noord-Nederland-11	NNE-11	BPM	1044	1939
103.	Norg-1	NOR-1	NAM	3329	1965
104.	Norg-2	NOR-2	NAM	3260	1977
105.	Norg Zuid-1	NRZ-1	NAM	3956	1984
106.	Nieuw-Scheemda-1	NWS-1	NAM	2829	1965
107.	Ommen-1	OMM-1	BPM	659	1943
108.	Ommen-3	OMM-3	NAM	2788	1979
109.	Ootmarsum-1	OOT-1	BPM	688	1943
110.	Oude-Pekela-1	OPK-1	NAM	3812	1989
111.	Opende-Oost-1	OPO-1	NAM	3100	1979
112.	Oosterhesselen-1	OSH-1	NAM	3410	1973
113.	Oosterhesselen-2	OSH-2	NAM	3700	1977
114.	Pasop-1	PSP-1	NAM	3604	1991
115.	Punthorst-1	PTH-1	NAM	1922	1984
116.	Raalte-2	RAL-2	BP	1679	1983
117.	Rammelbeek-2	RAM-2	NAM	2606	1970
118.	Radewijk-1	RAW-1	NAM	3045	1970
119.	Reutum-1	REU-1	NAM	2551	1970
120.	Roden-101	ROD-101	NAM	3235	1970
121.	Roden-102	ROD-102	NAM	3848	1976
122.	Roden-201	ROD-201	NAM	3410	1976
123.	Roode Til-1	ROT-1	NAM	2940	1968
124.	Roswinkel-1	RSW-1	NAM	2299	1976
125.	Roswinkel-3	RSW-3	NAM	2620	1977
126.	Roswinkel-8	RSW-8	NAM	4129	1985
127.	Ruinen-1	RUI-1	NAM	1489	1950
128.	Ruinen-2	RUI-2	NAM	1287	1954
129.	Sappemeer-1	SAP-1	NAM	3027	1964
130.	Sappemeer-4	SAP-4	NAM	2885	1965
131.	Schoonebeek-197	SCH-197	NAM	1919	1953
132.	Schoonebeek-313	SCH-313	NAM	2987	1957
133.	Schoonebeek-447	SCH-447	NAM	3977	1968
134.	Schoonebeek-449	SCH-449	NAM	3344	1971
135.	Schoonebeek-463	SCH-463	NAM	3131	1974

Overview of wells used

Well nr.	*Name*	*Code*	*Owner*	*Final depth*	*Year*
136.	Schoonebeek-537	SCH-537	NAM	3510	1979
137.	Schoonebeek-540	SCH-540	NAM	986	1979
138.	Schoonebeek-548	SCH-548	NAM	845	1979
139.	Schoonebeek-580	SCH-580	NAM	3170	1982
140.	Sebaldeburen-1	SEB-1	NAM	3173	1989
141.	Sleen-1	SLN-1	NAM	1161	1950
142.	Sleen-4	SLN-4	NAM	4484	1977
143.	Sleen-5	SLN-5	NAM	2124	1977
144.	Slochteren-1	SLO-1	NAM	2709	1959
145.	Slochteren-3	SLO-3	NAM	2880	1963
146.	Smilde-1	SML-1	NAM	2550	1974
147.	Sleen-Dommerskanaal-1	SND-1	NAM	1795	1983
148.	Schoonlo-1	SOL-1	BPM	641	1947
149.	Schoonlo-2	SOL-2	BPM	832	1947
150.	Schoonlo-3	SOL-3	BPM	718	1947
151.	Schaapbuiten-1	SPH-1	NAM	3131	1971
152.	Spitsbergen-101	SPI-101	NAM	2997	1966
153.	Staphorst-1	STA-1	NAM	1495	1950
154.	Staphorst-3	STA-3	NAM	1485	1950
155.	Stadskanaal-1	STK-1	NAM	2795	1981
156.	Schildwolde-1	SWO-1	NAM	3103	1973
157.	Scheemderszwaag-101	SZW-101	NAM	3025	1966
158.	Ter Apel-1	TAP-1	NAM	2691	1979
159.	Ter Apel-2	TAP-2	NAM	4900	1983
160.	Tripscompagnie-1	TCI-1	NZW	1822	1982
161.	Tubbergen-5	TUB-5	NAM	2824	1967
162.	Tubbergen-7	TUB-7	NAM	1543	1954
163.	Tubbergen-8	TUB-8	NAM	3206	1967
164.	Tubbergen-Mander-1	TUM-1	NAM	2456	1968
165.	Tubbergen-Mander-2	TUM-2	NAM	1859	1973
166.	Tusschenklappen-1	TUS-1	NAM	2836	1965
167.	Uitenburen-2	UTB-2	NAM	3220	1966
168.	Veendam-1	VDM-1	SHL	1770	1972
169.	Veelerveen-1	VLV-1	NAM	4191	1981
170.	Vlagtwedde-1	VLW-1	NAM	2009	1954
171.	Vlagtwedde-2	VLW-2	NAM	4457	1977
172.	Vries-1	VRS-1	NAM	3720	1968
173.	Vries-2	VRS-2	NAM	3264	1970
174.	Vries-3	VRS-3	NAM	3450	1976
175.	Vries-4	VRS-4	NAM	3451	1985
176.	Vriezenveen-1	VRV-1	BPM	701	1944
177.	Valthermond-1	VTM-1	NAM	4296	1977
178.	Wanneperveen 9	WAV-9	NAM	1425	1980
179.	Woudbloem-1	WBL-1	NAM	2996	1967
180.	Annerveen-Wildervank-1	WDV-1	NAM	3188	1967

Overview of wells used

Well nr.	*Name*	*Code*	*Owner*	*Final depth*	*Year*
181.	Westerbork-1	WES-1	NAM	1497	1951
182.	Winschoten-1	WSN-1	KNZ	1000	1952
183.	Winschoten-3	WSN-3	KNZ	1000	1953
184.	Winschoten-11	WSN-11	KNZ	1520	1964
185.	Westerdiep-2	WTD-2	NAM	3114	1973
186.	De Wijk-1	WYK-1	NAM	1174	1949
187.	De Wijk-4	WYK-4	NAM	1204	1951
188.	De Wijk-5	WYK-5	NAM	1475	1988
189.	De Wijk-6	WYK-6	NAM	2582	1953
190.	De Wijk-7	WYK-7	NAM	2696	1954
191.	De Wijk-13	WYK-13	NAM	2700	1973
192.	De Wijk-15	WYK-15-A	NAM	1450	1977
193.	De Wijk-16	WYK-16	NAM	1378	1978
194.	De Wijk-20	WYK-20	NAM	1309	1981
195.	De Wijk-21	WYK-21	NAM	2970	1982
196.	Zuidbroek-1	ZBR-1	NAM	3100	1980
197.	Zuidlaren-1	ZLN-1	NAM	3338	1976
198.	Zuidlaarderveen-1	ZLV-1	NAM	3115	1975
199.	Zuiderpolder-1	ZPD-1	NAM	3067	1970
200.	Zuidwolde-1	ZUW-1	NAM	2911	1954
201.	Zevenhuizen-1	ZVH-1	NAM	3270	1983
202.	Zuiderveen-1	ZVN-1	NAM	3013	1966
203.	Zuidwending-1	ZWD-1	NAM	3280	1974
204.	Zuidwending-zout-1	ZWD-KNZ-1	Akzo	1520	1964
205.	Zuidwending-zout-8	ZWD-KNZ-8	Akzo	1800	1988
206.	Zweelo-1	ZWE-1	NAM	1473	1952

German wells:

Well Nr.	*Name*	*Final depth*	*Source*
207.	Emlichheim-1	1153	Bentz (1947)
208.	Fehndorf-1	1839	Bentz (1947)
209.	Neusustrum-T-1	412	
210.	Oberlanger Tenge-1	800	Bentz (1947)
211.	Oberlanger Tenge-2	823	Bentz (1947)
212.	Oberlanger Tenge-4	770	Bentz (1947)
213.	Oberlanger Tenge-5	1162	Bentz (1947)
214.	Oberlanger Tenge-Z1	1571	Fabian et al. (1962)
215.	Rütenbrock-1	1151	Bentz (1947)
216.	Rütenbrock-2	1221	Bentz (1947)
217.	Wielen-Z-1	2735	Schuster (1962)

Reservoir calculations Limburg Group

The calculations in the table below have been given for each individual well. Cut-off values applied: clay content $V_{cl}(co)$=50%;effective porosity $Ø_e(co)$=8%. The cut-off value of the effective porosity is based on core data from wells in adjacent map sheets (Rijks Geologische Dienst, 1993; NITG-TNO, 1998). Wells in which the indicated sequence was only partially evaluated are marked with *.

Gross, Net in metres
$Ø_{em}$ = average effective porosity (in percentages)
V_{clm} = average clay content (in percentages)

De Lutte Formation

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-7	302.4	8.9	9.8	24.1
EMM-13*	138.0	1.6	10.0	28.2
TUB-5	145.3	19.9	11.0	31.4

Tubbergen Formation

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-7	345.0	79.0	10.2	14.0
DVD-1	216.8	90.4	12.2	21.4
GST-1*	216.1	75.2	11.2	27.4
HBG-3	75.5	31.9	13.8	18.8
OMM-3*	30.3	7.7	12.1	32.2
TUB-5*	484.9	183.9	11.4	19.1
TUM-1*	432.3	255.2	13.3	16.0

Maurits Formation

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-7	138.5	2.5	19.8	28.5
HBG-3	134.0	20.8	12.3	30.6

Show, status and test data Limburg Group

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
DAL-7	-	GAS	RFT	3370-3550			DCDT,DCHL
DVD-1	gas	GAS	RFT	2987-3218	-		DCDT,DCCU
			PRP1	2977-3149	G	265(pa)	DCDT
EMM-13	-	D&A	RFT	4159			DCHL
			RFT	4222			DCHL
GST-1	-	D&A	-				
HBG-3	-	D&A	-				
OMM-3	-	D&A	-				
TUB-5	-	GAS	PRP	2154-2383	G	275	ROSL,DCDT
					C	3	
					W	1	
TUM-1	-	D&A	-				

Legend for appendices C, D, E, F, G, H, I, J, K and L

Status:

GAS	=	gas production
D&A	=	dry and abandoned
SUS	=	suspended (gas or oil-bearing and temporarily abandoned)
E&A	=	exhausted and abandoned

Test:

DST	=	drill stem test (quantity in litres)
PRP	=	production test (flow gas, Q_{50}, in 1000 m^3/d; water/condensate in m^3/d)
RFT	=	repeat formation test (quantity in litres)
FIT	=	formation interval test (quantity in litres)

Test interval in metres log depth

Yield/flow:

G	=	gas
O	=	oil
C	=	condensate
GCM	=	gas cut mud
W	=	water
M	=	mud
MF	=	mud filtrate
FW	=	formation water
SW	=	salt water
(u)	=	in uppermost chamber of RFT
(l)	=	in lowermost chamber of RFT
pa	=	post acidity

Unit	=	formation or member
DCCU	=	Maurits Formation
DCDT	=	Tubbergen Formation
DCHL	=	De Lutte Formation
ROSL	=	Slochteren Formation
ROSLU	=	Upper Slochteren Sandstone
ROCLT	=	Ten Boer Member
ZEZ2C	=	Z2 Carbonate
ZEZ3G	=	Grey Salt Clay
ZEZ3C	=	Z3 Carbonate
RBMVL	=	Lower Volpriehausen Sandstone
RBMDL	=	Lower Detfurth Sandstone
RNSOB	=	Basal Solling Sandstone
KNNCV	=	Bentheim Claystone
KNNSP	=	Bentheim Sandstone
KNNCE	=	Ruinen Member
KNNCW	=	Westerbork Member
KNNSG	=	Gildehaus Sandstone
KNNSF	=	Friesland Member

Appendix E

Reservoir calculations in Upper Rotliegend Group

The calculations in the table below have been given for each individual well. Cut-off values applied: clay content V_{cl}(co)=50%;effective porosity $Ø_e$(co)=6%. The cut-off value of the effective porosity is based on core data. The data has been supplemented from relevant wells in surrounding map sheets (Rijks Geologische Dienst, 1991, 1993; NITG-TNO, 1998). Wells in which not all of the stratified sequence was evaluated are marked with *.

Gross, Net in metres
$Ø_{em}$ = average effective porosity (in percentages)
V_{clm} = average clay content (in percentages)

Upper Rotliegend Group

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
ALO-1	161.7	125.9	19.8	19.9
ANN-5	126.7	101.0	12.8	22.5
BHM-2	103.6	68.7	11.6	20.6
BRA-1	261.2	200.7	18.2	22.2
GLH-1*	115.7	82.8	14.3	25.9
HGL-1*	123.6	83.4	15.0	21.4
MAL-1	182.6	134.3	21.0	16.8
MLA-1	172.7	115.2	12.5	20.6
NOR-1*	137.2	111.2	16.0	17.3
OPO-1	201.2	149.2	18.2	22.7
ROD-102	221.8	175.0	18.6	20.6
VRS-4	200.5	154.5	16.5	28.3
WYK-15	15.8	15.4	16.7	22.1

Slochteren Formation

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
ALO-1	121.3	120.9	20.1	19.0
ANN-5	113.8	99.8	12.7	22.3
BHM-2	71.4	68.7	11.6	20.6
BRA-1	204.8	197.4	18.2	21.9
GLH-1	91.8	82.6	14.3	25.9
HGL-1	95.0	83.4	15.0	21.4
MAL-1	136.2	133.5	21.1	16.8
MLA-1	135.2	105.0	12.7	19.1
NOR-1*	118.5	106.6	16.2	16.9
OPO-1	155.5	148.4	18.2	22.5
ROD-102	198.3	174.3	18.7	20.5
VRS-4	187.0	154.5	16.5	28.3
WYK-15	15.8	15.4	16.7	22.1

Show, status and test data Upper Rotliegend Group

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
ALO-1	-	D&A	RFT1	2770	SW+MF(u)	10.3	ROCLT
					SW+MF(l)	3.8	
			RFT2	2782	G(u)	0.5	ROCLT
					FW(u)	3.6	
					FW(l)	9	
			PRP1	2762-2790	SW		ROCLT
					G		
ANN-5	gas	GAS	PRP	2922-3028	G	3760	ROSL
BHM-2	gas	GAS	PRP	3579-3641	G	445	ROSL
			RFT	3590-3640			
BRA-1	gas	GAS	PRP	2932-3002	G	2500	ROCLT+ROSL
					W		
					C		
			RFT	2938-3152			ROCLT+ROSL
			FIT	2985	G(u)	1.7	ROSL
					C(u)		
					MF(u)	0.2	
					G(l)	1.7	
					C(l)	0.2	
					MF(l)	1.1	
GLH-1	gas	D&A	RFT	3109	SW+MF(u)	4	ROSL
					SW+MF(l)	10	ROSL
			RFT	3109-3198			ROSL
HGL-1	gas	GAS	RFT	2763-2798			ROSL
MAL-1	gas	SUS	RFT6	2899			ROCLT
			RFT7	2930	G+W (u)	3.8	ROSLU
					G+W (l)	10.4	ROSLU
			RFT	2930-3079			ROSL
MLA-1	gas	GAS	RFT	3175-3331			ROCLT+ROSL
			FIT	3213	MF	5.5	
NOR-1	gas	SUS	PRP	2838-2844	G	350	ROSL
					C	5.9	
					(W)		
OPO-1	gas	GAS	RFT	2545	G(u)	19.8	ROSL
					G(l)	622	
					MF+W+C(u)	2.3	
			PRP	2513-2549	G	840	ROSL
					W	0.7	
					C	12.5	
ROD-102	gas	GAS	PRP	3585-3675	G	2750	ROCLT+ROSL
					W	15	
					C	250	
VRS-4	gas	GAS	PRP	3257-3305	G	475	ROSL
WYK-15	-	D&A	RFT1	3017			ROSL

Reservoir calculations Zechstein Group

The tables below give the reservoir calculations for the Z2 and Z3 Carbonate. Cut-off values applied: effective porosity $Ø_e$(co)=1%. Data have been supplemented from relevant wells in Map Sheet X (NITG-TNO, 1998). Wells in which not all of the stratified interval was evaluated are marked with *.

Gross, Net in metres
$Ø_{em}$= average effective porosity (in percentages)
V_{clm} = average effective clay content (in percentages)

Z3 Carbonate

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
CLDV-1	9.4	6.3	5.6	9.7
COV-28	25.2	15.3	2.4	2.7
GST-1	36.1	35.1	6.2	2.8
HES-1	41.3	40.9	9.7	2.7
HGW-1	19.6	1.1	1.4	4.7
KLH-1	32.2	16.6	5.8	3.5
OMM-3	32.0	27.7	6.1	2.7
RAM-2	27.4	15.8	3.1	3.3
RAW-1*	19.3	0.8	1.1	2.0

Z2 Carbonate

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
CLDV-1	62.3	61.1	16.5	3.4
COV-28	46.3	21.2	2.5	2.6
DAL-1	35.8	32.9	2.0	1.9
DVZ-1	24.1	23.0	2.9	2.8
ELV-101	14.9	14.5	3.9	2.0
EMC-1	21.3	21.3	7.6	2.2
EMM-13	96.5	84.7	3.5	2.2
GST-1	32.3	28.0	6.0	3.5
HES-1	56.0	56.0	8.8	3.5
HGW-1	51.7	50.8	7.5	3.3
KLH-1	50.9	36.3	6.4	2.6
OMM-3	41.9	37.3	3.8	2.6
RAM-2	55.4	6.0	2.1	2.4
RAW-1	71.9	71.9	4.3	2.7
TUB-5*	30.8	17.2	4.2	6.2

Show, status and test data Zechstein Group

Well	Show	Status	Test	Interval	Yield	Flow	Unit
CLDV-1	gas	GAS	RFT1	2425-2471	G(u)		ZEZ2C
					G(l)		
			PRP2	2416-2472	G	3800(pa)	ZEZ2C
					C	110(pa)	
					W	10(pa)	
			RFT	2375-2386	-		ZEZ3C,ZEZ3G
COV-28	-	D&A	-				
DAL-1	gas	GAS	PRP1	3005-3068	G	565	ZEZ2C
					C	16	
DVZ-1	gas	GAS	RFT	4230-2451	MF		ZEZ3C
					G	traces	
ELV-101	-	D&A	-				
EMC-1	gas	D&A	-				
EMM-13	gas	D&A	RFT	3918-4003	MF(u)	3.5	ZEZ3C
					MF(l)	9.5	
GST-1	-	D&A	-				
HES-1	-	D&A	-				
HGW-1	gas	GAS	RFT	2443	-		ZEZ3C
			RFT	2465-2501	W+MF(u)	1.5	ZEZ2C
					G	traces	
					MF(l)	2	
			PRP1	2465-2495	G	465(pa)	ZEZ2C
KLH-1	gas	D&A	RFT	2114-2116	MF(u)	0.3	ZEZ3C
					SW(l)	0.2	
			RFT	2152-2167			ZEZ2C
OMM-3	-	D&A	RFT	2375-2386	-		ZEZ3C
RAM-2	gas	SUS	PRP	2057-2110	G	1000(pa)	ZEZ2C
					C	230(pa)	
					W	2(pa)	
			PRP	1975-2000	G	100(pa)	ZEZ3C
					C	160(pa)	
RAW-1	-	D&A	PRP1	2557-2567	W	(pa)	ZEZ2C
			PRP2	2523-2542	W	(pa)	ZEZ3C
					O		
TUB-5	-	D&A	DST7	1769-1780	GCM+C		ZEZ2C
			DST8	1769-1790	GCM+C	500	ZEZ2C
			DST9	1769-1814	GCM+C	3000	ZEZ2C

Reservoir calculations Lower and Upper Germanic Trias Group

The tables below give the reservoir calculations for the sandstones of the Lower and Upper Germanic Trias Group. The sandstones of the Lower Detfurth Sandstone have been calculated separately. Cut-off values applied: effective porosity $Ø_e(co)$=5%; clay content V_{co} =50%.

Gross, Net in metres; $Ø_{em}$ = average effective porosity (in percentages); V_{clm} = average clay content (in percentages).

Basal Solling Sandstone

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
DVZ-1	8.5	8.3	13.1	9.5
RSW-1	14.1	13.5	13.6	14.2
SCH-537	7.5	6.7	9.8	17.3
SLN-5	7.9	7.0	12.5	14.6
VLV-1	7.9	4.0	9.7	17.4

Main Buntsandstein Subgroup

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
DVZ-1	140.0	37.5	17.2	17.4
RSW-1	191.3	54.6	15.4	25.6
SCH-537	170.9	61.4	16.7	23.8
SLN-5	162.3	50.7	17.8	23.6
VLV-1	134.3	36.1	12.5	24.8

Lower Detfurth Sandstone

Well	*Gross*	*Net*	$Ø_{em}$	V_{clm}
DVZ-1	29.5	19.5	14.7	19.0
RSW-1	28.8	16.5	18.3	17.8
SCH-537	26.9	16.0	17.8	15.8
SLN-5	35.1	24.2	17.0	18.7
VLV-1	33.0	23.5	13.5	24.2

Lower Detfurth Sandstone: uppermost sandstone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DVZ-1	4.4	3.9	17.8	11.6
RSW-1	6.4	6.3	18.7	17.0
SCH-537	6.1	5.9	16.7	14.3
SLN-5	6.1	5.9	18.5	16.2
VLV-1	4.2	4.0	15.8	13.8

Lower Detfurth Sandstone: bottommost sandstone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DVZ-1	15.8	15.5	14.0	20.7
RSW-1	11.6	10.1	18.1	18.1
SCH-537	11.2	10.1	18.5	16.8
SLN-5	18.1	18.1	16.6	19.4
VLV-1	19.9	19.4	13.0	26.2

Lower Volpriehausen Sandstone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DVZ-1	21.5	16.1	21.1	14.9
RSW-1	22.3	19.4	17.2	21.0
SCH-537	21.3	21.3	23.0	13.6
SLN-5	18.0	16.3	24.6	19.1
VLV-1	6.1	5.1	13.7	21.0

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

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
DVZ-1	gas	D&A	-				
RSW-1	gas	GAS	PRP1	2233-2244	G	1900	RBMVL
					W	3.8	
			PRP2	2049-2063	G	270	RNSOB
					W	0.5	
			FIT1	2236.5	G	9.5	RBMVL
					M	0.7	
			FIT2	2134	G	8.7	RBMDL
					M	1.5	
SCH-537	-	D&A	-				
SLN-5	gas	GAS	PRP1	2267-2305	G	1200	RBMDL
					W	1.0	
			PRP2	2241-2243	G	145	RNSOB
					W	0.05	
VLV-1	-	D&A	FIT1	3276	-		RBMVL
			FIT2	3137	-		RBMDL

Reservoir calculations Rijnland Group

The tables below give the reservoir calculations for the Rijnland Group. Cut-off values applied: effective porosity $Ø_e$(co)=8%.

Gross, Net in metres
$Ø_{em}$=average effective porosity (in percentages)
V_{clm}= average effective clay content (in percentages)

Gildehaus Sandstone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-2	9.0	8.1	21.9	31.2
HBG-5	52.8	35.1	14.7	41.6
SCH-548	10.5	9.8	24.8	36.8
SND-1	52.5	40.2	21.4	38.4

Bentheim Sandstone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-2	12.6	11.9	23.6	12.6
EMM-8	20.8	20.6	22.3	15.8
SCH-548	27.4	27.4	28.0	13.8
SND-1	50.0	49.0	21.7	13.6
STK-1	9.7	7.8	16.3	39.2
VTM-1	23.3	22.8	18.0	25.9

Friesland Member

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
WYK-20	11.3	9.4	18.3	32.3
ZWD-1	22.1	10.3	12.5	36.4

Vlieland Claystone Formation

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-2	30.2	1.7	26.4	47.2
EMM-8	52.4	1.4	17.8	48.6
HBG-5	7.7	0	-	-
SCH-548	3.9	0	-	-
SND-1	9.4	0	-	-
STK-1	5.8	0	-	-
VTM-1	58.5	0.3	17.2	48.9
WYK-20	27.1	0	-	-
ZWD-1	24.2	0	-	-

Middle Holland Claystone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
SCH-548	10.5	0.9	20.6	44.6

Ruinen/Westerbork Member

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-2	8.2	0.2	16.2	37.6
HBG-5	49.6	2.0	13.7	41.8
SCH-548	20.4	0	-	-
SND-1	72.4	0	-	-

Bentheim Claystone

Well	*Gross*	*Net*	*$Ø_{em}$*	*V_{clm}*
DAL-2	3.8	0	-	-
EMM-8	21.8	3.7	14.3	44.9
STK-1	3.4	0	-	-
VTM-1	6.2	0	-	-

Show, status and test data Rijnland Group

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
DAL-2	-	D&A	-				
EMM-8	-	D&A	-				
HBG-5	-	D&A	-				
SCH-548	oil	D&A	-				KNNSP
SND-1	-	D&A	RFT	1417-1607			KNNSG,KNNCW. KNNCE,KNNSP
STK-1	-	D&A	-				
VTM-1	-	D&A	-				
WYK-20	gas	GAS	RFT	1492.5	G (u)	3.8	KNNSF
					G (l)	10.3	
					MF(l)	0.2	
			PRP	1475-1491	G	>300	KNNSF
ZWD-1	-	D&A	-				

References

Literature references

Baldschuhn, R. & Jaritz, W. (1977) *Korrelation der Bohrlochdiagramme und des Kernmaterials. In: Stratigraphie der Oberkreide in Nordwestdeutschland (Pompeckjsche Scholle),* Geol. Jb. A 38, p.7-9.

Baldschuhn, R., Best, G. & Kockel, F. (1991) *Inversion tectonics in the Northwest German Basin.* In: Spencer, A.M. (ed.) *Generation, Accumulation and Production of Europe's Hydrocarbons,* Spec. Publ. Europ. Ass. Petrol. Geosc. 1, p.149-159.

Baldschuhn, R., Frisch, U. & Kockel, F. (1996) *Geotektonischer Atlas von NW-Deutschland* 1:300.000. 17 parts. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

Baldschuhn, R., Frisch, U. & Kockel, F. (1998) *Der Salzkeil, ein strukturelles Requisit der saxonischen Tektonik.* Z. dt. geol. Ges. 149, p.59-69.

Baldschuhn, R., Binot, F., Fleig, S, & Kockel, F. (1999) *Geotektonischer Atlas von NW-Deutschland und dem deutschen Nordsee-Sektor.* Geol. Jb. A 153 (in druk).

Battsche, H. & Klarr, K. (1980) *Beobachtungen und Gedanken zur Gipshutgenese.* Fifth Symp. on Salt, p.9-19.

Begeleidingscommissie Onderzoek Aardbevingen (1993) *Eindrapport multidisciplinair onderzoek naar de relatie tussen Gaswinning en aardbevingen in Noord-Nederland.* De Bilt, 76pp.

Bentz, A. (1947) *Geotektonische Karte von Nordwestdeutschland,* Amt für Bodenforschung, Hannover-Celle.

Best, G. (1989) *Die Grenze Zechstein-Buntsandstein in Nordwestdeutschland nach Bohrlochmessungen,* Z. dt. geol. Ges. 140, p.73-85.

Best, G. (1996) *Floßtektonik in Norddeutschland: Erste Ergebnisse reflexionsseismischer Untersuchungen an der Salzstruktur Oberes Allertal.* Z. dt. geol. Ges. 147, p.455-464.

Betz, B., Führer, F., Greiner, G. & Plein, E. (1987) *Evolution of the Lower Saxony Basin.* Tectonophysics 137, p.127-170.

Beutler G., Rockel, W., Röhling, H.-G., Schulz, R. & Werner, K.H. (1992) *Regionale Untersuchungen von geothermischen Reserven und Resources in Nordwestdeutschland.* Geothermische Fachtagung 1992 Tagungsband, p.301-310.

Binot, F., Gerling, P., Hiltmann, W., Kockel, F. & Wehner, H. (1991) *The petroleum system in the Lower Saxony Basin.* In: Spencer, A.M. (ed.) *Generation, Accumulation and Production of Europe's Hydrocarbons III,* Spec. Publ. Europ. Ass. Petrol. Geosc. 3, p.121-139.

Bischoff, G. & Wolburg, J. (1963) *Zur Entwicklung des Ober-Malm im Emsland.* Erdoel Zeitschr. 79, p.445-472.

Boigk, H. (1961) *Zur Fazies und Erdgasführung des Buntsandsteins in Nordwestdeutschland.* Erdöl und Kohle-Erdgas-Petrochemie 14, p.998-1005.

Brouwer & Coenen (1968) *Nederland = Aardgasland.* Roelofs van Goor, Amersfoort, 300 pp.

Brueren, J.W.R. (1959) *The stratigraphy of the Upper Permian 'Zechstein' Formation in the Eastern Netherlands.* In: *I Giacimenti Gassiferi dell' Europa Occidentale,* Atti del Conv. Milano, 1957, vol. I, p.243-274.

Bruijn, A. (1996) *De Wijk gas field (Netherlands): reservoir mapping with amplitude anomalies.* In: Rondeel, H.E., Batjes, D.A.J.& Nieuwenhuizen, W.H. (eds), *Geology of gas and oil under the Netherlands,* Kluwer, Dordrecht, p.243-253.

Clark, D.N. (1986) *The distribution of porosity in Zechstein carbonates.* In: Brooks, J., Goff, J. & Van Hoorn, B. (eds) *Habitat of Paleozoic gas in NW Europe.* Geol. Soc. Spec. Publ. 23, p.121-149.

Coelewij, P.A.J., Haug G.M.W. & Van Kuijk, H. (1978) *Magnesium-salt exploration in the northeastern Netherlands.* Geol. Mijnbouw 57, p.487-502.

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

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

David, F. (1990) *Sedimentologie und Beckenanalyse im Westfal C und D des nordwestdeutschen Beckens.* DGMK Bericht 384, 270pp.

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

Eigenfeld, R.W.F. & Eigenfeld-Mende, I. (1986) *Niederländische permokarbone basische Magmatite als Fortzetsung der spilitisierten effusiva in NW-Deutschland.* Meded. Rijks Geol. Dienst 40, p.11-21.

Fabian, H.J., Gaertner, H. & Müller, G. (1962) *Oberkarbon und Perm in der Bohrung Oberlanger Tenge Z1 im Emsland.* Fortschr. Geol. Rheinl. u. Westf. 3, p.1075-1096.

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

Franke, D. (1990) *Der präpermische Untergrund der Mitteleuropäischen Senke - Fakten und Hypothesen.* Nieders. Akad. Geowiss. Veröff. 4, p.19-75.

Frieg, C. & Kemper, E. (1989) *Mikropaläontologische Gliederung und Abgrenzung von Ober-Alb und Unter-Cenoman in Nordwestdeutschland.* Geol. Jb. A 113, p.73-193.

Frisch, U. & Kockel, F. (1997) *Altkimmerische Bewegungen in Nordwestdeutschland.* Brandenburger Geowiss. Beitr. 4, p.19-29.

Füchtbauer, H., Jankowski, B., David, E., David, F., Frank, F., Kraft, T., Sedat, B., Selter, V. & Strehlau, K. (1991) *Sedimentologie des nordwestdeutschen Oberkarbon.* DGMK Bericht 468, p.75-115.

Gdula, J.E. (1983) *Reservoir geology, structural framework and petrophysical aspects of the De Wijk gas field.* Geol. Mijnbouw 62, p.191-202.

Geluk M.C. (1995) *Stratigraphische Gliederung der Z2-(Stassfurt) Salzfolge in den Niederlanden: Beschreibung und Anwendung bei der Interpretation von halokinetisch gestörten Sequenzen.* Z. dt. geol. Ges. 146, p.458-465.

Geluk, M.C. (1997) *Palaeogeographic maps of Moscovian and Artinskian; contributions from the Netherlands.* In: Crasquin-Soleau, S. & De Wever, P. (eds), *Peri-Tethys stratigraphic correlations,* Geodiversitas 19, p.229-234.

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

Geluk, M.C. (1999b) *Palaeogeographic and structural development of the Triassic in the Netherlands -- new insights.* In: Bachmann, G.H. & Lerche, I. (eds) *The Epicontinental Triassic Vol. 1,* Halle 1998, Zentralblatt f. Geol. Paläol. p.545-570.

Geluk, M.C. (2000) *Late Permian (Zechstein) carbonate facies maps, the Netherlands.* Netherlands Journ. Geosc./Geol. Mijnbouw 79, p.17-27.

Geluk, M.C., A.N. Plomp & Th.H.M. van Doorn (1996) *The development of the Permo-Triassic succession in the basin fringe area, southern Netherlands.* In: Rondeel, H.E., Batjes, D.A.J. & Nieuwenhuijs, W.H. (eds), *Geology of gas and oil under the Netherlands,* Royal Geol. Mining Soc. KNGMG, Kluwer Academic Press, p.57-79.

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

Geluk M.C. & Röhling, H.-G. (1999) *High-resolution sequence stratigraphy of the Lower Triassic Buntsandstein: a new tool for basin analysis.* In: Bachmann, G.H. & Lerche, I. (eds) *The Epicontinental Triassic Vol. 1,* Halle 1998, Zentralblatt f. Geol. Paläol., p.727-745.

Geluk, M.C., Van Wees, J.D., Grönloh, H. & Van Adrichem Boogaert, H.A. (1997) *Palaeogeography and palaeotectonics of the Zechstein (Upper Permian) in the Netherlands.* Proc. XIII Int. Congr. on Carboniferous-Permian, September 1995, Krakow, Poland, Prace Panstwowego Instytut Geologicznego CLVII, part 2, Warszawa, p.63-75.

Glasbergen, P. (1982) *Proefboring te Nieuweschans; resultaten van het geohydrologisch en geohydrochemisch onderzoek.* RID Meded. 82-3, 47 pp.

Glennie, K.W. (1983) *Lower Permian Rotliegend desert sedimentation in the North Sea area.* In: Brookfield, M.E. & Ahlbrandt, T.S. (eds) *Developments in Sedimentology* 38, p.521-541.

Gramann, F., Heunisch, C., Klassen, H., Kockel, F., Dulce, G., Harms, F.-J., Katschorek, T., Mönnig, E., Schudack, M., Thies, D. & Weiss, M. (1997) *Das Niedersächsische Oberjura-Becken - Ergebnisse interdisziplinärer Zusammenarbeit.* Z. dt. geol. Ges. 148, p.165-236.

Haenel, R. & Staroste, E. (1988) *Geothermal resources in the European Community, Austria and Switzerland,* 69 pp.

Hancock, J.M. & Scholle, P.A. (1975) *Chalk of the North Sea.* In: Woodland, A.W. (ed.) *Petroleum and the continental shelf of North West Europe,* Geology Applied Sc. Publ. for Inst. of Petroleum, London, p.413-427.

Harsveldt, H.M. (1980) *Salt resources in The Netherlands as surveyed mainly by AKZO.* Fifth Symp. on Salt, p.65-81.

Hedemann, H.A. & Teichmüller, R. (1971) *Die Paläogeographische Entwicklung des Oberkarbons.* Fortschr. Geol. Rheinl. u. Westf. 19, p.129-142.

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

Jaritz, W. (1973) *Zur Entstehung der Salzstrukturen in Nordwestdeutschland.* Geol. Jb. A 10, 77pp.

Kemper, E. (1976) *Geologische Führer durch die Grafschaft Bentheim und die angrenzenden Gebiete, mit einem Abriß der emsländischen Unterkreide.* 5. ergänzte Auflage, Verlag Heimatverein der Grafschaft Bentheim e.V. Nordhorn - Bentheim, 206pp.

Kemper, E. (1992) *Die tiefe Unterkreide im Vechte-Dinkel Gebiet.* Stichting Het Staringmonument te Losser, 95pp.

Koch, J., Kockel, F. & Krull, P. (1997) *Coalification at the base of the Zechstein and the pre-Permian surface in Northern Germany.* Geol. Jb. D 103, p.33-42.

Koyi, H., Jenyon, M.K. & Petersen, K. (1993) *The effect of basement faulting on diapirsm.* Journ. Petr. Geol. 16, p.285-312.

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

Lögters, H. (1951) *Paläogeographie, Tektonik und Erdölvorkommen im Emsland.* Z. dt Geol. Ges. 102, p.8-42.

Lorenz, V. & Nicholls, I.A. (1976) *The Permo-Carboniferous Basin and Range province of Europe. An application of plate tectonics.* In: Falke, H. (ed.) *The Continental Permian in Central, West, and South Europe*, Reidel Publ. Company, Dordrecht, Holland, p.313-342.

Maureau, G.F.T.R. & Van Wijhe, D.H. (1979) *The prediction of porosity in the Permian (Zechstein 2) carbonate of eastern Netherlands using seismic data.* Geophysics 44, p.1502-1517.

Meyer, K. (1969) *Zur Paläogeographie der Stufen Rhät bis Alb im Emsland.* Erdöl-Erdgas Zeitschr. 85, p.484-505.

Milius, G. & Van der Vlugt, W.R. (1967) *De gasuitbarsting van Sleen 2.* Geogr. Tijdschrift van het K.N.A.G., nieuwe reeks 1, p.20-28.

Mulder, A.J. (1950a) *De zoutpijler van Schoonlo.* Geol. Mijnbouw 12, p.169-176.

Mulder, A.J. (1950b) *Oil in the Netherlands and Emsland (Germany).* Journ. Inst. Petroleum, vol. 36, no. 315, p.123-136.

NITG-TNO (1998) *Geological Atlas of the Subsurface of the Netherlands, Explanations to Map Sheet X: Almelo-Winterswijk.* Netherlands Institute of Applied Geoscience TNO, Haarlem, 143pp.

NLfB (Niedersächsisches Landesamt für Bodenforschung (1999) *Erdöl und Erdgas in der Bundesrepublik Deutschland 1998*, Hannover, 125pp.

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

Peryt, T.M. (1975) *Significance of stromatolites for environmental interpretations of the Buntsandstein (Lower Triassic) Rocks.* Geol. Rundschau 64, p.143-158.

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

Plein, E. (1995) *Stratigraphie von Deutschland I, Norddeutsches Rotliegendbecken*, Rotliegend-Monographie Teil II. Courier Forsch.-Inst. Senckenberg 183, 193pp.

Quast, P. (1986) *The construction of the caverns in the gas storage project Ll. Torup, Denmark.* Solution Mining Research Institute, Autumn meeting 1986.

Quirk, D.G. (1993) *Interpreting the Upper Carboniferous of the Dutch Cleaver Bank High.* In: Parker, J.R. (ed.) *Petroleum Geology of Northwest Europe*: Proceedings of the 4th Conference, p.697-706.

Ramsbottom, W.H.C. (1979) *Rates of transgression and regression in the Carboniferous of NW Europe.* J. Geol. Soc.136, p.147-154.

Rappol, M. (red.) 1992 *In de bodem van Drenthe.* Linguae Terrae, Amsterdam, 283pp.

Remmelts, G. (1995) *Fault-related salt tectonics in the southern North Sea, The Netherlands.* In: Jackson, M.P.A., Roberts, D.G., & Snelson, S. (eds), *Salt tectonics: a global perspective*, AAPG Mem. 65, p.261-272.

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

Rijks Geologische Dienst (1979) *Geologische kaart van Nederland 1:50000, Blad Emmen West & Oost 17W/17O,* Haarlem.

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

Rijks Geologische Dienst (1984) *Geologische en hydrologische inventarisatie van Tertiaire en Onder-Kwartaire afzettingen in Noord-Nederland t.b.v. ondergrondse opslag en winning van warm water.* Rapport nr. 84KAR08EX.

Rijks Geologische Dienst (1990) *Geologische kaart van Nederland 1:50000, Blad Assen West & Oost, 12W/12O,* Haarlem.

Rijks Geologische Dienst (1991) *Geological Atlas of the Subsurface of the Netherlands, Explanations to Map Sheet II: Ameland-Leeuwarden.* RGD, Haarlem, 87pp.

Rijks Geologische Dienst (1993a) *Geological Atlas of the Subsurface of the Netherlands, Explanations to Map Sheet V: Sneek-Zwolle.* RGD, Haarlem, 126pp.

Rijks Geologische Dienst (1993b) *Evaluation of salt bodies and their overburden in the Netherlands for the disposal of radioactive waste; b. Salt movement.* RGD, Haarlem, 47pp.

Rijks Geologische Dienst (1993c) *Evaluation of salt bodies and their overburden in the Netherlands for the disposal of radioactive waste; c. Caprock formation and subrosion.* RGD, Haarlem, 88pp.

Rijks Geologische Dienst (1995) *Geological Atlas of the Subsurface of the Netherlands, Explanations to Map Sheet III: Rottumeroog-Groningen.* RGD, Haarlem, 114pp.

Ross, C.A. & Ross, R.P. (1987) *Late Paleozoic sea levels and depositional sequences.* Cushman Foundation for Foraminiferal Research, Spec. Pub. 24, p.137-149.

Sannemann, D., J. Zimdars & E. Plein 1978 *Der basale Zechstein (A2-T1) zwischen Weser und Ems.* Z. dt. geol. Ges. 129, p.33-69.

Schott, W. (1950) *Die obere weiße Jura und die tiefste Unterkreide im Deutsch-Holländischen Grenzgebiet.* Geol. Jb. 65, p.213-270.

Schott, W., Jaritz, W., Kockel, F., Sames, C.-W., Stackelberg, U., Stets, J. & Stoppel, D. (1967a) *Zur Paläogeographie der Unterkreide im nördlichen Mitteleuropa mit Detailstudien aus Nordwestdeutschland. Bemerkungen zu einem Atlas.* Erdöl Kohle 20, p.149-158.

Schott, W., Jaritz, W., Kockel, F., Sames, C.-W., Stackelberg, U., Stets, J. & Stoppel, D. (1967b) *Paläogeographischer Atlas der Unterkreide von Nordwestdeutschland mit einem Übersichtsdastellung des nördlichen Mitteleuropa.* Bundesanstalt für Bodenforschung, Hannover.

Schuster, A. (1962) *Das Stefan in der Bohrung Wielen Z1.* Fortschr. Geol. Rheinl. u. Westf. 3, p.1097-1108.

Selter, V. (1990) *Sedimentologie und Klimaentwicklung im Westfal C/D und Stefan des nordwestdeutschen Oberkarbon-Beckens.* DGMK-Bericht 384-4, Hamburg, 311pp.

Sørensen, S. & Martinsen, B.B. (1987) *A paleogeographic reconstruction of the Rotliegend deposits in the Northeastern Permian Basin.* In: Brooks, K. & Glennie, K. (eds) *Petroleum geology of North West Europe,* Graham & Trotman, p.497-508.

Stancu-Kristoff, G. & Stehn, O. (1984) *Ein großregionaler Schnitt durch das nordwestdeutsche Oberkarbon-Becken vom Ruhrgebied bis in der Nordsee.* Fortschr. Geol. Rheinl. u. Westf. Bd. 32, p.35-38.

Tantow, M.S. (1992) *Structural development of inversion-related oil and gas fields, Emsland, NW Germany.* In: Spencer, A.M. (ed.) *Generation, accumulation and Production of Europe's Hydrocarbons,* Spec. Publ. E.A.P.G., No. 2, Springer, Berlin, p.77-84.

Tantow, M.S. (1993) *Stratigraphie und seismisches Erscheinungsbild des Oberkarbons (Westfal, Stefan), Emsland.* Berliner geowiss. Abh. 148, 66pp.

Taylor, J.C.M. (1998) *Upper Permian - Zechstein.* In: Glennie, K.W. (ed.) *Petroleum Geology of the North Sea,* Fourth Edition, Blackwell Science, p.174-212.

Thieme, B. & Rockenbauch, K. (1999) *Floßtektonik ('rift-raft tectonics') in der Trias der Südlichen Nordsee.* DGMK-Tagungsbericht 9901, p.65-79.

't Hart, B.B. (1969) *Die Oberjura- und Unterkreide Sedimentation in den nördlichen und östlichen Niederlanden.* Erdöl und Kohle-Erdgas-Petrochemie.22, p.253-261.

Teichmüller, M., Teichmüller, R. & Bartenstein, H. (1984): *Inkohlung und Erdgas - eine neue Inkohlungskarte der Karbon-Oberfläche in Nordwestdeutschland.* Fortschr. Geol. Rheinld. u. Westf. 32, p.11 – 34.

Thiadens, A.A. (1963) *The Paleozoic of the Netherlands.* Verh. Kon. Ned. Geol. Mijnb. Gen. 21(1), p.9-28.

Trusheim, F. (1963) *Mechanism of salt migration.* AAPG Bull. 44, p.1519-1540.

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

Van de Sande, J.M.M., T.J.A. Reijers & N. Casson (1996) *Multidisciplinary exploration strategy in the Northeast Netherlands Zechstein 2 Carbonate play, guided by 3D seismic.* In: Rondeel, H.R., D.A.J. Batjes & W.H. Nieuwenhuijs (eds): *Geology of Gas and Oil under the Netherlands,* Kluwer Acad. Publ. Dordrecht, p.125-142.

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

Van der Meer, M. & Pagnier, H.J.M. (1996) *The sediment petrography of sandstone bodies of borehole 'De Lutte 6' (East Twente, the Netherlands) and its regional significance.* Meded. Rijks Geol. Dienst 55, p.31-60.

Van der Zwan, C.J., Van de Laar, J.G.M., Pagnier, H.J.M. & Van Amerom, H.W.J.(1993) *Palynological, ecological and climatological synthesis of the Upper Carboniferous of the well De Lutte-6 (eastern Netherlands).* Comptes Rendus XII ICC-P, Buenos Aires, vol. 1, p.167-186.

Van Rossum, B. (1978) *Geology and appraisal development of the Groningen Field.* European Petroleum and Gas Conference, RAI Amsterdan, May 23-25.

Van Tongeren, P.C.H. (1996) *The Gronau Fault Zone: its tectonic setting and relation to the formation of the Ems Graben and to the Late Carboniferous sedimentation in Twente (the Netherlands).* Meded. Rijks Geol. Dienst 55, p.107-145.

Van Wijhe, D.H. & Bless, M.J.M. (1974) *The Westphalian of The Netherlands with special reference to miospore assemblages.* Geol. Mijnbouw 53, p.295-328.

Van Wijhe, D.H., Lutz, M. & Kaasschieter, J.P.H. (1980) *The Rotliegend in The Netherlands and its gas accumulations.* Geol. Mijnbouw 59, p.3-24.

Veenhof, E.N. (1996) *Geological aspects of the Annerveen gas field, the Netherlands.* In: Rondeel, H.E., Batjes, D.A.J.& Nieuwenhuijs, W.H. (eds), *Geology of Gas and Oil under the Netherlands,* Kluwer, Dordrecht, p.79-92.

Visser, W.A. & Sung, G.C.L. (1958) *Oil and natural gas in north-eastern Netherlands.* In: Habitat of oil, Am. Assoc. Petr. Geol., Tulsa, p.1067-1089.

Voigt, E. (1963) *Über Randtröge vor Schollenrändern und ihre Bedeutung ins Gebiet der Mitteleuropäische Senke und angrenzender Gebiete.* Z. dt. geol. Ges. 114, p.378-418.

Wagner, R. (1994) *Stratygrafia osadów i roswój basenu Cechsztynskiego na nizu Polskim.* Prace Panstwowego Instytutu Geologicznego, CXLVI, Warszawa, 71pp. (Stratigraphy and evolution of the Zechstein basin in the Polish Lowlands).

Wolburg, J. (1949) *Ergebnisse der Biostratigraphie nach Ostracoden im Nordwestdeutschen Wealden.* Erdöl und Tektonik in NW-Deutschland, p.349-360.

Wolburg, J. (1961) *Sedimentations Zyklen und Stratigraphie des Buntsandsteins in NW-Deutschland.* Geotekt. Forsch. 14, p.7-74.

Wolburg, J. (1967) *Zur Wesen der Altkimmerische Hebung, mit einem Überblick über die Muschelkalk und Keuper-Entwicklung in Nordwest-Deutschland.* Z. dt. geol. Ges. 119, p.516-523.

Wolburg, J. (1969) *Die epirogene Phasen der Muschelkalk und Keuper-Entwicklung in Nordwest-Deutschland, mit einem Rückblick auf den Buntsandstein.* Geotekt. Forsch. 32, p.1-65.

Zagwijn, W.H. (1989) *The Netherlands during the Tertiary and Quaternary: a case history of Coastal Lowlands evolution.* Geol. Mijnbouw 68, p.107-121.

Ziegler, P.A. (1987) *Late Cretaceous intra-plate compressional deformations in the Alpine foreland, a geodynamic model.* Tectonophysics 137, p.389-420.

Ziegler, P.A. (1988) *Evolution of the Arctic - North Atlantic and the Western Tethys.* AAPG Mem. 43, 198pp., 30 plates.

Ziegler, P.A. (1989) *Evolution of Laurussia - A study in Late Paleozoic Tectonics.* Kluwer Academic Publ., Dordrecht, 102pp.

Ziegler, P.A. (1990) *Geological Atlas of Western and Central Europe; second and completely revised edition.* Shell Internationale Petroleum Maatschappij BV, 239pp, 56 encl..

Internal Reports

NITG 1997a, Rijkers, R.H.B. & Van Doorn, Th.H.M. *Atlas of Geothermal Resources in the European Community,* The Netherlands. NITG 97-024-A.

NITG 1997b, Remmelts G. *Gebruiksmogelijkheden van de Diepe Ondergrond van Nederland.* NITG 97-223-B.

RGD, 1990, Schuurman, H.A. *Stratigrafische interpretatie van het kerntraject in boring Vlagtwedde-1.* Micropal. Mes. 345A.

RGD 1994a, Munsterman, D.K. & Herngreen, G.F.W. *De resultaten van het palynologisch onderzoek naar de ouderdom en het afzettingsmilieu van de kernen uit de boring (WES-1) Westerbork-1, traject 1080-1497.5 m.* Palyn. Mes. 2291.

RGD 1994b, Munsterman, D.K. & Herngreen, G.F.W. *De resultaten van het palynologisch onderzoek naar de ouderdom en het afzettingsmilieu van de kernen uit boring EMM-5 (Emmen-5), traject 993.55-1141.7m.* Palyn. Mes. 2292.

RGD 1994c, Lissenberg, Th. *Biostratigrafische interpretatie (revisie) van het Onder Krijt/Jura traject van boring RUI-1 (Ruinen-1).* Micropal. Mes. 006a.

RGD 1994d, Lissenberg, Th. *Biostratigrafische interpretatie (revisie) van het Onder Krijt/Jura traject van boring VLW-1 (Vlagtwedde-1).* Micropal. Mes. 345/B.

RGD 1994e, Lissenberg Th. *Biostratigrafische interpretatie van het traject van 855 m t/m 1892 m van boring SCH-197 (Schoonebeek-197).* Micropal. Mes. 539.

RGD 1995a, Munsterman, D.K. & Herngreen, G.F.W. *De resultaten van het palynologisch onderzoek naar de ouderdom van de kernen uit boring De Wijk-5, traject 1238-1282 m.* Palyn. Mes. 2303.

RGD 1995b, Munsterman, D.K. & Herngreen, G.F.W. *De resultaten van het palynologisch onderzoek naar de ouderdom van de top (op 956,5 m) van de kern uit de Gildehaus Sandstone Member in boring Ruinen-1.* Palyn. Mes. 2012B.

RGD 1995c, Lissenberg, Th. *Biostratigrafische interpretatie van een Onder-Krijt traject (1179 - 1261 m) van boring EMM-2 (Emmen-2).* Micropal. Mes. 622.

RGD 1995d, Van Tuijl, A.E. *Biostratigrafische interpretatie van het Boven-Krijt traject van boring VLW-1 (Vlagtwedde-1).* Micropal. Mes. 345C.

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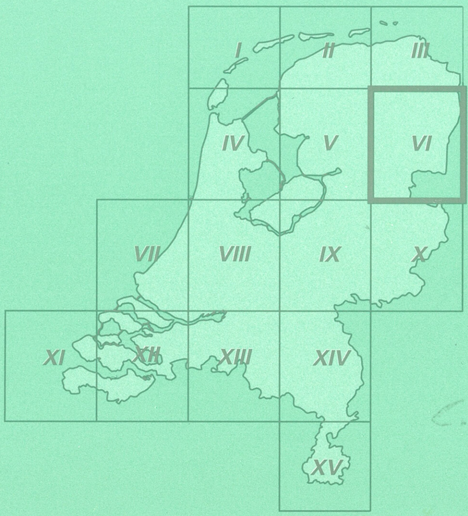
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