Rijks Geologische Dienst **RGD**

Explanation to map sheet III Rottumeroog-Groningen

Geological Atlas of the Subsurface of The Netherlands

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Contents

One of the main tasks of the Geological Survey of The Netherlands (Rijks Geologische Dienst, 'RGD') is to collate knowledge about the geology of The Netherlands. This information is being reported to the general public by the Geological Survey, mostly in the form of maps and explanations to map sheets which, up to now, only dealt with the subsoil geology of The Netherlands and the North Sea. Reports on the deeper subsurface geology (deeper than 500 m) were limited because of the status of the data required. These data are acquired from deep drilling and seismic investigations which are nearly exclusively carried out by oil companies. Because of the great commercial interests involved for the oil industry these data are classified.

The data are made available to the Geological Survey, as delineated in the mining act. To the extent that they were compiled on the continental shelf of The Netherlands, they are made available after a period of 10 years, thus enabling everyone to acquire an understanding of the deeper subsurface geology of The Netherlands and the North Sea. Interested parties may make their own interpretations. As far as the mainland of The Netherlands is concerned, existing mining legislation does not permit release of such information. Agreements with the oil companies concerning the use of these data enable The Geological Survey to compile and publish this information, provided the data are older than 10 years. Data from concession areas have a restriction of 5 years. This agreement enables the RGD to bring the geological subsurface of The Netherlands to wider attention.

The Rottumeroog-Groningen map sheet of the Geological Atlas of the Subsurface of The Netherlands is the fifth sheet to be published in the framework of the systematic mapping of The Netherlands based on these data, which will comprise 15 map sheets 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 Geological Survey of The Netherlands gives an overview of the progress of this mapping.

Each map sheet has its own features. The map sheet in question outlines the geology of an important part of the province of Groningen. Maps and sections show a comparatively stable area with the Groningen High as the principal structural unit. The major movements in the subsurface here were initiated by the plastic Zechstein salt which resulted in the formation of salt pillows or large salt-structures. These salt structures often significantly determine the areal extent and the thickness of the overlying Mesozoic and Cenozoic sediments. The discovery of the gigantic Groningen gasfield situated in the map sheet area (1955) has been the cause of intensive research into the subsurface with its mineral resources. The data obtained from these surveys enabled the mapping of the subsurface of The Netherlands to be performed.

The Geological Survey anticipates that this series of map sheets will contribute to a greater understanding of the structure and composition of the subsurface of The Netherlands. This is important not only to companies who are active in the fields of exploration and exploitation for mineral and natural resources, but also to the government, provincial and local authorities, state and semi-governmental institutions and various other non-governmental organisations. They are all increasingly confronted with questions relating to opportunities for sustainable development of the subsurface of The Netherlands. These may, for example, concern issues of storage or disposal of waste, energy storage, and geothermal energy as an alternative energy source.

The explanation accompanying the map sheet is not only aimed at professional earth scientists in industry and government, but should also be of interest to teachers, scientists and non-professional geologists.

As well as those people acknowledged in the credit column who are directly responsible for compiling this map sheet, many other employees of the Geological Survey have been involved, whose efforts are greatly appreciated. Pertinent and constructive criticism from Dr. W.J.M. van der Linden and the reviewing committee added much to the quality of the explanation. Especial mention should be made of the excellent working relationship established with Dr. F. Kockel of the BGR, which enabled the accomplishment of a reliable map sheet, extending up to the border with Germany. Special thanks are due to the companies which provided data used in this map sheet.

Chr. Staudt
Director

1 Introduction

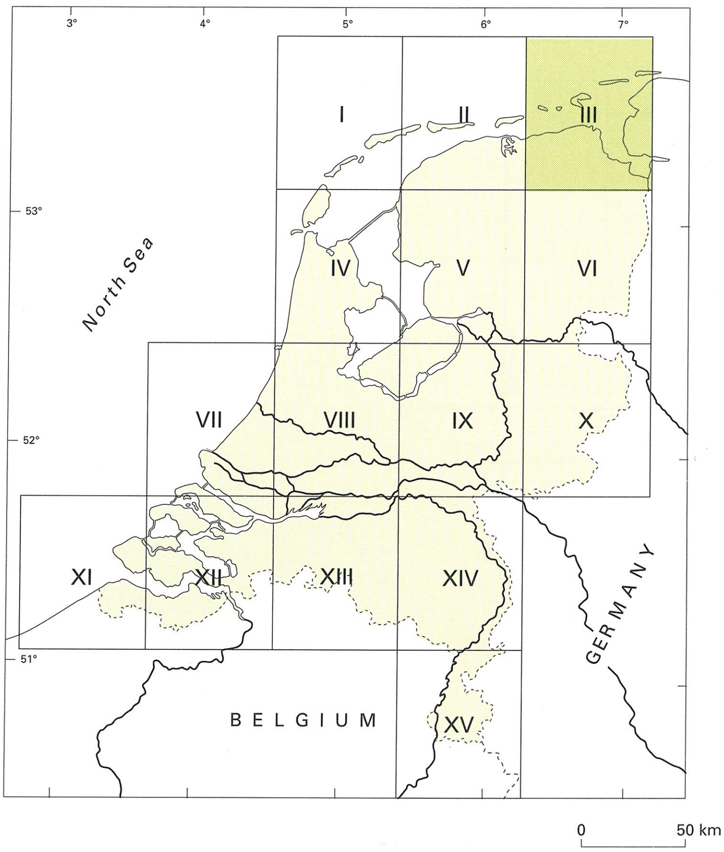
1.1 Extent of area studied

Map sheet III: Rottumeroog - Groningen is situated in the extreme northeast of The Netherlands and extends as far as the border formed by the territorial waters (fig. 1.1). The map sheet encompasses parts of the provinces of Groningen and Drenthe.

1.2 Data base

The mapping of the subsurface of The Netherlands is based primarily on the data compiled by the oil companies. In the case of the map sheet area this is the Nederlandse Aardolie Maatschappij B.V. (NAM), the owner of the Groningen and Drenthe concessions (fig. 1.2). In addition to the many gas wells present within the map sheet area, some 25 salt wells have been drilled by several companies: Shell Delfstoffen Nederland N.V. (SHL), Billiton Delfstoffen B.V. (BIL), Noordelijke Zoutwinning B.V. (NZW), now NedMag Industries, and the Koninklijke Nederlandse Zoutindustrie (KNZ), now AKZO-Nobel. A total of 403 boreholes have been drilled in the map sheet area, 387 of which have exceeded

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



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

the five-year limitation after the year of completion and whose data have consequently been released for mapping purposes (see Preface). Part of these 387 wells are grouped in 57 clusters. Figure 1.3 shows the location of the wells used in this explanation. Together with the many kilometres of seismic lines shot in this area, the wells provide a good understanding of the geology. Selected lines from 3D surveys were used for mapping on land (fig. 1.4), whereas Wadden Sea mapping had to rely on lower quality 2D seismics, tending to be less recent in origin. In addition to these data, the available literature has also been consulted. Knowledge from the regional geological framework has been adopted from publications by, inter alia, Ziegler (1982, 1990), Glennie (1986) and Heybroek (1974).

1.3 Mineral and natural resources

1.3a The history of exploration and production of the Groningen gasfield

The relatively large number of wells within the map sheet area is directly related to the discovery of the Groningen gasfield in 1959. The first borehole in the province of Groningen was drilled near Haren in 1952, with the Zechstein carbonates forming the target for exploration. Until the end of the fifties, these were the deepest gas-productive rock units (particularly in Drenthe). However, the carbonates in

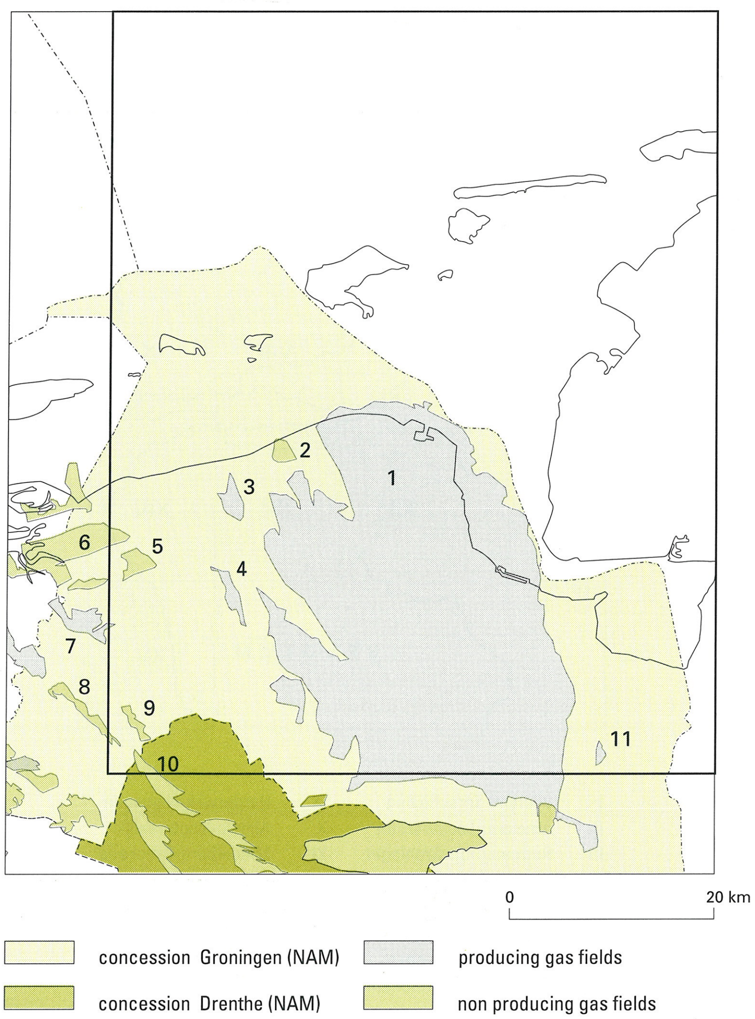
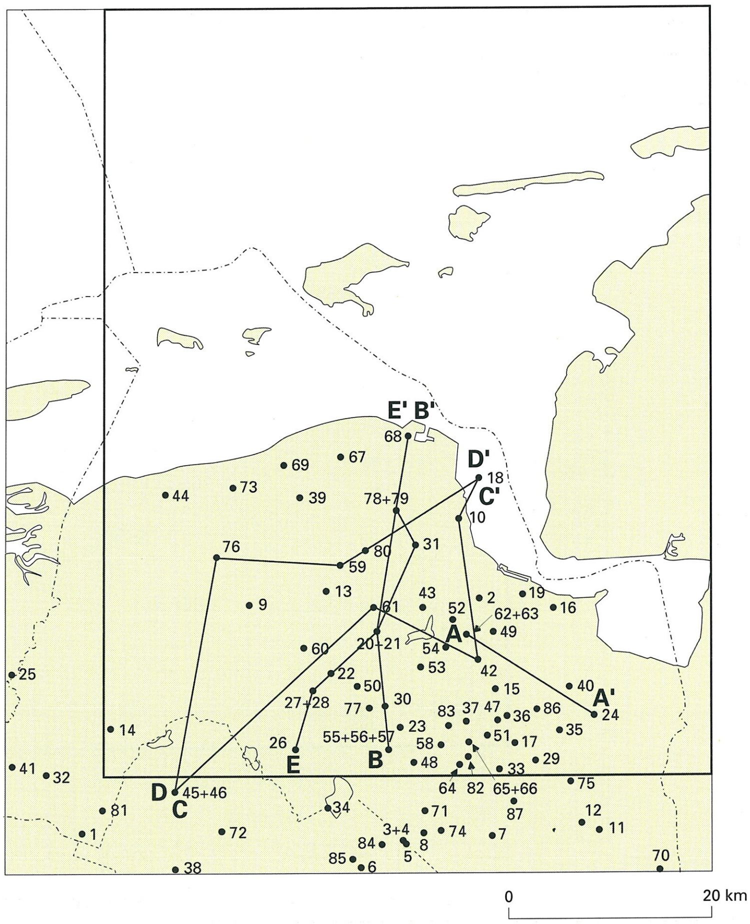


Figure 1.2 Overview map of the concession licence areas within the map sheet area: Groningen and Drenthe. The NAM is the licence holder in both concessions. In the case of all identified gasfields (as of 1/1/1995) the reservoir is located in the sandstone of the Upper Rotliegend Group. The gasfields situated in the map sheet area are: 1 Groningen, 2 Usquert, 3 Warffum, 4 Bedum, 5 Saaksum, 6 Munnekezijl, 7 Grijpskerk, 8 Boerakker, 9 Pasop, 10 Roden, 11 Blijham.

the Haren-1 well proved to be anhydritically developed and thus lacked reservoir quality. Fortunately, an underlying continental sandstone of the Upper Rotliegend Group was encountered exhibiting very good reservoir properties but which transpired to be water-bearing in the case of this well site.
The second reconnaissance drilling of the Rotliegend, the Ten Boer-1 well (1955), detected the Rotliegend incorporated in a claystone facies (later called the Ten Boer Member). Despite the identification of several prospective structures on the seismic lines, the Suez crisis in 1956 brought about a change in the drilling programme. The drilling rigs were used to expand the development of the oil fields previously found to be present in Zuid-Holland. Not until four years after the completion of the Ten Boer-1 well, was another borehole, the historic Slochteren-1 well (1959), drilled in the northeast of The Netherlands (Knaap & Coenen, 1987). This well proved the Permian Rotliegend sandstone to be gas-bearing, and the discovery of the Groningen gasfield became a fact. After the successful wells Delfzijl-1, Slochteren-2, the deepened Ten Boer-1, Noordbroek-1 and Schildmeer-1, realisation gradually dawned that these boreholes had all reached a single large reservoir. This is reflected by the 1959 and 1960 newspaper headlines with, as time went by, estimates of reserves going up from some tens to over 1 billion (10^{12}) m^3 of gas. The Groningen gasfield was later shown to be 35 km long and 25 km wide, encompassing a major part of the province.

In 1963 the NAM was allocated the production licence for nearly the entire province of Groningen, and since then 57 well clusters have been drilled. The Groningen gasfield is exploited via 29 well clusters, each with a gas processing plant.

Figure 1.3 Location of the wells used for the geophysical and geological mapping. For the numbering, reference should be made to appendix B where the name, owner, final depth and date of the well is given. The location of the stratigraphic sections of the figures 2.2, 3.3, 8.1, 9.1 and 10.2 are also indicated.



Seismic mapping using improved methods produced more accurate, increasingly higher estimates of the gas volume of the Groningen gasfield. With a predicted total gas volume (GIIP) of 2.956 x 10^{12} m^3 (at 1-1-1995) the Groningen gasfield is the largest in Europe and one of the largest in the world. In 1994, the Groningen field produced 36.5 x 10^9 m^3 natural gas, roughly equivalent to total annual national consumption. Figure 1.5 illustrates the total gas volume in 1964 up to 1994 (GIIP), subdivided into cumulative production, recoverable gas and non-recoverable gas remaining after abandonment of the field. Since 1990, new production methods enabled the calculated percentage of exploitable gas to be increased to over 90% of the GIIP. The remaining reserve at 1-1-1995 amounts to approximately 1.362 trillion m^3 of gas (Ministry of Economic Affairs, 1995).

In the area around the Groningen field, the map sheet incorporates the fields of Usquert, Warffum, Bedum, Pasop, Saaksum, Blijham and partly the fields of Munnekezijl, Grijpskerk, Boerakker and Roden (fig. 1.2). In all these fields, the reservoir rock is formed by the sandstones of the Upper Rotliegend.

1.3b Salt exploitation

After the presence of shallow salt-structures in the northeast of The Netherlands had been revealed by wells and gravimetric research at the end of the forties and beginning of the fifties, an interest in this

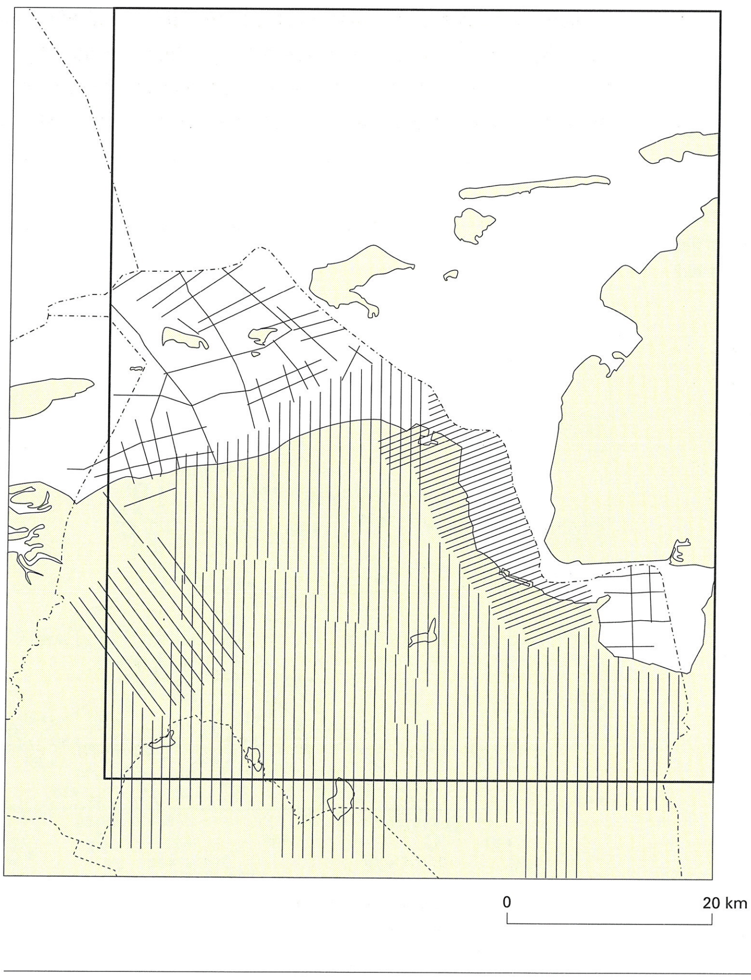


Figure 1.4 Location of the seismic lines used. Appendix A gives additional information on the owner and the age of the various 2D and 3D surveys.

area was expressed by the Koninklijke Nederlandse Zoutindustrie. In 1954, the Adolph van Nassau concession was allocated for the area surrounding the Zuidwending salt-structure to the south of the map sheet area. In 1967, it was expanded to include the area around the Winschoten salt-structure, since when twelve production wells have been placed in this structure. In 1994, the production from the Adolph van Nassau concession reached 2530 kilotons of rock salt from the Z2 (Stassfurt) Formation. A further addition was in 1980 with the Veendam concession, extending as far as the extreme south of the map sheet area, where potassium-magnesium salts are exploited by NedMag Industries. In 1994, 178.2 kilotons of potassium-magnesium salt were produced from the Z3 (Leine) Formation, 145 kilotons of which were magnesium salt. In both concessions, the salt production is carried out by solution mining. A reconnaissance well in the Pieterburen salt-structure (1970) has demonstrated the presence of internally strongly folded Zechstein salt layers. Activity here subsequently ceased.

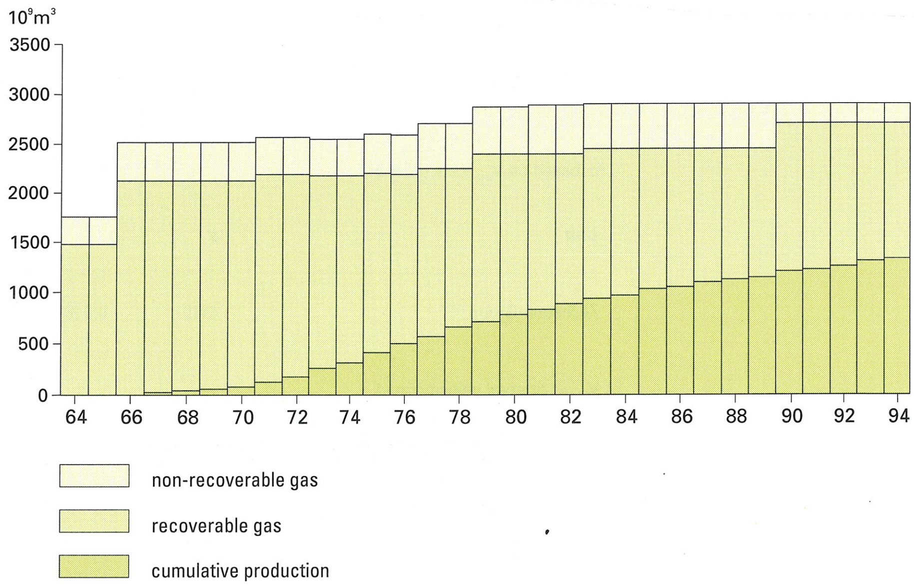
1.4 Research set up

Seismic mapping

The research was focused on the systematic, structural-geological mapping based on seismic reflection data. For the regional mapping it was decided to adopt a seismic line-grid of a maximum of 4 by 4 kilometres. A high line density could not be achieved in the Wadden Sea, partly owing to the restrictions imposed on the companies in the interest of environment conservation. Furthermore, the pronounced fluctuations in water depths on the tidal flat called for special recording techniques. Possibly, the assumed restricted prospectivity of this area did not promote a further seismic investigation at that time. The seismic lines used in the Wadden Sea date from 1964 to 1985. On land, for mapping purposes predominant use was made of 3D seismics, shot between 1983 and 1988.
The selected lines and the lines used for interpretation had a grid distance of 1000 m.

Appendix A provides an overview of the seismic data used. Their position is illustrated in figure 1.4.

Figure 1.5 Reserve- and production figures of the Groningen gasfield. The diagram illustrates both the increase in the expected total (exploitable) gas reserve and the increase in the total gas volume (GIIP).



The reflectors traced form the boundaries between the lithostratigraphic units (groups and formations). Calibration of the seismic data and well logging was carried out by means of acoustic logs and check-shot surveys.

The time-to-depth conversion of the seismic sections was carried out per layer (the so-called layer-cake method). The layers, corresponding to the lithostratigraphic units, each have a specific velocity distribution. For this a linear equation between the velocity and the depth of the layer was taken ($V_z = V_0 + kz$; see table 1). For the Zechstein Group, in view of the specific lithostratigraphic composition, a hyperbolic equation between the interval velocity and the time interval was selected ($V_{int} = a + [d/(\delta t - b)]^c$; see table 1).

To guarantee consistency between depth maps of adjacent map sheets, the same velocity equations have been applied to all the map sheets. The parameters of this regional velocity distribution were determined from the acoustic data from 65 wells located throughout The Netherlands. In the

Table 1 Applied velocity distribution

a. based on $V_z = V_0 + kz$

V_z= formation/group velocity at depth z (m/s)
V_0 = formation/group velocity at depth 0 (m/s)
k = constant (1/s)
z = depth (m)

Unit	*V_0*	*k*
North Sea Supergroup	1696	0.49
Chalk Group	2092	1.08
Holland Formation	2020	0.63
Vlieland Subgroup	2051	0.41
Niedersachsen Group	1507	0.82
Lower and Upper Germanic		
Trias Groups	2293	0.69
Upper Rotliegend Group	3535	0.18

b. based on $V_{int} = a + [d/(\delta t - b)]^c$

Unit	*a*	*b*	*c*	*d*
Zechstein Group	4410	– 0.018	1	47.36

V_{int} = interval velocity (m/s)
δt = time interval Zechstein (s)
a = asymptote interval velocity (m/s)
b = asymptote δt (s)
c = constant
d = constant (m)

determination of the parameters a maximum error of 5% in the seismically determined depth of a particular horizon was deemed acceptable. Table 1 gives an overview of the parameters used for the velocity distribution.

Geological research

The geological research focused on the lithostratigraphic composition of the rocks present in the map sheet area (fig. 1.6) and their geological history with respect to the regional developments.
The previously mentioned seismic data and well-log data were used, supplemented with data derived from lithostratigraphic and biostratigraphic research and rock samples. An overview of the wells used is given in appendix B. The locations are shown in figure 1.3. Figure 1.7 illustrates the geological timetable as used in this explanation (Harland et al., 1990).

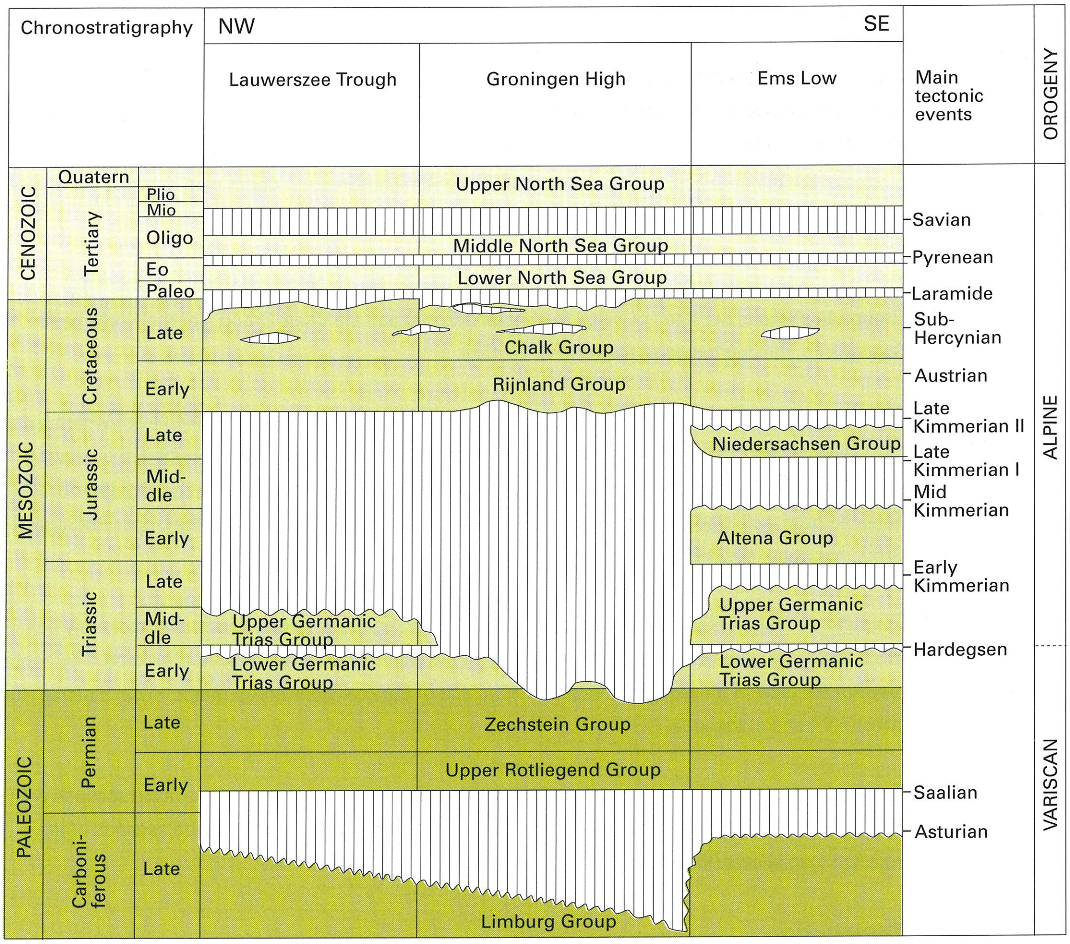


Figure 1.6 Diagram of the lithostratigraphic units and the main tectonic events for the geological development of the map sheet area. The vertical hatching indicates the hiatuses.

Petrophysical research

In addition to the geological research, the reservoir characteristics within the map sheet area have also been taken into account (RGD, 1993). Well-log data and core analyses have been processed from 20 wells for the calculation of porosities; these are categorised in appendix C. Appendix D exhibits a number of test data, five of which were derived from the Groningen gasfield.

Geochemical research

Vitrinite analyses have been performed on the coal-bearing intervals the Limburg Group as well as on the deposits of the Coppershale Member of the Zechstein Group in order to reconstruct the burial history of the map sheet area (RGD, 1994). The procedures, the results of the analyses and the reconstructions are discussed in section 11.4.

1.5 Maps and sections

The results of the seismic mapping are shown in a series of depth maps and thickness maps of the lithostratigraphic groups, on subcrop maps and in three sections. The subdivision into lithostratigraphic groups has been depicted schematically in figure 1.6. Depth maps have been plotted of the bases of the Upper Rotliegend Group, the Zechstein Group, the Lower Germanic Trias Group, the Altena Group, the Rijnland Group, the Chalk Group and the North Sea Supergroup. A depth map of the base of the Upper North Sea Group has been included as a text figure (fig. 10.4). A subcrop map has been plotted of the major unconformity on the base of the Rijnland Group. A depth map has also been plotted of the top of the Zechstein Group.

Thickness maps have been plotted of the Zechstein Group, the Lower and Upper Germanic Trias Groups as a whole, the Altena Group, the Rijnland Group and the Chalk Group. For the North Sea Supergroup, the depth map of the base will suffice.

In the Wadden Sea the base of the Upper Rotliegend Group could not be determined everywhere from (2D-) seismic data. The depth map of this group for this area has therefore been compiled by adding the regional thickness of the Upper Rotliegend Group to the depth of the base of the Zechstein Group obtained from well logs and regionally present 3D seismics. A thickness map of the Upper Rotliegend Group has been included as a text figure (fig. 3.2).

The subcrop map of the Rijnland Group illustrates the stratigraphic units occurring immediately below this unconformity and thus gives an impression of the extent of the pre-Cretaceous erosion. The depth maps of the base of the Upper Rotliegend Group and of the Zechstein Group (Maps 1 & 2) illustrate the structural trend of the area.

Finally, three intersecting cross-sections have been presented on a separate map. These sections with NW-SE and SW-NE orientations have been selected in such a way as to link up with sections of the adjacent map sheets (Map 15).

1.6 Explanation

The intention of the explanation is to clarify the information in the various maps and to outline the geology of the map sheet area as completely as possible. The lithological succession and development from old to young is explained chapterwise for each group in turn, referring to the lithostratigraphy,

Figure 1.7 Geological timetable as used in the explanation (after Harland et al., 1990). The tectonic phases which are referred to have also been indicated.

Age (Ma)	Era	Period		Epoch		Age	Orogeny: Main tectonic events	Orogeny
	CENOZOIC	Quaternary			Holocene/Pleistocene			ALPINE
1.64		Tertiary	Neogene		Pliocene	Reuverian		
						Brunssumian		
					Miocene	Messinian		
						Tortonian		
						Serravallian		
						Langhian		
						Burdigalian		
						Aquitanian	Savian	
			Paleogene		Oligocene	Chattian		
						Rupelian		
					Eocene	Priabonian	Pyrenean	
						Bartonian		
						Lutetian		
						Ypresian		
					Paleocene	Thanetian		
						Danian		
65	MESOZOIC	Cretaceous			Late Cretaceous	Maastrichtian	Laramide	
						Campanian	Sub-Hercynian	
						Santonian		
						Coniacian		
						Turonian		
						Cenomanian		
					Early Cretaceous	Albian		
						Aptian	Austrian	
						Barremian		
						Hauterivian		
						Valanginian		
						Ryazanian	Late Kimmerian II	
143		Jurassic		Late	Malm	Portlandian		
						Kimmeridgian		
						Oxfordian	Late Kimmerian I	
				Middle	Dogger	Callovian		
						Bathonian		
						Bajocian	Mid-Kimmerian	
						Aalenian		
				Early	Lias	Toarcian		
						Pliensbachian		
						Sinemurian		
						Hettangian		
208		Triassic		Late	Keuper	Rhaetian	Early Kimmerian	
						Norian		
						Carnian		
				M	Muschelkalk	Ladinian		
						Anisian		
				E	Buntsandstein	Scythian	Hardegsen	
245	PALEOZOIC	Permian		Late	Zechstein	Thuringian		VARISCAN
				Early	Rotliegend	Saxonian		
						Autunian	Saalian	
290		Carboniferous		Late	Silesian	Stephanian	Asturian	
						Westphalian		
						Namurian	Sudetian	
				Early	Dinantian	Visean		
						Tournaisian		
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the sedimentary development and the palaeogeography. Chapter 3 evaluates the petrophysics of the economically important Upper Rotliegend Group. Chapter 11, concluding the explanation, outlines the geological history of the map sheet area for each individual time period. This chapter is a compilation of the previous chapters in conjunction with the structural development. Furthermore the important role played by the salt movements is also examined; the chapter concludes with the gas generation, modelled on the burial history and the geochemical analyses of the Carboniferous and the Coppershale Member, the bituminous shale at the bottommost part of the Zechstein Group.

Unless stated otherwise, the lithostratigraphy applied conforms to the Stratigraphic Nomenclature of the Netherlands, revision and update by RGD and NOGEPA (Van Adrichem Boogaert & Kouwe, 1993-1995). The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members. The distribution is generally related to the major structural elements of the map sheet area, which are described in section 1.7.
Maps of the Niedersachsen Group and the Upper North Sea Group have been included as text figures in the explanation. The Cenozoic sediments are included as a whole in the North Sea Supergroup and not at a separate group level. Moreover, the description is limited to the Tertiary sediments.
The description of the Quaternary deposits will be published in the future in the map sheets of the near-surface geology: 'Toelichting van de geologische kaart van Nederland 1:50.000' by the Rijks Geologische Dienst.

1.7 Summary

1.7.1 Stratigraphic succession

The lithostratigraphic succession in the map sheet area is described below and is schematically illustrated in figure 1.6. The diagram shows a tripartite geographic subdivision in the map sheet area. As a result of the structural development, different sedimentary successions were deposited or preserved in the Lauwerszee Trough, the Groningen High and the Ems Low.

The fluvial and lacustrine sediments from the Westphalian exhibit a clastic composition and were deposited in a humid, tropical climatic environment. The sediments of the Upper Rotliegend Group, Early Permian, are also composed of clastic material and deposited in a lacustrine and fluvial setting, but this time in a playa area governed by arid conditions (fig. 3.5). This pronounced climate change was the result of the breaking up and drifting apart of the Gondwana supercontinent. The Zechstein Group from the Late Permian spans five evaporite cycles. These successions of clay, carbonate, anhydrite and rock salt were initially formed under marine conditions. The fourth and fifth cycles exhibit a terrestrial nature. The Lower Germanic Trias Group again consists of clastic, terrestrial (fluvial and lacustrine) deposits. The composition of the Upper Germanic Trias Group reflects an increasing marine influence demonstrated by the presence of carbonates and evaporites. The Jurassic Altena and Niedersachsen Groups consist of very fine-grained clastic material deposited in an environmental setting varying from full marine to lagoonal/lacustrine. These deposits are only present in the extreme southeast of the map sheet area. During the Cretaceous, deposition of marine sediments took place, these being subdivided into the clastic Lower Cretaceous sediments of the Rijnland Group and the marine carbonates of the Chalk Group from the Late Cretaceous. The Cenozoic succession consists of clastic sediments deposited under alternately marine and terrestrial conditions.
Periods or erosion produced several hiatuses as well as - in combination with tectonic phases - angular unconformities in the stratigraphic succession.

1.7.2 Structural units

Figure 1.8 shows the structural units in the north of The Netherlands. These units became very pronounced during the Late Kimmerian erosion phase, but are thought to have a Variscan origin. They were reactivated and modified during the later tectonic phases. The depth maps of the base of the Upper Rotliegend and Zechstein Group (Map 1 & 2) illustrate the structural trend of the map sheet area. The predominating fault direction of the Groningen High is NNW-SSE. However, in the south-west, within the Lauwerszee Trough, a WSW-ENE fault tendency is dominant (see chapter 6).

The map sheet area is dominated by the Groningen High, bounded in the southwest by the Lauwerszee Trough and in the east by the Ems Low. During the Jurassic, the Lower Saxony Basin developed to the south of the Groningen High.

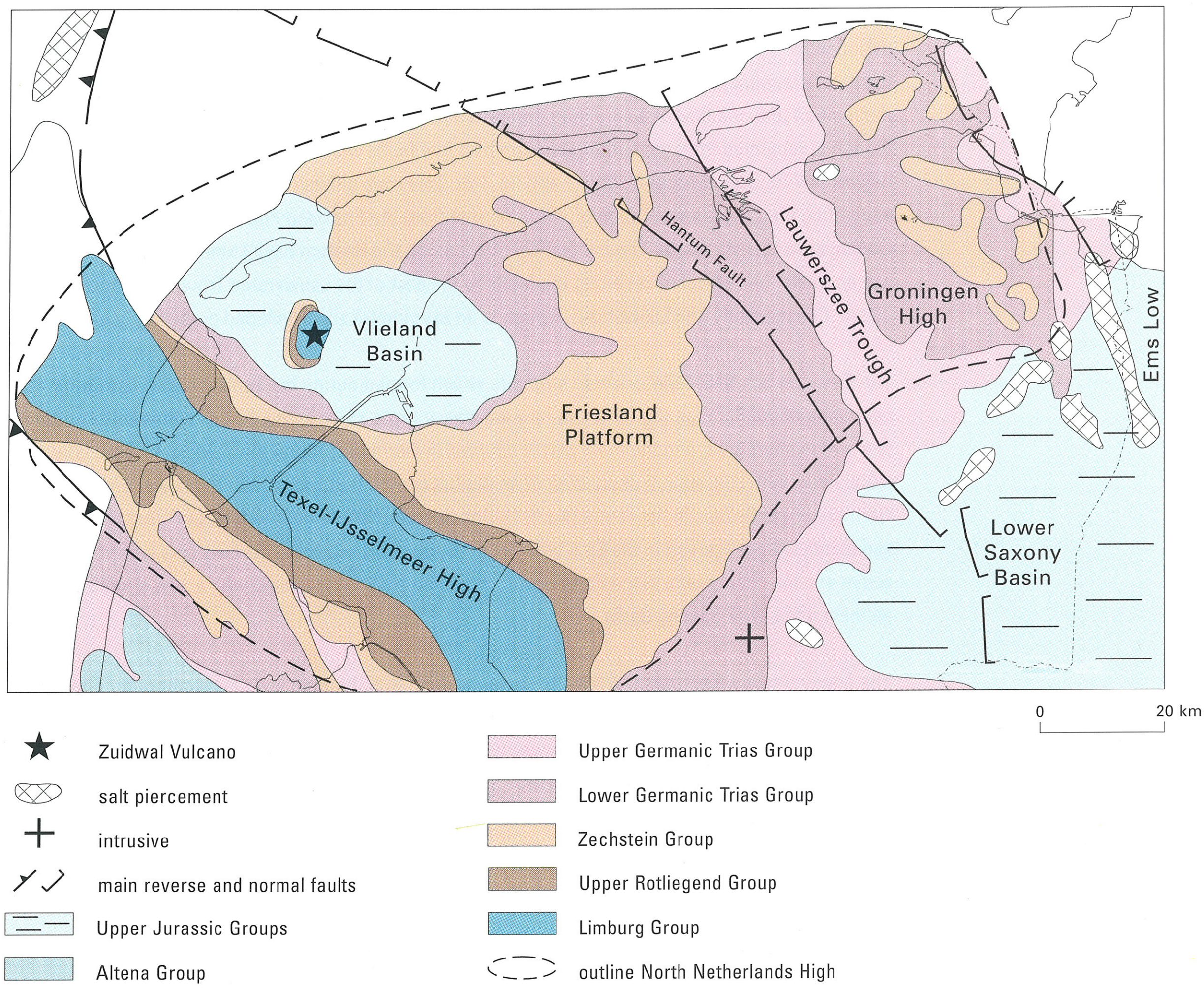


Figure 1.8 Subcrop geological map of the Late Kimmerian II unconformity (Early Cretaceous) in the north of The Netherlands. Variation in age of the subcropping stratigraphic units provides an indication of the relief at the time of the erosion. The main structural elements are shown in this figure.

The *Groningen High* is characterised by a relatively thin succession of Upper Carboniferous and Triassic deposits, and the absence of Jurassic deposits, a consequence of a period of uplift at the beginning of the Permian, the Saalian tectonic phase, and the Kimmerian tectonic phase at the end of the Jurassic. The subcrop map of the Rijnland Group (Map 14) shows that the Lower Cretaceous deposits of the Rijnland Group rest immediately upon the considerably older sediments of the Lower Germanic Trias Group or even the Zechstein Group (fig. 1.6). During the Cretaceous and Tertiary, the areal extent of the Groningen High changed. In this period, the northern margin of the high subsided more intensively than the central part, causing deposition of a thick sequence of Cretaceous and Tertiary sediments in the area of the Wadden Sea. The Groningen High has great economic importance, as it incorporates the gasfield of the same name.

The *Lauwerszee Trough* is a narrow, roughly NW-SE oriented element. Already in the Carboniferous, the trough was a more rapidly subsiding area than the Groningen High. Relative subsidence also set in during the Late Kimmerian phase (Late Jurassic). This subsidence facilitated the preservation of the sediments of the Lower as well as the Upper Germanic Trias Groups during the subsequent erosion period in the Lauwerszee Trough, in contrast to the erosional effects on the Groningen High. However, the most pronounced subsidence occurred during the Tertiary. Together with the associated salt movements, this resulted in a very thick Tertiary succession (over 1650 m, Map 13). The Lauwerszee Trough is separated from the Groningen High by a few faults with a relatively small, vertical offset in a narrow NW-SE zone (Section 2, Map 2 and fig. 1.8). This zone differs markedly from the *Hantum Fault*, separating the Lauwerszee Trough on the west side from the *Friesland Platform* (fig. 1.8; Rijks Geologische Dienst, 1991b). The net vertical offset along the Hantum Fault (zone) is 1100 m at some places, while the vertical offset along the faults to the east of the Lauwerszee Trough nowhere exceeds 300 m. Consequently, the Lauwerszee Trough is an asymmetrically developed graben structure.

The *Ems Low* is a NNE-SSW oriented structure which formed during the Saalian tectonic phase at the beginning of the Permian (fig. 2.1). Only the western margin of the Ems Low lies within the boundaries of the map sheet area, and the main part is situated in Germany. During the Triassic the Ems Low was reactivated, with consequent deposition of an almost complete succession of the Lower and Upper Germanic Trias Groups in the centre (fig. 5.1). Considerable amounts of Triassic and Jurassic sediments were preserved in the Ems Low. From the Jurassic onwards, the Ems Low was no longer active and the movements in the Earth's crust in this area were associated with a new structural element, the Lower Saxony Basin.

The *Lower Saxony Basin* has a WNW-ESE tendency and is of Jurassic and Cretaceous age. The northern margin is virtually analogous with the southern boundary of the map sheet area. These are the E-W trending faults in the extreme south of Map 2 (Depth Map of the Base of the Zechstein). Immediately to the north of the actual Lower Saxony Basin, a thin succession of Jurassic sediments was preserved (Map 8) in a halokinetically-induced salt-withdrawal basin between the Winschoten, Klein-Ulsda and Landschaftspolder salt structures.

1.7.3. Geological history

The last phase of the Variscan Orogeny in the Early Permian (Saalian phase) was accompanied by uplift of the Groningen High. The structures then formed a framework during the later deformation phases. The period from the Permian up to the Early Jurassic was determined by basin subsidence and sedimentation, interrupted only by slight differential subsidence and erosion during the Hardegsen and Early Kimmerian phases (fig. 1.6). The Late Jurassic was a period characterised by strong differential movements accompanied by erosion deeply cutting down, clearly illustrated by the Late

Kimmerian unconformity subcrop map (fig. 1.8, Map 14). Regional subsidence resumed in the Early Cretaceous. A compressive stress field interrupted this subsidence at the end of the Cretaceous and the beginning of the Tertiary, resulting in uplift and intensive salt movements, causing highly alternating thicknesses in the Upper Cretaceous and Tertiary sediments (Maps 12 & 13). Owing to the plastic properties of salt, the thick salt sequences of the second and third Zechstein cycle had a major influence on the structural and sedimentary development of map sheet area. The Zechstein salt caused a substantial decoupling in deformation of the underlying and overlying rocks. Furthermore, the development of salt structures had a substantial effect on the thickness development of the post-Zechstein sediments.

2 Limburg Group

2.1 Stratigraphy

The sediments of the Limburg Group form the oldest deposits drilled within the map sheet area. They are composed of a thick, monotonous succession of usually grey to black coloured fine-grained siliciclastic sediments. Coal seams and plant remains are found in the middle and uppermost parts and several fossil-rich marine bands in the basal parts of the group. The group also comprises light coloured massive sandstones, and coarse-grained as well as fine-grained siliciclastic intervals with primary red-colouring but without any coal seams. The uppermost part of the group usually exhibits a secondary red-colouring directly below the Saalian (or Asturian) unconformity. The Limburg Group in the map sheet area has been divided into four subgroups (Van Adrichem Boogaert & Kouwe, 1993-1995). Each subgroup represents a particular phase in the Late Carboniferous regressive megasequence.

The Group is of Namurian to Westphalian age (RGD, 1972, 1992b). Stephanian deposits in the map sheet area have not yet been demonstrated by boreholes but in adjacent areas of Germany are widely acknowledged (Hedeman et al., 1984; Selter, 1990; Tantow, 1993). Throughout the map sheet area the Limburg Group is unconformably overlain by the sediments of the Early Permian Upper Rotliegend Group.

The Limburg Group is found throughout the map sheet area, but the thickness has been greatly reduced as a result of erosion during the Late Carboniferous and Early Permian. The total depositional thickness of the Carboniferous is likely to have been over 4500 m. The erosion is related to the Asturian and Saalian tectonic phases respectively (fig. 2.1). Although the Carboniferous is not a primary target for exploration in the map sheet area, nonetheless the Limburg Group was encountered by more than 250 boreholes. However, many wells were terminated soon after the Limburg Group had been reached, which does not facilitate determination of the thickness of the formations.

2.2 Geul Subgroup

No direct information on the Geul Subgroup in the map sheet area is available. The description below has been based on the 'Stratigraphic Nomenclature of the Netherlands' (Van Adrichem Boogaert & Kouwe, 1993-1995).

The unit consists of a thick succession of predominantly fine-grained siliciclastic deposits and is devoid of coal seams. Within the map sheet area, the subgroup is composed entirely of the fine-grained Epen Formation.

2.2.1 Epen Formation

This formation, of Namurian to Early Westphalian A age, consists of a thick succession of dark claystones with intercalated very fine-grained to medium-grained sandstones. This stacked interval consists of several 50 to 300 m thick often coarsening-upwards sequences. Coal seams are, by definition, virtually non-existent. Shales and siltstones, some containing clear marine fossils, dominate the basal and middle parts of each succession.

The base of the formation is poorly documented, which can be ascribed to the small number of sufficiently deep wells. The upper boundary, with the Baarlo Formation of the Caumer Subgroup, has been placed at the base of the first prominent coal seam.

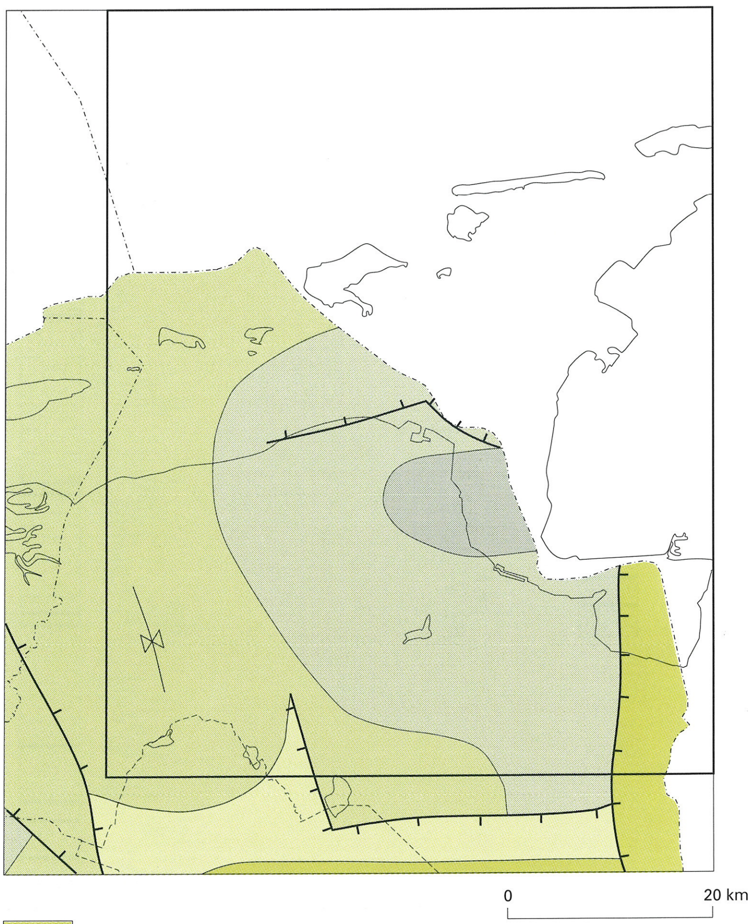
2.3 Caumer Subgroup

The Caumer Subgroup, Early Westphalian A to Late Westphalian C in age, consists of a thick succession of predominantly fine-grained siliciclastics and abundant coal seams. The Caumer Group in the map sheet area encompasses three formations, all of which contain coal seams.

2.3.1 Baarlo Formation

The formation consists of a thick succession of dark, brownish-grey or black claystones, grading into grey or beige siltstones and very fine sandstones, and is composed of a large number of 20 to 300 m thick, coarsening-upward sequences (fig. 2.2). The claystones at the base of a few of the sequences contain open-marine to brackish-water fossils (goniatites, *Lingula*). Fine to medium-grained sandstones are restricted to the top of these sequences. Although the sequences allow adequate correlation,

Figure 2.1 Subcrop geological map of the Saalian unconformity. Variation in age of the top of the Limburg Group and the Variscan fold axes give an indication of the palaeo-structures. The map is based on seismic interpretation, interpretation of well logs and palynological research (RGD, 1972, 1992a; Van Adrichem Boogaert & Kouwe, 1993-1995).



De Lutte Formation — Hunze Subgroup
Tubbergen Formation — Dinkel Subgroup
Maurits Formation
Ruurlo Formation
Baarlo Formation
} Caumer Subgroup

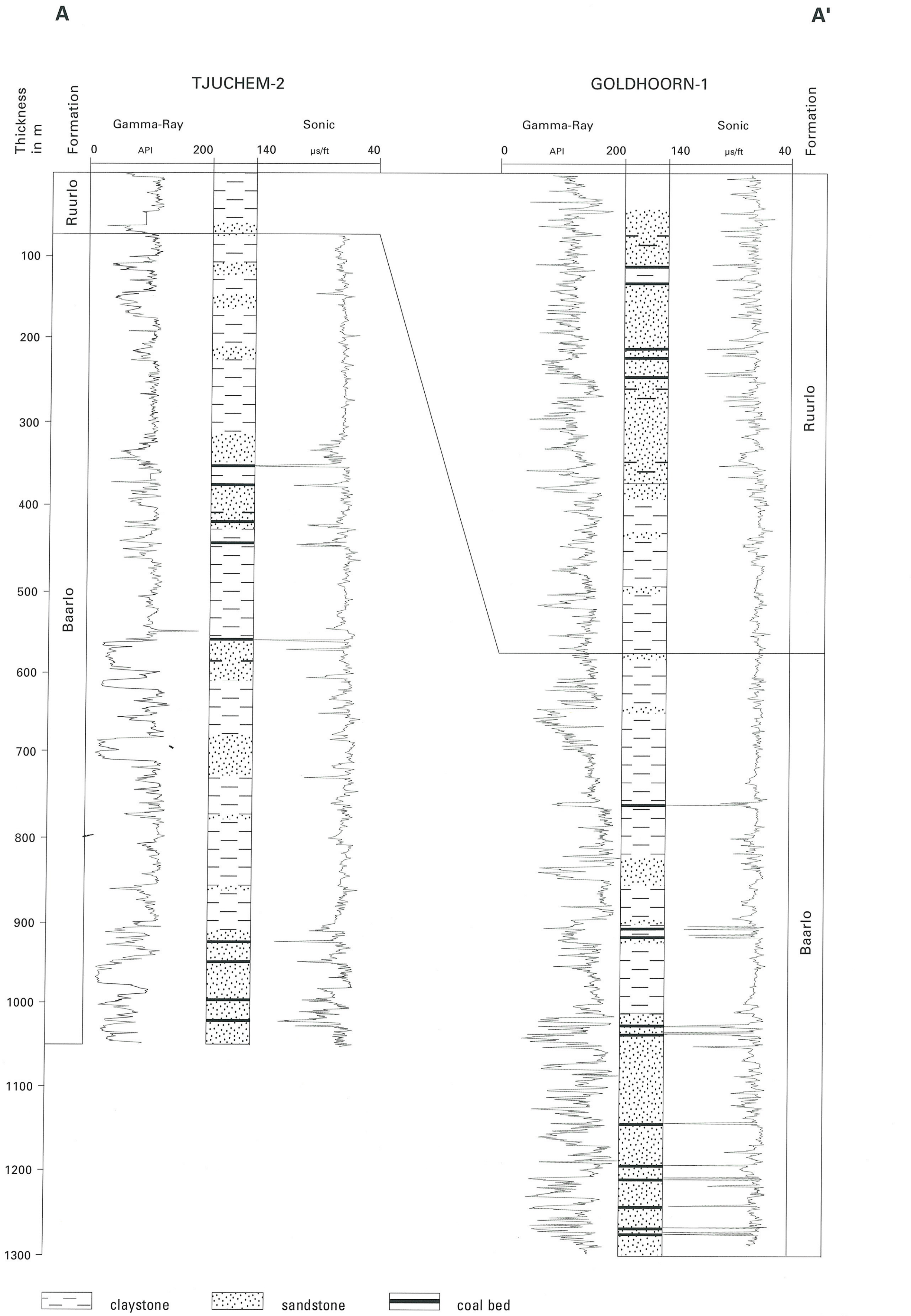


Figure 2.2 Stratigraphic section A-A' of the Ruurlo and Baarlo Formations (Limburg Group) in the Tjuchem-2 and Goldhoorn-1 wells. The location of the section is indicated in figure 1.3. Note that the base of the Baarlo has not been reached.

the individual sandstone bodies have a limited lateral continuity. There are normally fewer than 4 coal seams for every 100 m section and they are restricted to the top part of the sequences. The thickness of the coal seams usually measures a few decimetres, but may reach a maximum of 2 m. In the Tjuchem-2 well, the Baarlo Formation is over 1000 m thick (fig. 2.2).

The Baarlo Formation is found throughout the map sheet area and is of Early Westphalian A age (RGD, 1972). The basal contact with the Epen Formation has been set at the base of the bottommost coal seam. In one continuous section the transition with the Ruurlo Formation has been defined as the horizon where thick, coarsening-upwards sequences become fining/coarsening-upwards cycles.

2.3.2 Ruurlo Formation

The Ruurlo Formation, of Late Westphalian A to Early Westphalian B age, comprises a succession of dark-grey or black silty claystones with a variable number or coal seams (fig. 2.2), and grey or light-yellow fine-grained argillaceous sandstones (up to 5 m thick). The formation is characterised by a pattern of stacked sandstone bodies, averaging approximately 50 m in thickness, with fining/ coarsening-upward sequences. Sandstones developed in small channels and are also found as thin beds with fair lateral continuity. Coal seams, up to 2 m thick, are much in evidence, though laterally varying considerably in frequency.

The formation rests conformably on the Baarlo Formation. The top of the formation is marked by an abrupt transition to the claystone and coal-dominated Maurits Formation. The formation was deposited throughout the map sheet area but has, in whole or in part, been removed on the Groningen High by erosion (fig. 2.1). In the Goldhoorn-1 well, the minimum thickness is 550 m (fig. 2.2).

2.3.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Late Westphalian C age, mainly comprises light-grey claystones with a relatively large number of coal seams and a much smaller number of grey and light-yellow, very fine-grained to coarse-grained argillaceous sandstones. Some dark-grey claystones contain brackish-water fossils.

The contact made by the Maurits Formation with the underlying Ruurlo Formation is evident from a sandy development of the Ruurlo Formation. In the case of an argillaceous development the transition is difficult to detect because of strong lithological similarity. In a complete succession the top of the Maurits Formation coincides with the top of the Caumer Subgroup and this has been placed at the first thick sandstone layer of the Tubbergen Formation (fig. 2.3). The Maurits Formation is present in the Ems Low and the Lauwerszee Trough where it reaches a thickness of 150 m. In figure 2.3 the Aegir marine bed can be identified on the Westphalian B - Westphalian C boundary.

2.4 Dinkel Subgroup

The Dinkel Subgroup in the map sheet area is composed entirely of the Tubbergen Formation, which only occurs in the southwesterly part of the map sheet area and in the Ems Low.

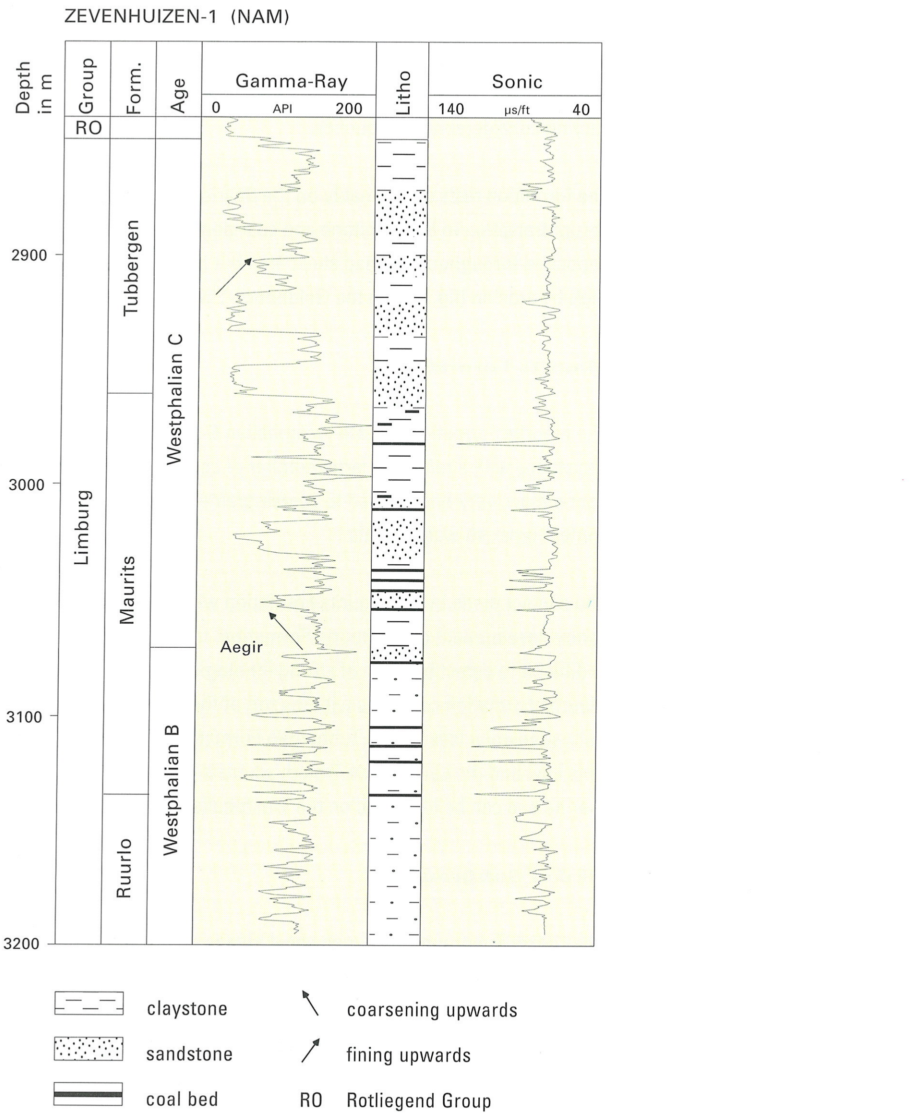
2.4.1 Tubbergen Formation

This formation, of Late Westphalian C to Early Westphalian D age, is a succession of predominantly grey or white, but also pink and red sandstones of varying thicknesses, alternating with grey and reddish-brown claystones, and a few coal seams. The sandstone intervals make up 30 to 70% of the succession. The sands are fine-grained to very coarse-grained, and sometimes contain small pebbles (fig. 2.3). The Tubbergen Formation is approximately 150 m thick in the Norg-Zuid-1 well (immediately to the south of the map sheet area).

The base of the Tubbergen Formation is marked by the first occurrence of thickly bedded sandstones. The formation is covered by the claystone-dominated De Lutte Formation of the Hunze Subgroup.

In the map sheet area the formation occurs in the most southerly part of the Lauwerszee Trough, to the south of the Groningen High and in the Ems Low. In the Dutch part of this Low the Tubbergen Formation has never been reached at any well site.

Figure 2.3 Log pattern of the Ruurlo, Maurits and Tubbergen Formations (Limburg Group) in the Zevenhuizen-1 well.



2.5 Hunze Subgroup

In the map sheet area the Hunze Subgroup only includes the De Lutte Formation which is only encountered in the Ems Low.

2.5.1 De Lutte Formation

The De Lutte Formation is a succession of predominantly reddish-brown and greenish-grey, silty to very fine-sandy claystones. As well as the claystones, a small part of the formation also consists of light-grey, white, purple or red sandstones allowing clear correlation. These sandstones are fine to medium-grained with intercalations of very coarse-grained sandstone and conglomerates. Coal seams are virtually not present.

The transition from the Tubbergen Formation to the De Lutte Formation varies in age from Late Westphalian C/Early Westphalian D in basins like the Ems Low, to Late Westphalian D on the basin margins. The presence of the Stephanian in the Ems Low, although never confirmed by wells, is inferred from log correlations with wells in the German part of the Ems Low, (Hedeman et al., 1984; Selter, 1990; Tantow, 1993). To the south of the Groningen High the De Lutte Formation can reach thicknesses of as much as 300 m or thereabouts.

The De Lutte Formation conformably overlies the uppermost massive sandstones of the Tubbergen Formation and is truncated by the Saalian unconformity. The formation is unconformably overlain by the Upper Rotliegend Group.

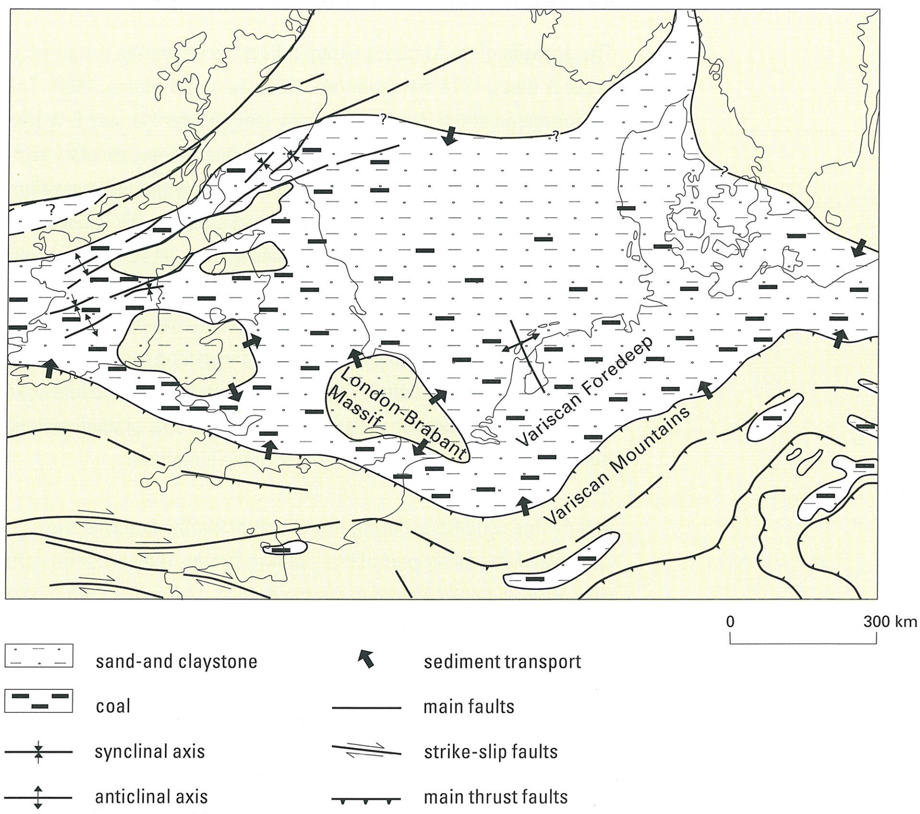
2.6 Sedimentary development and palaeogeography

The deposits of the Limburg Group reflect the regressive deltaic accumulation of a foreland basin (Van Wijhe & Bless, 1974; Ramsbottom, 1979; Guion & Fielding, 1988). This basin, which developed during the formation of the Variscan Orogeny (see chapter 11), was E-W trending and covered the area from England to Poland (fig. 2.4). As basin subsidence approximately kept pace with the rate of sedimentation, this thick succession contains only gradual transitions of the various facies. The source area of the sediments within the map sheet area was the Variscan mountain range. The basal part of the succession (Geul Subgroup) contains marine, lacustrine and deltaic deposits. The middle part (Caumer Subgroup) is the continuation of the regressive megasequence in the Late Carboniferous and is characterised by the replacement of dominant pro-delta deposits by delta plains and river deposits. The marshes on the delta plain are the initial setting for coal deposits. In the top part (Dinkel and Hunze Subgroup) the deltaic deposits intermittently passed into coarse-grained river deposits. The abrupt erosive truncation of large amounts of coarse-grained material and the small internal unconformities indicate tectonic uplift of the hinterland.

Full marine conditions during deposition of marine horizons were of brief duration but frequently occurred in the lower part of the Limburg Group. They occur less often in the middle section, whereas they are completely absent in the top section. During the Carboniferous, the glaciations were a consistent periodical force behind the cyclicity, influencing the sea level, the base level of erosion and the climate (Bless & Winkler Prins, 1972). In addition, non-periodical effects, such as variable tectonic activity, basin subsidence and change in pattern of sedimentation (e.g. sudden abandonment of the meander channel and compaction) played an important role (Read & Dean, 1973; Guion & Fielding, 1988; De Vries Klein & Kupperman, 1992).

Sediments, flora and fauna dating from the Namurian and the Westphalian A to C, indicate a tropical, humid climate without any clear seasonal influences. During the Late Westphalian C and D as well as the Stephanian the climate was drier (Hedeman et al., 1984; Van der Zwan et al., 1993). The red colour of the sediments, the calcareous soils and the sparse vegetation reflect a more season-dictated, tropical semi-arid climate.

Figure 2.4 Palaeogeography of the Carboniferous in Northwest Europe (after Ziegler, 1990).



3 Upper Rotliegend Group

3.1 Stratigraphy

The Upper Rotliegend Group, of Early Permian age, comprises clastic sediments and evaporites. The sediments generally display a characteristic red or reddish-brown colour and were deposited in a terrestial setting. The group consists of two formations passing laterally one into the other: the Slochteren Formation in the south and the Silverpit Formation in the north (fig. 3.1). In the area where both formations are found, they are divided into the following members, downwards: the Ten Boer Member, the Upper Slochteren Member, the Ameland Member and the Lower Slochteren Member. The Slochteren Formation is the proximally deposited fluvial sandstone, while the Silverpit Formation is its distal lacustrine equivalent.

The Upper Rotliegend Group thickens from 100 m in the southeast to 400 m in the northwest of the map sheet area. A thickening can also be observed in the Lauwerszee Trough (fig. 3.2) compared with the Groningen High.

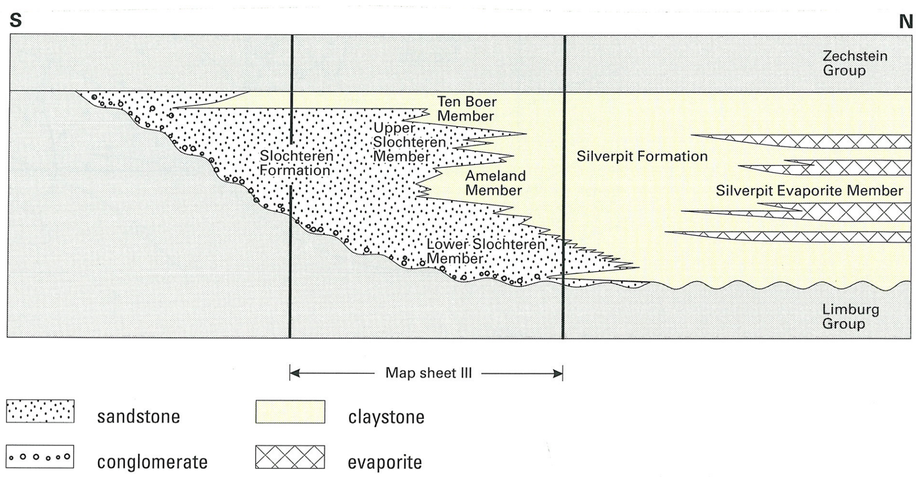
The Lauwerszee Trough and the Groningen High can be clearly identified on the depth map of the base of the Upper Rotliegend Group (Map 1). The Groningen High dips to the north with the depth of the base of the Upper Rotliegend Group increasing from 2750 m to 3000 m. A rapid increase in depth is visible after the step-over to the Lauwerszee Trough. In the trough the depth varies from 3500 m to over 4200 m in the vicinity of Rottumerplaat. On the east side of the Groningen High, in the Ems Low, there is also a rapid increase in depth to over 3900 m.

Owing to the Saalian tectonic phase, the Upper Rotliegend Group rests unconformably upon the deposits of the Limburg Group. The Rotliegend Group is directly overlain conformably by the Late Permian Zechstein Group deposits.

3.1.1 Slochteren Formation

In the south, the Slochteren Formation is composed of massive sandstones containing conglomerate intercalations. In the north, conglomerates on the base only occur locally, while the number of claystone intercalations increases. In the northern part, the Slochteren Formation interfingers with the Silverpit Formation and is subdivided into the Upper and Lower Slochteren Members (fig. 3.1).

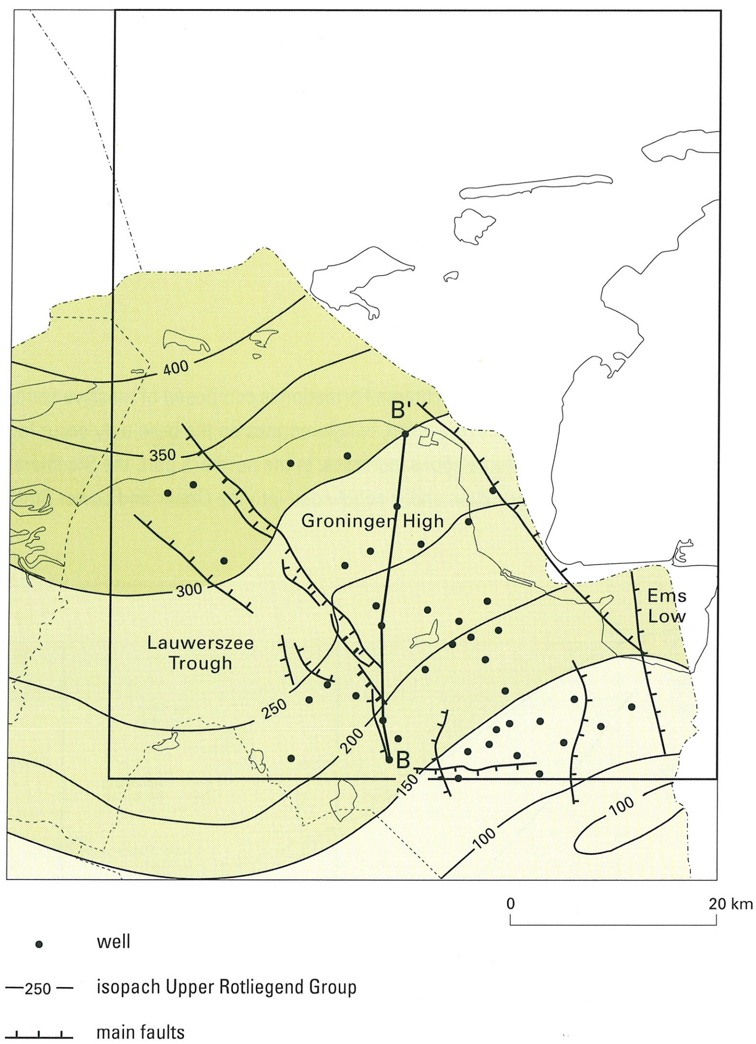
Figure 3.1 Schematic lithostratigraphic diagram of the Upper Rotliegend Group illustrating the lateral grading of the Slochteren Formation into the Silverpit Formation. The outlined section in the diagram marks the position of the map sheet area.



The thickness of the Slochteren Formation varies from 95 m in the southeast to a maximum of 235 m in the northwest of the area, thins rapidly north of the map sheet area (fig. 3.3).
In the Schiermonnikoog-Zee-1 well, situated in the northwest of the map sheet area, the thickness of the formation is a mere 72 m.

The *Lower Slochteren Member* is a sandstone-dominated succession with intercalated layers of conglomerates and claystones. The grey and light-red to dark-red sandstone beds consist of coarse to very fine sand, divergently sorted and poorly rounded, frequently showing small-scale cross-bedding, trough-cross-bedding or parallel or wavy lamination. The base of the formation is formed by beds consisting of fine to coarse-grained sandstones, conglomeratic sandstones and conglomerates, usually showing fining-upwards. The conglomerate contains 4 cm pebbles made up of rounded quartz, silicified claystone, chertified coal or hard clay lenticles and fragments. In places, dolomitic, calcareous claystones and anhydritical dolomite occur. The claystone beds are purple-red and often anhydritical. The thickness of the beds ranges from a few centimetres to several metres.

Figure 3.2 Thickness map of the Upper Rotliegend Group. The map is based on well-log data and seismic interpretation. B-B' indicates the position of the stratigraphic section shown in figure 3.3.



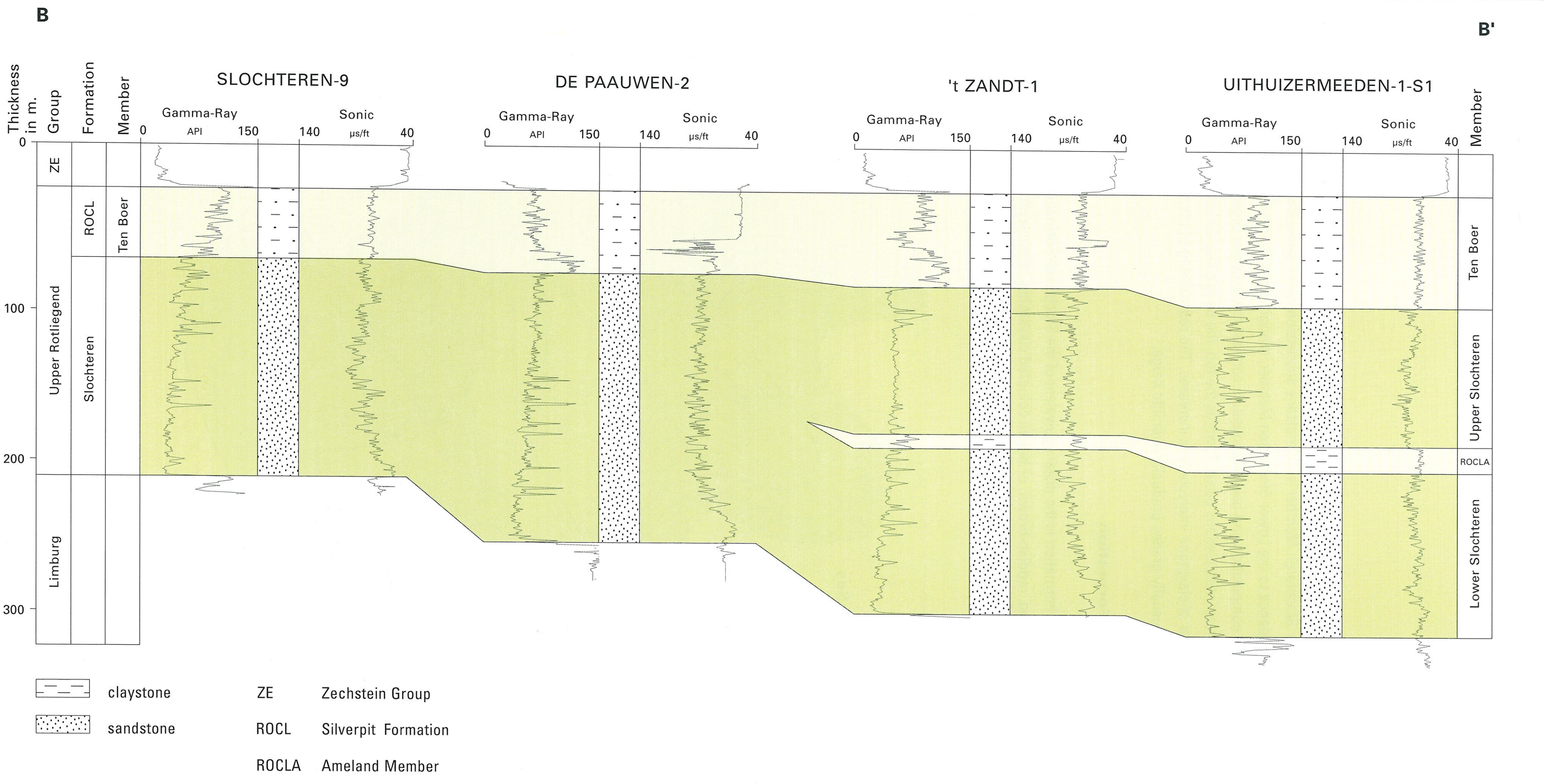


Figure 3.3 Stratigraphic section B-B' of the Upper Rotliegend Group in the Slochteren-9, De Paauwen-2, 't Zand-1, and Uithuizermeeden-1-S1 wells. The section shows the thickening of the Upper Rotliegend Group from south to north. In the wells to the north of the De Paauwen-2 well, the Ameland Member is interbedded between the Lower Slochteren and Upper Slochteren Formations.

The *Upper Slochteren Member* is a sandstone succession which generally shows a lithological correspondence to the Lower Slochteren Member, though more homogeneous and more finely grained in composition and better rounded. In contrast to the Lower Slochteren Member, fewer conglomerate intercalations occur. Towards the top, the conglomerate beds disappear completely and the number of claystone intercalations increases. The red staining of the sandstones in the uppermost ten metres usually grades gradually over into beige.

3.1.2 Silverpit Formation

The Silverpit Formation is the distal equivalent of the Slochteren Formation and consists mainly of alternating red, reddish-brown, or brown coloured claystones, silty claystones and sandstone intercalations with intercalations of thin dolomite and anhydrite beds in places. In the map sheet area,

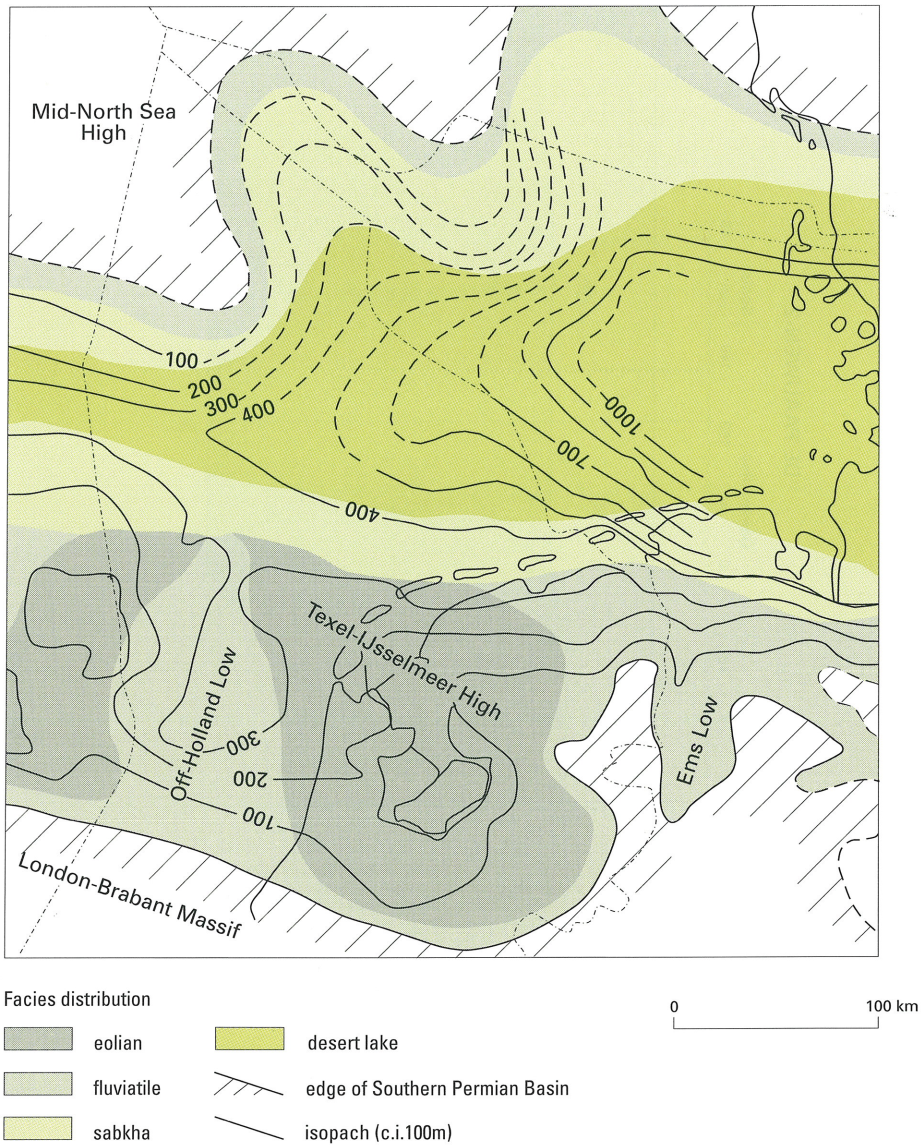


Figure 3.4 Palaeogeography of the Late Permian facies distribution of a part of the Southern Permian Basin. The map sheet area, situated in the southern part of the basin, was predominantly within range of the (prevailing) fluvial deposits. To the south of the map sheet area lay the Variscan mountain chain, the source area of the clastics. Immediately to the north of the map sheet area was a sabkha which, towards the basin, passed into a desert lake (after Van Wijhe et al., 1980).

the Slochteren Formation interfingers with the Silverpit Formation. From old to young, the individual claystone tongues form the Ameland and the Ten Boer Members (fig. 3.1).

The *Ameland Member* is located in the northern part of the map sheet area, and separates the Slochteren Formation into the Lower and Upper Slochteren Members. As these members contain thin siltstone and fine sandstone intercalations as well as claystones, the lower and upper boundaries are often gradual. The maximum drilled thickness in this map sheet area is 20 m. This thickness rapidly increases in a northwardly direction, to reach 208 metres under Schiermonnikoog.

The *Ten Boer Member* in the map sheet area forms the uppermost part of the Upper Rotliegend Group. The member consists of alternating siltstones and claystones with an occasional sandstone bed. The thinner claystone layers, in particular, may contain anhydrite nodules in places. The Ten Boer Member is conformably overlain by the Coppershale Member of the Zechstein Group and increases in thickness from around 30 m in the south to over 75 m in the north of the map sheet area (fig. 3.3). In the south, this unit becomes progressively sandier, finally passing laterally into the Slochteren Formation to the south of the map sheet area (fig. 3.1).

3.2 Sedimentary development and palaeogeography

During continental conditions, the Upper Rotliegend Group was deposited in the intra-cratonic Southern Permian Basin (fig. 3.4). The sediments mainly originated from spurs of the Variscan mountains, which formed the southern edge of the Southern Permian Basin. Alluvial fans with a flood plain were formed at the foot of the Variscan mountains (Stäuble & Milius, 1970; Van Wijhe et al., 1980). Under the influence of the arid climate, the area to the north became a playa or sabkha, a low lying desert area with in the central part a lake (playa lake), occasionally ephemeral.

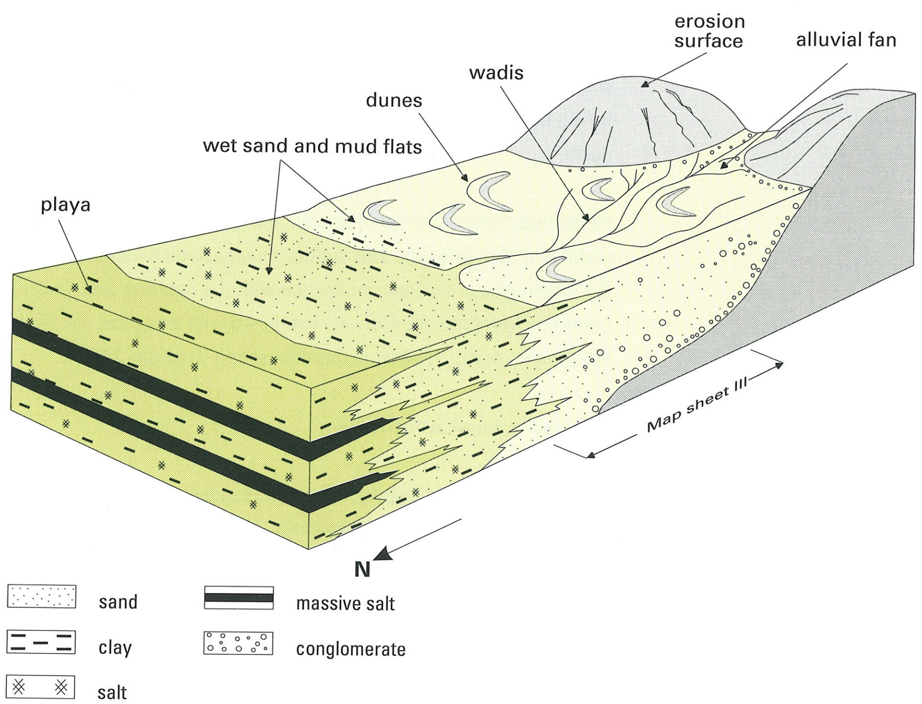


Figure 3.5 Schematic reconstruction of the depositional setting of the sediments of the Upper Rotliegend Group during the Late Permian.

Palaeogeographically, the map sheet roughly represents the zone between the fans and the lake, consisting of a flood plain with braided river and sheetflood deposits (extensive flood deposits; fig. 3.5).

Wet periods and contemporaneous rise of the water level in the playa lake favoured the advance of lacustrine deposits with respect to the fluvial regime. Two major high-water periods have thus resulted in the claystone sequences of the Ameland and Ten Boer Members, extending far to the south.
The somewhat coarser and more poorly sorted sandstone beds, conglomerate and claystone interbeds of the Slochteren Formation are interpreted as deposits in wadis or braided rivers. Well-sorted sandstone beds are in general described as aeolian sediments, deposited as cover sands or broad dune systems between the wadis. Fluvial deposits are dominant within the map sheet area. Aeolian deposits were probably very scarce (Van Wijhe et al., 1980) and are completely absent in the south of the map sheet area.

The sandstone beds occurring in the lacustrine sediments of the Silverpit Formation are interpreted as fluvial sheetfloods deposited in a lake (Van Rossum, 1978). The intercalated anhydrite nodules were formed in periods when the lake (partially) dried out. This indicates that the Ameland and the Ten Boer Members were deposited in a playa lake with a fluctuating water level.

The shifts in the facies boundaries during deposition of the Upper Rotliegend Group are due to changes in climate and (regional) tectonic movements. The combination of both these factors caused fluctuations in the (ground)water table and in supply and type of sediments. These fluctuations are reflected by the rhythmical alternation of sandstone beds and argillaceous intercalations in the Slochteren Formation, and of claystone beds and siltstones in the Silverpit Formation.

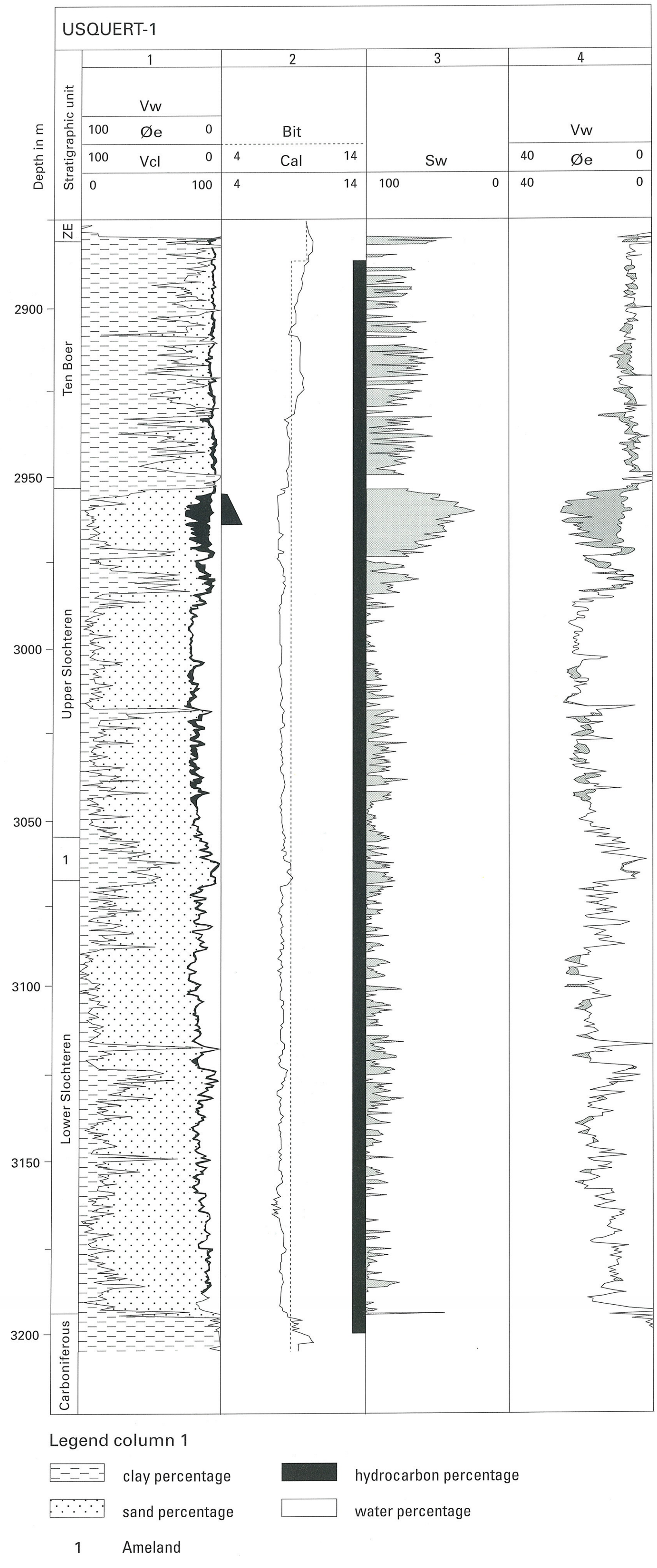
The increasing thickness of the Upper Rotliegend Group in a northerly direction is the result of more extreme subsidence in the central part of the basin. The difference in thickness between the Groningen High and the Lauwerszee Trough would appear to be the result of synsedimentary movements along the NW/SE trending faults in this area (Map 1 & fig. 3.3). The mainly fluvial deposits in the Ems Low can also be related to the synsedimentary adjustment of this depression. To the south of the map sheet area prolongations of the Variscan mountain range are encountered where sediment supply forced by erosion accumulated within the map sheet area, coarse in the south and fine-grained in the north.

At the beginning of the Late Permian, the Southern Permian Basin became a large inland sea as a result of a transgression. This sudden change, which marks the beginning of the Zechstein, was due to the emergence of an open connection with the Barentsz Sea. Development of graben structures between Greenland and Norway, combined with a eustatic sea-level rise caused by the melting of the Gondwana ice cap, facilitated this connection (Glennie, 1983).

3.3 Petrophysical evaluation

The sandstone of the Upper Rotliegend Group forms the reservoir rocks of the Groningen gas field and of the fields in their immediate vicinity. The Groningen gas field covers a large part of the map sheet area (fig. 1.2) and is the largest gas field in Europe with an initial gas volume of 2956 billion m^3 (fig. 1.4). The coal-bearing intervals of the underlying Carboniferous form the gas-source rock and the impermeable Zechstein salt seals the reservoir at the top. The Groningen gas field is situated in a northwesterly-dipping NW-SE oriented horst structure, bounded by large faults on all sides except to the north.

Figure 3.6a Petrophysical evaluation of the Upper Rotliegend Group in the Usquert-1 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained from sonic logs; the calculated log porosity was corrected for the clay content. Column 2: drill hole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the tested intervals (appendix D) are indicated by trapezia signs, and the cored interval by a black bar. Column 3: water saturation Sw %. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe (left curve) and the volume of water in the pores Vw (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the true depths.



A petrophysical evaluation of 20 boreholes has been carried out on the reservoir rocks of the map sheet area and the immediate vicinity. Appendix C contains reservoir calculations of effective porosity percentages of the different lithostratigraphic units: the Upper Rotliegend Group, the Slochteren Formation, the Upper Slochteren and Lower Slochteren Members. Many of the Upper Rotliegend Group sandstones drilled have been found to be gas-bearing (appendix D). To illustrate log-evaluations of the Upper Rotliegend reservoir sequence, figure 3.6 shows the results in the case of the Usquert-1 and Annerveen-5 wells. In the Usquert-1 well the topmost part of the Upper Slochteren and the Ten Boer are gas-bearing (fig. 3.6a). The entirely gas-filled Slochteren Formation in the Annerveen-5 well is representative of the Groningen gas field (fig. 3.6b).

Figure 3.6b Petrophysical evaluation of the Annerveen-5 well. For an explanation, see caption to figure 3.6a.

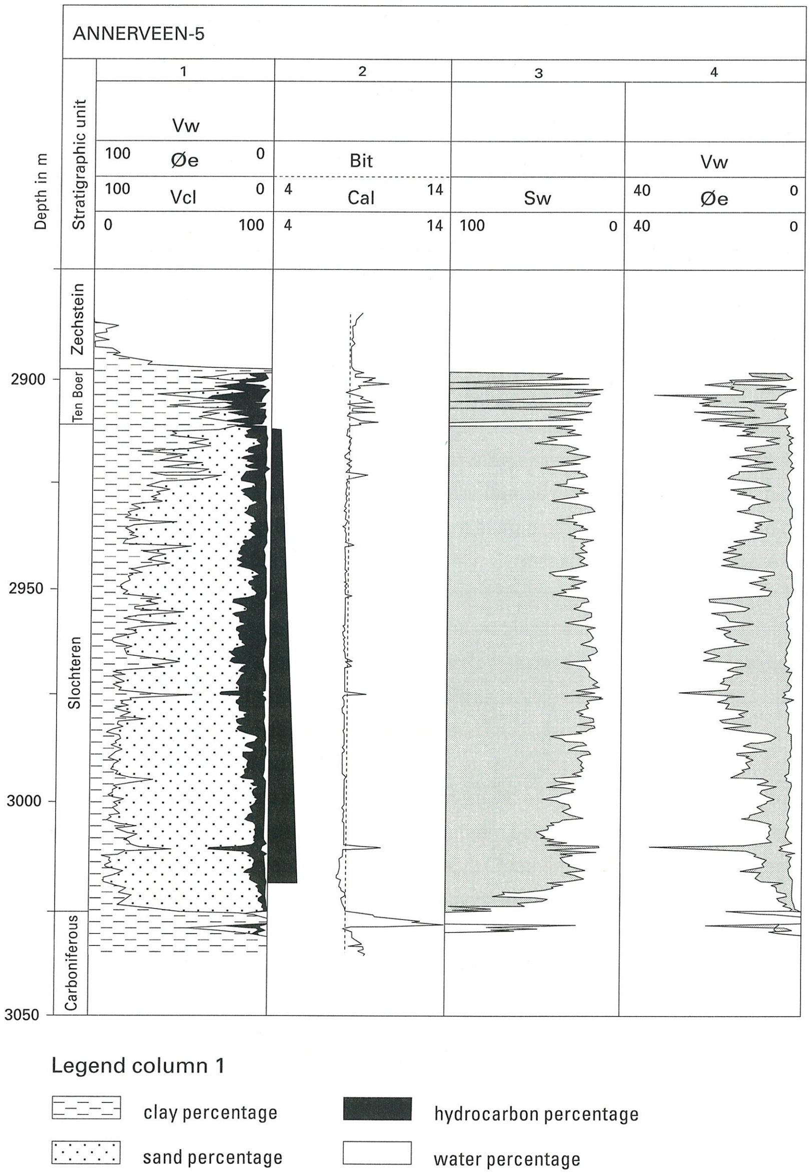
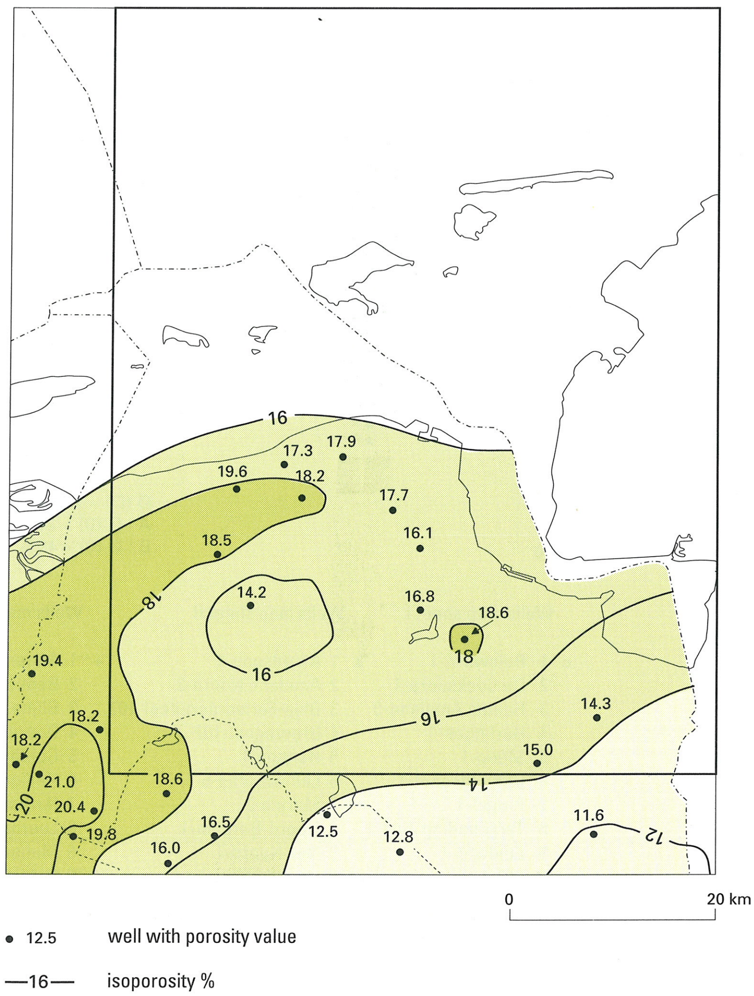


Figure 3.7 shows the distribution of the average effective porosity (Øem) of the Upper Rotliegend Group in the map sheet area. This varies from 13 to 20%, the highest at the centre of the map sheet area and decreasing towards the northwest and the south, which Van Rossum (1978) attributes to the increasing clay fraction to the north and the poorer sorting towards the south. The reservoir permeability reaches values up to 600 mD.

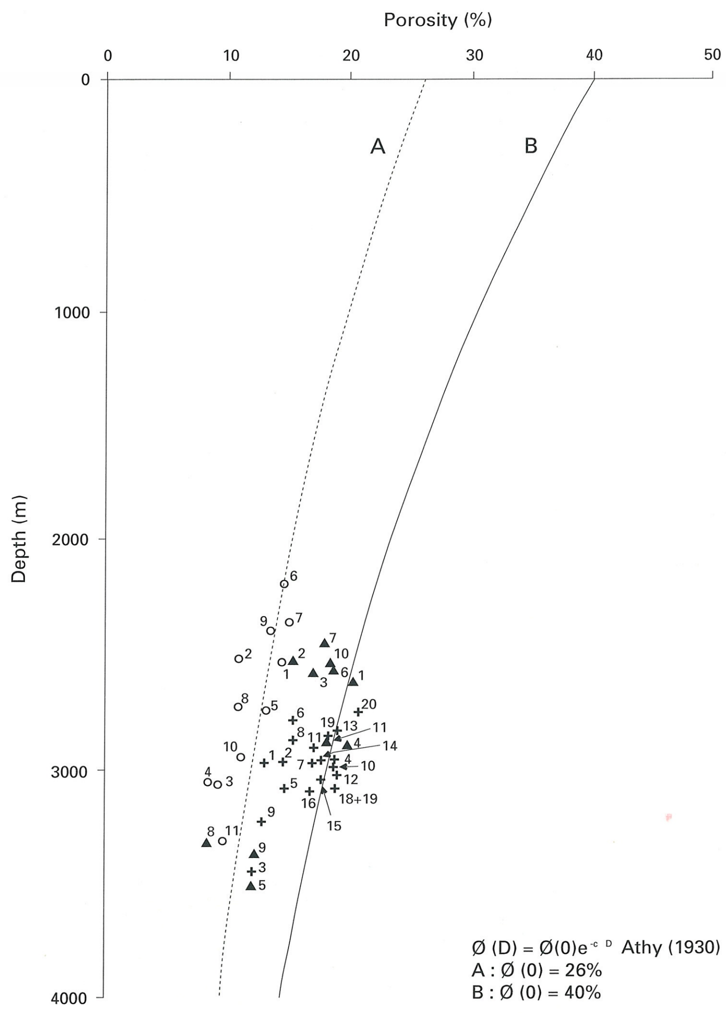
Figure 3.8 gives the porosity depth relation of the petrophysically evaluated boreholes in map sheet I, II and III. In contrast to map sheets I and II, the porosities of the Upper Rotliegend Group in map sheet III are concentrated at a depth of approximately 3000 m with an Øem of approximately 20%.
The compaction curves of Athy (1930) given in the figure are for sandstone with a surface porosity of 26% (wadis) and 40% (top of aeolian deposits). These figures have been defined by Nagtegaal (1979) for the Upper Rotliegend Group in the Southern North Sea. Although relatively few aeolian deposits occur on the map sheet, the majority of the measurements are nonetheless to be found around the latter curve. The average effective porosities of the Upper Rotliegend reservoir sequences in map sheet III are therefore higher than might have been expected from the present burial depth (fig. 3.8). This matter cannot be gone into in greater detail within the framework of this regional mapping.

Figure 3.7 Schematic contour map of the reservoir-average effective porosity Øem of the Upper Rotliegend Group (appendix C).



Studies of burial history indicate that the Upper Rotliegend Group in the map sheet area has never been more deeply buried than at present (RGD, 1994; Van Wijhe et al., 1980; Perrot & Van der Poel, 1987).

Figure 3.8 Porosity versus depth plot for the Upper Rotliegend Group for the evaluated relevant wells on map sheets I, II and III. Curve A is the compaction curve according to Athy's (1930) exponential relation, with a surface porosity Ø(0) = 26% (for a wadi depositional setting). Curve B is the compaction curve for a surface porosity of 40% (for an aeolian depositional setting. For the constant c the value of 0.0002734 per metre was taken (Sclater & Christie, 1980). The data points represent the reservoir-average effective porosity of the Upper Rotliegend Group as a whole (see appendix C; Rijks Geologische Dienst, 1991a,b).



Wells map sheet I

o
1 Bolsward-1
2 De Cocksdorp-1
3 Hollum Ameland-3
4 Harlingen-1
5 Meep-1
6 Oude Inschot-1
7 Riepel-1
8 Terschelling Zuid-1
9 Zuidwal-2
10 L12-1-A
11 M7-1

Wells map sheet II

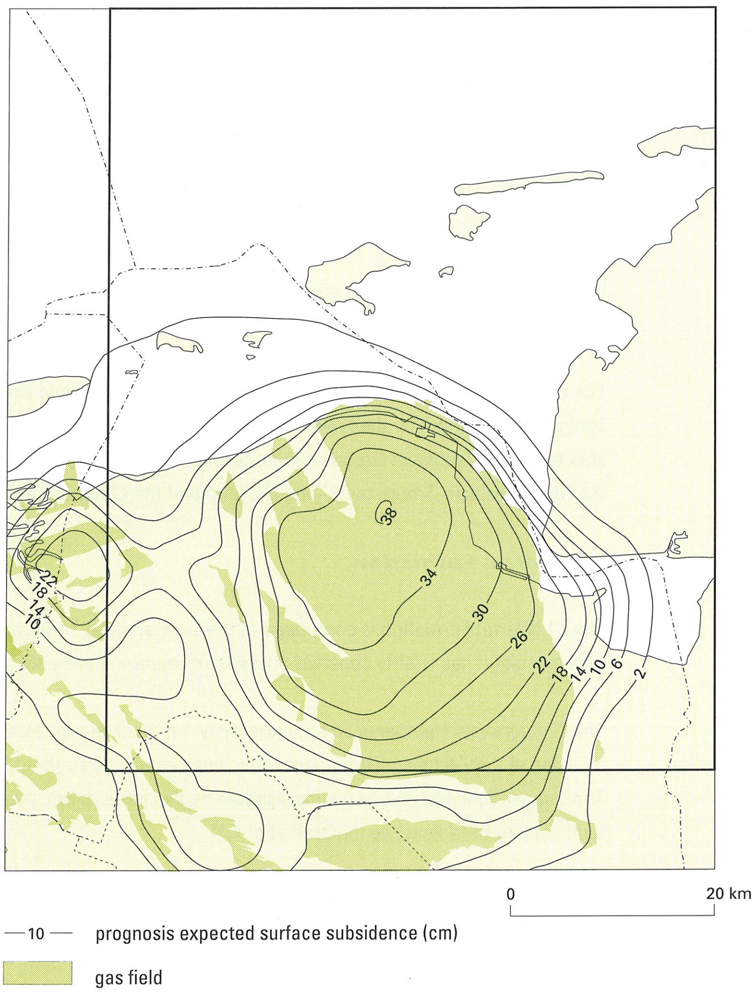
▲
1 Allardsoog-1
2 Ameland Noord-3
3 Blija-Ferwerderadeel-102
4 Grootegast-102
5 Hantum-1
6 Leeuwarden-5
7 Marum-2
8 Noord-Bergum-1
9 Nes Noord-1
10 Opende Oost-1
11 Sint-Annaparochie-1

Wells map sheet III

+
1 Annerveen-Veendam-5
2 Bedum-1
3 Blijham-2
4 Boerakker-1
5 Goldhoorn-1
6 Heiligerlee-1
7 Harkstede-1
8 Leermens-7
9 Midlaren-1
10 Oldorp-1
11 Overschild-1
12 Roden-102
13 Tjuchem-2
14 Uithuizen-1
15 Usquert-1
16 Vries-4
17 Warffum-1
18 Winsum-1
19 't Zandt-1
20 Zevenhuizen-1

As a consequence of the Groningen field gas production from 1963 onwards, the surface above the centre of the field had subsided 18 cm in 1990 (Doornhof, 1992). Surface subsidence is a result of compaction of the Upper Rotliegend reservoir following gas withdrawal. According to the prognosis made by the Nederlandse Aardolie Maatschappij (NAM, 1995), surface subsidence at the centre of the field is likely to reach a maximum of 36 cm in the year 2050 (fig. 3.9). Interference in the surface subsidence above smaller fields around the Groningen field may still influence this picture, certainly at the margins. This is particularly the case above the Munnekezijl and Grijpskerk fields. For indications on the gas production in the area reference should be made to appendix D.

Figure 3.9 Expected surface subsidence in the province of Groningen corresponding roughly with the map sheet area, in the year 2050 as a result of natural gas exploitation (after NAM, 1995).



4 Zechstein Group

4.1 Stratigraphy

The Zechstein Group, of Late Permian age, is composed of five formations which each represent an evaporite cycle, and the Zechstein Upper-Claystone Formation (fig. 4.1). The cycles were formed by episodic influx and subsequent seawater evaporation. From bottom to top, they have been named the Z1 to Z5 Formation. In relation to the strong salt flow or halokinesis in this area, two other names have been used to describe specific Zechstein successions. These are the Zechstein salt, a salt member containing rock-salt deposits from various cycles, and the Zechstein caprock, the residual deposit of the Zechstein sediments. The Zechstein Group succession is illustrated in the Warffum-1 well, where a nearly complete section has been encountered (fig. 4.1).

The Zechstein Group deposits are found throughout the map sheet area. Salt flow gave rise to depletion areas considerably reduced in thickness and accumulation areas with salt ridges, salt plugs and salt pillows considerably thicker than the original depositional thickness (fig. 11.2). As a result of this salt flow, there is a thickness ranging from some tens of metres to over 2500 m (Map 4). In the Pieterburen salt-structure the salt has pierced up to approximately 150 m below ground level.

The depth map of the base of the Zechstein Group displays a similar pattern to that of the base of the Upper Rotliegend Group, with the same structural highs and lows and the same NNW/SSE and WSW/ENE trending faults (Maps 1 & 2 respectively). On the Groningen High, the base lies at a depth of between 2650 and 2900 m, while in the Lauwerszee Trough the base is situated at a depth of between 3200 and 3500 m. In the Wadden Sea region the base is at a maximum depth of 3900 m. The depth map of the top of the Zechstein Group displays an entirely different picture, mainly as a result of the halokinesis (Map 3 and Map 15). Not only the depth pattern, but also the fault pattern has changed in consequence. The NNW/SSE and WSW/ENE trending faults intersecting the base of the Zechstein Group have been accommodated as a result of the plastic behaviour of salt (Map 15). The deformation of the overlying succession has thus become decoupled from the substratum. There is, however, a link between the position and the orientation of the salt structures and the underlying fault patterns. Collapse structures are usually found above the largest salt plugs and salt ridges (see also Chapter 11).

The Zechstein Group rests conformably on the Upper Rotliegend Group and in most of the area is conformably overlain by the Lower Germanic Trias Group (Map 5). Above one or two large salt structures, the Zechstein Group is unconformably overlain by the Upper Germanic Trias Group, the Niedersachsen Group, the Rijnland Group and the Chalk Group (fig. 4.2).

4.1.1 Z1 (Werra) Formation

The Z1 (Werra) Formation is composed of the Coppershale, Z1 Carbonate and Z1 Anhydrite Members. This formation has a fairly constant thickness of approximately 35 m in the map sheet area.

The *Coppershale Member* is an approximately 1 m thick black shale rich in organic material, lying at the base of the Zechstein Group and occurring virtually throughout the Southern Permian Basin. The Coppershale Member is distinguishable by its characteristic peak on gamma-ray logs caused by a high content of radioactive minerals (fig. 4.1).

The *Z1 Carbonate Member* is a grey-brown, dolomitic limestone approximately 10 m thick. The lower part of this unit contains some clay and anhydrite and demonstrates upwards-decreasing.

The *Z1 Anhydrite Member* is a usually 20 to 25 m thick unit consisting of anhydrite with some dolomite stringers.

4.1.2 Z2 (Stassfurt) Formation

The Z2 Formation is composed of the Z2 Carbonate, Z2 Basal Anhydrite, Z2 Salt and Z2 Roof Anhydrite Members. The Z2 Formation comprises a nearly complete evaporite cycle.

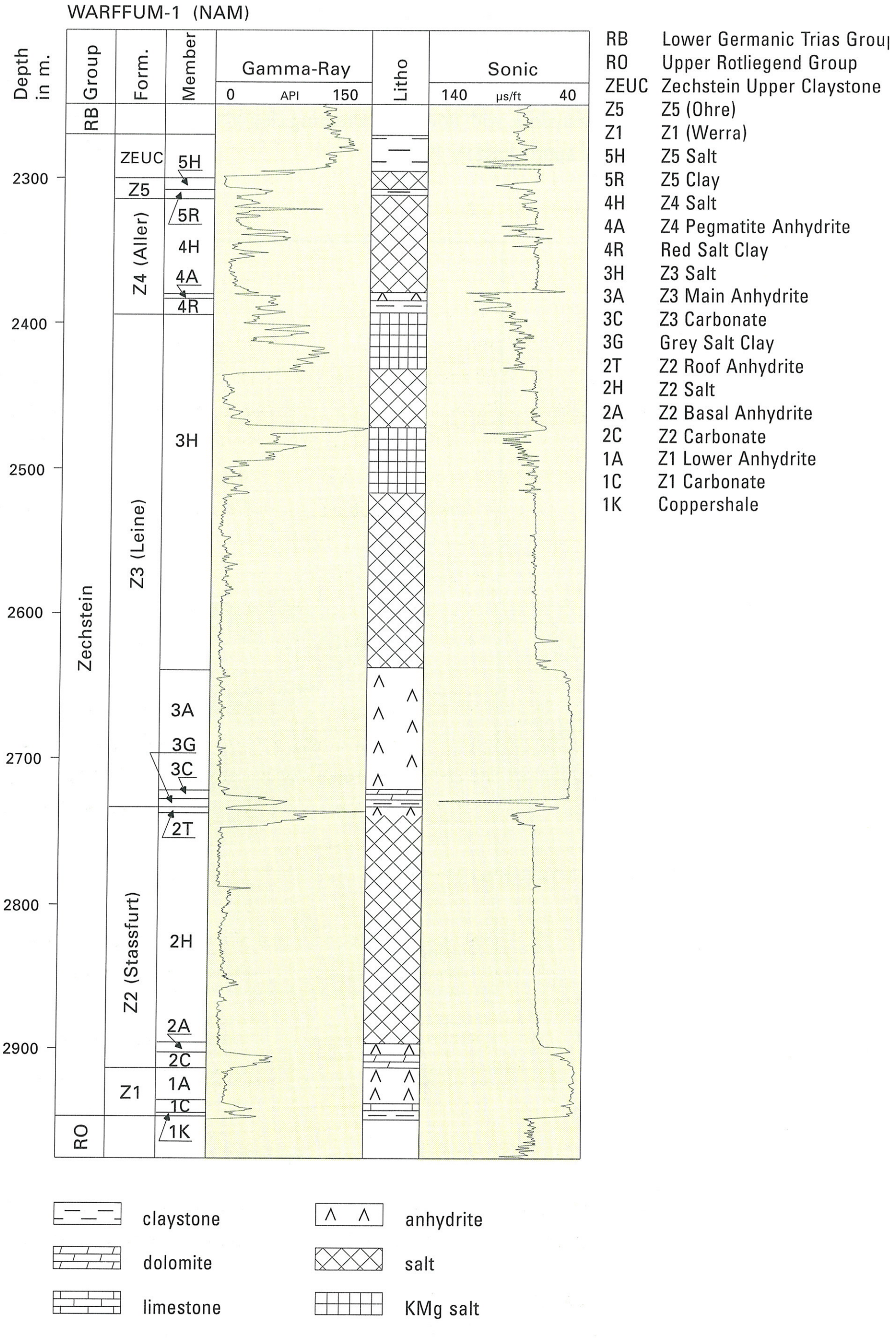
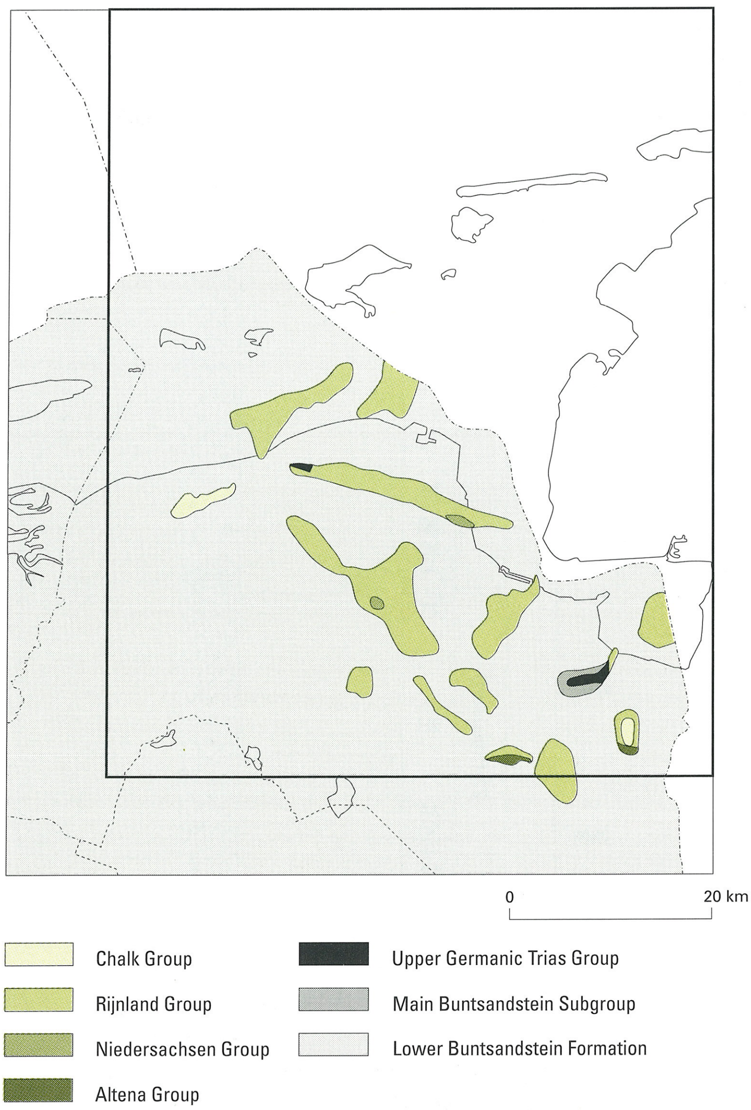


Figure 4.1 Lithological succession of the Zechstein Group with accompanying log pattern in the Warffum-1 well. The Z2 Salt Member is subdivided into three salt cycles by thin polyhalite-bearing anhydrite interbeds (visible as peaks on the gamma-ray log). In the topmost part of the Z3 Salt, three thick (up to 30 m) magnesium salt successions can be distinguished by the high radioactivity (gamma-ray log) and by the low acoustic velocity (sonic log).

The present variation in thickness in the Z2 Formation is the consequence of halokinesis, but the original depositional thickness of this formation in the map sheet area is likely to have been fairly constant. This may be inferred from the uniform thickness of the rigid Z2 Carbonate member which exhibits only a minor difference in depositional thickness between the Groningen High and the Lauwerszee Trough and from the fact that the Z2 Roof Anhydrite and the Grey Salt Clay (Z3) are found above the Z2 Salt throughout the area. This indicates that during deposition of the Z2 Salt little or no relief developed in the basins. The maximum present-day thickness of the Z2 Formation is found in the Pieterburen salt-structure with 2700 m of halokinetically disrupted Zechstein sediment. In depletion areas where the Z2 Salt has completely disappeared as a result of salt flow, only about 15 m of Z2 Carbonate and Anhydrite remain.

The *Z2 Carbonate Member* consists of a dark, fine-laminated alternation of limestone, dolomite and Anhydrite, with upwards-increasing clay content. The Z2 Carbonate Member has an average thickness of approximately 10 m.

Figure 4.2 Areal distribution of the lithological units overlying the Zechstein Group. Except for the areas where salt accumulations are found, the Zechstein Group is conformably overlain by the Lower Germanic Trias Group. Above salt accumulations, the Zechstein Group may be unconformably overlain by younger groups.



The *Z2 Basal Anhydrite Member* is 2 to 5 m thick and is composed of a white to beige coloured anhydrite.

The *Z2 Salt Member* is white to translucent, generally coarse and sometimes finely crystalline. Three salt cycles can be distinguished within the Z2 Salt Member, separated from each other by thin polyhalite-bearing ($Ca_2K_2Mg(SO_4)_4.2H_2O$) anhydrite interbeds. These beds can be differentiated from the pure rock salt by the higher gamma radiation and lower velocity as registered on the gamma-ray logs and the sonic logs. This triple unit can be correlated in the North-Netherlands and on the adjacent Continental Shelf (Geluk, 1995). In the map sheet area the polyhalite beds are locally absent as a result of halokinesis. In figure 4.1. only the uppermost salt cycle can be differentiated from the middle salt cycle. The salt cycles consist of extremely pure rock salt with, at the top of the Z2 Salt Member only, a 5 m thick layer of potassium/magnesium salt forming the equivalent of the 'Kaliflöz Stassfurt' which occurs at the same stratigraphic level in Germany (Kulick & Paul, 1987).

The great variation in thickness in the Z2 Salt Member is due to tilting and salt flow, and the greatest thickness within the map sheet area is reached in the Winschoten salt-structure (2200 m). The pure rock salt (97-99% pure NaCl) is exploited by solution mining in the production locations of Zuid-wending and Winschoten situated in the 'Adolph van Nassau' concession.

The Z2 (Stassfurt) Formation ends with the *Z2 Roof Anhydrite Member*, a pure anhydrite, a maximum of a few metres thick.

4.1.3 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 Z3 *(Leine)* Formation is conformably overlain by the Z4 (Aller) Formation in most of the area but halokinesis or erosion has also brought about an unconformable contact with the Lower Germanic Trias Group or the Rijnland Group.

The *Grey Salt Clay Member* consists of 2 to 3 m thick grey claystone, which gives a higher reading on the gamma-ray log compared with the underlying Z2 Anhydrite and the overlying Z3 Carbonate Members (fig. 4.1).

The *Z3 Carbonate Member* (or Platy Dolomite), varying from 15 m to 30 m in thickness, is composed of a finely crystalline, beige to light-brown dolomite and can be clearly identified throughout the area.

The *Z3 Main Anhydrite Member* consists of white anhydrite, with carbonate interbeds and claystone beds in the bottommost part. The variation in thickness from 15 to 80 m within the map sheet area may be attributed not only to a primary sedimentary difference in thickness but also to tilting in response to salt flow, with the result that the drilled thickness appears to be greater than the actual thickness.

The *Z3 Salt Member* can be subdivided into 2 units consisting of a thick succession of massive rock salt on the base grading into a succession consisting of magnesium salt and potassium salt and a few small claystone beds. In figure 4.1 the basal pure rock-salt unit is approximately 110 m thick. The second succession consists of K-Mg salt, a succession of moderately pure rock salt again overlain by K-Mg salts with intercalated claystone layers. This subdivision can be correlated throughout the area.

The rock salt is translucent white or pink to yellow and varies from 98% pure NaCl to rock salt with thin anhydrite layers and potassium-magnesium salt interbeds. The potassium-magnesium salts consist mainly of carnallite ($KCl.MgCl_2+6H_2O$) completed by halite (NaCl) and kieserite ($MgSO_4+H_2O$). In the bottommost succession the rarely occurring magnesium salt bischofite ($MgCl_2+6H_2O$) is also encountered. At the base of a magnesium salt interval sylvite (KCl) and langbeinite ($K_2Mg_2(SO_4)_3$) are found. In the Veendam salt-structure, situated just to the south of the map sheet area, differential salt flow caused thickening of the potassium-magnesium-bearing salt member, thus bringing it to an exploitable depth (1500-2000 m). The valuable magnesium-bearing salt is exploited by means of solution mining (Coelewij et al., 1978). Exploitation is carried out by NedMag Industries (formerly the Noordelijke Zoutwinning BV) for the production of magnesium oxide.

4.1.4 Z4 (Aller) Formation

The Z4 (Aller) Formation was originally deposited throughout the area. The formation is no longer found above salt structures, having been removed by salt-flow related erosion. The formation consists of the *Red Salt Clay Member, a maximum of 7 m thick, the 1 to 4 m thick Z4 Pegmatite-Anhydrite Member* and the locally 80 m thick *Z4 Salt Member.* Despite the occasional strong deformation of the underlying Zechstein member, this succession can be fairly well correlated.

The Z4 Salt Member can be divided into two sequences, representing an increasing and decreasing salinity respectively. The first-mentioned sequence comprises a 40 to 50 m thick salt succession containing two beds, with an increased potassium-magnesium content, of 10 and 15 m thick respectively. The second-mentioned succession comprises an alternation of salt and claystone and forms the top of the Z4 Formation. This succession is 20-40 m thick. The drilled thickness of the Z4 Salt Member varies from a few metres to approximately 80 m. The member is the thickest in the area beyond the limits of the Groningen High and locally between (minor) salt accumulations on the Groningen High.

The Z4 (Aller) Formation is conformably overlain by the Z5 (Ohre) Formation or, possibly via a hiatus, by the Zechstein Upper-Claystone Formation. Diapirism causes the formation above salt structures to be overlain by younger deposits.

4.1.5 Z5 (Ohre) Formation

This formation represents the youngest evaporite cycle in The Netherlands. The formation is present on the western half of the Groningen High with prolongations towards the Rottumerplaat.

The Z5 (Ohre) Formation consists of an approximately 5 m thick basal claystone covered by a rock salt deposit which is a maximum of 15 m thick (fig. 4.1). The rock salt deposit thickens towards the south and east.

4.1.6 Zechstein Upper Claystone Formation

The Zechstein Upper-Claystone Formation is an anhydrite claystone sequence between the topmost identifiable evaporite cycle Z5 (Ohre) or Z4 (Aller) Formation and the base of the Lower Germanic Trias Group. On the base, the formation usually displays a hiatus. The claystones of the Zechstein Upper-Claystone Formation are characterised by low acoustic velocities. The base consists of a thin clay bed (1 m) beneath a small anhydrite bed (approximately 2 m) which is identifiable on the logs by the extremely low gamma-ray readings. These bottommost 3 m may represent the basin fringe deposits of a higher Zechstein cycle. The top of the succession is formed by a 10 to 15 m thick anhydritical claystone, slightly thickening towards the east and the south as in the case of the halite deposition of the Z5 (Ohre) Formation.

4.1.7 Zechstein salt

Zechstein salt is the name given to the halokinetically disturbed sequence above the Z2 Basal Anhydrite Member, in which the depositional cycles Z2 to Z4 Salt cannot be recognised any more.

4.1.8 Zechstein caprock

The Zechstein caprock is an interval consisting of anhydritical gypsum or gypsum-bearing anhydrite and occurs above salt structures which have at some stage been situated just below ground level. Subrosion, the subterranean dissolving of salt layers by percolating groundwaters, has caused an insoluble residue to be formed consisting of the less soluble salts and sulphates. The variable thickness of this succession is related to factors such as depth and geohydrological conditions.
The caprock is 33 m thick in the Winschoten salt-structure and 100 m thick in the less deeply situated Pieterburen salt-structure.

4.2 Sedimentary development and palaeogeography

When the Zechstein Group was deposited, the map sheet area was part of the Southern Permian Basin, as it was when the Upper Rotliegend Group was deposited (fig. 3.4). At the beginning of the Late Permian a rapid transgression took place in the depression which was formed during the Early Permian (Glennie & Buller, 1983). Thick successive cycles of evaporites precipitated during prevailing arid climate conditions, facilitated by the shape of the basin and the periodic influx of fresh seawater.

In the Zechstein Group the 5 evaporite cycles represent a succession of transgressions and regressions. During transgressive periods, clays and carbonates were deposited when lower saline conditions prevailed. Arid climate conditions increased the salinity during regressive periods, resulting in evaporite deposits. The sea-level fluctuations are presumed to be related to the alternation of Late Permian glacials and interglacials (Ziegler, 1988).

The first sedimentary cycle of the Zechstein Group began with a transgression while deposition of the Coppershale occurred in an anoxic environment in a basin with a restricted water circulation (Taylor, 1986). The carbonates were formed in an open marine environment under normal saline conditions. Withdrawal of the sea and the increasing isolation of the basin caused a rapid increase in salinity, partly because of the high rate of evaporation under the prevailing arid conditions. Sulphates were the first to precipitate from the brine formed in this manner, initially in the form of gypsum, which turns into anhydrite after dehydration. The lower water level led to precipitation of these sulphates in a more restricted area than the carbonates. The carbonates interbedded in the anhydrite indicate fluctuations in the quantity of inflowing seawater. During deposition of the Z1 (Werra) Formation only a non-complete evaporation of the seawater column took place, restricting the salinity, thus impeding deposition of rock salt except at a few places along the margin of the Southern Permian Basin.

The Z2 (Stassfurt) Formation reflects a complete evaporite cycle. Carbonate and anhydrite deposition was followed by the deposition of rock salt (halite), which precipitates when the body of sea water has dried up to one tenth of the original volume. If the influx of fresh sea water keeps pace with its evaporation, the concentration of the salts remains constant and the precipitation of halite will continue. The different rock salt sequences within the Z2 Salt are separated by polyhalite beds. Polyhalite ($Ca_2K_2Mg(SO_4)_4.2H_2O$) is a salt which is precipitated whenever brine saturated with polyhalite or $MgSO_4$ and KSO_4 mixes with $CaSO_4$-rich sea water (Braitsch, 1971). The rhythmical alternation of polyhalite with rock salt is an indication of a cyclical fluctuation of inflowing fresh sea water (Geluk, 1995). The extremely pure rock salt in the uppermost salt sequence of the Z2 Salt might be an indication of redeposited salt. The potassium-magnesium salts precipitated in the basin during periods of supersaturation of the brine.

The third sedimentary cycle is characterised by a major transgression, which caused a drop in salinity of the brine present in the basin to a normal seawater value, subsequently followed by a new evaporite cycle leading to the deposits of the Z3 (Leine) Formation.

The hypersaline character (no deposition of carbonates occurred), the increasing prominence of claystones and the sparser distribution of the Z4 (Aller) and Z5 (Ohre) Formations, point to emergence of the Southern Permian Basin. The deposits of these 2 latter formations levelled much of the remaining relief, which accounts for the uniform thickness of the Zechstein Upper-Claystone Formation, deposited in the fringe area under playa-like conditions. This formation is indicative of a clear transition between the marine salt succession and the continental sand/clay successions of the Lower Germanic Trias Group.

The differences in thickness particularly in the Z4 (Aller) and Z5 (Ohre) Formations and the presaline substratum formed by the Z1 (Werra) Formation, Z2 Carbonate and Z2 Basal Anhydrite Members, reflect the palaeorelief and differential subsidence. These thickness differences, although minimal, point to the presence of small basins and shallows in this area during the Late Permian. The thinnest deposits are in an area that broadly coincides with the northeastern part of the Groningen High. Furthermore, the Z5 (Ohre) Formation is absent here, possibly owing to non-deposition or erosion.

5 Lower and Upper Germanic Trias Group

5.1 Stratigraphy

The Triassic deposits, Late Permian to Late Triassic, consist of red and green coloured clastics, grey coloured carbonates as well as marls and evaporites. Within the Triassic deposits, a Lower and Upper Germanic Trias Groups can be distinguished.

Whereas the Lower Germanic Group is found throughout the map sheet area, the Upper Germanic Trias Group is restricted to the Lauwerszee Trough and the Ems Low. Both groups have undergone considerable erosion (fig. 5.1). The first erosional phase, related to the formation of the Netherlands Swell (fig. 5.2), set in at the end of the Early Triassic and resulted in an unconformable contact between the two groups. The degree of truncation shows that the relief of the Netherlands Swell was slight. Post-Triassic erosion, related to the Kimmerian deformation phases, cut deep down into the Upper Germanic Trias Group, even reaching as far as deep into the Lower Germanic Trias Group on the Groningen High. In the area of subsidence, a large part of the Upper Germanic Trias Group has been preserved, and is even almost complete in the Ems Low.

The thickness of the total Triassic succession ranges from around 200 m on the Groningen High to over 1800 m in the Ems Low (Map 6). The base of the Triassic deposits is at a depth of around 2000 metres on the Groningen High, increasing to over 3500 m both in the Lauwerszee Trough and in the Ems Low (Map 5). Extreme local changes in thickness and depth have been brought about by salt flow.

The stratigraphic composition of the Triassic deposits is illustrated by the Goldhoorn-1 well (fig. 5.3).

5.2 Lower Germanic Trias Group

5.2.1 Stratigraphy

The Lower Germanic Trias Group, latest Permian to Scythian in age, is composed of the Lower Buntsandstein Formation - consisting predominantly of claystone - and the Main Buntsandstein Subgroup, which comprises an alternation of sandstone and claystone (fig. 5.3). The clastic sediments were deposited under continental conditions, and have a characteristic red colour.

The Lower Germanic Trias Group is found in the greater part of the map sheet area and is only absent above some of the salt culminations (Map 6) on the Groningen High. The thickness of the complete group increases in an easterly direction from approximately 350 to 450 m.

The Lower Germanic Trias Group rests conformably upon the Zechstein Group, though with a rather abrupt change in facies. On the upper surface it is unconformably overlain by different lithological units: in the west, south and east the Upper Germanic Trias Group. The part of the map sheet area which roughly coincides with the Groningen High is unconformably overlain by the Early Cretaceous sediments of the Rijnland Group (fig. 1.8).

5.2.2 Lower Buntsandstein Formation

The Lower Buntsandstein Formation is composed of the Main Claystone and Rogenstein Members (fig. 5.1). The present extent of the formation corresponds to the areal extent of the Lower Germanic Trias Group (fig. 5.2). Where the formation is complete, the maximum thickness is approximately 365 m.

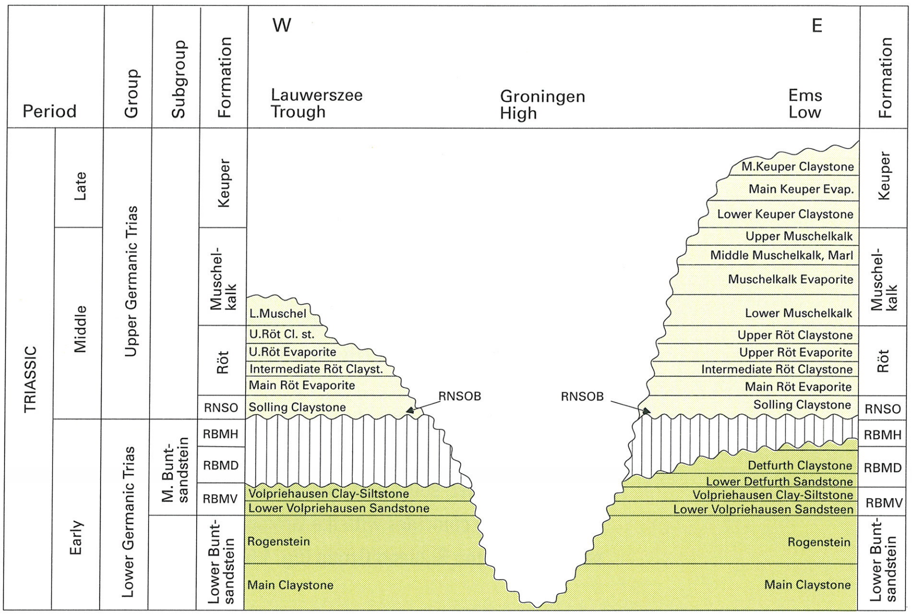
The Lower Buntsandstein Formation is overlain conformably by the Main Buntsandstein Subgroup, or unconformably by the Solling Formation or the Rijnland Group.

The *Main Claystone Member* is composed of a cyclical succession of fining-upwards claystone/siltstone sequences, with thin fine-grained sandstone beds at the base. The rocks are locally anhydritical and are predominantly reddish-brown, or sometimes alternating green and dark grey. The cyclical repetition is well traceable on the acoustic velocity log (fig. 5.3), and is regionally extremely easy to correlate. The development within the map sheet area shows a remarkable analogy with that in North Holland and Northwest Germany (Brüning, 1986; Geluk & Röhling, in prep). The thickness of the Main Claystone Member, where complete, is around 190 m.

The *Rogenstein Member* consists of red and green coloured finely laminated claystones and siltstones with many black and white layers of mica and oolites. Anhydrite nodules may occur in the claystones in places. The oolite layers give the Rogenstein Member a characteristic log reading (fig. 5.3).
The calcareous oolite layers have low gamma-ray values, high density and high acoustic velocity.
The oolites are cemented grainstones, with ooliths up to a few millimetres in size. The base of the Rogenstein Member has been placed at the first oolite layer which is clearly identifiable throughout the map sheet area. The first 75 m, which contains a few thin oolite layers, is succeeded by three conspicuous oolite layers, which can also be traced throughout the map sheet area.

The Rogenstein Member is probably the thickest at the centre of the Lauwerszee Trough.
The Rogenstein Member in the southwest of the map sheet area is 170 m thick, whereas in the north

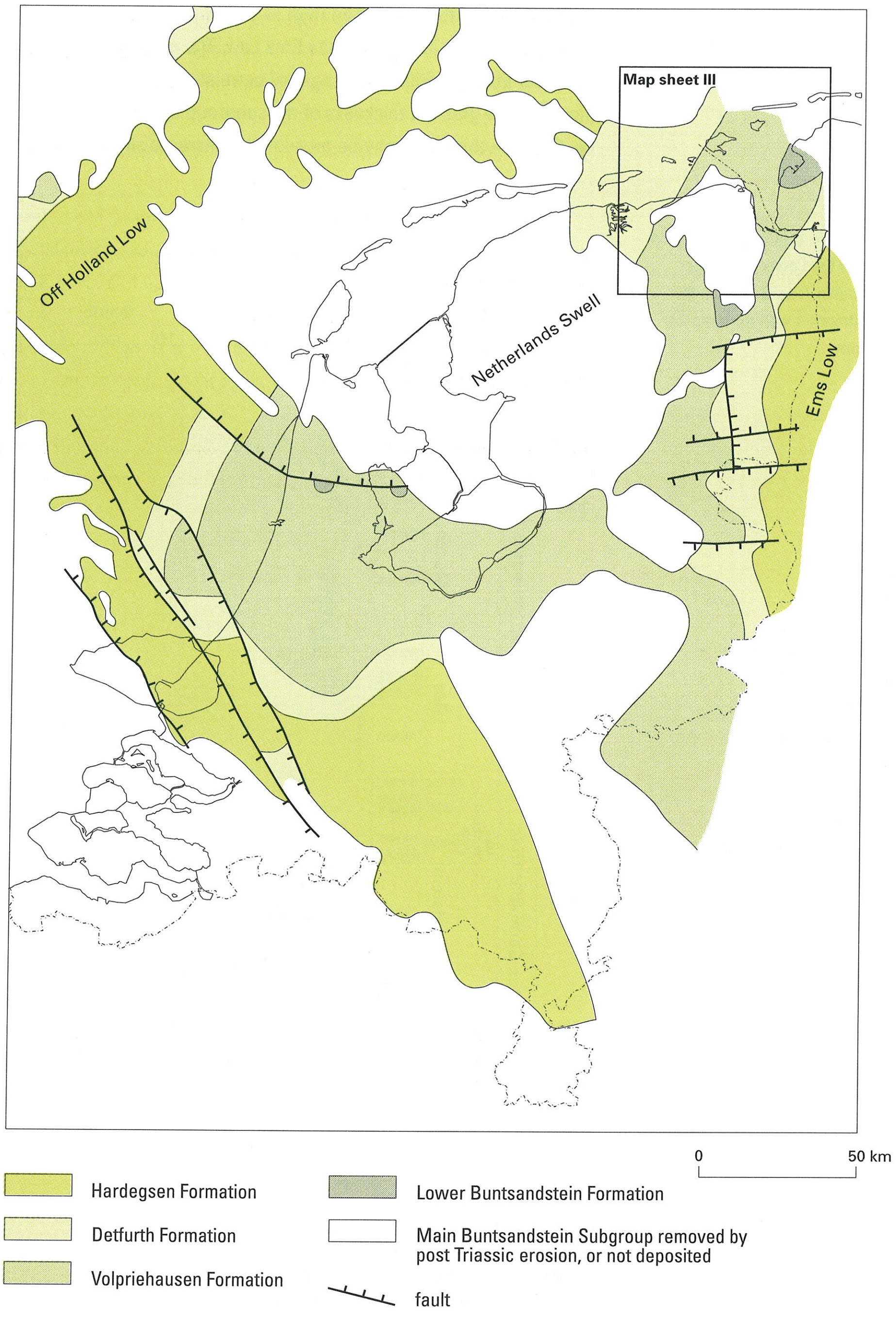
Figure 5.1 Schematic stratigraphic diagram of the Lower and Upper Germanic Trias Groups. The hiatus, indicated by vertical hatching, at the end of the Early Triassic, is due to the Hardegsen deformation phase. Kimmerian movements at the end of the Jurassic are reflected in the varying degree of erosion in the Lauwerszee Trough, on the Groningen High and in the Ems Low.



RNSO Solling Formation
RBMH Hardegsen Formation
RBMD Detfurth Formation
RBMV Volpriehausen Formation
RNSOB Basal Solling Sandstone Member

Hiates related to Base Solling Unconformity and northeast the thickness is approximately 140 m. This variation could point to an erosive contact with the overlying Lower Volpriehausen Sandstone Member. In places the Rogenstein Member may well be unconformably overlain by the Basal Solling Sandstone of the Upper Germanic Trias Group. The Rogenstein Member is often incomplete or absent on the Groningen High owing to subsequent erosion.

Figure 5.2 Subcrop map of the Base Solling unconformity. The extent of the Netherlands Swell is apparent from the erosion outline. The map sheet area is situated in the north of the Netherlands Swell (Van Adrichem Boogaert & Kouwe, 1993-1995).



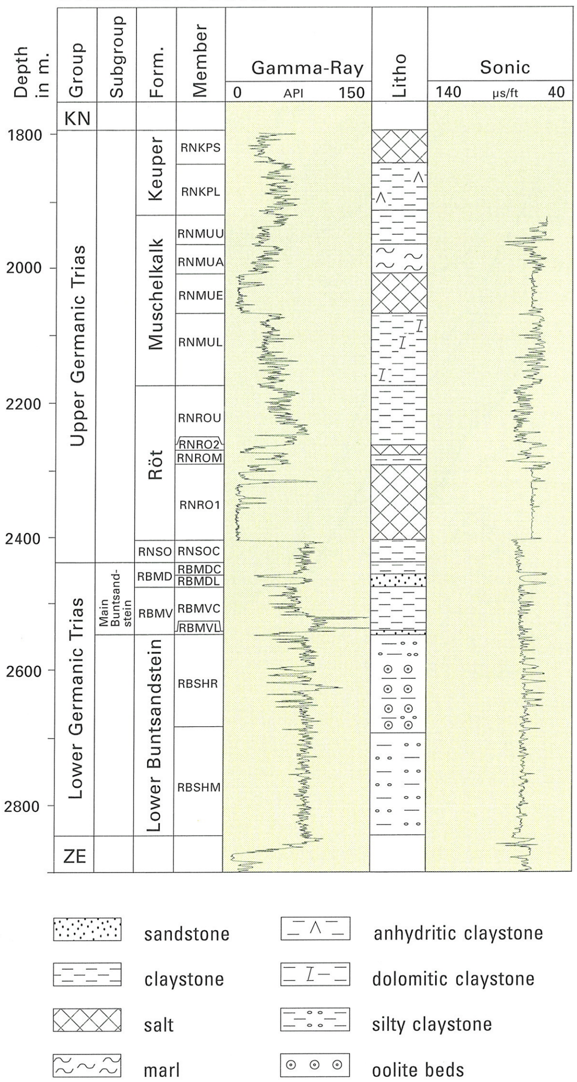
5.2.3 Main Buntsandstein Subgroup

The Main Buntsandstein Subgroup consists of three sandstone/claystone cycles: going up, these are the Volpriehausen, the Detfurth and the Hardegsen Formations.

The subgroup was deposited throughout the map sheet area but because of subsequent erosion it has been entirely removed from the Groningen High. The Main Buntsandstein Subgroup is now restricted to the margin of the Groningen High in a few synclines formed as a result of salt depletion as well as to the Lauwerszee Trough and the Ems Low. The Hardegsen Formation in the map sheet area has not been identified by drilling but regional correlations indicate its occurrence in the extreme southeast (fig. 5.2). The greatest thickness of the subgroup observed in boreholes is 107 m (Goldhoorn-1, fig. 5.3). The thickness may be presumed to increase slightly in an easterly direction.

Figure 5.3 Stratigraphic subdivision of the Lower and Upper Germanic Trias Groups in the Goldhoorn-1 well from the log pattern.

GOLDHOORN-1 (NAM)



KN	Rijnland Group
ZE	Zechstein Group
RNSO	Solling Formation
RBMD	Detfurth Formation
RBMV	Volpriehausen Formation
RNKPS	Main Keuper Evaporite
RNKPL	Lower Keuper Claystone
RNMUU	Upper Muschelkalk
RNMUA	Middle Muschelkalk Marl
RNMUE	Muschelkalk Evaporite
RNMUL	Lower Muschelkalk
RNROU	Upper Röt Claystone
RNRO2	Upper Röt Evaporite
RNROM	Intermediate Röt Claystone
RNRO1	Main Röt Evaporite
RNSOC	Solling Claystone
RBMDC	Detfurth Claystone
RBMDL	Lower Detfurth Sandstone
RBMVC	Volpriehausen Clay Siltstone
RBMVL	Lower Volpriehausen Sandstone
RBSHR	Rogenstein
RBSHM	Main Claystone

The Main Buntsandstein Subgroup rests conformably upon the Lower Buntsandstein Formation, and is unconformably overlain by the Upper Germanic Trias Group or the Rijnland Group.

5.2.3a Volpriehausen Formation

The Volpriehausen Formation comprises the Lower Volpriehausen Sandstone Member and the Volpriehausen Clay-Siltstone Member.

The *Lower Volpriehausen Sandstone Member* forms the base of the formation (fig. 5.1) and consists of reddish-brown and grey-green, sometimes argillaceous, sandstone layers (anhydrite-bearing in places) with interbedded reddish-brown claystone. The sandstones are poorly consolidated and moderately sorted. The member is approximately 8 m thick. The lower and upper boundaries of the unit are characterised by abrupt transitions (fig. 5.3).

The *Volpriehausen Clay-Siltstone Member* consists of alternating soft reddish-brown and green to grey, marly clay, claystone and anhydrite siltstone with thin sandy horizons and anhydrite nodules. The sand content increases upwardly, making the upper boundary difficult to define. To the east of the Groningen High the member reaches a maximum thickness of approximately 70 m but in the remainder of the map sheet area the thickness is drastically reduced or the member has been completely eroded away. The Volpriehausen Clay-Siltstone Member is unconformably overlain by the Detfurth Formation, the Solling Formation or the Rijnland Group.

5.2.3b Detfurth Formation

Within the map sheet area, the Detfurth Formation is composed of the Lower Detfurth Sandstone and the Detfurth Claystone Members. The *Detfurth Sandstone Member* comprises two distinct sandstone units with an intercalated layer of reddish-brown, anhydritical siltstone or silty claystone. The *Detfurth Claystone Member* is a unit of homogeneous, occasionally somewhat silty, anhydrite-rich claystones. The Detfurth Claystone Member is conformably overlain by the Hardegsen Formation or unconformably by the Solling Formation or the Rijnland Group. The Detfurth Formation is 30-35 m thick.

5.2.3c Hardegsen Formation

The Hardegsen Formation consists of a regular alternation of beige to pink sandstone and red claystone. The member rests conformably on the Detfurth Formation and is unconformably overlain by the Solling Formation. The formation has not been encountered in wells in the map sheet area and is only present in the extreme southeast of the map sheet (fig. 5.3).

5.3 Upper Germanic Trias Group

5.3.1 Stratigraphy

With the exception of the Basal Solling Sandstone Member, the Upper Germanic Trias Group is composed of clay/siltstones, evaporites, marls and limestones. The group can be subdivided into the Solling, Röt, Muschelkalk and Keuper Formations (fig. 5.1).

Deposits of the Upper Germanic Trias Group, of latest Scythian to Norian age, are found around the perimeter of the Groningen High but have been removed from the top of the Groningen High owing to subsequent erosion (fig. 1.8 & 5.1). The thickest Upper Germanic Trias Group deposits occur in the area to the east of the Groningen High in the Ems Low, in which are located two rim synclines resulting from the salt withdrawal to the salt structures of Winschoten and Klein-Ulsda. This is the site of the Goldhoorn-1 well shown in figure 5.2, where the maximum thickness exceeds 650 m. In the extreme southeast of the map sheet area the group reaches its greatest thickness, 1400 m.

Separated by the Base Solling unconformity, the Upper Germanic Trias Group rests unconformably upon the Lower Germanic Trias Group. Figure 5.3 indicates which formations are covered by the Upper Germanic Trias Group which, towards the Netherlands Swell, rests unconformably on increasingly lower units of the Triassic succession. In most of the map sheet area the Upper Germanic Trias Group is unconformably overlain by the Rijnland Group, but unconformably by the Altena Group in the extreme southeast by the Altena Group.

5.3.2 Solling Formation

The Solling Formation consists of a claystone with anhydrite intercalations and a thin basal sandstone. (fig. 5.3). It is subdivided into the Basal Solling Sandstone and Solling Claystone Members.

The *Basal Solling Sandstone Member* consists of a fine-grained, sometimes anhydritical sandstone with limestone, dolomite and reddish-brown to grey-green siltstone intercalations. This sandstone is slightly more cemented than the underlying sandstone members, displaying high resistivity and higher acoustic velocity readings on well logs. However, to the west of the Groningen High the Basal Solling Sandstone Member is difficult to distinguish from the sandy top of the Volpriehausen Clay-Siltstone Member or the top of the Rogenstein Member. It is unclear whether the member was deposited widespread. The sandstone has been reached by drilling to the east of the Groningen High and identified in the wells outside the map sheet area in the southern part of the Lauwerszee Trough. The sandstone varies in thickness from 3 to 10 m.

The *Solling Claystone Member* is composed of grey-green and red claystone, which is sometimes marly and anhydritical and has thin siltstone, limestone and dolomite intercalations. As in the Basal Solling Sandstone Member, the Solling Claystone Member is present in the Lauwerszee Trough and the Ems Low, with a thickness of approximately 40 m in the Ems Low.

5.3.3 Röt Formation

The Röt Formation, of latest Scythian to Early Anisian age, consists of four Members: the Main Röt Evaporite, the Intermediate Röt Claystone, the Upper Röt Evaporite and the Upper Röt Claystone.
The Röt Formation occurs around the perimeter of the Groningen High throughout the areal extent of the Upper Germanic Trias Group. The maximum thickness of the formation, over 200 m, is found to the east of the Groningen High.

The Röt Formation rests conformably on the Solling Formation. In the surroundings of salt accumulations, the Röt Formation may rest directly upon the Lower Buntsandstein Formation or even on the Zechstein Group, which are indicative of very early salt flows (see also chapter 11.3).

The *Main Röt Evaporite Member* consists of a thin basal anhydrite (approximately 2 m) and a rock salt unit sealed with a 10 to 15 m thick anhydritical claystone member with rock salt intercalations.
The thick rock salt succession (50 to 100 m) contains a few intercalations of clay and anhydrite.
The transition from the Solling Claystone Member to the Main Röt Evaporite Member is sharp and well identifiable on logs. The Main Röt Evaporite Member is 65 to 113 m thick, with local thickness

variations near large salt accumulations as a result of early Zechstein or Röt salt flows. In several places in the map sheet area the Main Röt Evaporite Member has been plastically deformed, resulting in clear collapse structures in the overlying member.

The *Intermediate Röt Claystone Member*, approximately 15 m thick, is a reddish-brown, silty, anhydritical claystone which may sometimes be calcareous. The claystone is an intercalation in an evaporitic succession.

The *Upper Röt Evaporite Member*, an average of 7 m thick, consists of a thin, argillaceous anhydrite bed with occasional rock salt intercalations and is comparable to the top 15 m of the Main Röt Evaporite Member.

The *Upper Röt Claystone Member* comprises a reddish-brown to violet coloured claystone.
The bottommost layer of the succession is anhydritical while the topmost part reveals an increasing carbonate content (fig. 5.3). The transition to the Muschelkalk Formation is gradual. The average thickness of this succession is 60 m, with a maximum of 88 m in the Goldhoorn-1 well (fig. 5.3).

5.3.4 Muschelkalk Formation

The Muschelkalk Formation, of Middle Anisian to Early Ladinian age and a maximum thickness in excess of 300 m (in the extreme southeast), consists of a limestone and marl alternation with an evaporite intercalation. In the map sheet area the formation is subdivided into the Lower Muschelkalk, Muschelkalk Evaporite, Middle Muschelkalk Marl and Upper Muschelkalk Members (fig. 5.3). The Muschelkalk Formation is found only in a small area to the southeast of the Groningen High in the Ems Low, but the considerable thickness of the Triassic deposits in the northern part of the Lauwerszee Trough, 500 to 800 m (Map 6), indicates the likely presence of one or more members of the Muschelkalk Formation.

The formation rests conformably upon the Röt Formation and is conformably overlain by the Keuper Formation. Where erosion of the Keuper Formation has occurred, the Muschelkalk Formation is unconformably overlain by the Rijnland Group.

The *Lower Muschelkalk Member*, with an average thickness of 105 m, consists mainly of grey marls and (calcareous) claystone which may be reddish-brown and anhydritical in places. Limestone and dolomite intercalations are also found.

The *Muschelkalk Evaporite Member* (in the Meeden-1 well) consists of an alternation of anhydrite and claystone with, at the top, a 15 m thick rock salt succession which becomes thicker towards the Ems Low. In the Goldhoorn-1 well the Muschelkalk Evaporite Member mainly comprises rock salt with a few thin anhydrite and claystone intercalations (fig. 5.3). The total thickness of this evaporite unit is 57 m in the Goldhoorn-1 well and 42 m in Meeden-1.

The *Middle Muschelkalk Marl Member* is a light to dark grey marl, reddish-brown in places, containing siltstone, claystone and dolomite intercalations. At the base, the marl is anhydritical, with traces of pyrite. In the Goldhoorn-1 well the Middle Muschelkalk Marl Member is 44 m thick (fig. 5.3).

The *Upper Muschelkalk Member* consists of reddish-brown and light grey dolomite, dolomitic shale and marl. The Upper Muschelkalk Member is separated from the Middle Muschelkalk Marl Member by an approximately 5 m thick basal dolomite bed which can be identified by a slightly lower reading on the gamma-ray log and an extremely high acoustic velocity. The unit has been encountered in Meeden-1 and in Goldhoorn-1, where the thickness reaches 43 m (fig. 5.3).

5.3.5 Keuper Formation

In the map sheet area the Keuper Formation, of Late Ladinian to Carnian age, consists of silty calcareous claystones with interbedded anhydrite/dolomite beds and rock-salt beds. The Keuper Formation can be subdivided into the Lower Keuper Claystone, Main Keuper Evaporite, Red Keuper Claystone, Dolomitic Keuper and Upper Keuper Claystone Members. At the base of the Red Keuper Claystone Member, the prominent Early Kimmerian unconformity is situated, present here as an intraformational unconformity (fig. 5.1). The Keuper Formation rests conformably on the Muschelkalk Formation and is conformably overlain by the Altena Group or unconformably by the Rijnland Group. It is probable that the formation only occurs to the southeast of the Groningen High and directly to the west of the Winschoten salt-structure. The Keuper Formation has only been found in two wells, namely Meeden-1 and Goldhoorn-1. The topmost members are absent in the Goldhoorn-1 well (fig. 5.3).

In the extreme southeast of the map sheet area the Keuper Formation achieves its greatest thickness, probably over 700 m. As the formation has not been reached here, the lithological succession has not been proven but is assumed to comprise several salt members.

The *Lower Keuper Claystone Member* is composed of greenish-grey to reddish-brown calcareous claystone which is anhydritical in places and contains siltstone and dolomite intercalations. The Lower Keuper Claystone Member is difficult to distinguish from the Upper Muschelkalk Member, but the maximum gamma-ray response in the Lower Keuper Claystone Member is slightly higher than in the Upper Muschelkalk Member and the acoustic velocity is slightly lower. The thickness in the Goldhoorn-1 well is 80 m (fig. 5.3).

The *Main Keuper Evaporite Member*, approximately 70 m thick, has a comparable lithology to that of the Lower Keuper Claystone Member but a slightly higher anhydrite content and is shaly at the top. These strata form the equivalent of the rock-salt succession which was deposited in the south of the map sheet area.

The *Red Keuper Claystone Member*, approximately 20 m thick, comprises variegated claystone.

The *Dolomitic Keuper Member*, up to 35 m thick, is composed of alternating light coloured limestone, dolomite and claystone beds.

The *Upper Keuper Claystone Member* consists of an over 10 m thick brown to grey silt/claystone.

5.4 Sedimentary development and palaeogeography

The incipient influx of clastics at the end of the Late Permian was prolonged in the Triassic.
The absence of the anhydritical intercalations, still frequently found in the topmost Zechstein deposits, marks the beginning of the Triassic deposits. The Southern Permian Basin (fig. 11.1) continued to exist as such during the Triassic. In this basin, also known as the Permo-Triassic Basin, a regression was effective at the end of the Permian, resulting in a setting where predominantly terrestrial, lacustrine deposits prevail. These deposits were strongly influenced by sea-level fluctuations, displaying a variety of sequences. The sequences exhibit a tendency towards a rising sea level, reaching a

maximum during the deposits of the marine carbonates demonstrated by the Muschelkalk. Subsequently, this period is followed by a new regressive phase. The fluctuations in the groundwater table are presumed to be related to eustatic sea-level fluctuations, as published by Haq et al. (1987). As well as changes in the water table, climate changes and tectonic activity in the hinterland also has an impact on diversity and extent of the sandstones and claystones.

The Lower Buntsandstein Formation is of uniform lithology and thickness throughout the area, indicating deposition in an extremely vast plain. In view of the terrestrial character of the deposits, the good correlatable properties in the region and the fine-grained composition, the sedimentation probably occurred in a lacustrine setting. The oolites in the Rogenstein Member were formed in brackish calcareous water during periods of low clastic influx and prominent current regime (Peryt, 1975; Brüning, 1986). The alternation of green and red staining is an indication of alternating redox conditions, pointing to a fluctuating water table.

From the uniformity of the Main Claystone Member it may be concluded that at the beginning of the Early Triassic the Groningen High had no significance as a separate tectonic element.

The Main Buntsandstein Subgroup, together with the Solling Formation, formed four cyclical recurrences of sandstone and claystone: the Volpriehausen, Detfurth, Hardegsen and Base Solling Formations. The cyclicity indicates water table fluctuations in an extremely flat area. In the Triassic in the Netherlands and Germany (small) unconformities have been revealed under the Volpriehausen, the Detfurth and the Solling Formations (Röhling, 1991; Geluk & Röhling, in prep.), supporting the view that these deposits represent three sequences. Only the Base Solling unconformity is prominently present in the map sheet area. Each cycle comprises a basal sand unit deposit reflecting a fluvial system and the claystone deposits of a transgressive lacustrine setting. The successive fluvial systems prograde in a northwesterly direction and represent periods of low stand. Sand distribution studies indicate that the sediments have been transported from the south. The depositional thickness, particularly of the fluvial sediments, clearly diminishes towards the Netherlands Swell, but increases towards the Ems Low. After the deposition of the Hardegsen Formation, uplift of the Netherlands Swell became prominent within the map sheet area accompanied by erosion. The erosion on the Groningen High cut down locally into the Lower Buntsandstein Formation. The tectonic phase initiating the erosion probably intensified the halokinesis in a large part of the area (see section 11.4).

The sedimentation of the Solling Formation marks the beginning of a period during which several marine transgressions occurred, demonstrated by the evaporite and limestone deposits. The evaporites in the Röt Formation were formed through evaporation of seawater during a regression or standstill. The augmented carbonate content in the topmost part of the Röt Formation points to a new transgression, which largely submerged the source areas of the clastic sediments, thus further raising the carbonate content during deposition of the Muschelkalk Formation. Marls with limestone and dolomite intercalations were deposited in the map sheet area. Further towards the margin of the Permo-Triassic Basin (fig. 11.1), in the south of The Netherlands, carbonates were deposited in a shallow sea. The Muschelkalk Evaporite, compared with the Röt Evaporite, has a smaller areal extent and is thinner. After the evaporite deposition, marly shallow-marine clay deposition resumed.

At the end of the Muschelkalk a regression prevailed, proceeded by deposition of the Keuper Formation. Owing to the regression, the erosion base-line shifted towards the map sheet area. As the source area of the clastics was much closer, the Keuper Formation is sandier and precipitation of thick successions of rock salt became restricted to small basins to the north of The Netherlands.

Here, the formation is built up of a rhythmical alternation of claystone and evaporite successions. The depositions in the map sheet area occurred under terrestrial and deltaic conditions.

During the deposition of the Keuper Formation an uplift related to the Early Kimmerian tectonic phase coincided with the associated erosion which removed the topmost part of the Triassic in the map sheet area. With the exception of a small area in the southeast, this unconformity can no longer be identified in the map sheet area owing to the intense erosion at the end of the Jurassic as a result of the Late Kimmerian phase.

6 Altena Group

6.1 Stratigraphy

After a brief period of erosion during the Late Triassic, a transgression resulted in renewed deposition. During the Late Triassic (Rhaetian) and Early and Middle Jurassic, deposition of the Altena Group occurred. In the map sheet area, the Altena Group is only found to the southeast of the Groningen High (Maps 7 & 8) and may be seen as the northern prolongations of a much larger occurrence of the group in the Lower Saxony Basin, to the east and south of the map sheet area (fig. 1.8). The presence of the Altena Group is strongly affected by halokinesis and corresponds to depletion areas of the large salt accumulations of Winschoten, De Eeker, Klein-Ulsda, Landschaftspolder and the Zuidwending salt-structure situated to the south of the map sheet area (fig. 11.2). The deposits of the Altena Group found within the map sheet area comprise the marine calcareous clays and shales of the Sleen and Aalburg Formations, the bituminous Posidonia Shale Formation and the bottommost member of the Werkendam Formation. In the Lower Saxony Basin, the Altena Group also incorporates the Brabant Formation. In the remainder of the map sheet area the Altena Group was eroded during the Mid- and Late Kimmerian tectonic phase.

The stratigraphic composition of the Altena Group is illustrated by the Meeden-1 well (fig. 6.1).

The base of the Altena Group lies at a depth of 1300 to 2100 m (Map 7). The thickness ranges from 0 to 500 m (Map 8), this variation being mainly due to erosion associated with salt flow.

The Altena Group rests upon the Upper Germanic Trias Group separated by a small hiatus and is unconformably overlain by the Rijnland Group and, where this occurs, by the Niedersachsen Group.

The Altena Group in the map sheet area is of Rhaetian to Aalenian age.

6.1.1 Sleen Formation

The Sleen Formation, of Rhaetian age, consists of grey to greenish-grey and sometimes reddish-brown, marly claystone with shale and siltstone intercalations. The deposits occur in the area southeast of the Groningen High (Map 7). The base of the Sleen Formation is characterised by a much lower acoustic velocity than the underlying anhydritical Keuper members (fig. 6.1). This significant contrast can be identified on seismics by strong reflection in a relatively monotonous sequence with low amplitudes.

The Sleen Formation is 34 m thick in the Meeden-1 well (fig. 6.1). This is greater than the average thickness in the wells to the south of Meeden-1 and is probably synsedimentary thickening as a result of early salt depletion.

The formation rests upon the Upper Germanic Trias Group separated by a small hiatus and is conformably overlain by the Aalburg Formation or unconformably by the Lower Cretaceous strata of the Rijnland Group.

6.1.2 Aalburg Formation

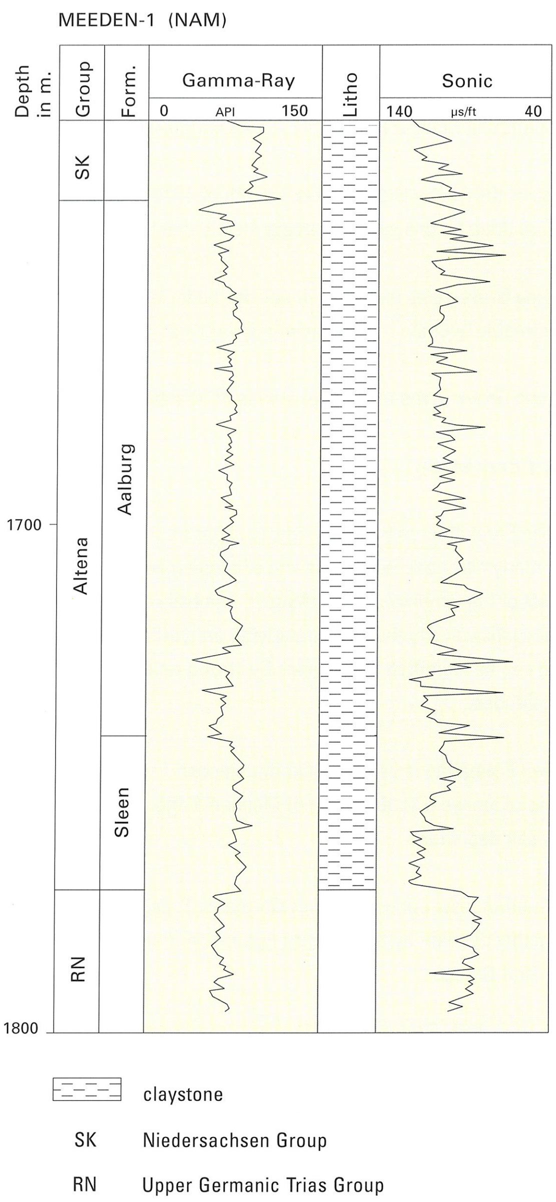
The Aalburg Formation, of Hettangian to Pliensbachian age, comprises a monotonous sequence of marine calcareous claystones and shales. The shales are grey to dark-grey with dark-grey siltstone intercalations. In addition, a few fine-grained sandstone and limestone beds are present, particularly in the bottommost part of the formation. The Aalburg Formation can be differentiated from the Sleen

Formation on logs by its lower gamma-ray reading and higher acoustic velocity (fig. 6.1).
The limestone beds at the base of the Aalburg Formation, in particular, are responsible for the peaks with low gamma-ray values and high acoustic velocities.

The Aalburg Formation cannot be clearly identified on seismic readings. In view of the great thickness (123 m) in the Meeden-1 well, the formation is presumed to occur in the same area of distribution as the Sleen Formation (fig. 6.1).

In most of the area of distribution, the Rijnland Group rests unconformably upon the Aalburg Formation. In places, however, the formation is overlain conformably by the Posidonia Shale Formation or unconformably by the Niedersachsen Group.

Figure 6.1 Stratigraphic subdivision and log pattern of the Altena Group in the Meeden-1 well.



6.1.3 Posidonia Shale Formation

The Posidonia Shale Formation, deposited during the Toarcian, is a dark-grey to black bituminous shale, differentiated on logs from the surrounding units by the high readings on the gamma-ray and resistivity logs. Immediately above the formation some bituminous horizons are still found in the Werkendam Formation.

The Posidonia Shale Formation manifests itself as a clearly identifiable strong reflection on the seismics, caused by the low acoustic velocity of the bitumen present in the shale. The presence of the bitumen makes the formation an important oil-source rock. The Posidonia Shale Formation spans the areal extent of the Werkendam Formation. It has only been identified in a few boreholes to the south of the map sheet area where the depositional thickness is approximately 25 m. The Posidonia Shale Formation is conformably overlain by the Werkendam Formation.

6.1.4 Werkendam Formation

The marine, grey, marly clay of the Werkendam Formation is subdivided into the Lower, Middle and Upper Werkendam Members. Only the bottommost member is found in a very confined area in the southeast of the map sheet area. During the Mid- and Late Kimmerian tectonic phases, these deposits were preserved in a small rim syncline to the south of the Klein Ulsda salt ridge. The marine *Lower Werkendam Member*, of Toarcian to Early Bajocian age, comprises a sometimes calcareous and silty, grey claystone, which is similar to the Aalburg Formation. The maximum thickness, approximately 100 m, can be deduced from seismic readings. The complete formation is around 400 m thick in the Lower Saxony Basin situated to the south.

The Werkendam Formation overlies the Posidonia Shale Formation conformably and is unconformably overlain by the Rijnland Group. The Niedersachsen Group may be unconformably present scattered in between the Werkendam Formation and the Rijnland Group.

6.2 Sedimentary development and palaeogeography

The end of the Triassic is characterised by a major change-over in the depositional environment. After a long period of continental conditions, a transgression favoured an open-marine depositional environment which extended over a large part of Western and Central Europe. A brief regressive period during the Late Rhaetian gave the top of the Sleen Formation more of a lagoonal character (Haanstra, 1963), superseded by basin deepening accompanied by deposition of the open-marine sediments of the Aalburg Formation. The Early Toarcian is characterised by deposition of sediments under euxinic conditions. Under these circumstances, caused by the stratification of a warm, salt-water body from the Tethys Sea and cold Arctic sea water, the bituminous Posidonia Shale Formation was laid down. Open-marine conditions were again re-established from the Toarcian to the Late Bajocian, when deposition of the Werkendam Formation occurred.

The good correlation properties of the Aalburg Formation in the eastern Netherlands indicate a negligible regional differentiation in basin subsidence during the early Jurassic. Not until the Middle Jurassic (Bajocian-Bathonian) did the basin become shallower and smaller, presumably in conjunction with the uplift of the North Netherlands High, incorporated in the Central North Sea Dome (Ziegler, 1990). It is likely that the map sheet area lay outside the basin from this period onwards and underwent erosion (fig. 6.2).

The Brabant Formation, the youngest formation of the Altena Group, was probably never deposited here, in view of the above mentioned. During the Late Jurassic, the high extended further eastwards as a result of the first main pulse of the Late Kimmerian tectonic phase (Ziegler, 1990; fig. 7.2).

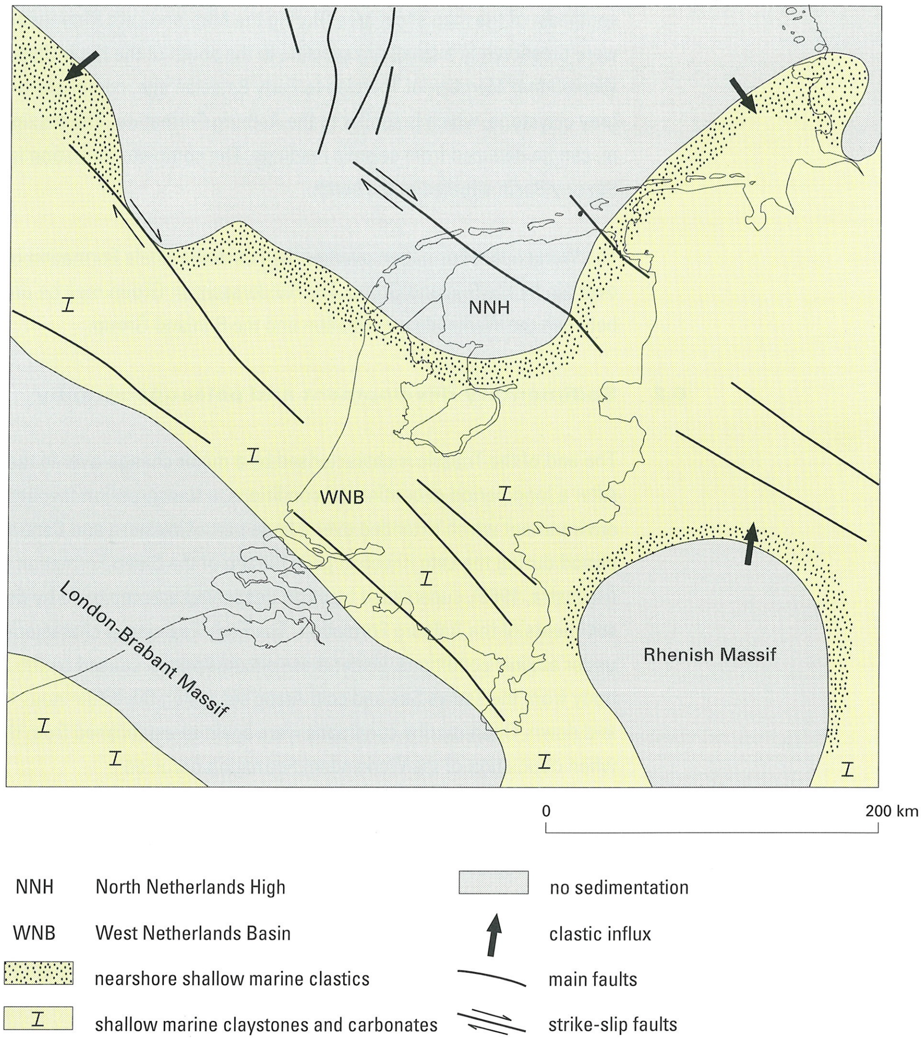


Figure 6.2 Palaeogeography of the Middle Jurassic (Bajocian-Bathonian) in The Netherlands and the surrounding area (after Ziegler, 1990).

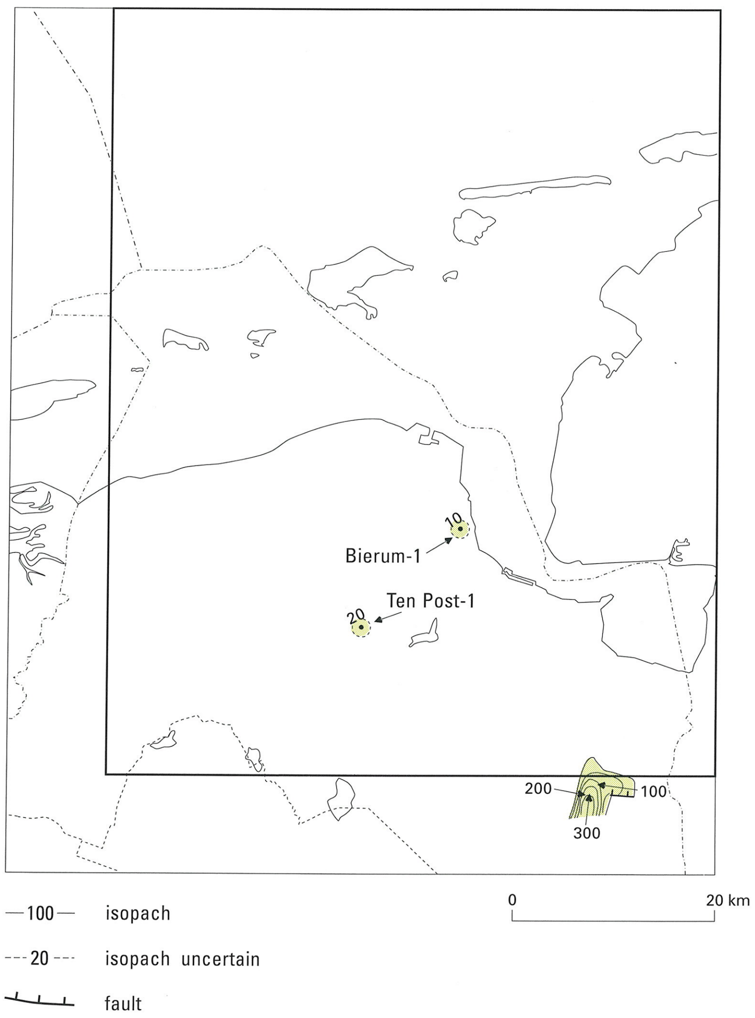
7 Niedersachsen Group

7.1 Stratigraphy

The calcareous claystones, marls and evaporites of the Niedersachsen Group were mainly deposited in the Lower Saxony Basin to the east and south of the map sheet area, during the Late Jurassic and the earliest Cretaceous. Within the map sheet area, the Niedersachsen Group is found in the depression formed as a result of salt depletion, between the Winschoten and the Klein-Ulsda salt-structures.
Its presence has also been demonstrated in two wells on the Groningen High (Bierum-1, Ten Post-1, fig. 7.1 & 8.1; RGD, 1992b). In two local depressions formed as a result of salt depletion, an erosional relic of terrestrial fine-grained sandstone was encountered below the marine deposits of the Lower Cretaceous. These sandstones, the *Weiteveen Formation*, are the youngest deposits of the Niedersachsen Group of Valanginian age (RGD, 1992b). However, these occurrences are insuffiicent for a clarification of the original areal extent, thickness and composition of the Niedersachsen succession on the Groningen High.

The Niedersachsen Group, with a maximum thickness of 50 m, has its base at a depth of 1800 to 2000 m.

Figure 7.1 Thickness map of the Niedersachsen Group based on wells and seismics. The southern occurrence is an extremity of the Lower Saxony Basin. In addition, isolated occurrences have been demonstrated in the Ten Post-1 and Bierum-1 wells.



Between Winschoten and Klein-Ulsda the Group has not been penetrated. Information from some drill holes in Drenthe to the south of the map sheet area indicates that the succession here probably comprises the bottommost 50 m of the Weiteveen Formation. This is a grey to dark-grey marly claystone.

The Niedersachsen Group was deposited from the Kimmeridgian possibly into the earliest Valanginian.

7.2 Sedimentary development and palaeogeography

The Niedersachsen Group deposits in the map sheet area are part of a much larger occurrence in the Lower Saxony Basin. The remainder of the map sheet area was probably situated above sea level

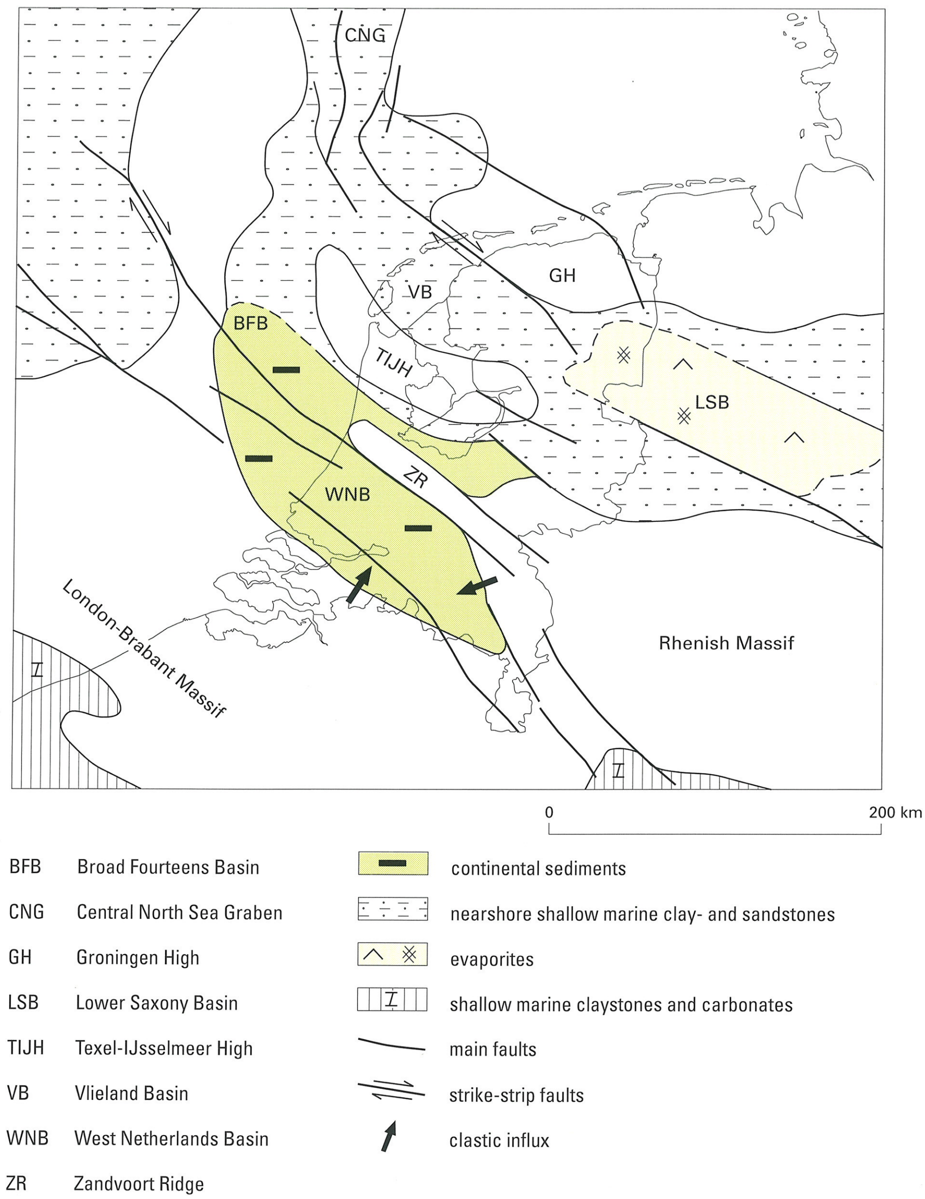


Figure 7.2 Palaeogeography of The Netherlands and surrounding area during the Late Jurassic (after Ziegler, 1990).

during the Kimmeridgian to the Valanginian (fig. 7.2). The sedimentation may have taken place on the high (Ten Post-1 and Bierum-1) facilitated by the slight relief on the high enabling periodic flooding to occur. However, Late Kimmerian erosion removed virtually all traces.

Deposits in the Lower Saxony Basin represent a predominantly lacustrine setting with intervening periods of marine and hypersaline conditions. Minimal influx of siliciclastics is evidenced, the adjacent highs to the north being largely covered by the calcareous claystones of the Lower Jurassic.
The Niedersachsen Group sediments present in the map sheet area formed the northern basin-margin deposits of the Lower Saxony Basin. It is highly likely that the Niedersachsen Group here consists of incomplete sections with intraformational hiatuses. This succession has a variable thickness owing to synsedimentary salt flow.

The Late Kimmerian tectonic phase resulted in uplift and erosion of the map sheet area during the Late Jurassic and the earliest Cretaceous. Southeast of the Groningen High, in the depressions initiated by salt depletion, the erosion did not progress further than the youngest part of the Niedersachsen Group. On the Groningen High, however, the erosion even affected the Zechstein Group locally.
The centre of the Lower Saxony Basin is characterised by continuous sedimentation.

8 Rijnland Group

8.1 Stratigraphy

The Rijnland Group in the map sheet area is composed mainly of marly claystone and silty marls. In a few places, the base of the Rijnland Group is made up of sandstone. The sediments of the Rijnland Group were accumulated in an initially shallow open-marine setting which gradually deepened. The group is subdivided into the Vlieland Subgroup, which comprises the Vlieland Sandstone Formation and Vlieland Claystone Formation and the younger Holland Formation.

The Rijnland Group deposits are found practically throughout map sheet area (Map 10) except above the Pieterburen and Klein-Ulsda salt-structures. Above the other salt accumulations a number of hiatuses may occur in the succession. The transgressive nature of the base of the Rijnland Group is responsible for the diachronous appearance over the Groningen High. The ages of these deposits vary from Early Valanginian to Late Albian (RGD, 1992c). Pre-depositional erosion accounts for the unconformable contact of the Rijnland Group with underlying rocks of varying ages (fig. 1.8), the Lower Germanic Trias Group on the Groningen High and the Zechstein Group above the salt structures. In the Lauwerszee Trough and the Ems Low, the Rijnland Group covers the Upper Germanic Trias Group and in the extreme southeast, early and Late Jurassic deposits. On the Groningen High, Late Jurassic deposits (Niedersachsen Group) may occur locally, directly below the Rijnland Group.

In the major part of the map sheet area the thickness of the Rijnland Group is 50 to 100 m, less above salt structures and greater in rim synclines. To the northwest, in the Lauwerszee Trough, the thickness increases to over 200 m.

The depth of the base of the Rijnland Group on the Groningen High averages 1850 m, and is shallower above the salt structures. In the Lauwerszee Trough the base of the Rijnland Group is at a maximum depth of 2900 m (Map 9).

The Rijnland Group is of Early Valanginian up to Albian age. At least three hiatuses are apparent in the group.

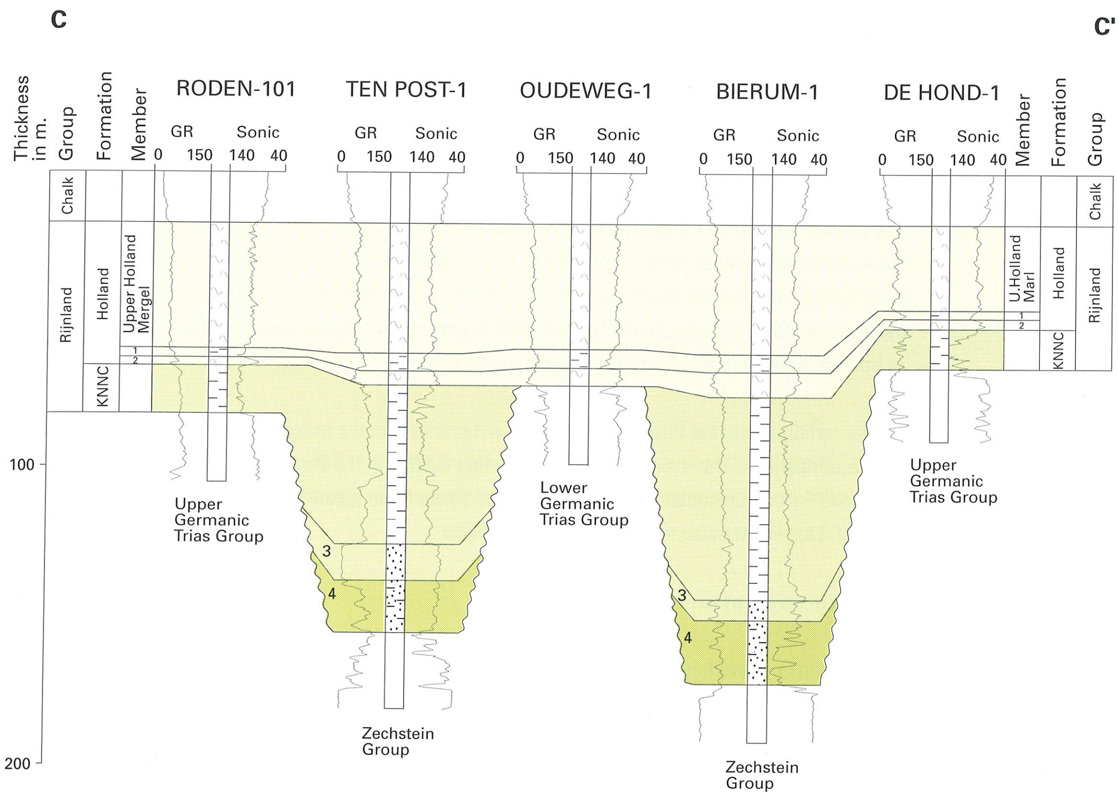
8.1.1 Vlieland Subgroup

The Vlieland Subgroup, Early Valanginian to Barremian in age, is present virtually throughout the map sheet area, except for a few areas above salt accumulations. The areal extent of the Vlieland Subgroup corresponds to that of the Rijnland Group (Map 9). The thickness distribution has an almost identical appearance as the thickness map of the complete Rijnland Group (Map 10), with thinnings above salt structures and thickenings in the rim synclines. The maximum thickness is 100 m. The thickness variation reflects the probable filling up of the existing relief by the Vlieland Subgroup or the differential erosion of the upper surface. In figure 8.1 the palaeorelief can be extrapolated from the different ages of the formations of the Vlieland Subgroup, immediately above the unconformity horizon.

Owing to drastic erosion preceding deposition of the Vlieland Subgroup, the sediments of the different formations lie below the base of the Rijnland Group, as indicated on Map 14, the subcrop geological map. The formation is in general conformably overlain by deposits of the Holland Formation, displaying a hiatus. Along the margin of salt accumulations the contact is unconformable in places, owing to contemporaneous erosion above salt accumulations, caused by the ascent of the Zechstein salt.

8.1.1a Vlieland Sandstone Formation

The Vlieland Sandstone Formation in the map sheet area comprises the *Friesland Member.* The sandstones of this member have been encountered infrequently, and are generally very thin (less than 5 m), on the Groningen High possibly only deposited in depressions of the palaeorelief. An alternative explanation is that in a large part of the area it was deposited and subsequently eroded, with remnants preserved in rim synclines or locally in salt depletion areas. The hiatus between the Friesland Member



sandstone — KNNC Vlieland Claystone Formation

claystone — 1 Middle-Holland Claystone Member

marl — 2 Lower-Holland Marl Member

3 Vlieland Sandstone Formation

4 Niedersachsen Group

Figure 8.1 Stratigraphic section C-C' of the Rijnland Group from palynological research and the log pattern of the Roden-101, Ten Post-1, Oudeweg-1, Bierum-1 and De Hond-1 wells (RGD, 1992b,c). This SW-NE section shows several hiatuses which are due to periods of non-deposition and possible erosion. The base of the Rijnland Group displays a variation in age indicative of the presence of a palaeo-relief. In the Ten Post-1 and Bierum-1 wells, relics of the Niedersachsen Group have been encountered below the Vlieland Subgroup. (N.B. the distance between the wells is not to scale). For the positioning of the section, see figure 1.3.

and the Vlieland Claystone Formation in the Ten Post-1 well does indeed indicate the likelihood of such a period of erosion. The Friesland Member may occur in the region of the present Wadden Sea.
The Friesland Member in the map sheet area comprises an alternation of green-grey and dark grey occasionally marly and glauconitic claystone, siltstone and very fine sandstone, in contrast to the westerly province of Friesland, where the Friesland Member consists of well developed sandstones which form a major reservoir rock. Only in the Ten Post-1 well has a pure, basal 12 m thick sandstone sequence been found (fig. 8.1) similar to the sandstones in Friesland.

The transition of the Friesland Member to the Vlieland Claystone Formation is rather abrupt and is clearly identifiable on gamma-ray and sonic logs (fig. 8.1). The thickness is a maximum of 35 m.

The Friesland Member is probably of Early Valanginian age. The top is Early to Middle Valanginian in age (Herngreen et al., 1991; RGD, 1992c).

8.1.1b Vlieland Claystone Formation

The Vlieland Claystone Formation comprises shale and claystone which is sometimes silty, sometimes marly and which may be differing shades of brown, green or grey. In the claystone, just above the base, a small hiatus is apparent above which iron-bearing claystone and oolites occur. The iron-bearing claystone reflects a period of non-deposition and the development of a hard ground.
At the top of the unit, the claystone is somewhat marly.

The formation is present throughout the map sheet area with the exception of the areas above large salt accumulations. The maximum drilled thickness is 68 m in the Bierum-1 well (fig. 8.1). The Vlieland Claystone Formation contains an obvious hiatus; beneath the hiatus the age is Middle Valanginian and above it, Late Hauterivian to Barremian (RGD, 1992c).

8.1.2 Holland Formation

The Holland Formation is the youngest unit of the Rijnland Group and comprises grey and green, sometimes yellow-brown marls and marly claystone. The formation has a major subdivision into three members which are fairly prominent on the gamma-ray and sonic logs (fig. 8.1). From old to young these are the Lower Holland Marl, the Middle Holland Claystone and the Upper Holland Marl Members.

The formation is widespread throughout the map sheet area, although not always complete.
The formation does not occur above the Pieterburen salt-structure and the Klein-Ulsda salt ridge.
The thickness distribution pattern is comparable to that of the entire Rijnland Group (Map 10).
The thickness of the Holland Formation, likewise, was strongly influenced by salt flow during its deposition. The maximum thickness reached is 100 m in the Bolderij-1 well and the average thickness on the Groningen High is approximately 60 m.

The Holland Formation rests upon the Vlieland Claystone Formation, generally with a hiatus (which may span the entire Barremian) (fig. 8.1). Around large salt accumulations, the contact forms an angular unconformity, owing to erosion associated with salt flow. The Holland Formation is conformably overlain by the Texel Formation of the Chalk Group. The deposits are of Aptian and Albian age, possibly separated by a hiatus spanning the Late Aptian.

The *Lower Holland Marl Member,* of Aptian age, comprises a light to dark grey, sometimes brown or yellowish coloured marl containing belemnites and shell debris. The samples studied show the base to be a 5 m thick shallow grey, white laminated marl/shale succession similar to the Fischschiefer from the Lower Saxony Basin (RGD, 1992c). The Lower Holland Marl Member can be clearly distinguished from the Vlieland Claystone Formation by a higher carbonate content, which displays on logs low gamma-ray and high acoustic-velocity readings (fig. 8.1). The maximum penetrated thickness of the member is 19 m (Froombosch-1), whereas on the Groningen High the thickness averages 10 m.

The *Middle Holland Claystone Member,* of Early Albian age, comprises a dark grey claystone with an average thickness of 7 m. In the Bolderij-1 well a thickness of 16 m has been drilled. The Middle Holland Claystone rests upon the Lower Holland Marl Member, separated by a hiatus with a conformable contact.

The *Upper Holland Marl Member* comprises grey and green marls. The maximum drilled thickness is 65 m (Heiligerlee-1). The average thickness of this unit on the Groningen High is approximately 45 m. The contact with both the Middle Holland Claystone Member, of Middle to Late Albian, and the overlying Chalk Group is conformable. Biostratigraphic datings and log correlations suggest the presumed occurrence of several (very) small hiatuses within the Upper Holland Marl Member (RGD, 1992c).

8.2 Sedimentary development and palaeogeography

At the beginning of the Cretaceous, the largest part of the map sheet area consisted of a high area spreading out towards the northwest (fig. 8.2a). The Cretaceous is characterised by a transgressive megasequence, which can be divided into two clear sequences.

The first transgressive sequence stretches from the Early to Middle Valanginian up to and including the Aptian. The sequence commences with coastal barriers formed on less elevated parts of the Groningen High. These occurrences of the Vlieland Sandstone Formation are the oldest and the thickest in the depressions related to the area which underwent halokinesis or active faulting (fig. 8.1). As the sea level continued to rise at the end of the Valanginian, a change in sedimentation set in. The sediments became finer and a thick sequence of Vlieland Claystone Formation was formed. This change may have been related to the flooding of the source areas of the sand. The presence of a substantial amount of carbonate in the youngest part of the claystone (derived from predominantly planktic organisms) points to a transition to an open-marine setting. Locally, the halokinetically controlled relief, had an influence on the thickness trend of the claystone. The first transgression reached its maximum flooding in the Aptian. A period of non-deposition (Late Barremian) was followed by sedimentation of the Lower Holland Marl Member, reflecting the most open-marine setting of this transgression.

The second transgressive sequence began in the Albian when the rise in sea level overshadowed the tectonic uplift (Crittenden, 1987). The boundary between the two transgressive sequences is related to the Asturian deformation phase, and is characterised by a period of non-deposition. Resumed sedimentation is demonstrated by the Middle Holland Claystone Member with a rather sandy transgressive interval at the base. Open marine characteristics re-appear in the Upper Holland Marl Member, the youngest unit of the Lower Cretaceous (fig. 8.2b). The transgressive sequence persisted until the end of the Late Cretaceous.

Figure 8.2a Palaeogeography of the oldest Early Cretaceous (Ryazanian-Valanginian) in The Netherlands and surrounding area (after Ziegler, 1990).

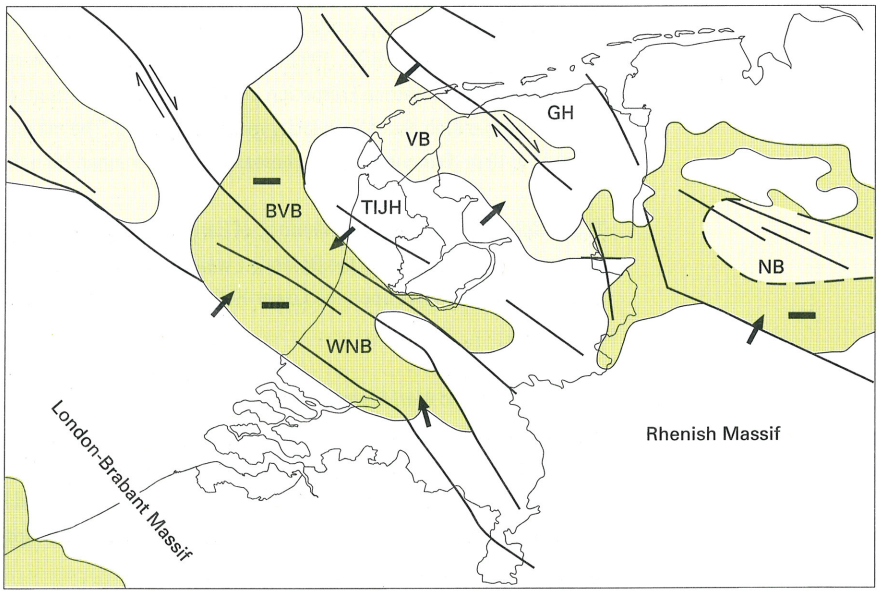
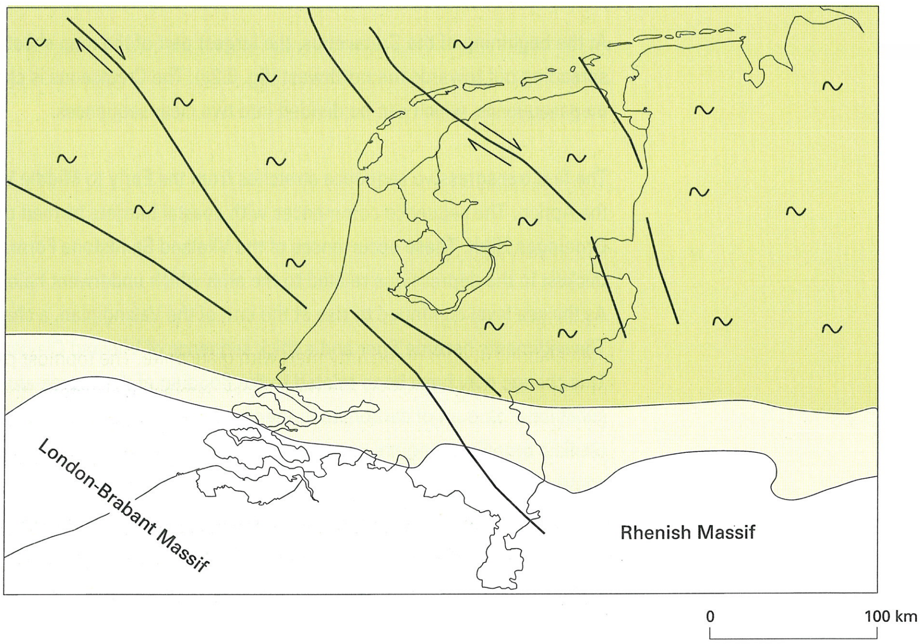


Figure 8.2b Palaeogeography of the later Early Cretaceous (Aptian-Albian) in The Netherlands and surrounding area (after Ziegler, 1990).



BFB	Breeveertien Bekken	▬	continental sediments
GH	Groningen High	∾ ∾	shallow marine claystones, marls and carbonates
LSB	Lower Saxony Basin		nearshore shallow marine clay-and sandstones
TIJH	Texel-IJsselmeer High	—	main faults
VB	Vlieland Basin	⇌	strike-slipe faults
WNB	West-Netherlands Basin	↑	clastic influx

9 Chalk Group

9.1. Stratigraphy

The Chalk Group consists of a succession of well cemented, light coloured, fine-grained chalk and marly limestones. It is a characteristic feature that the main constituents of these chalky sediments are calcareous skeletons of planktic and benthic organisms (coccoliths, foraminifera, sponges, bryozoa, etc), with little influx of terrigenous material. The Chalk Group is subdivided from bottom to top into the Texel and Ommelanden Formations (fig. 9.1).

The Chalk Group deposits occur throughout the map sheet area. The greatest thickness is found in small, salt flow-induced depressions in the northeast of the map sheet area (Map 12), where the thickness exceeds 1000 m. Above salt structures the deposits are much thinner, with a thickness of less than 100 m above the Pieterburen salt-structure. It is also notable that the average thickness of the Chalk Group in the eastern part of the Lauwerszee Trough is less than on the Groningen High.

The base of the Chalk Group on the Groningen High lies at an average depth of 1700 m and on the Lauwerszee Trough the depth ranges from 1800 m to over 2500 m (Map 11).

The lower boundary of the Chalk Group is placed at the base of the marly chalk succession which rests conformably on the marls of the Rijnland Group. The Chalk Group is overlain unconformably by the clastic sediments of the North Sea Super Group.

The age of the Chalk Group within the map sheet area extends from Cenomanian up to and including Maastrichtian. Log correlations of the four biostratigraphically studied wells, Roden-101, Winsum-1, Stedum-1 and De Hond-1, demonstrate the presence of small hiatuses and condensed sequences (RGD, 1992d, fig. 9.1). These are found particularly above salt walls (Winsum-1 well). The Upper Maastrichtian is presumed only to occur in the northeast of the map sheet area in the salt depletion areas (De Hond-1 well).

9.1.1 Texel Formation

The Texel Formation consists of white and light grey chalk and marly limestone with scattered intercalations of light green limy marl with glauconite. The topmost part of the Texel Formation is formed by an approximately 3 m thick, black, laminated claystone, the *Plenus Marl Member* (Van Adrichem Boogaert & Kouwe, 1993-1995). This member is very widely distributed and exhibits good correlation properties: demonstrated by a distinctive peak on the gamma-ray and sonic logs (fig. 9.1).

The Texel Formation occurs throughout the map sheet area. The thickness shows a similar variation to that of the whole Chalk Group, with greater thicknesses in salt depletion areas and condensed sequences above salt structures. The average thickness in the map sheet area is 50 m.

The formation is overlain conformably by the Ommelanden Formation. The formation is of Cenomanian age, and it should be mentioned that mainly the oldest Cenomanian has been encountered in the four biostratigraphically studied wells (RGD, 1992d).

9.1.2 Ommelanden Formation

The Ommelanden Formation, of Turonian to Maastrichtian age (RGD, 1992d), consists mainly of a white to light-grey chalk, with limestone beds and a few marly intercalations. In addition, several layers of white to nearly black chert nodules parallel to the bedding are found, particularly at the top.

In contrast to the gamma-ray log reading, which has a highly monotonous character, the chert nodules produce a more serrated pattern on the sonic log (fig. 9.1). Although the monotonous lithological character of the formation makes a mappable subdivision of the Ommelanden Formation extremely difficult, it is nevertheless highly probable that sonic logs would enable correlation (fig. 9.1).

The map sheet area exhibits great variations in the thickness of the formation. Above salt structures, thicknesses of less than 100 m occur. On the other hand, the Ommelanden Formation in the northeast of the map sheet area reaches a thickness exceeding 1000 m in the salt depletion areas.
In the southeastern part of the Lauwerszee Trough, the average thickness of the formation is less than the average thickness on the Groningen High.

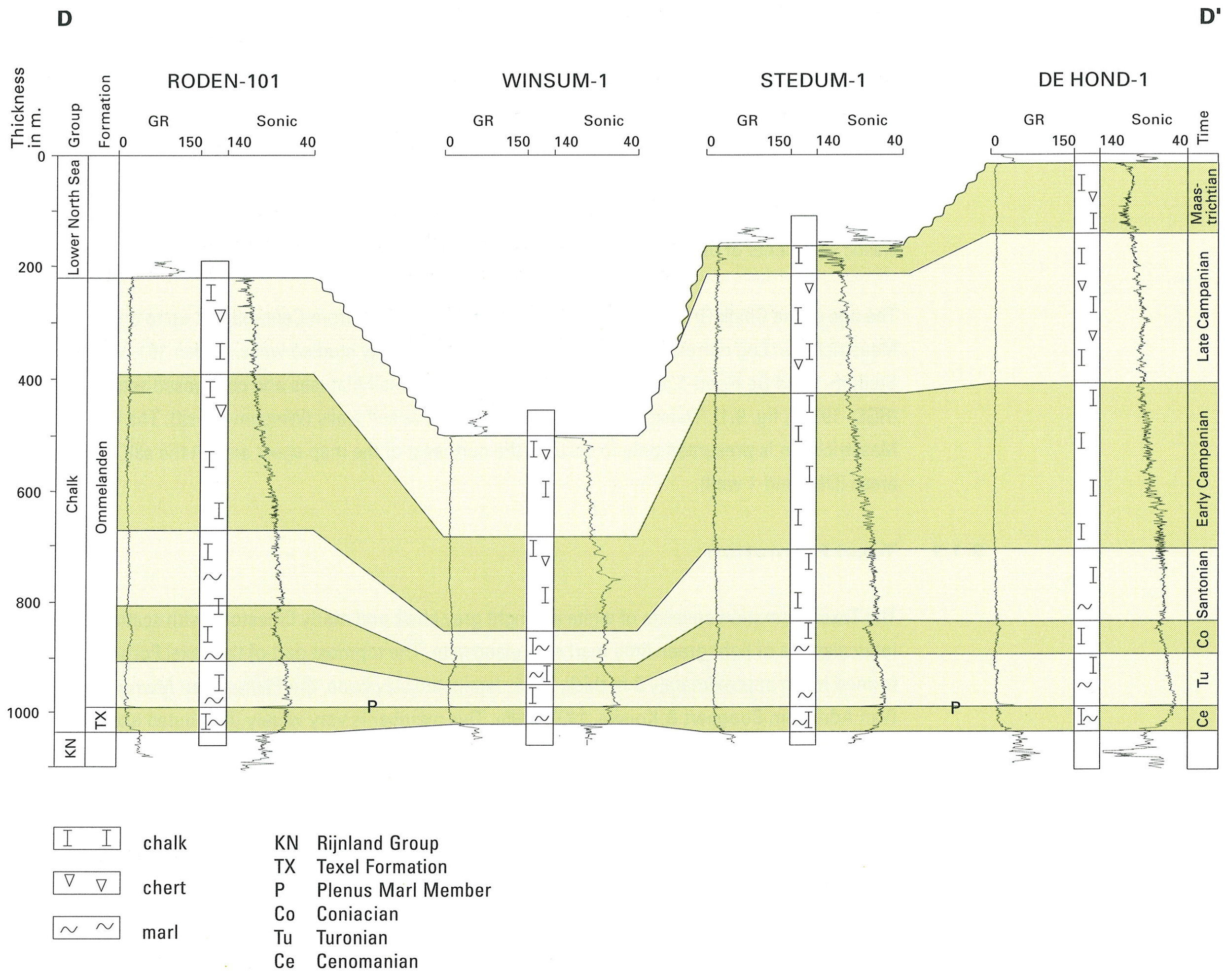


Figure 9.1 Stratigraphic section D-D' of the Chalk Group from palynological research (RGD, 1992d) and the log pattern, gamma-ray and sonic log, of the Roden-101, Winsum-1, Stedum-1 and De Hond-1 wells. The reference-level is the Plenus Marl. The sequence of the Winsum-1 well clearly demonstrates in particular the thinning of the Santonian and of the Early Campanian and later of the Maastrichtian, caused by the ascent of the underlying salt structure associated with the Subhercynian and Laramide tectonic phases. For the positioning of the section, see figure 1.3.

At the base, the formation is bounded by a black laminated claystone, the Plenus Marl Member. The top is unconformably overlain by the clastic deposits of the Tertiary North Sea Supergroup. This unconformity is the result of the Laramide tectonic phase which was accompanied by slight erosion. As a consequence, the Upper Maastrichtian does not occur in the greater part of the map sheet area. Only in the northeastern salt depletion areas has the Upper Maastrichtian been preserved. Condensed sequences and small hiatuses can be determined by means of log correlation and seismostratigraphic studies. The hiatuses can often be identified by a shift in the curve of the sonic log (fig. 9.1) and are confirmed by biostratigraphic datings (RGD, 1992d).

9.2 Sedimentary development and palaeogeography

The eustatic sea-level rise which had already commenced during the Albian developed during the Late Cretaceous into a global transgression (Pitman, 1978; Donovan & Jones, 1979). The coastline migrated to the south of The Netherlands, receding from the map sheet area, and the influx of terrigenous sediments diminished. The largely bioclastic constituents of the deposits of the Late Cretaceous may be due to a combination of flooding of the source areas of clastic sediments and a bloom of organisms with a calcareous skeleton. The transition to the Holland Formation is rather abrupt.

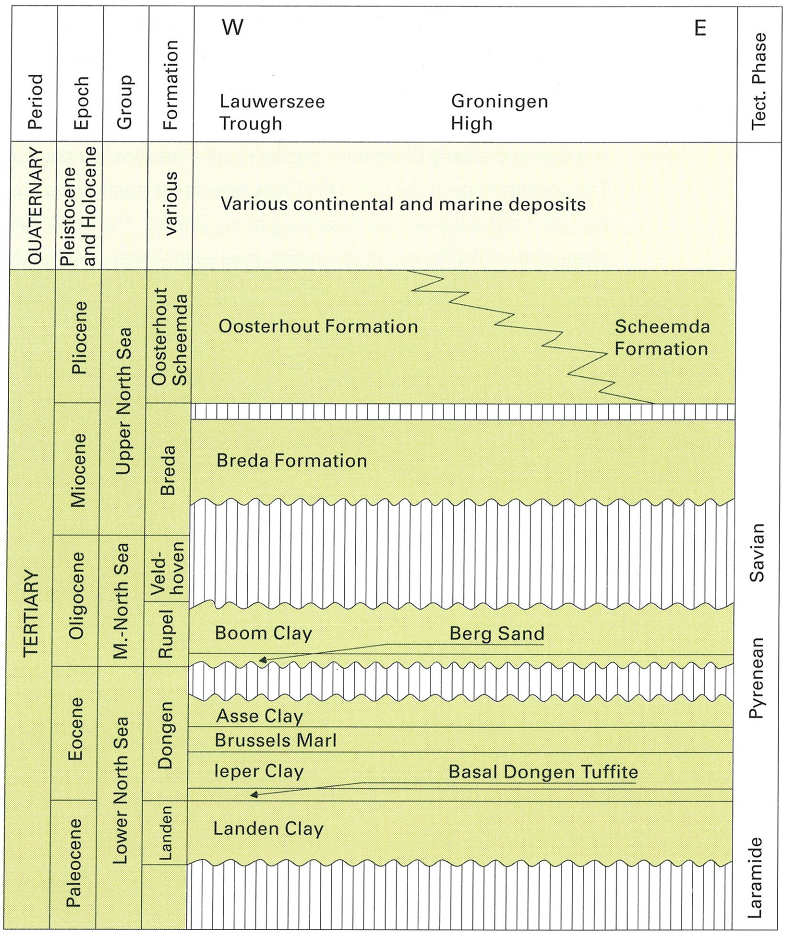
The great thickness of the Ommelanden Formation can be attributed to the lengthy and continuous pelagic rain of coccoliths. The maximum depositional depth in the Chalk Sea was 150-200 m (Hancock & Scholle, 1975). In the overall advancing transgression, however, the Plenus Marl Member reflects a period of maximum regression and increased supply of terrigenous material. The variations in thickness within the map sheet area in the Texel and Ommelanden Formations are mainly due to synsedimentary halokinesis related to tectonic activity. The unconformity at the base of the Santonian and during the Early Campanian are the result of tectonic pulses during the Subhercynian phase. The unconformity at the top of the Chalk reflects the uplift of the area and the low stand at the end of the Late Cretaceous and the beginning of the Tertiary. The uplift was caused by the Laramide tectonic phase and marks the end of the undisturbed sedimentation of hundreds of metres of bioclastics.

10 North Sea Supergroup

10.1 Stratigraphy

The North Sea Supergroup, of Tertiary and Quaternary age, is composed of clays with few sandy arenaceous intercalations and a sandy sequence at the top. The supergroup is subdivided by intraformational hiatuses into the Lower North Sea, Middle North Sea and Upper North Sea Groups.
The stratigraphic succession is illustrated by figure 10.1. The description of these deposits is based mainly on reports by the Rijks Geologische Dienst (1984).
The North Sea Supergroup is found throughout the map sheet area. The lower boundary is determined by the unconformable contact with the Chalk Group, and the surface level is taken as the upper boundary. The thickness of the supergroup is the greatest in the Lauwerszee Trough (1150 - 1650 m). This is considerably greater than on the Groningen High (approximately 850 m). Locally, the regional thickness is highly disturbed by salt flow. In general, the thickness of the North Sea Supergroup diminishes above the salt structures. However, in collapse structures, for example above the Winsum and Klein-Ulsda salt structures, the North Sea Supergroup exceeds a thickness of 1000 m (Map 13). Above the Pieterburen salt-structure, a thickness of only 157 m has been encountered (Map 13).
In the Lauwerszee Trough (particularly the part in the Wadden Sea), large quantities of Tertiary and Quaternary sediments were able to accumulate owing to the (synsedimentary) depletion of the Zechstein salt,

Figure 10.1 Stratigraphic diagram of the North Sea Supergroup. The hiatuses are indicated by vertical hatching.



superimposed on the general subsidence of the area. Figures 10.1 and 10.2 illustrate the composition of the North Sea Supergroup.

10.1.1 Lower North Sea Group

The Lower North Sea Group consists mainly of clays with a few sandy intercalations. The group is subdivided into the Landen and Dongen Formations.

The Lower North Sea Group which, except above a few salt structures, is found throughout the map sheet area, rests unconformably on the Chalk Group and, as a result of the Pyrenean tectonic phase of the Alpine orogeny and related erosion, is unconformably overlain by the Middle North Sea Group.

The thickness pattern of the group is similar to that of the North Sea Supergroup. The maximum drilled thickness reached, 573 m, is in the Usquert-1 well.

The *Landen Formation* in the map sheet area consists entirely of the Landen Clay. The Landen Formation, of Palaeocene age, is a black to dark green-grey clay or claystone and averages a thickness of approximately 13 m. The clay contains glauconite, mica and pyrite. The formation rests unconformably on the Chalk Group.

The *Dongen Formation*, of Eocene age, consists of the Basal Dongen Tuffite, the Ieper Clay, the Brussels Marl and the Asse Clay. The thickness pattern of the formation is influenced by halokinesis and by erosion appearing at the end of the Eocene (fig. 10.1 and 10.2) and was the most intense above

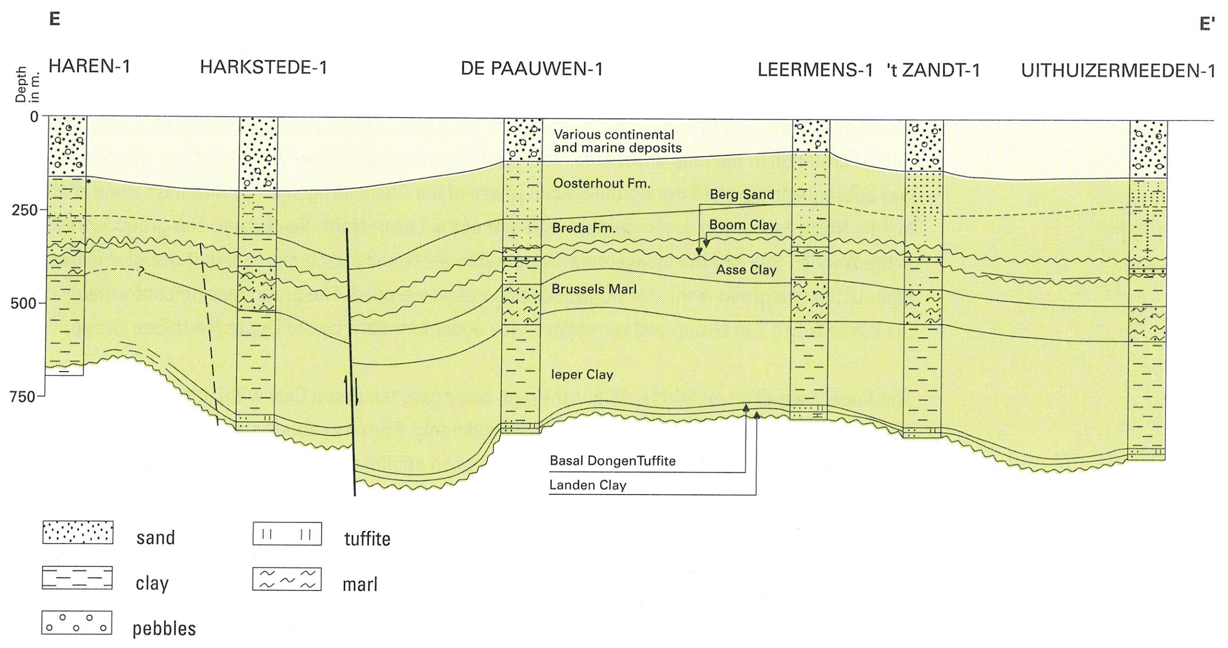


Figure 10.2 Schematic section E-E' through the North Sea Supergroup from the Haren-1, Harkstede-1, De Paauwen-1, Leermens-1, 't Zandt-1 and Uithuizermeeden-1 wells (after Rijks Geologische Dienst, 1984). For the positioning of the section, see figure 1.3.

the salt structures. The formation is the thickest in the Lauwerszee Trough and in the Wadden Sea, over 570 m (Usquert-1).

The *Basal Dongen Tuffite*, of Early Eocene age and of thicknesses ranging from 10 to over 20 m in this area, is composed of glauconitic-bearing dark grey clays with tuffaceous intercalations.

The *Ieper Clay*, of Early Eocene age, consists of silty clay which is grey, dark grey, green to brown and, at the top, purple to reddish brown. The upper part contains sand and silt lenticles with scattered occurrences of pyrite and glauconite. The clay, locally calcareous, may contain pyrite, shell debris and coal fragments. The thickness averages 300 m. The Ieper Clay is thinner above the salt structures but exhibits only minor thickness variations.

The *Brussels Marl*, of Middle and Late Eocene, is composed of glauconitic, calcareous, green-grey to light grey siltstone and sandstone. At the base, the siltstone and sandstone are argillaceous and less consolidated, with intercalations of thin green clay bands. The glauconite and carbonate content increases upwardly, except for approximately 20 m at the top which exhibits a decreasing trend. There is a considerable range in thickness (between 0 and 130 m) owing to halokinesis and erosion above salt structures. Elsewhere, the thickness is around 100 m (fig. 10.3).

The *Asse Clay*, of late Eocene age, is a plastic, green-grey to blue-grey clay containing glauconite and pyrite. The thickness pattern of the formation has been determined mainly by erosion. Above the large salt structures, the Asse Clay is completely absent. The average thickness of the Asse Clay is approximately 60 m, but may increase to over twice as much (160 m, Usquert-1) in the rim synclines.
In view of the erosive contact with the Berg Sand of the Middle North Sea Group, the depositional thickness is presumed to have been greater.

10.1.2 Middle North Sea Group

The Middle North Sea Group, comprising marine clays with a basal sand unit, consists of only the Rupel Formation in the map sheet area. The Veldhoven Formation may well have been deposited but was subsequently eroded during the Savian phase of the Alpine orogeny. The thickness trend of the Middle North Sea Group is comparable with that of the Lower North Sea Group. The group is thickest in the Wadden Sea and the Lauwerszee Trough. Above the salt structures, except those of Winsum and Klein-Ulsda, the group is thinner or has been completely eroded. The group rests unconformably on the Lower North Sea Group and is overlain, also unconformably, by the Upper North Sea Group.

The *Rupel Formation*, of Middle Oligocene age, comprises the Boom Clay with, at the base, the Berg Sand. The thickness of the formation varies considerably, from 0 m above salt structures to over 100 m locally in salt depletion areas. These figures have been obtained partly from wells and partly from seismic data.

The *Berg Sand* is a green-grey to dark grey, fine-sandy sequence with scattered occurrences of pyrite and glauconite and upwardly decreasing grain size. The Berg Sand is not uniformly well developed. The thinness of the Berg Sand, ranging from 0 to 12 m in wells, may restrict identification.

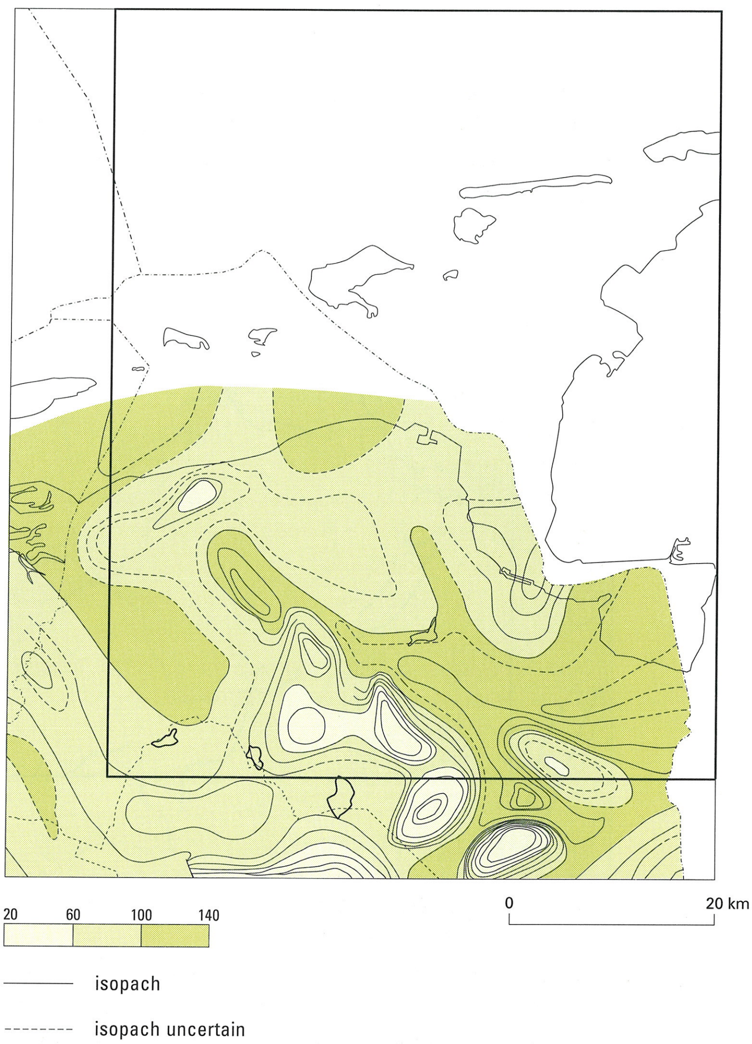
The *Boom Clay* consists of a stiff, fat, brown to dark green-grey clay containing pyrite, mica and glauconite. At certain levels septarian nodules (calcareous concretions) are found. The thickness range from 0 to 160 m is due to erosion during the Lower Miocene. The succession is unconformably overlain by the Breda Formation of the Upper North Sea Group.

10.1.3 Upper North Sea Group

The Upper North Sea Group, Miocene to recent in age, exhibits the youngest rocks present which consist mainly of (argillaceous) sand. In this explanation, the description is confined to the Tertiary deposits. For the Quaternary sediments reference should be made to Zagwijn & Van Staalduinen (1975) and to the map sheets of the near-surface geology ('Toelichting bij de Geologische Kaart van Nederland 1:50.000'), later to be published by the Survey (Rijks Geologische Dienst). The Tertiary Formations of Breda, Oosterhout and Scheemda have been subdivided on a basis of clays and glauconite content and depositional setting. The marine Breda Formation lies on the base and is found in the major part of the map sheet area. The deposits immediately above are lateral equivalents. These are, in the west, the marine Oosterhout Formation and in the (south)eastern part the continental Scheemda Formation.

The thickness of the Upper North Sea Group was controlled not only by halokinesis but also by the former Mesozoic structural elements (fig. 10.4). In the Lauwerszee Trough the Upper North Sea Group

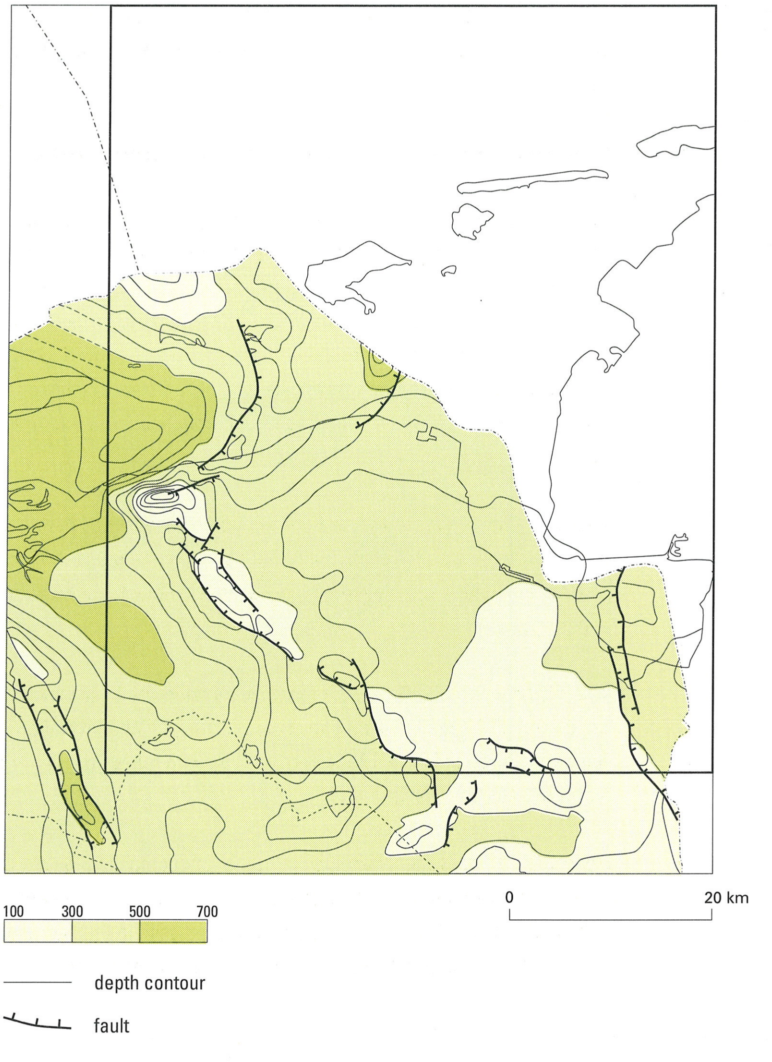
Figure 10.3 Thickness map of the Brussels Marl (Middle to Late Eocene) (Rijks Geologische Dienst, 1984). This map shows that the differences in thickness are strongly associated with the salt movements.



is approximately 500 m thick while on the Groningen High, outside the areas affected by halokinesis, around 315 thick m. The maximum thickness, 650 m, lies to the north of the Pieterburen salt-structure; the minimum thickness, above this structure, is 72 m. The Upper North Sea Group rests conformably on the Middle North Sea Group and its upper boundary is the present surface level.

The *Breda Formation,* deposited in this area from the Middle Miocene to the Early Pliocene, consists at the bottom, of a green-grey, glauconite-rich, argillaceous sandstone and a silty claystone approximately 7 m thick. The topmost part is represented by a fine to coarse-grained sand unit with intercalations of clay, mica, shell debris and glauconite. The basal succession is clearly identifiable on the gamma-ray log. The large amount of glauconite and the argillaceous character show a higher gamma ray response than the upper part. The Breda Formation is unconformably overlain by the Oosterhout or Scheemda Formations. The upper boundary of the Breda Formation may be difficult to trace on the logs. Consequently, the thickness of the formation cannot be determined with any degree of certainty. The thickness in the western part is assumed to be approximately 175 m, and in the eastern part around 75 m. Above salt structures the formation is partially or completely removed by erosion.

Figure 10.4 Depth map of the base of the Upper North Sea Group based on seismic interpretation and well information. The depth map is also the thickness map of the Miocene and Quaternary deposits of the Upper North Sea Group. Contour interval is 50 m.



The *Oosterhout Formation*, of Pliocene age, comprises light brown to grey, argillaceous to coarse-grained sands with occasional clay intercalations. The glauconite content is less than in the Breda Formation. The deposits are in general rich in shell debris, echinoderm fragments, fish remains and coalified wood. The Oosterhout Formation occurs throughout the map sheet area, except for the (south)east of the map sheet area and the areas above large salt structures. In the western part of the Lauwerszee Trough the formation is approximately 50 m thick. Towards the southeast, the formation passes into the Scheemda Formation.

The *Scheemda Formation*, of Pliocene age, comprises white, fine to coarse, sometimes argillaceous sands with gravel beds, which are glauconitic and micaceous in places. The formation can be identified by its contents of heavy minerals and gravel, transported from the east by rivers.
The formation passes laterally, westwards, into the Oosterhout Formation.
The Scheemda Formation is found in the (south)east of the map sheet area with a thickness of approximately 70 m. The formation may also occur on the Groningen High. The Scheemda Formation is overlain by Quaternary formations.

The remaining Quaternary formations of the Upper North Sea Group are built up of clay, sand and gravel deposited under continental and shallow-marine conditions (Zagwijn & Van Staalduinen, 1975). The thickness ranges from 37 m above the Pieterburen salt-structure to 200 m above collapse structures.

10.2 Sedimentary development and palaeogeography

During deposition of the North Sea Supergroup, the map sheet area formed part of the North Sea Basin. Deposition of the supergroup was to a considerable extent controlled by eustatic sea-level fluctuations (Haq et al., 1987). During periods of high stand the deposits were predominantly clays, whereas during periods of low stand, sands or arenaceous clays were accumulated. At extreme low stand, no deposition at all took place or erosion even occurred. Uplift related to a number of tectonic movements, contemporaneous with periods of low stand, resulted in stratigraphic hiatuses during the Tertiary (fig. 10.1). Furthermore, differential basin subsidence contributed to thickness variations of the deposits.

The sediments of the North Sea Supergroup were deposited during a period of a relative high stand, only interrupted by a brief fall during deposition of the Brussels Marl. Differentiated areal uplift, in combination with a sea-level drop, caused the sedimentation to cease during the Late Eocene and initiated a period of erosion.

The Middle North Sea Group demonstrates a rapid rise in sea level with high stand during the deposition of the Rupel Formation (Boom Clay). The Veldhoven Formation was deposited during a regressive phase, after which, in combination with renewed uplift of the area, deposition of the Middle North Sea Group ceased.

Deposition of the Upper North Sea Group was accompanied by a gradual fall in sea level; this is reflected by the continental deposits in the area during the Quaternary. This sea-level lowering exhibited a clearly fluctuating character, as expressed in the alternation of sands and clays in the sediments of the Breda, Oosterhout and Scheemda Formations.

11 Geological History

11.1 Introduction

This chapter gives an overview of the geological history of the map sheet area. The salt movements, the maturation of organic material and the hydrocarbon generation are also discussed. The geological history relates to the period from the Late Carboniferous to the Quaternary. Available information on the preceding period is insufficient for a reliable reconstruction. The Quaternary geology of The Netherlands will be described in future publications ('Toelichting bij de Geologische Kaart van Nederland 1:50.000') by the Survey (Rijks Geologische Dienst).

The geological history of each subsequent period is illustrated by the different tectonic phases active in the map sheet area (fig. 1.7). During the Late Carboniferous and earliest Permian these phases were in succession the Sudetic, Asturian and Saalian phases, related to the forming of the Variscan mountain chain in central Europe. The end of the Triassic as well as the Jurassic were marked by the Kimmerian tectonic phases, which show predominantly extensional tendencies and which are responsible for the major structural units. The Subhercynian and Laramide phases during the Late Cretaceous, and the Pyrenean and Savian phases during the Tertiary were associated with the Alpine Orogeny (mountain building). Compressive deformation reflects the collision between Africa and Europe. The tectonic phases had a pronounced effect on the supply of sediment.These, together with the climate and the sea level, are the determining factors in the development of the area. The specific development of the map sheet area has been examined in a regional context. All the major structures discussed in this chapter are illustrated in figure 1.8.

11.2 Basin development, sedimentation and tectonics

11.2.1 Late Carboniferous.

The geological development in the Late Carboniferous was largely governed by the Variscan Orogeny. During this period, Gondwana (Africa and South America) collided with Laurasia (Europe, North America and Asia). Although the Variscan Mountains were situated far to the south of this map sheet area, their evolution nonetheless had a considerable effect on the geological history of The Netherlands.

The Sudeticphase, at the beginning of the Late Carboniferous, reflects the collision between Gondwana and Laurasia. The N-S oriented compressive stress fields initiated the development of an E-W trending fold belt transecting Europe. In response to the thrust-loading of the earth's crust, induced by the stacking of the (Variscan) overthrusts, a foreland basin was formed to the north of the Variscan fold belt (fig. 2.4), in which vast quantities of erosion products from these mountains were deposited. This large sediment load, several thousands of metres thick in the map sheet area, contributed to an intensification or acceleration of the tectonics-related isostatic subsidence. Sedimentation occurred in a fluvial and lacustrine setting. The tropical climate and the luxuriant plant growth led to the formation of extensive peat marshes. High pressure and temperature consequent to deep burial ultimately changed the peat layers into coal seams (see par. 11.4).

The Asturian tectonic phase at the end of the Westphalian initiated the northward migration of the Variscan orogenic front (Lorentz & Nicholls, 1976). This caused the deposits in the foreland basin to become strongly folded and transported northwards, following a low-angle overthrust plane. Further to the north, approaching the map sheet area, open folds developed in the Carboniferous sediments (Read & Watson, 1975; Ziegler, 1988). In the east of The Netherlands and western Germany, these folds were probably WNW-ESE trending.

The folding was accompanied by uplift and erosion, with the result that part of the topmost Westphalian sediments was removed during the Asturian phase. The extent of the erosion cannot be precisely determined in the map sheet area as the Asturian unconformity was overprinted by the younger Saalian unconformity. However, in view of the fact that Stephanian sediments to the east of the map sheet area (in Germany) immediately overlie the Westphalian C, it may be assumed that the Westphalian D and a part of the Westphalian C sediments were eroded within the map sheet area likewise.

During the Saalian phase, at the end of the Carboniferous and the beginning of the Permian, a transpressional stress-field was caused by the dextral movement of Europe with respect to Africa (Arthaud & Matte, 1977; Ziegler, 1989), producing the N-S trending compressive stress-field to change to a regime of E-W trending, extensional forces. To the north of the Variscan fold belt, a roughly NW-SE and an E-W trending fault system thus developed, characterised by dextral strike-slip movements. Active faulting along this system initiated, in the Variscan foreland basin, the formation of several horsts and grabens (Ziegler, 1982, 1988); these features are prominently present in the Ems Low area.

Active faulting, particularly in northern Germany, Poland and the North Sea area, were accompanied by vulcanism (Lorentz & Nicholls, 1976). In the map sheet area, however, no indications of vulcanism from this period have been found. Nevertheless, immediately to the south of the area, volcanic deposits of the Lower Rotliegend Group have been encountered. The German part of the Ems Low also exhibits thick units of volcanic rocks. The vitrinite reflections of the Carboniferous also suggest a higher heat flow along the eastern margin of the Groningen High, possibly originating from plateau basalts which have been found just to the east of the map sheet area (Ziegler, 1990). There is no clear evidence of strike-slip tectonics in the map sheet area, although the Hantum Fault, to the west of the Lauwerszee Trough, may in fact be a strike-slip phenomenon and the Lauwerszee Trough may be a graben controlled by strike-slip tectonics. The anticlinorium, formed during the Asturian phase, was rejuvenated and transformed into the dome-shaped structure identified in the Carboniferous (fig. 2.1). Erosion cut deep into its central part, penetrating as far as the Westphalian A. This erosion is the consequence both of tectonic uplift and a eustatic sea-level lowering which was caused by a maximum extension of the Gondwana ice cap (Ziegler, 1990). Erosion resulting from the Asturian and Saalian phases as well as a possible period of non deposition on the regional high at the end of the Late Carboniferous caused a hiatus that at the most spanned a period from the Westphalian A up to and including the early Permian (fig. 1.6).

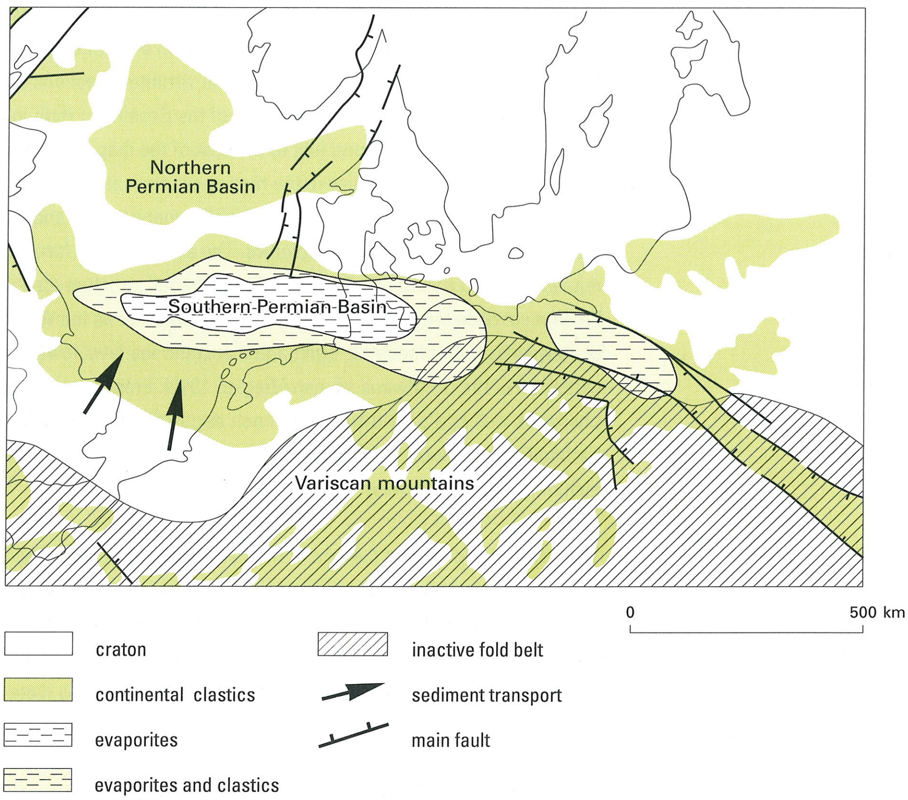
The structures formed at the end of the Carboniferous in and adjacent to the map sheet area appear to have determined the further development of this area. The subcrop map below the Upper Rotliegend (fig. 2.1) reveals some structural elements which may be regarded as precursors of later highs and lows. The erosion deeply cutting into the centre of the dome points to a structural high as part of the incipient Netherlands Swell (Triassic) and the Groningen High (Late Jurassic). The western extent of the Ems Low was also present in essence. The evolution of the Lauwerszee Trough however, was still very premature.

11.2.2 Permian.

At the end of the Saalian tectonic phase in the Early Permian a vast landmass was formed.
An adjustment of the abnormally high temperatures in the lithosphere resulting from the Variscan Orogeny produced subsidence of the earth's crust. A vast intra-cratonic continental basin developed: the Southern Permian Basin (Ziegler, 1982; fig. 11.1), in which clastic sediments originating from the Variscan Mountains and their associated foreland were deposited. As a result of the E-W trending Saalian extensional stresses, a number of N-S trending depressions were formed, such as the Ems Low and the Off-Holland Low, to which drainage converged from the more southerly Variscan hinterland. Figure 3.4 (Van Wijhe et al., 1980) illustrates the influence of the Ems Low in the map sheet area, where sedimentation was governed by a fluvial regime in a desert area. To the west of the map sheet area, outside the reach of the Ems Low, sedimentation was predominantly characterised by aeolian deposits.

Within the map sheet area sedimentation did not resume until the Late Permian. The sedimentary development during the Early Permian was governed not only by thermal subsidence and tectonism but also by water-level fluctuations of the salt lake. This (playa) lake was situated to the north of the map sheet area, in the centre of the Southern Permian Basin (fig. 11.1). A rise in the water level caused a southward extension of the lacustrine deposits, which entailed deposition of the Ameland and the Ten Boer Claystone Members in the map sheet area (fig. 3.1).

Figure 11.1 Palaeogeography of Northwest Europe during the Early Permian showing the position of the Southern Permian Basin (after Ziegler, 1982).



During the Late Permian an abrupt change in the sedimentation pattern took place. Graben formation in the North Atlantic/Arctic area combined with a eustatic sea-level rise as a consequence of melting of the Gondwana ice cap initiated the forming of an open connection between the Barentsz Sea in the north and the continental Northern and Southern Permian Basins (fig. 11.1). The basins had already subsided below the palaeo sea-level, facilitating a very rapid transgression in response (Glennie, 1986). A large Zechstein inland sea in both the Northern and Southern Permian Basins was the result.

The sedimentation pattern in the Zechstein sea was governed to a considerable extent by the influx of fresh sea water. This supply from the Barentsz Sea was episodically obstructed owing to the restricted passage, reflecting a probable barrier between the Zechstein inland sea and the Barentsz Sea.
Any subsequently slight fall in sea level would then have been sufficient to isolate the Zechstein inland sea from the ocean.

Stagnation of water supply and contemporaneous high evaporation caused by a warm, dry prevailing climate led to a sharp increase in the salinity of the sea water. At sufficient levels of concentration, series of carbonates and evaporite were formed. Each large-scale influx of sea water induced by glacio-eustatic sea-level rise marked the onset of a new evaporite cycle. Four such cycles can be differentiated in the map sheet area. Tectonically, the Zechstein was an inactive period, with sedimentation keeping pace with the regional subsidence in the area. The upper cycles exhibit a gradual filling up of the Southern Permian Basin, in which the 4th and 5th cycles, in particular, subsequently levelled the remaining relief, ultimately resulting in a widely extending plain. A sea-level fall at the end of the Zechstein induced the definitive transition to a terrestrial environment (Haq et al., 1987).

The thick salt successions, formed mainly in the 2nd and 3rd cycles, had a major effect on the deformation history of the map sheet area. The plastic property of salt makes it liable to deform much more easily than the other rocks. This led not only to decoupling from the deformations underlying and overlying the Zechstein salts but also to the forming of salt pillows and diapiric structures.
Section 11.3 goes into this in greater detail.

11.2.3 Triassic

The transition to the Triassic is principally characterised by a change in the sedimentary setting. Initially, very little changed in structural terms. The Southern Permian Basin persisted in essence and is therefore often referred to as the Permo-Triassic Basin. Clastic sediments were transported from the south across a widely extending, flat flood plain and were deposited in a lacustrine environment.

After the initially uniform subsidence at the beginning of the Early Triassic, the structural units dating from the Permian, such as the Off-Holland Low and the Ems Low, were reactivated. In the north of The Netherlands, uparching between both areas of subsidence initiated the development of the NNE-SSW-trending Netherlands Swell (fig. 5.2). The north-easterly extent of this high encompasses the major part of the map sheet area. Synsedimentary movements resulted in lateral facies differences in the younger Lower Buntsandstein Formation (the Rogenstein Member). The fluvial deposits of the overlying Main Buntsandstein Subgroup have been preserved predominantly in the areas of subsidence.

On the Netherlands Swell only a relatively thin, cyclic alternation of sand/claystone has been preserved beneath the Base Solling unconformity. The cyclicity was caused by fluctuations in water level in the Permo-Triassic Basin and possibly also by the rise of the hinterland. An additional uplift of the Netherlands Swell during the Late Scythian concluded the deposition of the Main Buntsandstein

Subgroup. Erosion subsequently removed thick sequences of Triassic rocks, which was responsible for the Base Solling unconformity which truncates the Lower Buntsandstein Formation locally in the map sheet area (fig. 5.2).

The first salt flows in the map sheet area, initiated by active faulting associated with differential subsidence of the Ems Low, appeared on the east of the Netherlands Swell (see section 11.3).

During the Middle Triassic, continuing subsidence and a net sea-level rise (Vail et al., 1977) led to a transgression. During deposition of the Muschelkalk the sea-level rise reached its maximum.

The sea gradually flooded the area that supplied the clastics from the Main Buntsandstein Subgroup. The subsequent decrease in clastic influx with respect to the map sheet area eventually resulted in the deposition of carbonates.

A regression during the Late Triassic (Keuper) re-established terrestrial conditions. Subsequent erosion scooped the Middle and Late Triassic deposits from the majority of the map sheet area but a thin sequence remained in the Lauwerszee Trough and the Ems Low owing to pronounced local subsidence. Lateral facies changes from the Ems Low towards the Netherlands Swell (Schröder, 1982) suggest that during the Middle and Late Triassic, the map sheet area - then part of the Netherlands Swell - was a relatively slowly subsiding area with deposition of condensed sequences in the fringe area.

During the Late Triassic a slight uplift affected the map sheet area, associated with the Early Kimmerian tectonic phase (Haanstra, 1963; 't Hart, 1969). This uplift was accompanied by a sea-level lowering causing the erosion of the previous Upper Triassic deposits.

11.2.4 Jurassic

The Jurassic and earliest Cretaceous represent a highly active tectonic period, characterising the onset of the opening of the Atlantic Ocean and the intensified disintegration of Pangaea. This was a continuing process during which a number of major (extensional) tectonic events can be differentiated. These so-called 'Kimmerian' phases dominated the structural evolution of northwest Europe. They are considered to be related to the major interruptions in the stratigraphic succession but the actual boundary between the different phases is less explicit (Stille, 1924; Ziegler, 1978, 1982).

After the short period of erosion caused by the Early Kimmerian tectonic phase during the Late Triassic, the area was subjected to renewed rapid subsidence at the beginning of the Jurassic. Combined with a sea-level rise, this resulted in the deposition of marine sediments. Although the Lower Jurassic sediments are encountered in separate basins (fig. 1.8), the uniform composition of the fine-grained marine sediments, devoid of nearshore characteristics, indicates that these sediments were originally deposited in a single vast continuous area occupying the approximate areal extent of the Southern Permian Basin.

During the Mid Kimmerian tectonic phase in the Middle Jurassic (Bajocian-Bathonian) a vast area in the North Sea region was uplifted, forming the Central North Sea Dome incorporating major highs - amongst which was the Mid North Sea High - and extending as far as the northern border of The Netherlands (Ziegler, 1990; fig. 6.2). The effect of the uplift was intensified by a contemporaneous sea-level fall (Vail et al., 1977). The main part of the map sheet area during the Middle Jurassic was probably situated above sea level (Ziegler, 1990), accounting for the regressive character and the very limited distribution of Middle Jurassic sediments to the southeast of the Groningen High (fig. 6.2).

The Late Jurassic is a period characterised by major tectonic events. This is named the Late Kimmerian phase, with a first pulse occurring at the beginning of the Late Jurassic, and a second pulse at the beginning of the Cretaceous. During the first pulse, the influence of the Central North Sea Dome diminished. E-W trending extensional stresses resulted in the southwards prolongation of the Central North Sea Graben. The stretching of the crust under the graben at the southern end were accommodated by transtensional dextral strike-slip movements along a system of reactivated NW-SE-trending fault systems (fig. 6.2). This was partly caused by the rigid London-Brabant Massif which impeded southwards progradation as well as being a consequence of the presence of a zone of relative weakness, an originally Variscan (possibly even Caledonian) fault system, to the north of this massif. The result was the formation of a number of NW-SE-trending basins and highs, parallel to the London-Brabant Massif (fig. 7.2, Ziegler, 1982). The Hantum Fault, in particular, as well as the formation of the North Netherlands High of which the Groningen High forms a part, had a direct effect on the geological evolution of the map sheet area (fig. 1.8 & 7.2). During the Early Kimmerian phase, the North Netherlands High was initially uplifted, tilted, eroded and subsequently broken up into different elements (Stäuble & Milius, 1970). Tectonically-controlled sedimentation took place in fault-bounded sedimentary basins, especially the Vlieland Basin and the Lower Saxony Basin (fig. 1.8 & 7.2). The adjacent elevated parts constituted the source area for the clastics in these basins. Differentiation between the Lauwerszee Trough and the Groningen High is presumed to have recurred in the map sheet area in this period. Upper Jurassic sediments, although not encountered in the Lauwerszee Trough, are likely to have been deposited and subsequently removed by erosion during the second pulse of the Late Kimmerian phase. The original configuration of the Ems Low attenuated during the Late Kimmerian phase. In this region, subsidence of the Lower Saxony Basin became dominant after the Late Kimmerian phase.

In the map sheet area, Late Jurassic sediments have only been encountered in two wells on the Groningen High and in the rim syncline of the Winschoten salt-structure. The terrestrial nature of these deposits indicates that the map sheet area remained part of the North Netherlands High. The west and north flanks of the high had reduced in size and contemporaneously extended in a southeasterly direction (fig. 6.2 & 7.2; Ziegler, 1990).

A further consequence of the second pulse of the Early Kimmerian phase was the ensuing drastic erosion of the higher parts. The overlapping hiatuses in the sedimentary succession impede differentiation of the movements of the individual Kimmerian tectonic pulses. The intensity of the erosion is demonstrated by the subcrop map beneath the Early Kimmerian Unconformity (fig. 1.8). However, the entire Kimmerian deformation phase is characterised by huge movements along the Hantum Fault and the Groningen High. The great difference in thickness of the Triassic sequence on either side of the Groningen High is illustrated by Section 2 (Map 15). On the east side of the Lauwerszee Trough, the Kimmerian movements were responsible for a net vertical offset of approximately 700 m (Map 6). This offset was induced partly by fault movements and partly by flexure of the Lauwerszee Trough (Map 15). On the western side of the Lauwerszee Trough, the movement along the Hantum Fault produced a maximum throw of 1100 m (Rijks Geologische Dienst, 1991b). The presumed dextral strike-slip component along this fault (Ziegler, 1982; Van Wijhe, 1987) is unquantifiable.

11.2.5 Cretaceous

The beginning of the Cretaceous is marked by a global sea-level rise. This Cretaceous transgression was presumably 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 sea-level reached its relative high stand in the Late Campanian (Hancock & Scholle, 1975). This sea-level rise, combined with the thermal subsidence of the Groningen High, culminated in a eustatic transgression which gradually flooded the entire high. The relief formed as a result of the Late Kimmerian phase was levelled by marine deposits in the Valanginian, Hauterivian and Barremian (Vlieland Subgroup). Initially, sedimentation was restricted to the basins but from the Hauterivian onwards, the more elevated areas were gradually flooded. During the Early Cretaceous, sea-floor spreading predominantly active in the northern part of the Atlantic Ocean and the Bay of Biscay (Hancock, 1984, Ziegler, 1989) further reduced graben formation in the North Sea region. However, this resulted in a continuous thermal subsidence in the entire North Sea Basin. During the Early Cretaceous, the uniform nature of the subsidence in the map sheet area is apparent from the thickness map of the Rijnland Group (Map 10). In this period, sedimentation underwent several interruptions as revealed by the hiatuses in the Vlieland Subgroup (fig. 8.1). At the beginning of the Aptian, the relief was gentle, which may be concluded from the fairly constant thickness of the Holland Formation. During the Early to Middle Aptian a brief regression took place, associated with the Austrian tectonic pulse and is reflected in the map sheet area by a small hiatus at the base of the Middle Holland Claystone Member (fig. 8.1; RGD, 1992c). The period from the Late Aptian to Middle (or Late) Albian was characterised by a new transgressive phase, the Albian transgression. The presence of a number of unconformities and hiatuses demonstrates that the transgression comprised several pulses, identifiable throughout northwest Europe. Ultimately, an open-marine setting evolved to the north of the present Alps and Carpathians extending over a large part of Europe (Hancock & Scholle, 1975). During the Albian transgression, the most elevated parts of the North Netherlands High were flooded (Crittenden, 1987), resulting in sedimentation throughout the map sheet area.

The Cretaceous transgression continued to prograde. Thereby, the distance between the source area of the clastics and the map sheet area increased, reducing the surface extent of this source area. Subsequently, the proportional decrease of terrigenous clastic material was responsible for the predominantly marine bioclastic components in the Upper Cretaceous deposits. The sedimentary succession exhibits a number of unconformities and hiatuses, partly caused by salt movement and partly associated with tectonism and sea-level fluctuations.

The end of the Cretaceous is marked by a change. After a period of relative inactivity, strong plate tectonic-related faulting began during the Late Cretaceous. Europe underwent a major plate reorganisation owing to an extensional stress regime and graben formation preceding the sea-floor spreading in the Arctic and North Atlantic Ocean and consequent to the collision of Africa with Europe. Coinciding with the incipient development of the Alpine fault belt in central Europe, the northwest European platform, where Cretaceous sedimentation prevailed, was again governed by a compressional tectonic regime. Pre-existing faults were reactivated as sinistral, transpressive shear movements (Van Wijhe, 1987). This resulted in the relative uplift of a number of former basins and subsidence of highs in northwest Europe (inversion). This inversion was completed in a series of pulses which have been grouped in two main phases: the Subhercynian phase during the Santonian and Campanian, and the Laramide phase, during the Late Cretaceous (Ziegler, 1982). The latter coincides with a major sea-level lowering causing the topmost Cretaceous (Late Maastrichtian) in the map sheet area to be removed by erosion. Ziegler (1982) directly associates this inversion with the collision of Africa with Europe. Baldschuhn et al. (1991) attribute compressive stress in the crust of NW Europe more to local processes than to the active orogenic belt at a great distance. Lastly, Coward (1991) suggests a connection between the inversion phases and the opening of the Atlantic Ocean.

Within the map sheet area, this did not produce inversion-induced uplift. There was, however, a perceptible shift in the subsidence rate from the Lauwerszee Trough to the Groningen High.
The Lauwerszee Trough, previously a half graben between the Friesland Platform and the Groningen High, subsided less rapidly during the Late Cretaceous than the Groningen High, with the result that the Late Cretaceous succession (Chalk Group) is thicker on the Groningen High than in the Lauwerszee Trough. It resulted also in deposition and preservation of the Maastrichtian in the northeast of the map sheet area (fig. 9.1).

The presence of thinnings as well as small intraformational hiatuses, truncations and mainly Santonian and Campanian-dated angular unconformities (Winsum well, fig. 9.1; RGD, 1992a) above salt pillows and diapiric structures can be attributed to salt movements. These data indicate intermittent diapirism, the speed of which dictated the occurrence either of deposition of a condensed sequence or else of incipient erosion. Contemporaneously, in areas where the salt depletion occurred, thicker sequences of Chalk were deposited. One such sequence has been encountered in De Hond-1 well (fig. 9.1), situated in the depletion area between the salt structures of Ems and Bierum (fig. 11.2, Map 4).

11.2.6 Cenozoic

After the Laramide tectonic phase, during the Cenozoic the North Sea Basin formed a basin which has controlled 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 centre of the North Sea resulted in the deposition of over 3500 m of sediment. The pronounced subsidence of the central axis of the basin, roughly in line with the Viking Graben and the Central North Sea Graben, may be attributed to the cooling and contraction of the lithosphere and to the isostatic subsidence owing to the sediment load in a post-rifting regime (McKenzie, 1978; Sclater & Christie, 1980). In the map sheet area, however, the subsidence was considerably less and the thickness of the Cenozoic sediments here does not exceed 900 m on average. Salt movements initiated collapse structures or depletion areas with deposits not exceeding 1600 m in thickness (Map 13).

In the North Sea Basin, siliciclastic sediments were laid down, in great quantities as a consequence of the Laramide uplift and erosion of the surrounding terrain, thus impeding the bioclastic sedimentation of the Late Cretaceous. During the Tertiary, the sedimentation was largely governed by sea-level fluctuations (Haq et al., 1987) and by a number of tectonic phases, related to the Alpine Orogeny and subsequent erosion, such as the Pyrenean (Early Oligocene) and the Savian (transition Oligocene-Miocene) phases (Letsch & Sissingh, 1983). Sea-level fluctuations caused alternating clay and sand sedimentation, with clays mainly being deposited during high stand and sands during low stand.

At the end of the Miocene, progressive shallowing and withdrawal of the sea on the Groningen High terminated the deposition of marine sediments, previously affected by intermittent flooding several times, and was superseded by terrestrial sedimentation (Scheemda Formation). However, marine sedimentation persisted in the Lauwerszee Trough.

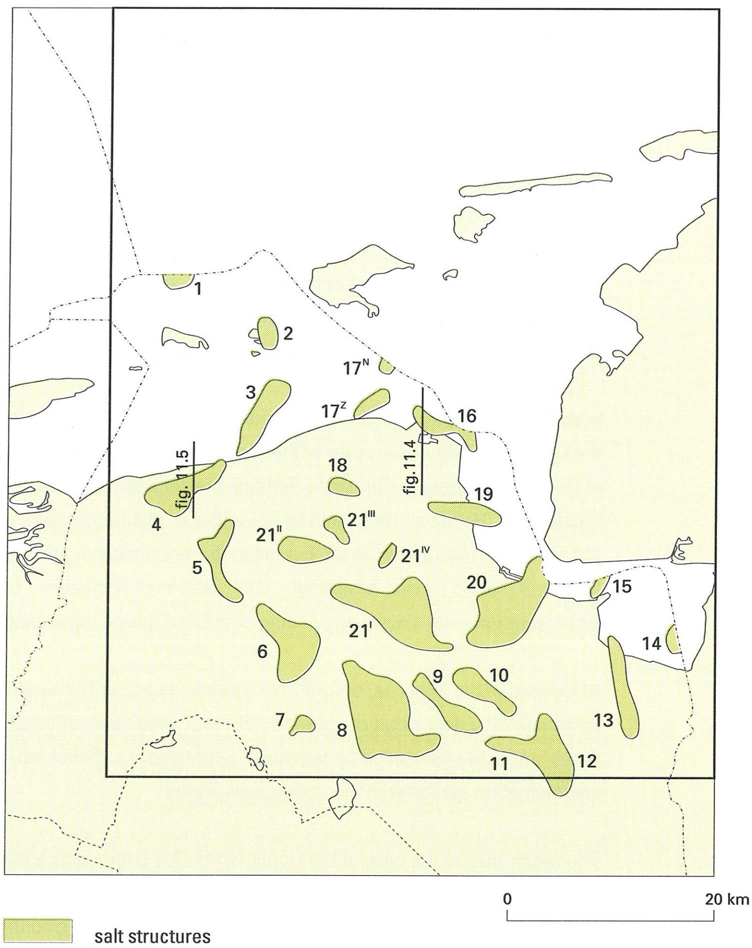
The depth map of the base of the Upper North Sea Group which was deposited during the Neogene and the Quaternary exhibits little evidence of salt movements (fig. 10.4). However, the Groningen High is distinguishable from the Lauwerszee Trough, indicating the continuing activity of these structural elements. During the tectonic phases, the movements appear to have refocused along the pre-existing fault systems, the Lauwerszee Trough being characterised by greater subsidence than on the Groningen High, as maintained throughout the period preceding the Late Cretaceous.

11.3 Salt movements

11.3.1 Introduction

As the previous chapters indicate, the plastic behaviour of the rock salt has exerted a considerable influence on the geological development of the northeast of The Netherlands. On the occurrence of regional deformation, the salt exhibits passive behaviour owing to the physical properties of the salt, and deformation in the basement is virtually absorbed. In this way, the deformation of the rock succession below the Zechstein salt became decoupled from the overburden (Maps 2 & 5).
On the other hand, the active role played by the salt during formation of salt structures is reflected in thickness variations in the overburden as a consequence of synsedimentary salt flow, and in deformation of the overburden induced by doming and piercement of this overburden by the salt.
The dimensions and the positions of the salt structures can best be determined from the depth map of the top of the Zechstein Group (Map 3) and the thickness map of this group (Map 4).
Thickness variations in the Mesozoic and Cenozoic successions reflect the effects of the vertical

Figure 11.2 Location of the salt accumulations in the map sheet area. Due to the salt movement and subsequent erosion, the salt structures are overlain by a number of different stratigraphic units (see figure 4.2). For the numbering, see table 11.1.



structural movements and the salt movements, providing an indication of the history of the movement of the salt structures during the corresponding epoch. Finally, the periods of accelerated salt flow prove to have coincided with the tectonic phases.

Within the map sheet area, twenty-one salt structures have been differentiated (table 11.1, fig. 11.2), a number of which continue into the adjacent German territory (NLfB, 1989; Jaritz, 1973, 1992).

Table 11.1

Table 11.1 Overview of salt structures stating some of the characteristics. The numbering of the salt structures refers to locations in firuge 11.2. The type of salt structure is indicated by P: pillow or D: diapiric. The thickness of the caprock refers to the maximum thickness as determined from boreholes. The overburden is the sedimentary succession immediately overlying the salt structure.

Name	*Type*	*Thickness (max)*	*Depth (top)*	*Caprock (thickness)*	*Overburden (age)*
1. Riffgrund	P	2000 m	1600 m		E. Triassic
2. Rottumeroog	P	2200 m	1400 m		E. Triassic
3. Groninger Wad I	D	1700 m	1400 m		E. Cretaceaous
4. Pieterburen	D	2700 m	150 m	90 m	E. Triassic/ L. Cretaceaous/Tertiary
5. Winsum	P	1500 m	1500 m		E. Triassic
6. Groningen	P	1600 m	1200 m		E. Triassic
7. Haren	P	1400 m	1700 m		E. Triassic
8. Hoogezand	P	1600 m	1000 m		E. Triassic/E. Cretaceous
9. Noordbroek	P	1100 m	1500 m		E. Triassic
10. Nieuw-Scheemda	P	1100 m	1600 m		E. Triassic/Jurassic
11. De Eeker	P	1100 m	1300 m		E. Cretaceous/E. Jurassic
12. Winschoten	D	2200 m	500 m	20 m	E. Triassic/E. Cretaceous
13. Klein-Ulsda	D	2200 m	1100 m		E. Triassic/L. Cretaceous
14. Landschaftspolder	D	2400 m	1100 m	40 m	E. Cretaceous
15. Dollart	P	1400 m	1600 m		E. Triassic
16. Eems	P	1300 m	1600 m		E. Cretaceous
17. Groningen Wad IIN	D	1400 m	1700 m		E. Cretaceous
Groningen Wad IIZ	P	1200 m	1400 m		E. Cretaceous
18. Usquert	D	1100 m	1600 m		E. Cretaceous
19. Bierum	P	1500 m	1800 m		E. Cretaceous
20. Delfzijl	D/P	1400 m	1400 m	30 m	E. Cretaceous
21. Ten Post I-IV	P	1100 m	1600 m		E. Cretaceous

11.3.2 Rock properties and process of formation

Salt deforms significantly more easily than competent rocks such as sandstone and limestone. Brittle faulting in competent rocks of this types will be accommodated by plastic behaviour of salt as the pressure gradient in the salt is relaxed by flow. Consequently, faults in the basement (thick-skin tectonics) do not usually progress into the salt, with the result that the deformation underlying and overlying the Zechstein has been decoupled (disharmonic). Deformation restricted to the topmost strata of the earth's crust, as in the north of The Netherlands, is termed "thin-skin tectonics".

Salt movements normally exhibit a lateral or upward direction. The driving forces are constituted by differential loading, the density contrast between the relatively light salt and the heavier overburden, and tectonic stress (Koyi, 1988).

The majority of the salt structures in the map sheet area, as in the case of the salt structures in and around the southern North Sea, related to faults in the basement (Jenyon, 1986; Jaritz, 1987; Koyi, 1991; Remmelts, in press). The original assumption was that the buoyancy force exerted by the salt as a result of its lower density (2.2 gr/cm^3) with respect to the overburden (up to 2.4 gr/cm^3 with sufficient compaction), was suitable for the formation of salt structures (Trusheim, 1957, 1960). However, recent studies have shown that the overburden is too resistant for this buoyancy force (VUA, 1992; Koyi et al., 1993). This strength is reduced by large-scale fault movements in the basement. Figure 11.3 shows the three stages of the formation of a salt structure initiated by faulting in the basement. The primary situation with the salt sequence resting on the basement and topped by an overburden (fig. 11.3a). In this situation, a buoyancy force in the salt is dominant owing to the density contrast with the sediment sequence. However, the uniform overburden gives rise to a state of (unstable) equilibrium. Where extensional stresses in the basement initiate a normal fault (fig. 11.3b.), a number of aspects in this situation are altered. In the first place, the faulting leads to weakening of the overburden. Despite accommodation of the faulting by the salt, deformation of the overburden nonetheless occurs, even though the faulting is not progressive in these strata. Accompanying extensional stresses produce small faults, thereby weakening the overburden strength. In the second place, the uniformly distributed pressure of the overburden on the salt is disrupted. Sedimentation increases differentially and is greater in the area subjected to downthrow than on the upthrown side of the fault. The ensuing difference in density contrast will cause the salt to flow upward from the deeper part to the higher fault block where it accumulates (fig. 11.3c). As illustrated by the Groningen High, the effect of the faulting in the basement may also be achieved by a steep monoclinal structure in the basement. An accumulation of this sort is called a salt pillow. In the case of continuing accumulation and piercement of the salt through the overburden, the term diapiric structure is used (see table 11.1).

An example of a salt pillow is the Ems structure (16) illustrated in figure 11.4. This seismic section shows the faults in the basement, with the salt structure on the upthrown side. The faults in the basement do not penetrate the overburden and the deformation above and below the salt is disharmonic. It is also obvious that the differential loading of the salt has caused widespread withdrawal of virtually all of the salt on the downthrown side of the fault, while a fairly thick salt sequence remains on the upthrown side of the fault.

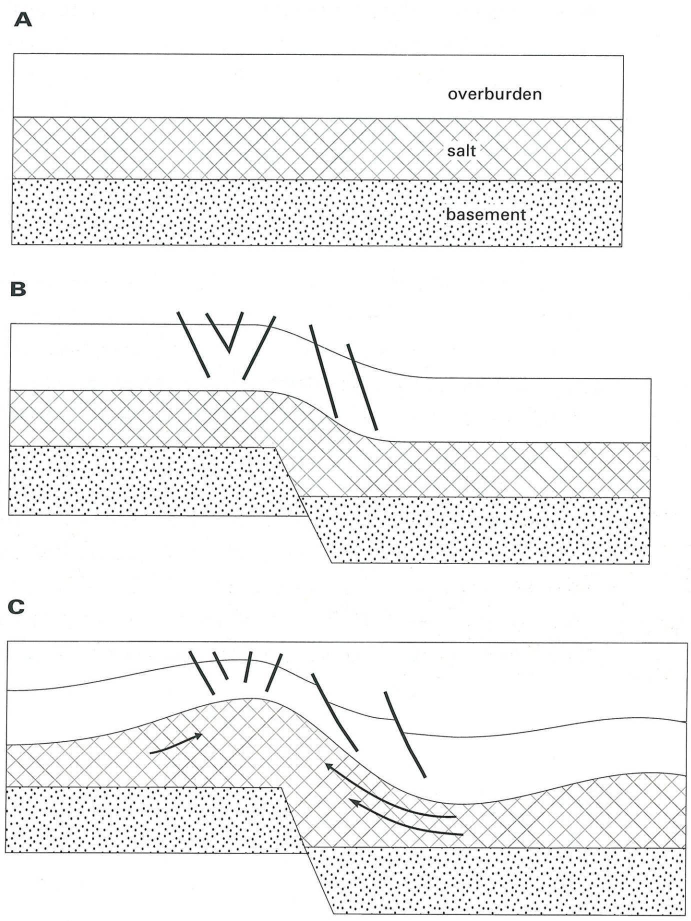
The connection between the movements along the faults in the basement and the position of salt structures is clearly illustrated in the depth maps of the base and the top of the Zechstein Group (or in the thickness map of the Zechstein group clearly displaying faults in the basement as well as in the salt structures; Map 2, 3 & 4). Most of the salt structures are situated along the largely fault-induced flanks of the Groningen High. The orientation of the salt structures is parallel to that of the underlying faults. Only the northern margin of the high is non fault-bounded, and determined by a steep monocline, but the result is similar.

11.3.3 Groups and individual salt structures

The salt structures along the northeastern and eastern flanks of the Groningen High are associated with the development of the Ems Low. They have a NNW-SSE orientation in the southeast of the map sheet area, becoming more NE-SE oriented towards the north. Figure 11.2 illustrates these structures, numbers 13 to 19 and the salt structures in adjacent area in Germany (Jaritz, 1987, 1992). It has been

demonstrated that Klein-Ulsda (13) and Landschaftspolder (14) and a number of salt structures in northwest Germany (Jaritz, 1973) were initially formed during the Scythian (salt pillow stage), when the Ems Low was undergoing a major extensional phase. Salt movement is revealed by the deep truncation of the Base Solling unconformity in the Lower Buntsandstein Formation. The salt structures are thought to have developed into diapirs during the Keuper (Carnian-Norian). Prominent internal differences in thickness of the Keuper deposits, as in the vicinity of the Klein-Ulsda salt-structure, are indicative of the influence of diapirism. The absence of Middle Triassic up to Upper Jurassic deposits means that the tectonic phases of the remaining structures of this group in The Netherlands cannot be clearly determined. However, the structural context would seem to indicate the likelihood of a second, later tectonic phase at the end of the Jurassic, associated with the Late Kimmerian phase.
For this period, Landschaftspolder salt-structure is a clear example of a salt structure reaching a diapir stage extending up to or immediately below the surface, forming a caprock. Lower Cretaceous deposits transgressively overlay this structure. During the Late Cretaceous (Santonian-Campanian) Klein-Ulsda and Landschaftspolder salt-structures were reactivated, as demonstrated by internal synsedimentary unconformities. On the flanks of Klein-Ulsda salt-structure the youngest Upper Cretaceous transgressively onlaps the structure, but near its top, this too was removed by erosion. During major periods of the Late Cretaceous, the salt structure reached the (near) surface; a caprock is thought to have formed on top of the Klein-Ulsda salt-structure at this time. Subsequently, during the youngest Eocene and Oligocene and during the Neogene, only minor movements occurred.

Figure 11.3 Schematic line drawing showing the development of a salt structure in relation to active basement faulting.



The collapse structure in the overburden above Klein-Ulsda salt-structure may probably be attributed to a combination of rock salt solution and possibly a withdrawal of the salt.

The Delfzijl salt-pillow (20) is fault-bounded on the east side, which is manifestly associated with the NNW-SSE fault in the basement, while the remainder of the structure has a NE-SW trend, not attributable to a fault in the immediate vicinity. The formation of this structure should be regarded more as a response to the development of the adjacent structures. The orientation differs from that of the Ems Low, which shows a greater correspondence to that of the Lower Saxony Basin which evolved during the Late Jurassic. The Bierum salt-structure has a WNW-ESE orientation and is associated with faults with a minor offset. This is represented in the less advanced development of the structure. The southeastern point of the structure is the most prominently developed, partly because here the fault in the basement has the greatest offset and also because salt flow was directed from the northern and southern areas to this point. The salt structure is situated on a horst-shaped spur of the Groningen High. To the northwest of Bierum it is clearly evident that the forming of the structure predates the Cretaceous, and can be attributed to possible extension of the overburden, facilitating salt ascent.

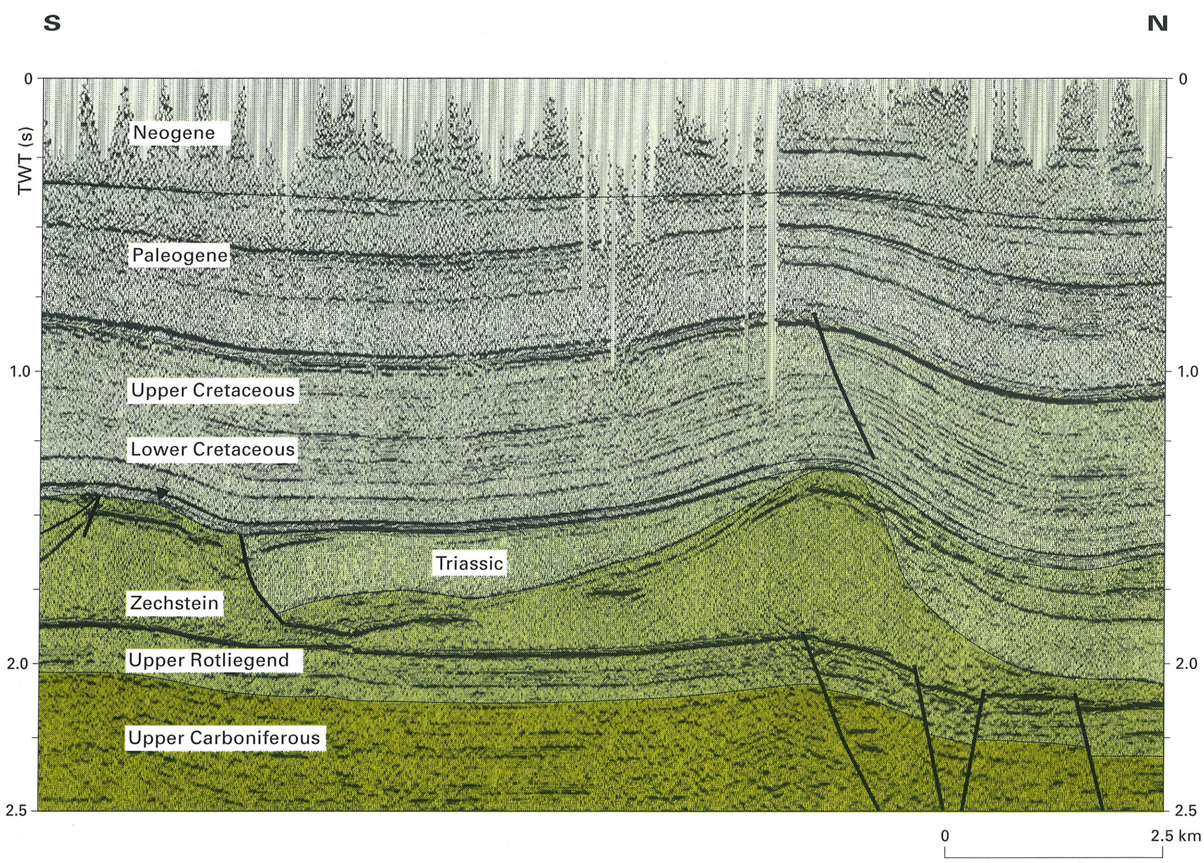


Figure 11.4 Seismic section through the Ems salt-pillow, situated on the edge of the Groningen High.

The erosion at the beginning of the Cretaceous cut into the structure, and resulted in solution of large quantities of salt. The structure has been inactive since the beginning of the Cretaceous.
The Ems salt-structure (16 in fig. 11.2) is associated with the actual margin of the high. From the southern point of the structure, faults run in a northwesterly and northerly direction, both accompanied by a salt structure. The salt structures in the Wadden Sea (particularly 1 and 2) were controlled by N-S oriented faults associated with the Ems Low. To the west (Groningen Wad I), however, the effect of the Lauwerszee Trough is dominant.

The southwestern margin of the Groningen High exhibits a double row of salt structures (4 to 11 and 21), the outermost row being the most strongly developed (Map 3). This double row is attributed to the structure of the basement. From the Lauwerszee Trough to the Groningen High, two successive fault scarps are distinguishable: firstly, a steep monocline to a horst and subsequently a half graben fault-bounded on the side of the Groningen High (Map 2). The hiatus in the overburden obscures the timing of the development of the structures. However, the unconformable contact between the Lower Cretaceous and the Triassic in the vicinity of the salt structures marks the development as prior to the Cretaceous. The salt movement was probably associated with the Late Kimmerian phase.
The pronounced thinning of the corresponding sediment successions (Maps 12 & 13) indicates phases of intensified salt flow during the Late Cretaceous (Campanian) and during the transition of the Eocene to Oligocene. The Ten Post salt-structure (21) incorporates four salt accumulations. Their positive relief was formed by the extraction of salt by other structures in the immediate vicinity. However, virtually no salt flow occurred to the Ten-Post structures owing to their position on a relatively undisturbed part of the Groningen High. In the case of the Groningen salt-structure, the initial movements occurred prior to the Cretaceous, with a renewed period of intensified salt movement during the Late Cretaceous probably in conjunction with the Subhercynian phase. An intraformational unconformity of the Upper Cretaceous deposits (circa Late Campanian) is overlain by Maastrichtian sediments.
The Palaeocene and the early Eocene represents an inactive period, followed by the development of a fault zone in the overburden during the latest Eocene and the Oligocene. This listric fault runs down over the flank of the salt structure, causing the overburden to slide down. The SW part of the structure was thrust upwards more intensively than the NW part, resulting either in greater erosion or in reduced sedimentation. As a result, the base of the Tertiary had an offset of 150 m along the fault already during the Palaeogene. The movements persisted into the Neogene, but the approximate difference in depth of the base of the Neogene deposits along the fault plain measures only 50 m. An asymmetrical structure of the overburden also highlights the Hoogezand salt-pillow (8). This fault zone was initiated during the Late Cretaceous, corresponding to the Subhercynian phase. The displacement by this active faulting resulted in an offset of some tens of metres. During the Palaeocene and Eocene salt movements were initially absent, although subsequently increasing during the course of the Eocene and Oligocene. In contrast to the Groningen salt-structure (6), however, the NE flank of the Hoogezand salt structure underwent an uplift. During the Palaeogene, the base of the Tertiary exhibited an offset of circa 150 m. The base of the Neogene had an additional offset of circa 100 m, indicating that the structure is likely to be still active.

The northern flank of the Groningen High is delimited by the Pieterburen and Groningen Wad I salt-structures. In particular, the Pieterburen salt-structure is highly developed (fig. 11.5), the top reaching up to 150 m below surface level. Seismics demonstrate a pronounced normal fault in the basement beneath the salt structure. Accurate dating of the initial salt movements is problematic owing to intensive erosion in the vicinity of the Pieterburen salt-structure; the erosion of the Lower Buntsandstein Formation where the present salt structure was situated at the beginning of the Cretaceous, points to the pre-existence of the Pieterburen salt-structure. Intensive movements prevailed, especially during the Late Palaeogene and Early Miocene, causing the salt structure to ascend very close to the earth's surface. Only the youngest Tertiary deposits are encountered on the top of this structure. In the Quaternary the salt structure appears to have determined the position of the coastline in this area (see Zagwijn, 1990). The development of graben structures on either side of the top of the salt structure was the compensational result of the extension of the overburden owing to the rise of the salt. The geographic orientation of the Pieterburen salt-structure displays two dominant directions: a more or less WNW-ESE orientation, associated with the highly inclined northern flank of the Groningen High (Map 2), and a NW-SE orientation associated with the fault direction characterising the west flank of the high. The top of the structure coincides with the intersection of the two edges of the Groningen High. In contrast to the other margins of the Groningen High, the boundary in the north is not entirely delimited by a fault but partly by a steep monocline, producing a differential loading of the salt and an overburden which is weakened by extension. This means that the same process of

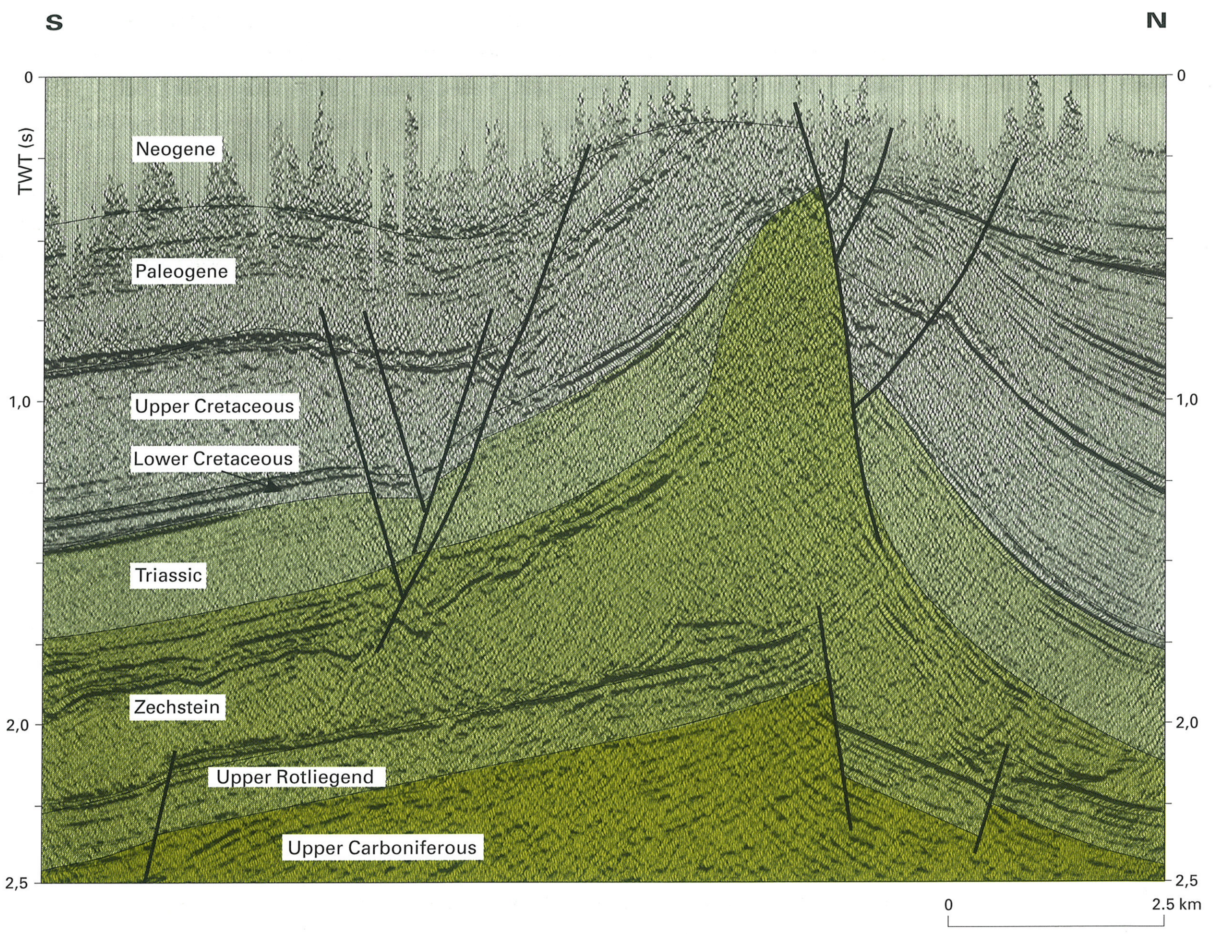


Figure 11.5 Seismic section over the Pieterburen salt-structure. The fault in the basement is notable. Thinning of the Upper Cretaceous and the Palaeogene reflects the main tectonic phases. At the south side of the salt structure a graben developed in the Neogene overburden as a result of salt depletion.

formation for salt structures can be applied. Harsveldt (1980) concluded that the Pieterburen salt-structure was associated with overthrusts. Modern seismics cannot account for the internal structure of the Zechstein salt but the configuration of the main faults both in the top of the salt structure and at the base of the Zechstein indicates the likelihood of normal faults (fig. 11.5). The interpretation given by Harsveldt (1980) of tectonically-induced repetition of the rock salt sequence is nowadays attributed to halokinetic deformation. Relaxation faults are found in the overburden above the Pieterburen and Groningen Wad I salt-structures. These normal faults are presumed to have developed after the attenuation of the compressional tectonic regime associated with the Pyrenean phase. The presence of these normal faults up to approximately 150 m below surface level is an indication of recent (geological) activity.

The southern margin of the Groningen High is considerably more complex than the northern margin. At this southern margin, the Lauwerszee Trough fault systems (NW-SE) interfere with those of the Ems Low (NNW-SSE) and the Lower Saxony Basin (E-W). This is reflected in the salt structures by a great variation in geographic tendency, particularly apparent in the Hoogezand (8) and Winschoten (12) salt-structures. The date of the onset of the movements is indeterminable owing to the hiatus in the sedimentary succession revealing a number of stages and tectonic phases. However, it is clear that the Late Kimmerian phase was an important event causing a number of salt structures (e.g. Winschoten) to reach the diapiric stage. This tectonic phase marked the evolution of the Lower Saxony Basin and the (re)activation of the other fault systems. The top of the Winschoten salt-structure, situated within the AKZO-Nobel "Adolph van Nassau" rock salt concession, lies at a depth of approximately 500 m and the caprock immediately overlain by the Rijnland Group indicates that this structure reached the surface during the Early Cretaceous. During the Early and Late Cretaceous, the rock salt was initially immobile but during the Campanian, the Winschoten salt-structure clearly developed as a positive relief element. At the end of the Cretaceous, the structure lay very closely beneath the surface level. After the earliest Palaeocene up to the Eocene, the period characterised by non-existent or minimal activity of salt movement was succeeded by the intensified diapiric movement of the Winschoten salt-structure during the Late Eocene and Oligocene. The presence of a secondary rim syncline on the southern side of the structure indicates diapirism during this period, owing to reduction in thickness of the sequence above the salt structure during the Late Cretaceous and Palaeocene. The depth of the base of the Neogene deposits points to an ascent of the salt of approximately 100 m. The trending direction of the Winschoten salt structure displays interference of three different structural directions (Map 2): the N-S tendency of the Ems Low, the NW-SE axis trend of the Lauwerszee Trough and the more E-W tendency of the Lower Saxony Basin.

11.4 Geochemical evaluation and burial history

11.4.1 Introduction

The gigantic Groningen gasfield and the surrounding smaller fields are filled with gas composed predominantly of methane. The gas of the Groningen gasfield is fairly constant in composition.
The source rock of the Groningen gas is the underlying coal-bearing strata of the Limburg Group (Upper Carboniferous) and, in particular, the deposits of the Caumer Subgroup (Westphalian A-B).
The total organic content in the Caumer Subgroup is approximately 4%. In the study area, the thickness of the Caumer Subgroup varies between 1000 and 1500 m.

By modelling the burial history, the degree of coalification of the gas-source rock in a well can be determined. The burial history can be inferred from the stratigraphic sequence penetrated.
The duration of the hiatuses in the succession is extrapolated from the thickness trend of the stratigra-

phical successions in the adjacent area. The modelled coalification must be adjusted using the petrographic and geochemical measurements on organic components of the rock from the well in question. Once the coalification interval for a particular period has been established, the process of gas generation from the source rock can subsequently be determined.

The reconstruction of the palaeo burial-history of the map sheet area is complex. A number deformation phases occurred, causing several hiatuses to appear in sedimentary documentation. The halokinetic tectonism is an additional complication (Map 4; fig 11.2). The following are the principal geologically uncertainties in the modelling: (1) the quantity of eroded Westphalian-Stephanian deposits, (2) the quantity of eroded Triassic-Jurassic deposits, (3) the varying thickness of the Zechstein salt through geological time as a result of halokinesis and (4) palaeo-heat flow.

In determining the burial-depth history, the total thickness of the Westphalian and Stephanian is taken to be approximately 2500 m (Caumer, Dinkel and Hunze Subgroup). The original thickness of the Zechstein succession in the map sheet area is estimated at 700 to 800 m. In the models, a gradual increase in the growth of the Zechstein salt has been presumed where necessary. The Zechstein salt, and particularly its flowage, affected the coalification of the underlying strata. From the Jurassic onwards (section 11.3), salt pillows and diapiric structures acted as 'chimneys' for high heat dissipation, owing to the high heat-conductivity of the salt. This 'chimney effect' makes a significant contribution to the coalification of the underlying strata and has therefore been incorporated in the modelling. The thickness of the Triassic succession in the Ems Low may be as much as 2000 m, but towards the Groningen High may rapidly attenuate to approximately 1000 m. For each well, a value within the interval has been adopted, depending on the location. Finally, the modelling is based on two phases of increased heat flow during the Carboniferous and the Jurassic. The heat flow augmented rapidly to approximately 60 mW/m^2, successively followed by a presumed logarithmic decay.

A study was made of the maceral material of the Limburg Group and Coppershale Member (Zechstein Group) from a number of wells within the map sheet area (Table 11.2; RGD, 1994) in order to test the burial model. The degree of coalification is determined from various parameters such as vitrinite reflections, RockEval Tmax (Veld et al., 1993; Veld, 1995), and various geochemical indices.
The activation-energy distribution of the Coppershale Member was also established. These data were used to reconstruct the history of oil and gas generation in the study area.

11.4.2 Results

The geochemical modelling relates to an area of 40x40 km in the southeastern of the map sheet area. Reliable vitrinite-reflection analyses of the Limburg Group were obtained from five wells (Table 11.2). The vertical coalification trend in the Tjuchem-2 well (1.23 %Rr/km) was used for extrapolation of reflection data towards the top of the Limburg Group (fig. 11.6). Together with data available on the map sheet area (Rijks Geologische Dienst, 1991a, 1993a, 1993b; Geologisches Landesamt Nordrhein-Westfalen, 1984; Teichmüller et al., 1985) these data present a picture of increasing coalification of the top of the Limburg Group in a northerly direction.

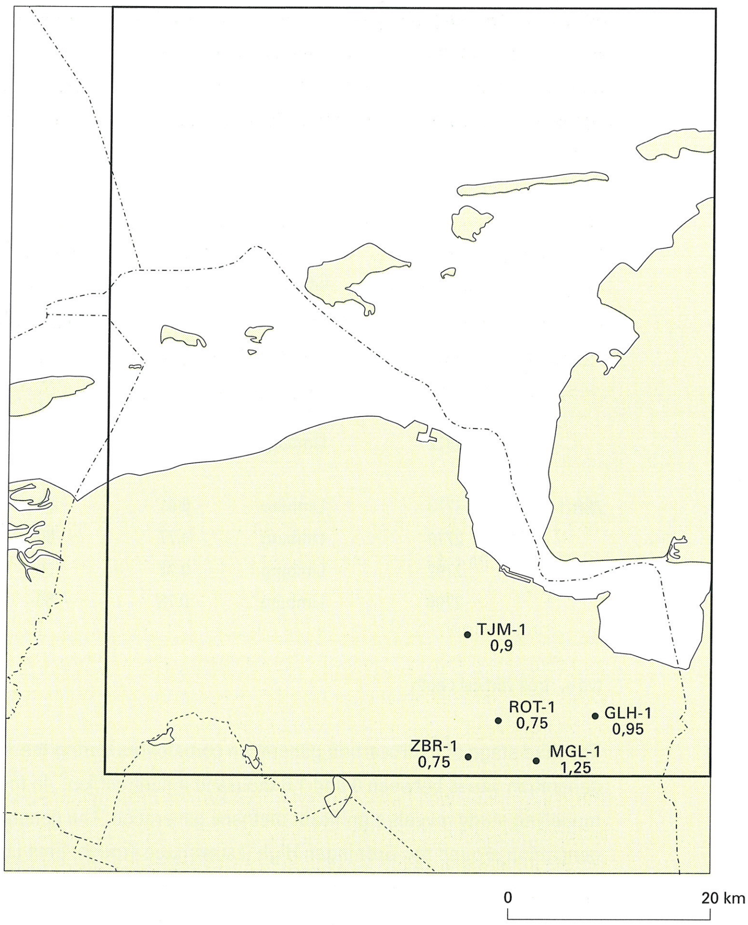
The Heiligerlee-1 well has a relatively high vitrinite reflection of approximately 1.1% at the top of the Limburg Group, which cannot be adequately clarified. Substantial causes could be intense local Varistic uplift and erosion, local heating by an intrusive body or local major basin subsidence during the Jurassic.

Deposits of the Coppershale Member from four wells were analysed (Table 11.2). Reflection measurements were carried out on the frequent occurrences of bituminite. As the genesis of this maceral matterial differs substantially from vitrinite, a direct comparison of the coalification data of the Coppershale Member with the Limburg Group was not feasible. The data have been presented in table 11.2 without any conclusions being drawn at this point.

The burial depth history of the Groningen High and the inferred hydrocarbon generation is illustrated by the Roode-Til-1 well (fig. 11.7a, b). The initial coalification stage occurred at the end of the Carboniferous. Nearly all the wells are devoid of gas expulsion during the Carboniferous. In spite of the somewhat arbitrary assumption of the total depositional thickness of the Westphalian and Stephanian (2500 m), the expulsion of hydrocarbons does not alter significantly if the assumed thickness varies within wide margins. The maximum burial depth during the Carboniferous was not sufficient to generate oil or gas in significant quantities. After uplift and partial erosion of the Westphalian, 1000 to 1500 m of coal-bearing Westphalian remain as source rock for later stages of hydrocarbon generation.

The second phase of coalification was initiated during the Late Jurassic. A combination of increased heat flow and deep burial during the Kimmerian rift phase generated significant quantities of gas. Quantitative analyses indicate that this was the main phase of hydrocarbon generation in the area.

Figure 11.6 Reflection value (Rr) at the top of the Limburg Group, and the positions of wells in Table 2. The Rr-values of Table 2 have been extrapolated towards the top of the Limburg Group (refer to text).



However, considerable differences in the simulated quantities of hydrocarbon in each well have been demonstrated. The methane expulsion varies between 0.1 and 5.5 thousand million m^3/km^2. The west and south of the map sheet area in particular exhibit high gas generation (fig. 11.8a: Ten Boer-1 and Heiligerlee-1 wells). The total hydrocarbon generation during the Late Jurassic varies between 1 and 16 million tons/km^2.

Table 11.2

Table 11.2 Vitrinite reflections (%Rr), population size (n) and standard deviation (s.d.) of the samples.

Well	*tvd*	*group*	*%Rr*	*n*	*s.d.*
GLH-1	2990	Zechstein	0.45	50	0.114
	3187	Limburg	1.01	50	0.037
	3377	Limburg	1.07	50	0.050
	3387	Limburg	1.10	50	0.050
HAR-1	3108.5	Zechstein	0.33	50	0.089
HGL-1	2884	Limburg	1.27	60	0.313
ROT-1	2775	Limburg	0.73	50	0.039
	2777	Limburg	0.82	50	0.027
	2787	Limburg	0.89	50	0.032
	2792	Limburg	0.79	50	0.040
SLO-1	2645	Zechstein	0.37	50	0.059
TBR-1	2767	Zechstein	0.84	50	0.111
TJM-2	3544.5	Limburg	1.70	50	0.154
	3833	Limburg	2.26	50	0.162
	4170	Limburg	2.16	50	0.456
	4304	Limburg	2.39	13	0.262
	4902	Limburg	3.69	10	2.320
	5702	Limburg	4.53	4	0.950
	5912	Limburg	4.68	14	0.499
ZBR-1	2773	Limburg	0.81	50	0.045
	2779	Limburg	0.77	50	0.032
	2792	Limburg	0.72	50	0.026
	2796	Limburg	0.78	50	0.051

tvd = true vertical depth

The third stage of hydrocarbon generation commences during the Tertiary. The Cenozoic methane generation varies between 0 and 1.8 thousand million m^3/km^2. In the southwest (Haren-1 well), the modelling study reveals significant methane generation. The general trend is relatively high methane generation around the Groningen High (Lauwerszee Trough, Ems Low; fig. 11.8b). The total hydrocarbon generation during the Cenozoic varies between 0 and 7.4 million tons/km^2.

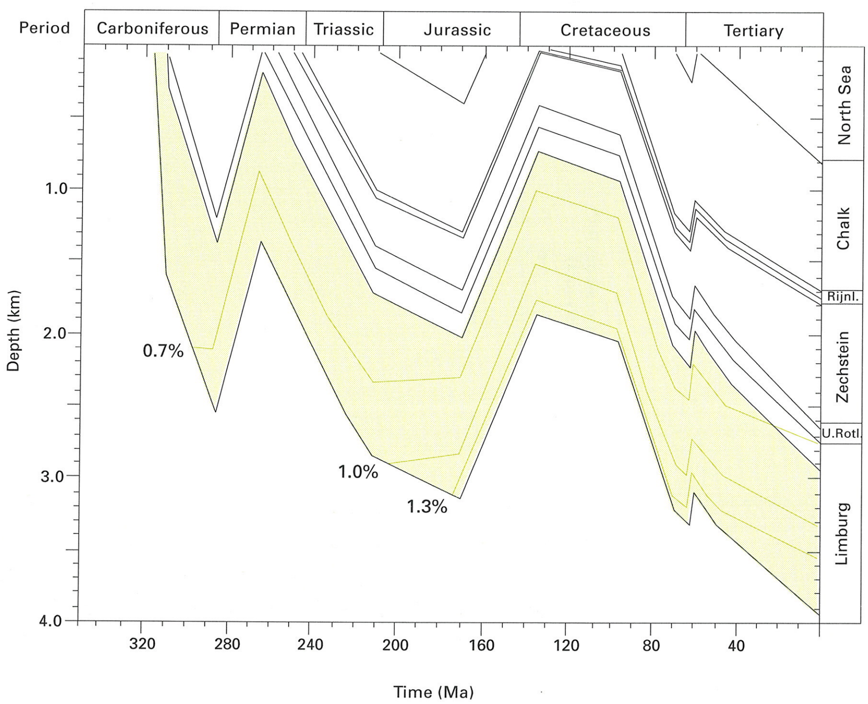
There is a considerable discrepancy between the composition of the generated hydrocarbons of the coal-bearing Westphalian and the composition of the accumulated gases. The following table illustrates the gas composition of the gas reservoirs of Slochteren-1 well, representative of the Groningen gasfield.

Table 11.3 Gas composition of the Groningen gasfield.

C1	*C2*	*C3*	*C4*	*C5*	*C6*	*C7plus*	*C*	*N2*	*H2S*
81.24	2.89	0.41	0.15	0.04	0.02	0.05	0.93	14.26	0.00

The source rocks contain a high yield of extracts characterised by predominant aromatic components and asphaltenes. The modelling study also shows that whereas one might anticipate a relatively large quantity of higher hydrocarbons from the Limburg Group deposits (fig. 11.7b), the gases contain a relatively low quantity of condensates and higher hydrocarbons. This discrepancy is very probably attributable to segregation during migration. The coal tends to obstruct heavier, aromatic components (while the lighter components migrate relatively rapidly). Hydrocarbons, likewise, may be transformed by either a secondary cracking process to a greater fractional residue or to an additional fraction of methane and condensates.

Figure 11.7a Burial history diagram of the Roode-Til-1 well. Gas generation takes place in coal seams occurring in the 'gas window' (Rr: 0.9-1.3). The Westphalian of the Roode-Til-1 well displays gas generation during the Jurassic and the Cenozoic.



In summary, it may be concluded from the modelling study that gas generation during the Jurassic was more than adequate to fill the Groningen gasfield. Additional gas suppletion during the Tertiary would appear to be highly probable.

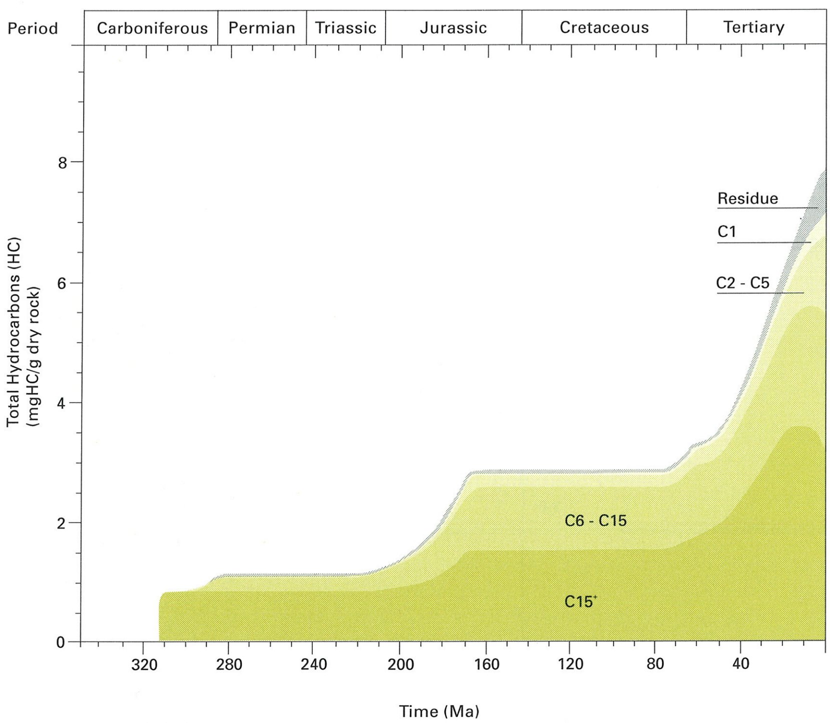


Figure 11.7b Hydrocarbon generation as a function of time in the Roode-Til-1 well.

Figure 11.8a Contour map of the gas generation during the Jurassic (in 10^9 m^3/km^2) on map sheet III. The largest quantities of gas were generated on the flanks of the Groningen High. The gas accumulated below the sealing Zechstein salt in the permeable sandstones of the Upper Rotliegend.
a Gas generation during the Jurassic
b Gas generation during the Cenozoic

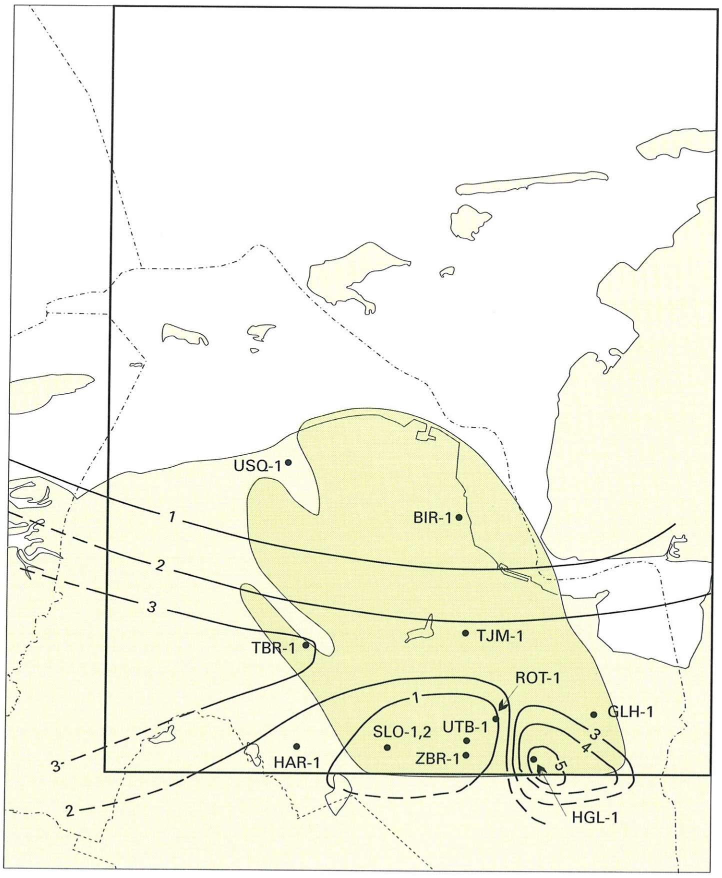
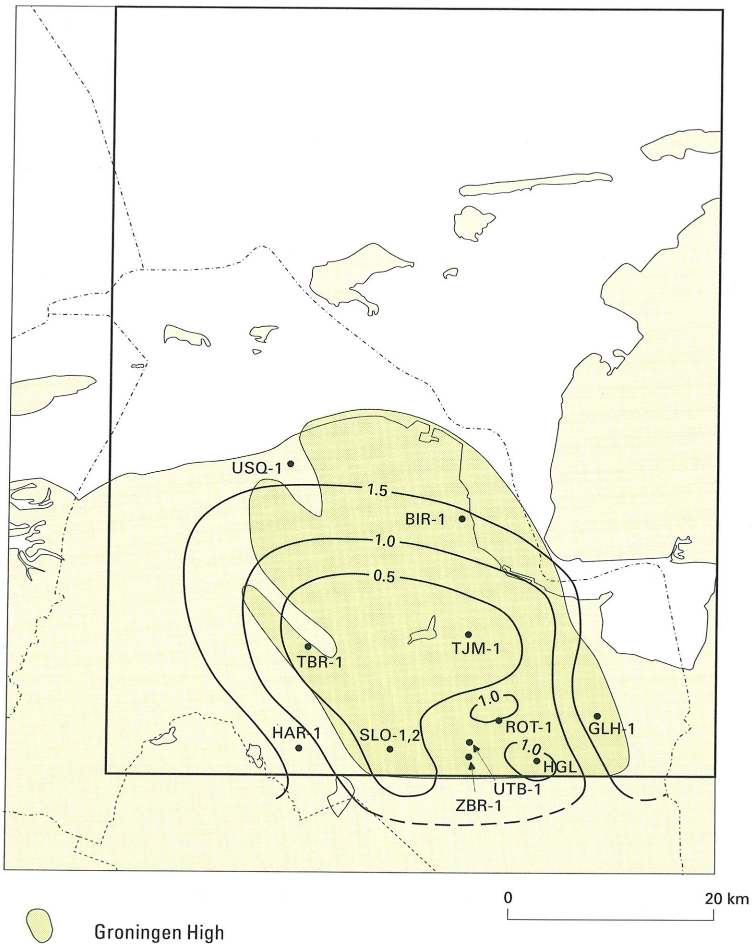


Figure 11.8b Contour map of the gas generation during the Cenozoic.



Appendices

Appendix A

Seismic data used

Survey	*Year*	*Owner*	*2D/3D*
7120**	1971	NAM	2D
7190**	1971	NAM	2D
7270**	1972	NAM	2D
7590**	1975	NAM	2D
7892**	1978	NAM	2D
8**	1964	NAM	2D
PN7-85-16A	1985	Placid	2D
Eemsmonding	1985	NAM	3D
Grootegast	1985/1986	NAM	3D
Groningen Westflank			
part 1 & part 2	1986/1987	NAM	3D
Groningen stad	1987	NAM	3D
Groningen veld	1988	NAM	3D
Lauwerszee	1983	NAM	3D
Uithuizen	1988	NAM	3D

** refer to specific line numbers

NAM = Nederlandse Aardolie Maatschappij B.V.

Appendix B

Overview of wells used[1].

No.	Well	Code	Owner	Total depth (along hole in metres)	Year (of completion)
1	Allardsoog-1	ALO-01	NAM	3180	1984
2	Amsweer-1	AMR-01	NAM	2974	1972
3	Annerveen-1	ANN-01	NAM	3057	1973
4	Annerveen-5	ANN-05	NAM	3060	1984
5	Annerveen-Anlo-1	ANA-01	NAM	3014	1962
6	Annerveen-Schuilingsoord-1	ANS-01	NAM	3190	1970
7	Annerveen-Veendam-1	ANV-01	NAM	3217	1969
8	Annerveen-Wildervank-1	WDV-01	NAM	3188	1967
9	Bedum-1	BDM-01	NAM	3566	1977
10	Bierum-1	BIR-01	NAM	3029	1963
11	Blijham-1	BHM-01	NAM	3502	1972
12	Blijham-2	BHM-02	NAM	4055	1979
13	Barnheem-1	BRH-01	NAM	3102	1973
14	Boerakker-1	BRA-01	NAM	3262	1984
15	Bolderij-1	BOL-01	NAM	2993	1972
16	Borgsweer-1 St2	BRW-01-S2	NAM	3363	1971
17	De Eeker-101	EKR-01	NAM	2745	1965
18	De Hond-1	HND-01	NAM	3277	1971
19	Delfzijl-1	DZL-01	NAM	3118	1960
20	De Paauwen-1	PAU-01	NAM	3397	1973
21	De Paauwen-2	PAU-02	NAM	3051	1985
22	Eemskanaal-1	EKL-01	NAM	3064	1970
23	Froombosch-1	FRB-01	NAM	2889	1966
24	Goldhoorn-1	GLH-01	NAM	4500	1980
25	Grootegast-1	GGT-01	NAM	3022	1961
26	Haren-1	HAR-01	NAM	3577	1953
27	Harkstede-1	HRS-01	NAM	3343	1977
28	Harkstede-2	HRS-02	NAM	3349	1980
29	Heiligerlee-1	HGL-01	NAM	3100	1982
30	Kooipolder-1	KPD-01	NAM	2994	1966
31	Leermens-7	LRM-07	NAM	3023	1975
32	Marumerlage-1	MAL-01	NAM	3152	1984
33	Meeden-1	MDN-01	NAM	3550	1983
34	Midlaren-1	MLA-01	NAM	3650	1985
35	Midwolda-1	MWD-01	NAM	2940	1965
36	Nieuw-Scheemda-1	NWS-01	NAM	2829	1965
37	Noordbroek-1	NBR-01	NAM	2889	1962
38	Norg-1	NOR-01	NAM	3329	1065
39	Oldorp-1	ODP-01	NAM	3539	1977
40	Oostwold-1	OLD-01	NAM	2985	1974
41	Opende-Oost-1	OPO-01	NAM	3100	1979

[1] The locations of the numbered wells are shown in figure 1.3.

Continuation of Appendix B

No.	*Well*	*Code*	*Owner*	*Total depth (along hole in metres)*	*Year (of completion)*
42	Oudeweg-1	OWG-01	NAM	3061	1971
43	Overschild-1	OVS-01	NAM	3014	1972
44	Pieterburen-1	PBN-01	KNZ	903	1972
45	Roden-101	ROD-101	NAM	3235	1970
46	Roden-102	ROD-102	NAM	3848	1976
47	Roode Til-1 St1	ROT-01-S1	NAM	2940	1968
48	Sappemeer-1	SAP-01	NAM	3027	1964
49	Schaapbulten-1	SCB-01	NAM	3131	1971
50	Schaaphok-1	SPH-01	NAM	2905	1966
51	Scheemderzwaag-101	SZW-101	NAM	3025	1966
52	Schildmeer-1	SMR-01	NAM	2969	1963
53	Schildwolde-1	SWO-01	NAM	3103	1973
54	Siddeburen-1	SDB-01	NAM	3037	1971
55	Slochteren-1	SLO-01	NAM	2709	1959
56	Slochteren-4	SLO-04	NAM	2987	1963
57	Slochteren-9	SLO-09	NAM	2857	1965
58	Spitsbergen-101	SPI-101	NAM	2997	1966
59	Stedum-1	SDM-01	NAM	3104	1966
60	Ten Boer-1	TBR-01	NAM	2890	1956
61	Ten Post-1	POS-01	NAM	3024	1972
62	Tjuchem-1	TJM-01	NAM	3083	1971
63	Tjuchem-2	TJM-02	NAM	5058	1972
64	Tusschenklappen-1	TUS-01	NAM	2836	1965
65	Uiterburen-1 St1	UTB-01-S1	NAM	2783	1966
66	Uiterburen-2	UTB-02	NAM	3220	1966
67	Uithuizen-1	UHZ-01	NAM	3131	1978
68	Uithuizermeeden-1 St1	UHM-01-S1	NAM	3331	1965
69	Usquert-1	USQ-01	NAM	3312	1968
70	Veelerveen-1	VLV-01	NAM	4191	1981
71	Veendam-1	VDM-01	SHL	1770	1972
72	Vries-4	VRS-04	NAM	3451	1985
73	Warffum-1	WRF-01	NAM	3621	1977
74	Westerdiep-1	WSD-01	NAM	3295	1973
75	Winschoten-1	WSN-01	KNZ	1000	1952
76	Winsum-1	WSM-01	NAM	3479	1979
77	Woudbloem-1	WBL-01	NAM	2996	1967
78	't Zandt-1	ZND-01	NAM	3020	1974
79	't Zandt-12	ZND-12	NAM	3300	1978
80	Zeerijp-1	ZRP-01	NAM	3125	1975
81	Zevenhuizen-1	ZVH-01	NAM	3270	1983
82	Zuidbroek-1	ZBR-01	NAM	3100	1980

Continuation of Appendix B

No.	*Well*	*Code*	*Owner*	*Total depth (along hole in metres)*	*Year (of completion)*
83	Zuiderveen-1	ZVN-01	NAM	3013	1966
84	Zuidlaarderveen-1	ZLV-01	NAM	3115	1975
85	Zuidlaren-1	ZLN-01	NAM	3338	1976
86	Zuidpolder-1	ZPD-01	NAM	3097	1970
87	Zuidwending-1	ZWD-01	NAM	3280	1974

St = Sidetrack
KNZ = Koninklijke Nederlandse Zoutindustrie N.V.
PET = Elf Petroland B.V.
NAM = Nederlandse Aardolie Maatschappij B.V.
SHL = Shell Delfstoffen Nederland

Reservoir calculations Upper Rotliegend Group

The calculations in the tables below were carried out for the entire Upper Rotliegend Group (incl. Ten Boer and Ameland Members), the Slochteren Formation, the Upper Slochteren and the Lower Slochteren Members. Cut-off values applied: clay content Vcl(co) = 50%; effective porosity Øe(co) = 6%. The cut-off value of the effective porosity is based on core data.
Øem average effective porosity; Vclm average clay content. Gross, Net in metres; Øem and Vclm in percentages. Wells in which not all of the indicated sequence was evaluated are marked with an * (a number of metres usually absent in the top of the Ten Boer Member).

Upper Rotliegend Group

Well	*Gross*	*Reservoir*		
		Net	*Øem*	*Vclm*
ANN-5	126.7	101.0	12.8	22.5
* BDM-1	261.4	198.2	14.2	20.3
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
* HRS-2	134.6	107.4	16.6	24.2
* LRM-7	249.1	182.9	15.1	18.9
MLA-1	172.7	115.2	12.5	20.6
* ODP-1	292.0	207.7	18.2	16.2
* OVS-1	200.5	166.0	16.8	21.7
ROD-102	221.8	175.0	18.6	20.6
TJM-1	196.5	145.3	18.6	22.0
* UHZ-1	290.5	211.2	17.9	17.3
USQ-1	314.1	228.1	17.3	16.6
VRS-4	200.5	154.5	16.5	28.3
WRF-1	322.7	224.1	19.6	20.4
WSM-1	323.9	227.4	18.5	15.7
* ZND-1	240.5	202.7	17.7	17.2
* ZVH-1	205.7	177.2	20.4	16.0

Slochteren Formation

Well	Gross	Reservoir		
		Net	Øem	Vclm
ANN-5	113.8	99.8	12.7	22.3
BDM-1	205.2	196.2	14.2	20.0
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
HRS-2*	109.3	101.3	16.7	23.0
MLA-1	135.2	105.0	12.7	19.1
ROD-102	198.3	174.3	18.7	20.5
TJM-1	145.4	140.6	18.8	21.6
VRS-4	187.0	154.5	16.5	28.3
ZVH-1	161.1	159.0	21.5	13.7

Upper Slochteren Member

Well	Gross	Reservoir		
		Net	Øem	Vclm
LRM-7	90.7	88.5	16.0	20.5
ODP-1	101.2	96.1	20.0	17.2
OVS-1	85.2	82.6	18.3	25.1
UHZ-1	96.2	87.6	20.2	18.2
USQ-1	102.3	95.0	19.6	15.8
WRF-1	111.6	101.0	21.3	20.4
WSM-1	104.9	101.8	17.5	15.9
ZND-1	96.4	93.0	19.1	19.6

Lower Slochteren Member

Well	Gross	Reservoir		
		Net	Øem	Vclm
LRM-7	93.5	84.8	14.5	15.8
ODP-1	110.4	103.6	16.9	13.9
OVS-1	90.0	78.6	15.1	17.5
UHZ-1	125.5	116.5	16.5	15.5
USQ-1	125.9	119.7	16.4	14.8
WRF-1	122.8	113.5	18.5	18.9
WSM-1	122.8	107.5	19.7	14.2
ZND-1	109.9	100.1	16.7	13.2

Show, status and test data Upper Rotliegend Group

GAS gas production; PRP produktion test (flow gas, Q50, in 1000 m^3/d; flow water and condensate in m^3/d); RFT repeat formation tester (test interval in metres log depth; quantities in litres); FIT formation interval test (quantities in litres); G gas; W water; C condensate; MF mud filtrate; M mud; u uppermost chamber; l lowermost chamber;
ROSL Slochteren Formation; ROSLU Upper Slochteren Member; ROCLT Ten Boer Member

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
ANN-5	gas	GAS	PRP	2922.0-3028.0	G	3760	ROSL
BDM-1	gas	GAS	PRP	3041.3-3113.5	G	715	ROSL
					W	5	
					C	7	
			RFT	3026.1-3256.0			ROCLT+ROSL
			FIT	3091.5	G	4.1	ROSL
					MF	1.4	
BHM-2	gas	GAS	PRP	3579.3-3641.3	G	445	ROSL
			RFT	3590.1-3640.5			ROSL
BRA-1	gas	GAS	PRP	2932.0-3001.5	G	2500	ROCLT+ROSL
					W		
					C		
			RFT	2938.2-3152.5			ROCLT+ROSL
			FIT	2985.0	G (u)	1.7	ROSL
					C (u)		
					MF(u)	0.2	
					G (l)	1.7	
					C (l)	0.2	
					MF(l)	1.1	
HGL-1	gas	GAS	RFT	2762.5-2798.0			ROSL
HRS-2	gas	GAS	PRP	3221.0-3270.1	G	3600	ROSL
					W	9	
					C	9	
MLA-1	gas	GAS	RFT	3174.8-3331.0			ROCLT+ROSL
			FIT	3212.5	MF	5.5	ROSL
OVS-1	gas	GAS	FIT	2832.0	G	3100	ROSLU
					M	1.5	
ROD-102	gas	GAS	PRP	3585.4-3674.8	G	2570	ROCLT+ROSL
					W	15	
					C	250	
USQ-1	gas	GAS	PRP	2970.0-2979.0	G	950	ROSLU
WRF-1	gas	GAS	PRP	3116.0-3123.0	G	4300	ROSLU
					W	15	
					C	61	
			FIT	3122.0	G	8.6	ROSLU
					MF	1.7	
ZND-1	gas	GAS	FIT	2846.5	G	671	ROSLU
					M	3.2	

References

Literature references

Arthaud, F. & Matte P. (1977) *Late Paleozoic strike-slip faulting in southern Europe and North Africa; results of a right-lateral shear zone between the Appalachians and the Urals.* Geol. Soc. Am. Bull. 88, p.1305-1320.

Athy, F. (1930) *Density, porosity and compaction of sedimentary rocks.* AAPG Bull., vol.14, p.1-14.

Baldschuhn, R., Best, G. & Kockel, F. (1991) *Inversion tectonics in the Northwest German Basin.* In: Generation, Accumulation and Production of Europe's Hydrocarbons (Spencer, A.M., ed.), Spec. Publ. E.A.P.G., No.1, Oxford University Press, p.149-159.

Bless, M.J.M., & Winkler-Prins, C.F. (1972) *Paleoecology and Paleogeography of the Aegir Marine Band and its equivalents in North-West Europe.* 72e C.R. Congr. Internat. Stratigr. Géol. Carbonif., Krefeld 1971, Vol.1, p.231-239.

Braitsch, O. (1971) *Salt deposits their origin and composition.* Springer Verlag, Berlin-Heidelberg-New York, 297 pp.

Brüning, U. (1986) *Stratigraphie und Lithofazies des Unteren Buntsandsteins in Südniedersachsen und Nordhessen.* Geol Jb, A90, p.3-125.

Coeleweij, P.A.J., Haug, G.M.W. & Van Kuijk, H. (1978) *Magnesium-salt exploration in the northeastern Netherlands.* Geologie en Mijnbouw, vol. 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., vol. 10, p.395-414.

De Vries Klein, G. & Kupperman, J.B. (1992) *Pennsylvanian cyclothems: methods of distinguishing tectonically induced changes in sea level from climatically induced changes.* Bull. Geol. Soc. America, 104, p.166-175.

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

Doornhof, D. (1992) *Surface subsidence in The Netherlands: the Groningen gas field.* Geologie en Mijnbouw, vol. 71, p.119-130.

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

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. 1-8.

Geologisches Landesamt Nordrhein-Westfalen (1984) *Nordwestdeutsches Oberkarbon (Teil 1).* Fortschr. Geol. Rheinland und Westf., Band 32, Krefeld, 399pp.

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

Glennie, K.W. (1986) *Early Permian - Rotliegend.* In: Introduction to the Petroleum Geology of the North Sea (Glennie K.W., ed.), Blackwell Scientific Publ., Oxford, Second edition, p.25-48.

Glennie, K.W. & Buller, A.T. (1983) *The Permian Weissliegend of NW Europe: the partial deformation of aeolian dune sands caused by the Zechstein transgression.* Sedimentary Geology, vol. 35, p.43-81.

Guion, P.D. & Fielding, C.R. (1988) *Westphalian A and B sedimentation in the Pennine Basin.* In: Sedimentation in a synorogenic basin complex - the Upper Carboniferous of Northwest Europe (Besly, B.M. & Kelling, G., eds.). Blackie, Glasgow, p.153-177.

Haanstra, U. (1963) *A review of Mesozoic geological history of The Netherlands.* Verh. Kon. Ned. Geol. Mijnb. Gen., vol. 21(2), p.35-55.

Hancock, J.M. (1984) *Cretaceous.* In: Petroleum Geology of the North Sea (Glennie, K.W., ed.), Blackwell Scientific Publ., Oxford, p.133-149.

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

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

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

Harsveldt H.M. (1980) *Salt resources in the Netherlands.* Geologica Ultraiectina, Spec. Publ. no.1, p.29-52.

Herngreen, G.F.W., Smit, R. & Wong, Th.E. (1991) *Stratigraphy and Tectonics of the Vlieland Basin, The Netherlands.* In: Generation, accumulation and production of Europe's hydrocarbons (Spencer, A.M., ed.), Special publication EAPG no. 1, Oxford University Press, Oxford, p.175-192.

Hedemann, H.A., Schuster, A., Stancu-Kristoff, G. & Lösch, J. (1984) *Die Verbreitung der Kohlenflöze des Oberkarbons in Nordwestdeutschland und ihre stratigraphische Einstufung.* Fortschr. Geol. Rheinland und Westf., 32, p.39-88.

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

Jaritz, W. (1973) *Zur Entstehung der Salzstrukturen Nordwestdeutschlands.* Geol. Jb, A10, 77pp.

Jaritz, W. (1987) *The origin and development of salt structures in north-west Germany.* In: Dynamical Geology of Salt and Related structures. (Lerche, I. & O'Brien J.J., eds) Academic Press Orlando p.480-493.

Jaritz, W. (1992) *Fortschritte und offene Fragen zur Entstehung der Saltzstrukturen NW-Deutschlands.* In: Veröffentlichungen: Salz in Niedersachsen. Niedersachsische Akademie der Geowissenschaften, Heft 8, p. 16-24.

Jenyon,M.K. (1986) *Salt Tectonics.* Elsevier Appl. Science Publ. London. 191pp.

Knaap, W.A. & Coenen, M.J. (1987) *Exploration for oil and natural gas.* In: Seventy-five years of geology and mining in The Netherlands (1912-1987). (Visser, W.A., Zonneveld, J.I.S. & Van Loon, A.J., eds.) Royal Geological and Mining Society of The Netherlands (K.N.G.M.G.), The Hague.

Koyi, H. (1988) *Experimental modelling of the role of gravity and lateral shortening in Zagros Mountain Belt.* AAPG Bull. vol. 72, p.1381-1394.

Koyi, H. (1991) *Gravity overturns, extension and basement fault activation.* Journ. Petrol. Geol., vol. 14, p.117-142.

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

Kulick, J. & Paul, J. (1987) *Zur Stratigraphie und Nomenklatur des Zechsteins, Glossar.* Int. Symp. Zechstein 1987, Niedersächsisches Landesamt für Bodenforschung, Hannover, p.25-34.

Letsch, W.J. & Sissingh, W. (1983) *Tertiary stratigraphy of The Netherlands.* Geologie en Mijnbouw, vol. 62, p.305-318.

Lorentz, V. & Nicholls, I.A. (1976) *Plate and intraplate processes of Hercynian Europe during the late Paleozoïc.* Tectonopyhics, 107, p.25-56.

McKenzie, D.P. (1978) *Some remarks on the development of sedimentary basins.* Earth Planet. Sci. Lett. 40, p.25-32.

Ministry of Economic Affairs (1995) *Oil and gas in The Netherlands, exploration and production 1994.* De grafische Haarlem, 98pp.

Nagtegaal, P.J.C. (1979) *Relationship of facies and reservoir quality in Rotliegendes desert sandstones, Southern North Sea region.* Journal of Petr. Geol., vol. 2, p.145-158.

NAM (1995) *Bodemdaling door aardgaswinning. Statusrapport 1995 en prognose tot het jaar 2050.* NAM rapport 27600.

NLfB (1989) *Darstellung und Benennung der Salzstrukturen in der deutschen Nordsee.* Erdöl, Erdgas, Kohle. 105, p.10-11.

Perrot, J. & Van der Poel, A.B. (1987) *Zuidwal - a Neocomian gas field.* In: Petroleum of Northwest Europe (Brooks.J. & Glennie, K.W., eds.), Graham & Trotman, London, vol.1, p.325-335.

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 eustasy and stratigraphic sequences on passive marginrand* Geol. Soc. Am. Bull., vol. 89, p.1389-1403.

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

Read, W.A. & Dean, J.M. (1973) *A statistical relationship between net subsidence and number of cycles in Upper Carboniferous paralic facies successions in Great Britain.* C. R. VII Congr. Int. Strat. Géol. Carb., Krefeld, 1971, 3, p.153-159.

Read, H.H. & Watson, J. (1975) *Introduction to Geology.* Earth History, part. II; Later Stages of Earth History, vol. 2. The Macmillan Press, London, 371 pp.

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

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 (1991a) *Geological Atlas of the Subsurface of The Netherlands, Explanation to map sheet I: Vlieland-Terschelling.* Geological Survey of The Netherlands RGD, Haarlem, 80pp.

Rijks Geologische Dienst (1991b) *Geological Atlas of the Subsurface of The Netherlands, Explanation to map sheet II: Ameland-Leeuwarden.* Geological Survey of The Netherlands RGD, Haarlem, 87 pp.

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

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

Röhling, H.G. (1991) *A lithostratigraphic subdivision of the Lower Triassic in the Northwest German Lowlands and the German sector of the North Sea, based on gamma-ray and sonic logs.* Geol. Jb. A.119, p.3-24.

Schröder, B. (1982) *Entwicklung des Sedimentbeckens und Stratigraphie der klassischen germanischen Trias.* Geologisches Rundschau, Band 71, p.783-794.

Sclater, J.G. & Christie, P.A.F. (1980) *Continental Stretching: an explanation of the Post-Mid-Cretaceous subsidence in the Central North Sea Basin.* J. Geophys. Res., vol. 85, p.3711-3739.

Selter, V. (1990) *Sedimentologie und Klimaentwicklung im Westphal C/D und Stephan des nordwestdeutschen Oberkarbon-Beckens.* DGMK-Bericht, 384-4, Deutsche wiss. Gesellsch. Erdöl, Erdgas und Kohle, Hamburg, 311 pp.

Stäuble, A.J. & Milius, G. (1970) *Geology of the Groningen gasfield, Netherlands.* In: Geology of giant petroleum fields (Halbouty, M.T., ed.). AAPG Mem. 14, p.359-369.

Stille, H. (1924) *Grundfragen der vergleichenden Tektonik.* Bornträger, Berlin, 443 pp.

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

Taylor, J.C.M. (1986) *Late Permian - Zechstein.* In: Introduction to the Petroleum Geology of the North Sea (Glennie, K.W., ed.), Blackwell Scientific Publ., Oxford, Second edition, p.86-111.

Teichmüller M., Teichmüller R. & Bartenstein H. (1985) *Inkohlung und Erdgas - eine neue Inkohlungskarte der Karbon-Oberfläche in Nordwestdeutschland.* Fortschr. Geol. Rheinland u. Westf., 32: 11-34.

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

Trusheim, F. (1957) *Über Halokinese und ihre Bedeutung fur die strukturelle Entwickelung Norddeutschlands.* Z. dt. geol. Ges. 109, p.111-151.

Trusheim, F. (1960) *Mechanism of salt migration.* AAPG Bull., vol. 44, no. 9, p.1519-1540.

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

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P. (1993-1995) *Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA.* Mededelingen Rijks Geol. Dienst, 50.

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 (East Netherlands).* C. R. XII Congr. Int. Strat. Géol. Carb., Buenos Aires, 1991, 1, p.439-457.

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

Van Wijhe, D.H. (1987) *Structural evolution of inverted basins in the Dutch Offshore.* Tectonophysics, 137, p.171-219.

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

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

Veld, H. (1995) *Organic Petrology of the Westphalian of The Netherlands. Deviations in vitrinite reflectance trends.* 190 pp. Thesis. Rijks Universiteit Utrecht.

Veld, H., Fermont, W.J.J. & Jegers, L.F. (1993) *Organic petrological characterization of Westphalian coals from The Netherlands: Correlation between Tmax, vitrinite reflectance and hydrogen index.* Organic geochemistry, 20, 6, p. 659-675.

VUA, 1992, *Intraplaattektoniek, bekkenmodellering en zoutdiapirisme.* Inhoudelijke deelstudie: Modellering Deel 1 en 2: Rapportage OPLA project augustus 1992, OPLA92-xx. Sectie Structurele Geologie/Tektoniek, Vrije Universiteit Amsterdam.

Zagwijn, W.H. (1990) *The Netherlands during the Tertiary and Quaternary: a case history of Coastal Lowlands evolution.* Geologie en Mijnbouw, vol.68, p.107-121.

Zagwijn, W.H., & Van Staalduinen, C.J. (eds.) (1975) *Toelichting bij geologische overzichtskaarten van Nederland.* Rijks Geologische Dienst, Haarlem.

Ziegler, P.A. (1978) *North-Western Europe: tectonics and basin development.* Geologie en Mijnbouw, vol. 57, p.589-626.

Ziegler, P.A. (1982) *Geological Atlas of Western and Central Europe.* Shell International Petroleum Maatschappij B.V., distributed by Elsevier, Amsterdam, 130 pp.

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

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

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

Internal Reports of the Geological Survey of The Netherlands[1]

RGD, 1972, Van Amerom, H.W.J. *Palynologisch onderzoek van het Carboon van de boring Tjuchem-2.* Rapport no. GB1287, GB1210.

RGD, 1992a, Van de Laar, J.G.M. *Palynologisch onderzoek van het Karboon van de boringen Bierum-1, Zuidwending-1, Delfzijl-1, Midwolda-1, Bedum-1, Oude Pekela-1, Slochteren-4, Midlaren-1, Goldhoorn-1, Heiligerlee-1, Roode Til-1, Tusschenklappen-1, 't Zand-12, Zuidbroek-1 en Uiterburen-2.* Rapport no. 2391, 2392, 2393, 2394, 2395, 2395, 2396, 2397, 2398, 2399, 2400, 2401, 2402, 2403, 2404, 2405.

RGD, 1992b, Herngreen, W. *Biostratigrafisch (palynologisch) onderzoek van de boring Ten Post-1.* Rapport no.2258.

RGD, 1992c, Schuurman, H.A. & Lissenberg, T. *Biostratigrafische interpretatie van het Onder-Krijt van de boringen de Hond-1, Bierum-1, Roden-101, Haren-1 en Oudeweg-1.* Rapport Micropal Mesozoïcum no.550a, 551, 552a, 553, 554.

RGD, 1992d, Schuurman, H.A. & Lissenberg, T. *Biostratigrafisch onderzoek aan het Boven-Krijt van de boringen Winsum-1, de Hond-1, Roden-101 en Stedum-01.* Rapport Micropal Mesozoïcum no.549, 550, 552, 556.

RGD, 1993, Ramaekers, J.J.F. & Neele, N.G. *Resultaten petrofysische evaluatie van de Boven-Rotliegend Groep op Kaartblad III.* Rapport no. 93KAR10.

RGD, 1994, Fermont, W.J.J., David, P., Jegers, L. & Milder, H. *Een modelstudie naar de timing van gasgeneratie in het Groningen gasveld (Kaartblad III).* Rapport no. GB 2427.

[1] Internal reports of the Geological Survey of The Netherlands are not generally available to third parties.

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Petrophysics
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Organic geochemistry
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D.K. Munsterman
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J.G.M. van de Laar
L.J. Witte
T. Lissenberg
H.A. Schuurman

Translation
F.R. Bianchi & V.A. Verkaik-Drew
Foundation Pangea, Huizen

Design
BRS Premsela Vonk, Amsterdam
J.A.M. Bruinenberg

Printing
Sdu, Den Haag

Project management

Th.H.M. van Doorn

ISBN 90-72869-31-1

Rijks Geologische Dienst, 1995 - Geological Atlas of the Subsurface of The Netherlands, Explanation to map sheet III: Rottumeroog-Groningen, RGD, Haarlem.

This publication is a translation of the Dutch version (ISBN 90-72869-30-3).
Deze publikatie is vertaald vanuit het Nederlands (ISBN 90-72869-30-3).