Rijks Geologische Dienst **RGD**

Explanation to map sheet IV
Texel-Purmerend

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 made widely available to the general public by the Geological Survey of The Netherlands, mostly in the form of maps and explanations to map sheets which, until a few years ago, only dealt with the subsoil geology of The Netherlands and the North Sea.

Reports on the deeper subsurfac e geology (deeper than 500 m) were limited because of the status of the data required. These data are acquired from seismic investigations and deep drilling which are nearly exclusively carried out by oil companies. Because of the great commercial interests involved for the oil industry these data are classified but made available to the Geological Survey of The Netherlands, as delineated in the mining act.
The existing mining legislation that applies to The Netherlands Onshore and Continental Shelf does not permit the general release of this classified information. Agreements with the oil companies concerning the use of these data enable The Geological Survey of The Netherlands to compile and publish this information, provided the data are older than 10 years. An exception is made for data derived from concession areas, with a restriction of 5 years. This agreement enables the RGD to bring the geological subsurface of The Netherlands to wider attention.

The Texel-Purmerend map sheet of the Geological Atlas of the Subsurface of The Netherlands is the third 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 Noord-Holland. Maps and accompanying explanations reveal that one of the flattest provinces in The Netherlands has essentially a highly eventful structural history. For a great part of the geological history, the north of the area was comparatively stable, whereas the south underwent continuous subsidence, resulting in a thick depositional build-up of marine sediments. During the Late Cretaceous, an inversion of tectonic movement caused strong uplift and erosion within the original areas of subsidence and led to deposits of thick chalk on the formerly stable highs. Gas-bearing reservoirs have been discovered in Permian dune sands and chalks and in fluvial Triassic sandstone layers. The gas traps were mainly initiated during the Late Cretaceous. The map sheet also clearly demonstrates that this area was subject to the influence of the sea over a long period, with the result that marine depositional environments continued into the Quaternary.
The Geological Survey anticipates that this map sheet, together with those already published or in progress, will contribute to a greater understanding of the structure and composition of the subsurface of The Netherlands. This is important not only to companies who are active in the fields of exploration and exploitation for minerals 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 the possible consequences of exploitation of natural resources and the other opportunities for sustainable development of the subsurface of The Netherlands. For example, these may 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, with especial mention of the substantial contributions made by J.B. Breeuwer, C.M. Elmers-Kathmann, J. Klijn, C.I. Leyzers Vis and N. Witmans. I greatly appreciate all their efforts. Pertinent and constructive criticism from Dr. W.J.M. van der Linden and the reviewing committee added much to the quality of the explanation. Special thanks are due to Amoco, Amoseas, BP, Chevron, Conoco, Elf Petroland, NAM, Mobil, Phillips, Placid, Shell, Superior and Western Geophysical, who all provided data used in this map sheet.

Chr. Staudt,
Director

1 Introduction

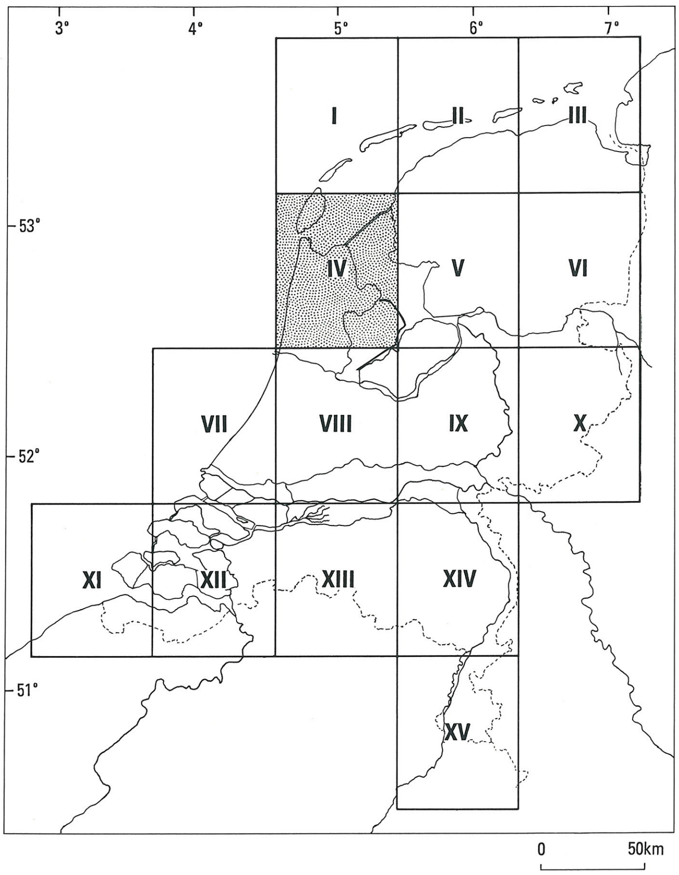
1.1 Extent of area studied

The map sheet area covers most of the province of Noord-Holland, including part of Dutch territorial waters (3 nautical miles) and also parts of the provinces of Friesland and Flevoland (fig. 1.1).

1.2 History of exploration and data base

Drilling activity in the map sheet area started in 1950 and the discovery of the Groningen gasfield occurred in 1958. The wells Hoogkarspel-1 and Warmenhuizen-1 were aimed at hydrocarbon accumulations in Lower Cretaceous sandstones. This exploration activity was provoked by discoveries in similar sands in Zuid-Holland and the eastern Netherlands. The negative results of both wells led to no further exploration being pursued in this area in the 1950s.

Figure 1.1. Subdivision of the regional map sheet areas of the subsurface of The Netherlands.



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		

This changed after the discovery of the Groningen gasfield. The exploration target was initially the Slochteren Sandstone of Permian age, the gas-bearing unit in the Groningen field. Many wells were drilled in the 1960s in the map sheet area, with about one in three being successful. In 1964 NAM found gas in the Slochteren Sandstone in the Middelie-1 well and in the Volpriehausen and Solling Sandstones of Triassic age in the Wimmenum-Egmond-1 well. Elf Petroland found gas in the Vlieland Sandstone (Harlingen-1). Amoco found gas in the Slochteren Sandstone (Bergen-1A and Groet-1) and also in carbonates of the Zechstein Group (Schermer-1). In 1965 Amoco discovered that the Volpriehausen Sandstone of Triassic age was gas-bearing in the Heiloo-1 well. Elf Petroland found gas in carbonates of the Zechstein Group (Slootdorp-1) and this company further made a unique gas find for The Netherlands in the Ommelanden Chalk (Harlingen-2). These finds have since led to exploration targeted at several potential reservoir levels. There was no further drilling in the area until 1969 because of a government-imposed drilling moratorium.

After the Act on Mineral Resources Exploration became law in 1967, concessions were granted based on the above-mentioned finds: Elf Petroland was granted 'Leeuwarden' and 'Slootdorp', Amoco acquired 'Bergen' and NAM acquired 'Middelie' (see fig. 1.2). Exploration continued within

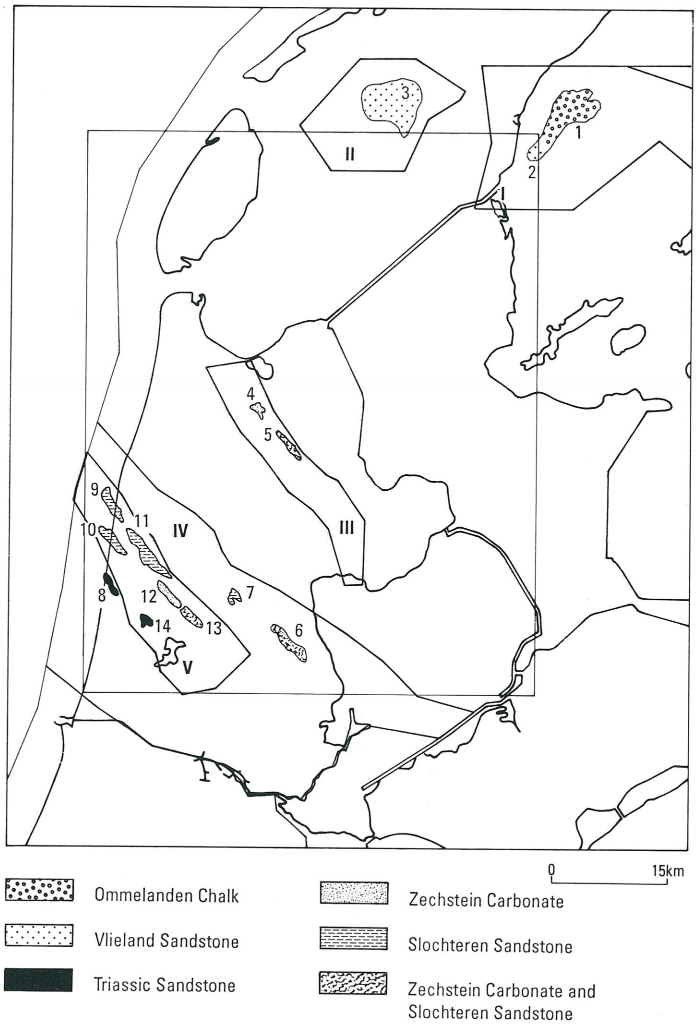


Figure 1.2. Overview map of the concession areas within the map sheet area, with the name of the concession holder in brackets and identified gas fields:

- I Leeuwarden (Elf Petroland)
  - 1 Harlingen
  - 2 Franeker
- II Zuidwal (Elf Petroland)
  - 3 Zuidwal
- III Slootdorp (Elf Petroland)
  - 4 Slootdorp
  - 5 Middenmeer
- IV Middelie (NAM)
  - 6 Middelie
  - 7 Rustenburg
  - 8 Wimmenum
- V Bergen (Amoco)
  - 9 Groet
  - 10 Bergen
  - 11 Bergermeer
  - 12 Alkmaar
  - 13 Schermer
  - 14 Heilo

these concessions leading to a gas discovery in 'Slootdorp' in the Slochteren Sandstone (Middenmeer-1; 1975). This unit also proved to be gas-bearing in 'Bergen' (Bergermeer-1; 1969) and in 'Middelie' (Rustenburg-1; 1977). It is worth noting a further gas discovery in carbonates of the Zechstein Group in the 'Bergen' concession (Alkmaar-1; 1975).

At the same time drilling licences were granted after 1967 that fell fully or partly in the map sheet area. These were given to various companies, including NAM and Elf Petroland. Elf Petroland's exploration was successful just to the north of the map sheet area when gas-bearing Vlieland Sandstone was penetrated. This led to the 'Zuidwal' concession being licensed in 1984, only a small part of which lies within the map sheet area. Figure 1.2 shows the concession areas and the proven gasfields and gas-bearing formations are indicated within this map sheet area (as of 1-1-1993).

During the 1970s one in two exploration wells was successful. However, this good ratio was not maintained: in the 1980s only one in four wells proved successful.

Exploring for gas accumulations is not easy in Noord-Holland because of the strongly fractured character of the reservoirs (see map 1, for example). There are good quality reservoirs in the map sheet area but the structures have often proved to be water-bearing. The main risks in the exploration of this area lie in the degree of maturity of the gas-source rock, the time at which the gas traps were formed, and in hydrocarbons migrating along faults.

The mapping of the subsurface of The Netherlands is based to a large extent on data collected by the above-mentioned companies. Much use has also been made of the available literature. The regional geological framework is based on our own research (RGD, 1991a, 1991b) and is also derived from Haanstra (1963), Heybroek (1974), Van Wijhe (1987) and various of Ziegler's publications (1975, 1977, 1978, 1982, 1988, 1989, 1990).

1.3 Research set up

Seismic mapping:

The research was focused on systematic structural geological mapping based on seismic data. A seismic line grid of maximally 4 x 4 km was chosen for the regional mapping. This line density could not always be achieved in the Wadden Sea and the IJsselmeer by the companies acquiring the data, because of limitations related to nature conservation, technical difficulties caused by the type of terrain conditions or because of the presumed low prospectivity for some parts of the area concerned. The seismic lines used date from the period 1961-1985, but most were recorded in the 1970s (see appendix A). Unmigrated seismic lines were used; the location of the lines are shown in figure 1.3.

The picked reflectors form the boundaries between the large lithostratigraphic units (groups and formations). Acoustic logs and well-shooting survey data were used to calibrate the seismic data with respect to well data. The vertical time-depth conversion of the seismic interpretations was carried out per layer (the 'layer-cake' method). For this purpose a linear equation ($Vz = Vo + kz$) between the interval velocity and the depth of the layer was taken.

The same velocity equations were used for all the map sheets in order to obtain a consistent fit for comparable maps of adjacent sheets. The parameters for the regional velocity distribution were determined from the acoustic data from 65 wells located throughout The Netherlands. In calculating the parameters, a maximum error of 5% between the drilled depths and the seismic interpretation was considered acceptable. Table 1 presents an overview of the parameters that were used for the linear-velocity distribution.

Two parameter sets for the velocity equations were adopted within the map sheet area: one for the area outside the Central Netherlands Basin and one for within the basin (see fig. 1.7 and under a. and b. in table 1, respectively). This distinction was applied because the deposits in the Central Netherlands Basin have been buried more deeply in their geological history than they are at present, which means that the deposits have a higher seismic velocity than can be calculated from their present depth of occurrence.

An exception to the linear relation is the Zechstein Group; because of its specific lithostratigraphical composition, a hyperbolic relation between the interval velocity and time interval was chosen:

$Vint = a + [d/(t-b)]^c$; (see table 1 under c).

Figure 1.3. Location of the seismic line grids used for the mapping. Appendix A gives additional information on the owner and the age of the varous lines.

Table 1. Applied velocity distribution:

a. The velocity distribution adopted beyond the Central Netherlands Basin is based on $Vz = Vo + kz$.

Vz =	average velocity at depth z (m/s);
Vo =	theoretical velocity at depth z=0 (m/s);
k =	specific constant (1/s);
z =	depth (m).

Unit	*Vo*	*k*
North Sea Super Group	1696	0.49
Chalk Group	2092	1.08
Holland Formation	2020	0.63
Vlieland Formation	2051	0.41
Central Graben Group	1507	0.82
Lower and Upper Germanic Trias Group	2293	0.69
Upper Rotliegend Group	3535	0.18

b. A different velocity distribution was adopted in the Central Netherlands Basin, also based on $Vz = Vo + kz$.

Unit	*Vo*	*k*
North Sea Super Group	1696	0.49
Chalk Group	2092	1.08
Holland Formation	2020	0.63
Vlieland Formation	2051	0.41
Central Graben Group	2297	0.62
Altena Group	2297	0.62
Lower and Upper Germanic Trias Group	3254	0.56
Upper Rotliegend Group	3535	0.18

c. Based on $Vint = a + [d/(\delta t-b)]^c$:

Vint	= average interval velocity (m/s)
δt	= time interval Zechstein (s)
a	= asymptote interval velocity (m/s)
b	= asymptote δt (s)
c	= constant
d	= constant (m)

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

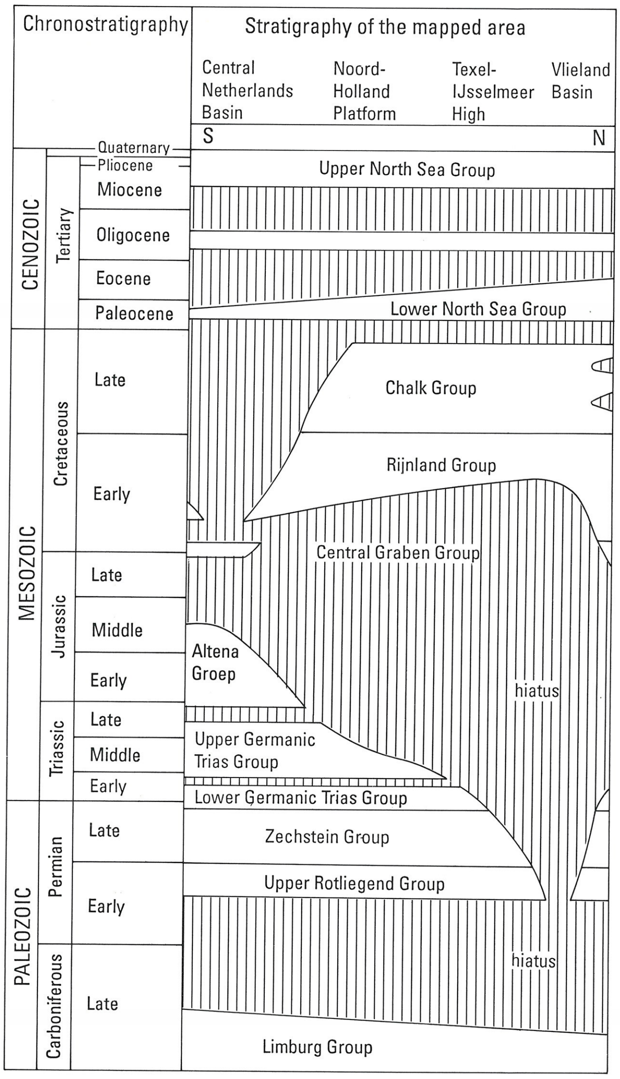
Geological research:

The geological research was focused on the lithostratigraphic composition of the rocks present in the map sheet area (see fig. 1.4 for an overview), and their geological history with respect to the regional geological development. Seismic records and well measurements were used for this work, supplemented by lithological and biostratigraphical research on rock samples. A list of the wells used is given in appendix B and their locations are shown in figure 1.5.

Petrophysical research:

As well as the geological research, the characteristics of the reservoir rocks were also studied. Well-log data records were processed to calculate porosities, water saturation and hydrocarbon content. The calculations were calibrated against core analysis data.

Figure 1.4. Diagram of the lithostratigraphic units within the map sheet area. Vertical hatching indicates hiatuses in the stratigraphic succession.



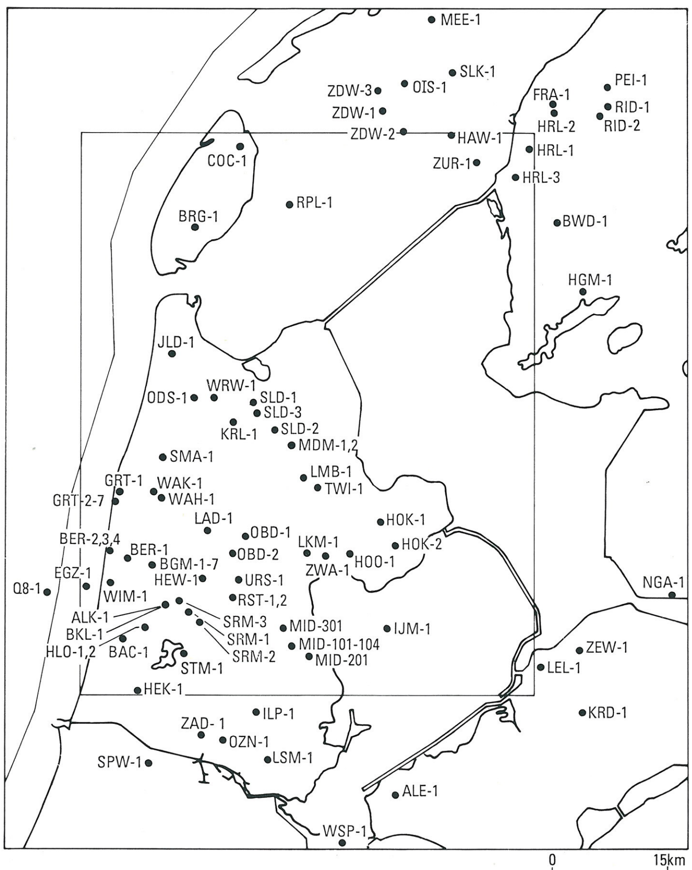
1.4 Maps and Sections

The results of the seismic mapping are shown in a series of maps and three sections. Depth and thickness maps have been made per group (following the divisions in fig. 1.4). Depth maps have been plotted to the bases of the Upper Rotliegend Group, the Zechstein Group, the Lower Germanic Trias Group, the Altena Group, the Central Graben Group, the Rijnland Group, the Chalk Group and the North Sea Super Group, as well as a depth map to the top of the Zechstein Group. The depth maps to the bases of the Upper Rotliegend Group, Zechstein Group and Lower Germanic Trias Group reflect the structural trend in the area. This runs NW-SE, superimposed on a WNW-ESE tendency originating in the Carboniferous. Subcrop maps of the most important unconformities at the base of the Central Graben Group, Rijnland Group and North Sea Super Group have been plotted.

Thickness maps were made of all the above-mentioned stratigraphic units, except for the Lower Germanic Trias Group and the North Sea Super Group. The Lower Germanic Trias Group is presented with the Upper Germanic Trias Group as one map, while the depth map of the North Sea Super Group also serves as a thickness map for this unit.

The seismic lines used for mapping the map sheet area were of poor to reasonable quality; the base of the Upper Rotliegend Group could not be determined from the seismic data. The depth

Figure 1.5. Location of the wells used for the mapping. Appendix B gives additional information on the owner, final depth and the date of the wells.



map of this group is therefore based on the depth map of the base of the Zechstein Group and includes a regional thickness map of the Upper Rotliegend Group based on well data (fig. 3.1).

The depth and thickness maps do not indicate drill holes where faults are present in the particular group or where the final depth of drilling is reached.

The depth maps based on seismic data may show local deviations from the depths determined in wells because the conversion of time to depth was carried out with a regionally determined velocity distribution. The depth maps have not been corrected for these deviations.

The quality of the maps depends on the quality and density of the data available. In the Wadden Sea and the IJsselmeer both factors have had a negative influence on the results of the mapping. Seismic coverage was thin (fig. 1.3) and some of the seismic lines date from the 1960s.

The subcrop maps of the base of the Central Graben Group, the Rijnland Group and the North Sea Super Group (Maps 15, 16, 17) show the stratigraphic units which occur below the unconformities and thus give an impression of the degree of erosion which took place prior to the deposition of these groups.

Finally, one NW-SE and two SW-NE trending sections are shown on a separate map. These were chosen in such a way as to link up with the sections of the adjacent map sheets.

1.5 Explanation

The explanation, with the various maps, is intended to provide a picture of the geology of the map sheet area. The first part of the text comprises a description of the lithostratigraphy, and the second part gives more detail on the geological history of the mapped area. In the descriptions of the lithostratigraphy, the emphasis lies on the variation and extent of the different groups, formations and members. The extent of a succession is mainly related to the important structural features of the map sheet area (see section 1.6.2). In chapters 2 to 10, the lithostratigraphic composition and development is considered per group, from old to younger, in the light of these structural features. Unless stated otherwise, the nomenclature and age follow the Stratigraphic Nomenclature of The Netherlands (NAM & RGD, 1980).

Figure 1.6 gives an overview of the stage names adopted by the RGD which are used in this explanation. In addition, each chapter has a section on the depositional environment and palaeogeography. Finally, in the relevant chapters we highlight six economically important reservoir rocks, as well as two oil/gas source rocks.

In a number of cases units have been mapped at formation or member level and these are included as figures in the text. The Cenozoic sediments are not treated as separate groups but discussed in their entirety as the North Sea Super Group. This description is limited to Tertiary sediments. For the Quaternary deposits reference should be made to RGD (1975) and the 'Explanation of the geological map of The Netherlands 1:50.000' (Toelichting van de geologische kaart van Nederland 1:50.000) of the Geological Survey of The Netherlands. The double sheet Alkmaar (19 East and West) is relevant to this area and it was published in 1987.

Finally, the last chapter outlines the geological history compiled from the sedimentary setting and structural development of the area.

Figure 1.6. Geological timetable, as used in the explanation. The tectonic phases which are referred to have also been indicated (from Harland et al., 1990).

Age in Ma	Era	Period			Epoch	Age	Orogenesy (Main Tectonic Events)	
1.64	CENOZOIC	Quaternary			Holocene/Pleistocene	Reuverien		ALPINE
		Tertiary	Neogene		Pliocene	Brunssumian		
						Messinian		
					Miocene	Tortonian		
						Serravallian		
						Langhian		
						Burdigalian		
						Aquitanian	Savian	
			Paleogene		Oligocene	Chattian		
						Rupelien	Pyrenean	
					Eocene	Priabonian		
						Bartonian		
						Lutetian		
						Ypresian		
					Paleocene	Thanetian		
65						Danian	Laramide	
	MESOZOIC	Cretaceous			Late Cretaceous	Maastrichtian		
						Campanian	Sub-Hercynian	
						Santonian		
						Coniacian		
						Turonian		
						Cenomanian		
					Early Cretaceous	Albian		
						Aptian	Austrian	
						Barremian		
						Hauterivian		
						Valanginian	Late Kimmerian II	
143						Ryazanian		
		Jurassic		Early	Malm	Portlandian	Late Kimmerian I	
						Kimmeridgian		
						Oxfordian		
				Middle	Dogger	Callovian		
						Bathonian		
						Bajocian	Mid-Kimmerian	
						Aalenian		
				Late	Lias	Toarcian		
						Pliensbachian		
						Sinemurian		
208						Hettangian		
		Triassic		Late	Keuper	Rhaetian	Early Kimmerian	
						Norian		
						Carnian		
				M	Muschelkalk	Ladinian		
						Anisian		
245				E	Buntsandstein	Scythian	Hardegsen	
	PALEOZOIC	Permian		Late	Zechstein	Thuringian		(VARISCAN)
				Early	Rotliegend	Saxonian	Saalian	
290						Autunian		
		Carboniferous		Late	Silesian	Stephanian	Asturian	
						Westphalian	Malvernian	
						Namurian	Sudetian	HERCYNIAN
				Early	Dinantian	Visean		
363						Tournaisian	Bretonian	

1.6 Summary

1.6.1 Stratigraphic sequence

Figure 1.4 shows the stratigraphic column of the map sheet area. The (current) distribution of the sediments is determined to a large extent by the structural development of the area. Late Carboniferous sediments are clastics and predominantly of fluvial and lacustrine origin. The Upper Rotliegend Group from the Early Permian is also built up of clastic material and in this area is mainly composed of fossil sand dunes indicative of a desert environment. The Zechstein Group, Late Permian, contains a number of evaporite cycles. These sequences of clay, carbonates, sulphates and rock salt were formed under marine conditions. The Lower Germanic Trias Group is also composed of clastics and is of continental origin (fluvial and lacustrine). Carbonates and evaporites of the Upper Germanic Trias Group reflect marine episodes in the basin. The Altena Group (Early and Middle Jurassic) comprises fine-grained marine sediments. The Central Graben Group (Late Jurassic to Early Cretaceous) represents mainly clastic, continental deposits. Marine sediments were accumulated during all the remaining Cretaceous and these can be divided into the clastic sediments of the Rijnland Group (Early Cretaceous) and the carbonates of the Chalk Group (Late Cretaceous). During the Tertiary the clastic sediments of the North Sea Super Group (Tertiary and Quaternary) started to accumulate in a marine environment which altered transitionally into a continental one.

Periods of erosion related to the phases of deformation have resulted in distinct hiatuses in the stratigraphic sequence. The extent of the hiatus and its place in the stratigraphic column reflect the geohistory of the map sheet area.

1.6.2 Structural units

The geological history is described using the structural units distinguished in the map sheet area (fig. 1.7). To a greater or lesser degree, these units contain Hercynian elements, which have been reactivated or modified during later tectonic phases.

During the Triassic, the western edge of the *Netherlands Swell*, a NNE-SSW trending ridge, coincides with the position of the present map sheet area (fig. 11.4). This swell has characteristic thin deposits of the Main Buntsandstein Formation. During the Middle and Late Triassic the part lying within the map sheet area started to subside as part of the Central Netherlands Basin.

The northern half of the map sheet area, belongs to a differentially uplifted area, the *North Netherlands High*, which extends over much of the northern Netherlands. It links the Pompeckj Swell in NW Germany with the Texel-IJsselmeer High ('t Hart, 1969; Stäuble & Milius, 1970). The North Netherlands High was formed during the Middle and Late Jurassic phases of deformation. In the map sheet area, the Vlieland Basin and Friesland Platform can be distinguished as separate units of this high.

The *Vlieland Basin* lies partly within the map sheet area; the larger part extends to the north, over the Vlieland-Terschelling map sheet (RGD 1991a). The Vlieland Basin developed during the Late Jurassic and the delineation of the basin is determined by the extent of the Late Jurassic deposits.

The *Friesland Platform* is located to the southeast of the Vlieland Basin, where the Rijnland Group lies directly on sediments of Permian or Early Triassic age because there are no Late Jurassic deposits.

The *Texel-IJsselmeer High* is the most uplifted part of the northern Netherlands; its extent is determined by the lack of the Upper Rotliegend Group (Map 1). During the Permian this high had a definite influence on the geological history and covered a greater area. The crest lay to the north of the present position of the high (compare fig. 3.1 with Map 1).

The *Noord-Holland Platform*, in the central part of the map sheet area, lay between the Texel-IJsselmeer High and the Central Netherlands Basin. Like the Friesland Platform, this high is characterised by the Rijnland Group lying on Permian or Early Triassic deposits.

The *Central Netherlands Basin*, in the southern half of the map sheet area, formed a differentially subsiding area during the Permian, Triassic, Jurassic and Early Cretaceous, in which thick sedimentary units were laid down. The deepest part of this basin lay in the extreme south of the map sheet area (Map 1) and is known as the *Gouwzee Trough*. The basin was inverted during the Late Cretaceous. On its northern margin the basin is separated from the Noord-Holland Platform and Texel-IJsselmeer High by a number of prominent faults. The southern boundary, which lies outside the map sheet area, is formed by a complex fault zone.

The *Zuiderzee Low*, which developed in the east and southeast of the map sheet, represents an area of subsidence during the Cenozoic. This depression is characterised by a thickening of Oligocene to Pliocene deposits. The depocentre lay just outside the map sheet area (fig. 10.2).

1.6.3 Geological history

During the last phase of the Variscan orogeny in the Late Carboniferous and Early Permian (Saalian phase), the map sheet area was part of a widespread uplifted area and erosion resulted. This was

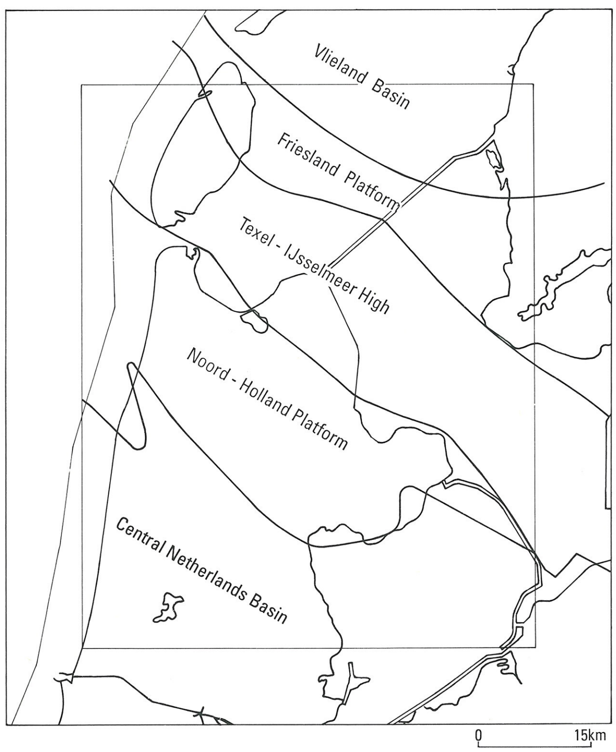


Figure 1.7. Reproduction of the structural configuration of the map sheet area.

followed by basin subsidence and sedimentation during the Permian, Triassic and Cretaceous. The basin configuration was influenced by the structural units formed during the Saalian phase. Some important phases of uplift took place during the Late Jurassic (Kimmerian phases; Maps 16 and 17) leading to erosion of the post-Carboniferous sediments present on the highs. Renewed subsidence and sedimentation occurred during the Cretaceous and Tertiary, interrupted in the Mesozoic basins by a couple of phases of uplift and erosion (inversion) during the Late Cretaceous and Early Tertiary (Sub-Hercynian and Laramide phases). The Vlieland Basin was uplifted only during the first phase, whereas the Central Netherlands Basin was strongly uplifted as a result of both phases. This is evident from the structural sections (Map 19) and from a comparison of the thicknesses of the Rijnland Group and the Chalk Group (Maps 12 and 14). The greatest subsidence since the beginning of the Tertiary has taken place in the Zuiderzee Low, as illustrated by the depth map of the base of the North Sea Super Group (Map 15).

2 Limburg Group

2.1 Stratigraphy

The sediments of the Limburg Group form the oldest deposits drilled within the map sheet area. They comprise predominantly claystones with intercalations of sandstones, siltstones and coal seams. The coal-bearing sediments belong to the so-called Coal Measures and are of Late Carboniferous (Westphalian A and B) age.

The Limburg Group occurs throughout the map sheet area. In much of the area the group is, separated by the Saalian unconformity, overlain by the Upper Rotliegend Group of Early Permian age (Map 1). The hiatus includes the younger Westphalian, Stephanian and the earliest Permian. On the Texel-IJsselmeer High the Limburg Group is, separated by the Late Kimmerian unconformity, overlain by the Rijnland Group of Early Cretaceous age (Map 17). The top of the Limburg Group lies at a depth of less than 2000 m on the Texel-IJsselmeer High, at a depth of 3500 m in the Vlieland Basin and at more than 4000 m in the Gouwzee Trough (Map 1). The group is strongly intersected by faults in the map sheet area.

The Limburg Group was reached by nearly 40 boreholes in the map sheet area, but since these deposits are not often an exploration target most of the wells have only been drilled a few tens of

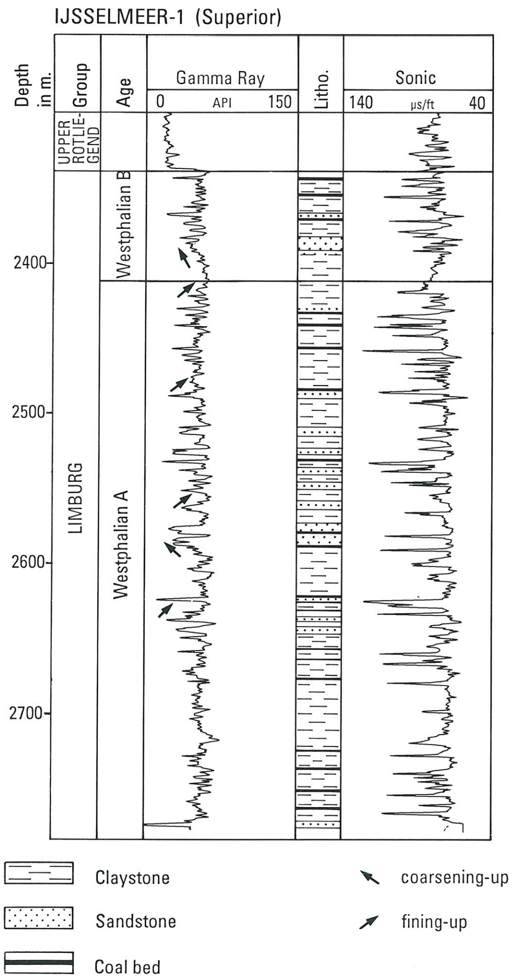


Figure 2.1. Composition of the Limburg Group in the IJsselmeer-1 well. The interpretation of the lithologies is based on gamma-ray log and sonic log readings. The gamma-ray log is in API units, the sonic log in µs/ft.

metres into the group. However, the Den Burg-1, IJsselmeer-1, Oostzaan-1, Sint Maarten-1 and Warmenhuizen-Krabbendam-1 wells penetrated more than 250 m. The greatest thickness of the Limburg Group, approximately 1300 m, was drilled to the east of the map sheet area in the Nagele-1 well, and reached the base of the Coal Measures. In the Oostzaan-1 well 1280 m was drilled without reaching the base of this formation. The maximum estimated thickness of the Coal Measures in the map sheet area is 1500 to 2000 m.

The succession of the Coal Measures is illustrated by the IJsselmeer-1 well (fig.2.1) and a SE-NW trending log correlation section (fig. 2.2). The log correlations and environmental interpretations used in this description are taken from RGD (1989a) and the Geological Survey of The Netherlands (1991a and b).

2.1.1 Coal Measures

The Coal Measures comprise mainly dark grey to violet coloured claystones, with interbedded white to light grey fine-grained sandstone and siltstone layers and several coal seams. The sand- and siltstones are micaceous and contain some coalified plant remains. The sandstones are calcite, dolomite or quartz cemented.

The above lithologies are associated with both coarsening-upwards and fining-upwards sequences, which are evident in core material and well-log data records (fig. 2.1). Coal seams are associated with both types of sequences and also occur independently within the claystones.

The greater part of the map sheet area reveals only the oldest deposits of the Coal Measures, with a Westphalian A age (fig. 2.3). These deposits generally show an upward increase in grain size throughout the area. The lowest part of the sequence was drilled in Nagele-1, while other wells exhibit the upper part and the transition to Westphalian B. The lowest part of the drilled sequence consists of claystone with interbedded coal seams. Some thin sandstone beds are also evident in this lowest part, at times as part of a coarsening-upwards sequence. The uppermost part of the Westphalian A is clearly more sandy, as seen in several wells. The maximum thickness of the sandstone layers is 7 m. The series contains less coal in the northern (Den Burg-1) and eastern (Nagele-1) parts of the map sheet area than in the southern part (IJsselmeer-1 and Oostzaan-1). The total thickness of this unit is at least 1300 m (Nagele-1).

The base of the Westphalian B contains a claystone horizon characterised by a high natural gamma radiation. It is a marine deposit, known as the Catharina band, and it can be distinguished on well logs, although not always with certainty (RGD, 1989a). The Westphalian B generally contains more coal seams than the Westphalian A. In the former unit thicker sandstone beds occur with alternating, well-developed, coarsening-upwards and fining-upwards sequences. The minimum thickness of the Westphalian B is more than 400 m (Oostzaan-1).

Log correlations (RGD, 1989a) and palynological studies (RGD, 1985a, 1985b, 1987c & 1988c) broadly confirm the outline given by Van Wijhe (1987a) in figure 2.3. In most of the map sheet area Westphalian A deposits are found under the Saalian unconformity, although in the northwest Westphalian B is also present (RGD, 1988c), in contrast to Van Wijhe (1987a). At the moment the relatively slight density of data does not justify adapting the interpretation given by Van Wijhe (1987). The variations in the age of the Carboniferous deposits under the Saalian unconformity seem to be of a regional character; they vary little in consequence of fault tectonics.

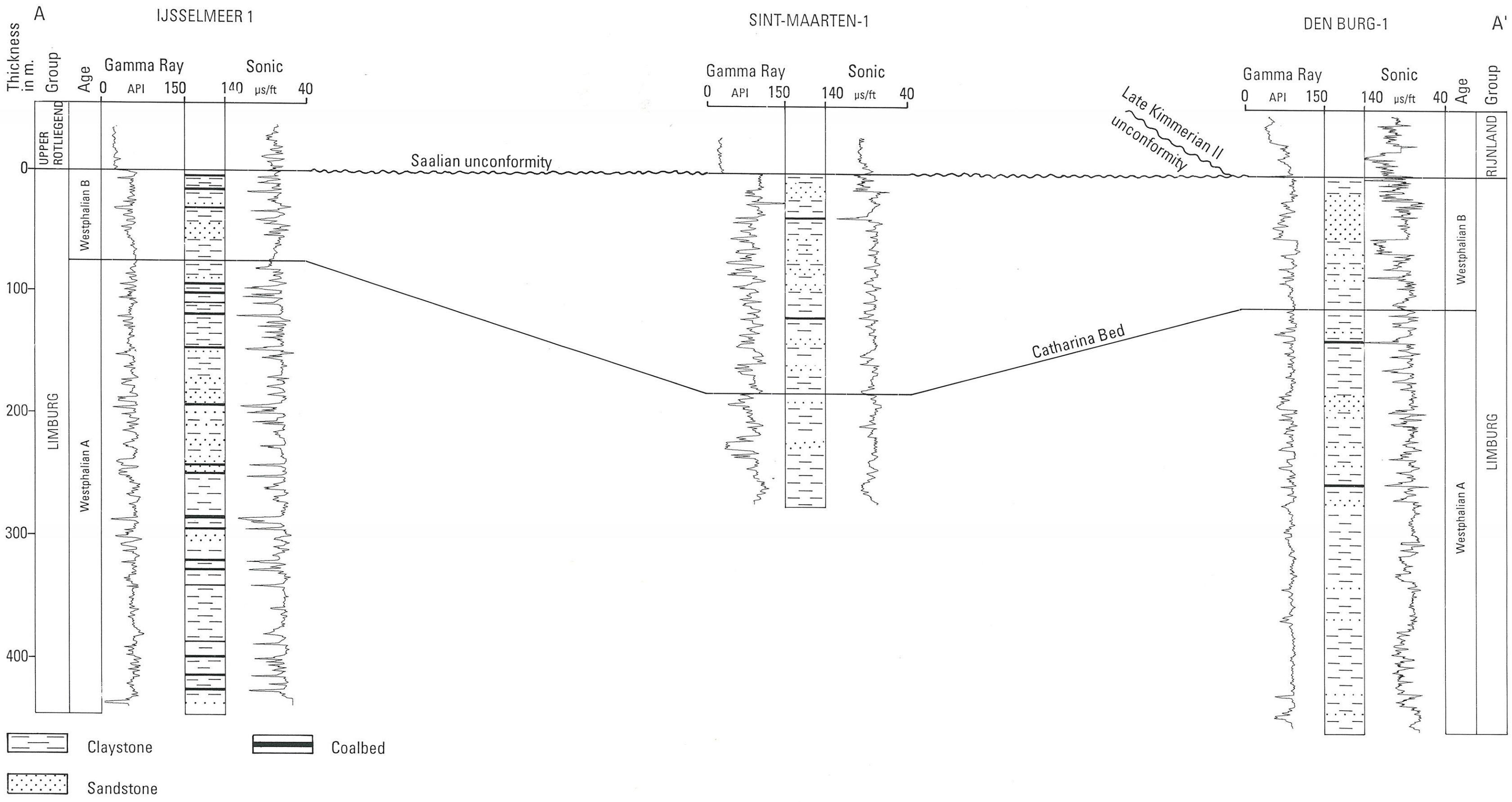


Figure 2.2. Stratigraphic section AA' of de Limburg Groep. The reference level is the Saalian unconformity at the top of the Limburg Group. The correlations are based on the gamma-ray log (in API) and the sonic log in µs/ft) readings. The location of this section is shown in figure 2.3.

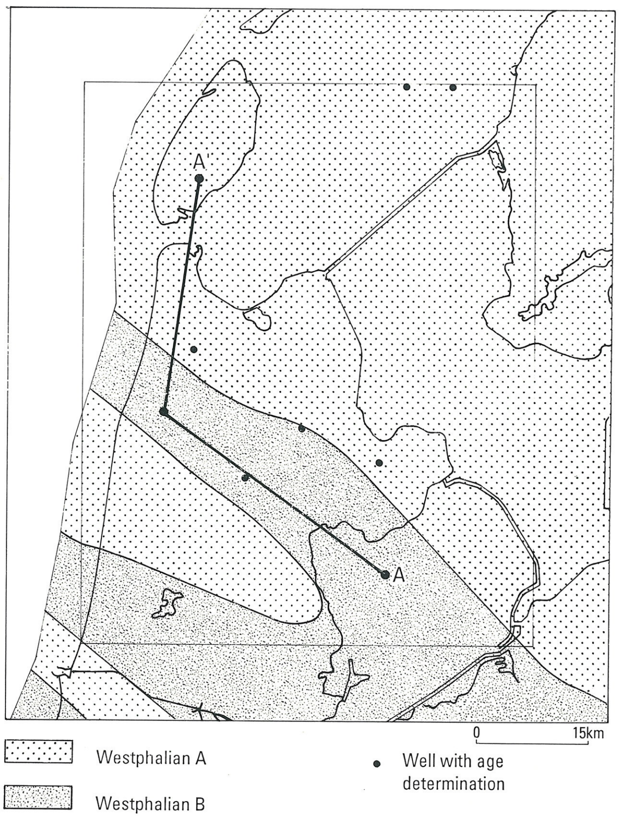
2.2 Sedimentary development and palaeogeography

Sedimentation took place in lakes and marshes during the Westphalian A and crevasses and lacustrine crevasse deltas developed (RGD, 1989a). The wide distribution of the interbedded marine sediments indicates a very flat landscape. During the Westphalian B the fluvial influence increased and sedimentation took place in a lacustrine to flood-plain environment with meandering rivers, characteristic of areas of low relief. There were marshes between the river channels and where the rivers flowed into lakes the coarsening-upwards sequences accumulated. Excess water flowed through breaks in natural levees, which led to the crevasse deposits. The prevailing tropical climate, with its abundant plant growth, facilitated extensive peat formation in the marshes and cut-off meander channels.

2.3 Geochemical evaluation

About 15 wells in the map sheet area and direct vicinity were investigated to determine their geochemical features (RGD, 1989b), including the degree of coalification based on the vitrinite reflectance (%Rm). The coal seams of the Coal Measures belong to the so-called Type III source rock (coalified plant remains). Gas is formed if there is sufficient coalification (%Rm values of 1.2 to 3.2; Teichmüller, 1968); the degree of coalification is considered to be mainly dependent on temperature. Theoretically, organic-rich marine intercalations could occur in the Carboniferous deposits. These intercalations could belong to the oil-generating Type I/II source rock; however, the available data do not support their presence.

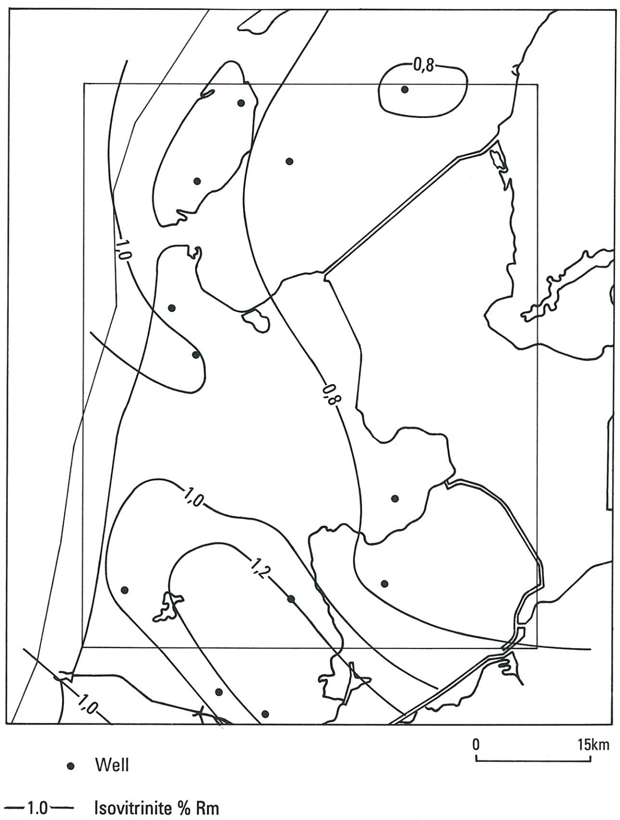
Figure 2.3. Subcrop map of the base of the Upper Rotliegend Group (Saalian unconformity). Variation in age of the top of the Limburg Group gives an indication of the palaeorelief (from Van Staalduinen et al., 1979 and Van Wijhe, 1987a). AA' is the location of the section shown in figure 2.2.



The degree of coalification of the top of the Coal Measures shows notable differences within the map sheet area (fig. 2.4). This map should be regarded with some reserve given the scarce data and the variance of values measured. The vitrinite reflectance increases towards the southwest, from about 0.7 %Rm in the north and east to more than 1.2 %Rm in the Gouwzee Trough. The area with the lowest Rm values in the northeast roughly coincides with the Texel-IJsselmeer High, which is also the area of least coal content and where the oldest layers of the Coal Measures subcrop under the Saalian unconformity (Westphalian A; fig. 2.3). Locally, around the Zuidwal Volcano, the degree of coalification is slightly higher . Analysis of compaction data for the Lower Buntsandstein Formation around the Texel-IJsselmeer High shows that this unit's maximum depth of burial agrees with its present depth. For the method used see Van Wijhe et al. (1980) and section 5.2.1.1.

Coalification in the north and east of the map sheet area appears to have occurred mainly during the Late Cretaceous and Cenozoic, since the deposits were at their maximum burial depth. The boundary fault of the Central Netherlands Basin forms the southern edge to this area. Extrapolating from the measurements of increased values of coalification with respect to depth, 1.2 %Rm/km (Oostzaan-1; RGD, 1989b) indicates that gas can be generated at depths more than 400-500 m beneath the top of the Carboniferous. In the vicinity of volcanic rocks this boundary will be shallower since the temperature gradient will be higher, as is the situation near the Zuidwal Volcano located within the map sheet area.

Figure 2.4. Isovitrinite map of the top of the Limburg Group, based on well data.



The area of high vitrinite reflectance values coincides with the Central Netherlands Basin, where the degree of coalification of the Coal Measures bears no relation to their present burial depth. Analysis of compaction data for the Lower Buntsandstein Formation has shown that there are large differences between the unit's maximum burial depth and its present depth. These differences can be attributed to the Late Cretaceous inversion. In the Gouwzee Trough the current degree of coalification of the top of the Limburg Group had already been reached in the earliest Late Cretaceous, prior to the inversion. With %Rm values of 1.2 and higher, gas could have been generated within the whole Carboniferous sequence in this area. The gas generation was ended by the uplift of the Central Netherlands Basin during the Late Cretaceous to Early Tertiary, although gas could have been generated again in the Gouwzee Trough during subsidence in the Tertiary.

Data from the area to the west of the map sheet (Van Wijhe, 1987b) show that the degree of coalification at the top of the Coal Measures increases from 1.0 to 2.4 in the centre of the Broad Fourteens Basin. The main period of gas generation in this basin took place prior to the Late Cretaceous inversion according to Van Wijhe (1987b).

3 Upper Rotliegend Group

3.1 Stratigraphy

The Upper Rotliegend Group, Early Permian, is mainly represented in the map sheet area by the Slochteren Sandstone Formation, which is nearly all composed of a red to grey-white coloured sandstone. There are claystone intercalations belonging to the Silverpit Claystone Formation in the northern part of the map sheet area. These two formations are lateral equivalents; to the north of the Dutch mainland the Upper Rotliegend Group is nearly wholly composed of the Silverpit Claystone Formation (Geological Survey of The Netherlands, 1991a).

The deposits of the Upper Rotliegend Group overlie the Limburg Group, separated by the Saalian unconformity; they are strongly fractured (map 1). In most of the area they are conformably overlain by the Zechstein Group (map 2). Deposits of the Rijnland Group (Lower Cretaceous) lie unconformably on the Upper Rotliegend Group in the north and northeastern part of the map sheet area (map 17). Around the Texel-IJsselmeer High the base of the group is at less than 2000 m depth, increasing northwards and southwards to 3500 m in the Vlieland Basin and to more than 4000 m in the Central Netherlands Basin.

The Upper Rotliegend Group is absent on the Texel-IJsselmeer High because of later erosion (Geological Survey of The Netherlands, 1991a) (map 1). The reconstructed thickness of the Upper Rotliegend Group ranges from 150 m in the east of the map sheet area to more than 250 m in the west (fig. 3.1). The thickness map shows WNW-ESE trends within the map sheet area, which are also evident from the thickness and distribution maps of the overlying formations. These trends are indicative of synsedimentary faults.

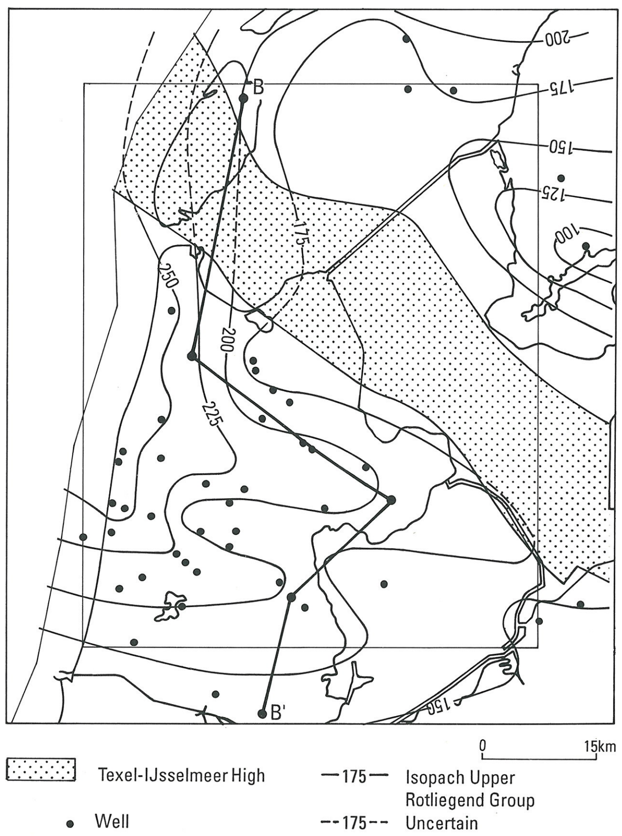


Figure 3.1. Reconstructed thickness map of the Upper Rotliegend Group. Thickness in metres. The map is based on well data. BB' is the location of the stratigraphic section shown in figure 3.3.

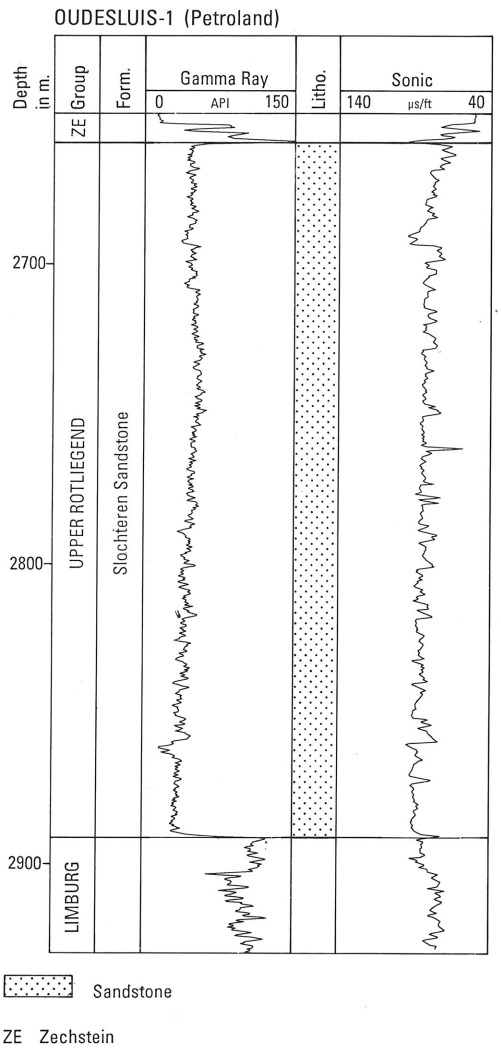
The succession of the Upper Rotliegend Group is illustrated by the Oude Sluis-1 well (fig. 3.2) and a north-south oriented correlation section (fig. 3.3).

3.1.1 Slochteren Sandstone Formation

In most of the map sheet area, this unit comprises a massive sand unit that is not subdivided into members because of the lack of intercalated claystones of the Silverpit Claystone Formation. However, core studies and well logs reveal differences that allow three facies types to be distinguished in the formation.

The basal part of the formation is up to 60 m thick and composed of relatively poorly sorted, coarse-grained sandstones and conglomerates. Channel-shaped incisions and small-scale cross-

Figure 3.2. Composition of the Upper Rotliegend Group in the Oude Sluis-1 well. In this well the group is represented by the Slochteren Sandstone Formation. The gamma-ray log is in API units, the sonic log in µs/ft.



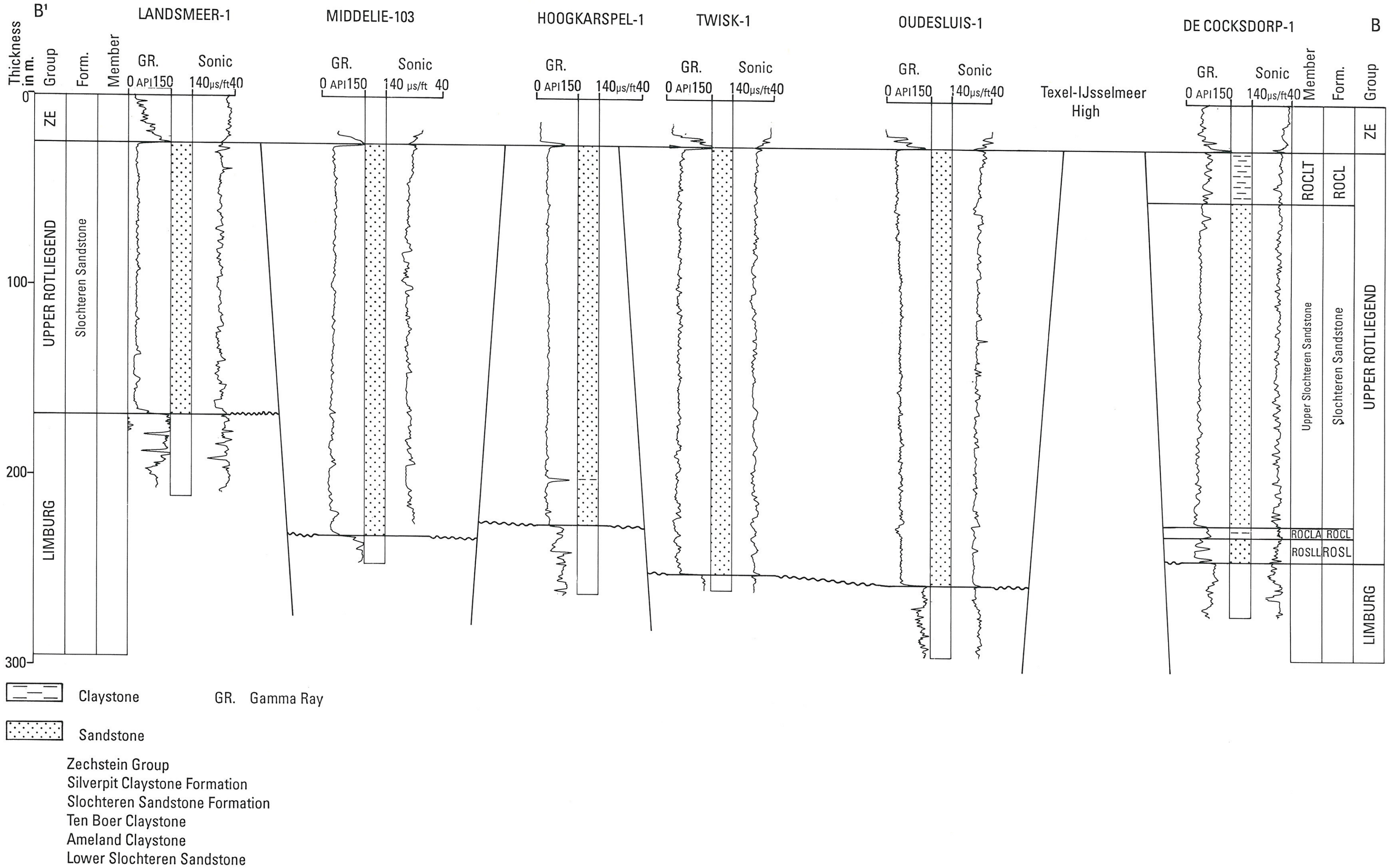


Figure 3.3. Stratigraphic section BB'. The location of the section is shown in fig. 3.1. This section shows the composition of the Upper Rotliegend Group within the map sheet area. Synsedimentary faults influenced the thickness pattern. The likelihood of the presence of these faults is presumed from thickness variations in the Upper Rotliegend Group and facies variations in the overlying Zechstein Group. The correlations are based on gamma-ray (in API) and sonic log (in µs/ft) readings. The reference level is the top of the Upper Rotliegend Group.

bedding are observed in the sandstone. The unit is characterised by a slightly higher clay content and stronger cementation than the other two facies types. The unit can be distinguished from the overlying sandstone sequence on well logs because its gamma-ray log is characterised by more peaks. The distribution of this facies type is mainly limited to the Central Netherlands Basin (fig. 3.3).

The middle and normally thickest part of the formation comprises red coloured, very well sorted, coarse-grained sandstone with very sharply bounded cross-bedding. A distinction can be made between low and high angle cross-bedding; these vary over a couple of metres. Measurements in the cross-bedding of this unit in the Landsmeer-1 well indicate transport westwards (Van Wijhe et al., 1980). The unit is poorly cemented except for a few layers cemented with anhydrite or dolomite. These can be easily found on the acoustic log. This middle unit can reach a thickness of 200 m.

The top part of the formation comprises grey-white to yellow coloured, well sorted, fine-grained sandstones. This part shows the same features as the underlying red coloured part, as evident in the stable gamma-ray log (fig. 3.3). In some wells however massif sandstones occur. The lack of colour and stronger cementation are the main differences from the middle part of the formation. The cements are poikilitic mottled cements and pore-filling cements which fill whole zones. The main constituent cementing minerals are dolomite, anhydrite and clay with smaller quantities of calcite, quartz, hematite, siderite, ankerite, celestite, and barytes as pore-filling cements. Hematite (mixed with clay minerals), illite and quartz are present as grain coatings. The degree of cementation increase upwards, which is clearly evident on the acoustic log (fig. 3.3). This top part is normally a few metres to, at most, some tens of metres thick but in the Bergermeer-3 and Heiloo-1 wells, where the formation is almost completely composed of this type of sandstone, it is more than 120 m thick.

The thickness of the Slochteren Sandstone Formation virtually corresponds with that for the whole group (fig. 3.1). The clear WNW-ESE trends are interpreted as resulting from synsedimentary faults; further evidence for synsedimentary faulting appears in the clear facies and thickness variations with similar trends found in the overlying Zechstein Group.

3.1.2 Silverpit Claystone Formation

The Silverpit Claystone Formation is the distal equivalent of the Slochteren Sandstone Formation and, as already stated, occurs only in the most northern part of the map sheet area. The Silverpit Claystone Formation is composed of alternations of red, reddish-brown and brown coloured silty claystones and siltstones. These sediments have only been found in one well, De Cocksdorp-1 (fig. 3.3), in which the Ameland and Ten Boer Claystone Members can be distinguished. For a more detailed description, see the adjacent map sheets to the north (Geological Survey of The Netherlands, 1991a, b).

The interpretation of De Cocksdorp-1 well differs from the interpretation given by Geological Survey of The Netherlands (1991a). New studies reveal that the lower claystone interval should be considered as Ameland Claystone and not as Hollum Claystone.

3.2 Sedimentary development and palaeogeography

The Upper Rotliegend Group was deposited under continental conditions in the intra-cratonic Southern Permian Basin (fig. 11.1). A lake formed in the centre of the basin in which the claystones and evaporites of the Silverpit Formation were deposited.
The Slochteren Sandstone Formation in the map sheet area was originally deposited by braided rivers. The relief became less pronounced under the influence of a slow rise in the lake's water level and a desert formed in the map sheet area (fig. 11.2) with sand dunes developing under the influence of the NE trade winds that dominated the area (Glennie, 1983, 1986). The sands and conglomerates at the base of the Slochteren Sandstone Formation are erosion products of the Variscan mountains situated further to the south (Stäuble & Milius, 1970). The aeolian sands probably originated from a much larger area which extended far to the east of the map sheet area. Deflation of the sediments, originally deposited by braided rivers and wadis, probably took place (Glennie, 1983).

In the north the map sheet area was separated from the central part of the Southern Permian Basin by a high, the Texel-IJsselmeer High. A hypersaline lake existed in this central part of the basin (Glennie, 1983). Directly to the north of the high were extensive sandy areas, which became playas to the north. During periods of high water level, the lake flooded the sandy areas covering them with lacustrine deposits; these are represented in the clay- and siltstones of the Silverpit Formation in the northern part of the map sheet area. The Texel-IJsselmeer High proved an effective barrier to the lake extending any further, although the water level changes in the lake did influence the desert area to the south of this high (Yang & Baumfalk, 1991). This aspect has not been studied in detail in the map sheet area but it is possible that the more strongly cemented layers in the middle part of the Slochteren Sandstone Formation are related to the periods of high water level in the lake.

The sediment's red staining is considered to be caused by fluctuations in the groundwater level shortly after deposition. In periods of low groundwater, iron-bearing minerals were oxidised and hematite was formed; this was subsequently spread by the groundwater through the sediment as a thin coating on the grains (Walker, 1967). The presence of this cortex on the quartz grains can prevent cement growth on the grains during later diagenesis (Füchtbauer, 1974).

The grey-white colour of the top part of the formation is thought to be a consequence of decolorisation. The transition from white/grey to red is gradual and the loss of colour is related to the Zechstein transgression and evaporite sedimentation. No indications have been found for a relation between the grey-white coloured deposits and the depositional environment, as was suggested by Van Lith (1983). There are indications in some wells of local resedimentation in connection with the Zechstein transgression. The transgression greatly affected previous deposits because the Southern Permian Basin had subsided below sea level by the end of the Early Permian (Glennie, 1986; Glennie & Buller, 1983).

3.3 Petrophysical evaluation

The sandstones of the Upper Rotliegend Group form one of the principal exploration targets in the territory of The Netherlands and on the continental shelf, and various gasfields are productive from this reservoir within the map sheet area, viz: Bergermeer, Groet, Middelie, Middenmeer and Schermer (see fig. 1.2).

In contrast to the Vlieland-Terschelling map sheet (Geological Survey of The Netherlands, 1991a), the Upper Rotliegend Group is characterised by a nearly complete lack of claystone intervals

(Ameland and Ten Boer Claystones), which means that the group can be considered as a single petrophysical unit throughout the map sheet area. The deposits of the group were evaluated from 16 wells in the map sheet area and immediate vicinity (appendix C; RGD, 1991b). These revealed both gas- and water-bearing sandstones. The result of a log evaluation in Bergermeer-1 (fig. 3.4) gives an example of an Upper Rotliegend Group reservoir sequence.

The distribution of the average effective porosity (Øem) of the Upper Rotliegend Group in the map sheet area and surroundings is shown schematically in figure 3.5. In contrast to the more northern map sheets (Geological Survey of The Netherlands, 1991a, b), the average effective porosity shows large variations between the different wells. This is also evident in figure 3.6 which shows the relation between porosity and present burial depth. This variance is thought to be caused by the strongly fractured character of the Upper Rotliegend Group in the map sheet area, which has a positive effect (from faults) as well as a negative effect (cementation) on the porosity. A contour interval of 5% was therefore chosen to the southwest of the Texel-IJsselmeer High. In part of the map sheet area the group's porosity is more than 20%, while lower porosities are found around the Texel-IJsselmeer High and locally in the Central Netherlands Basin. The permeability of the group

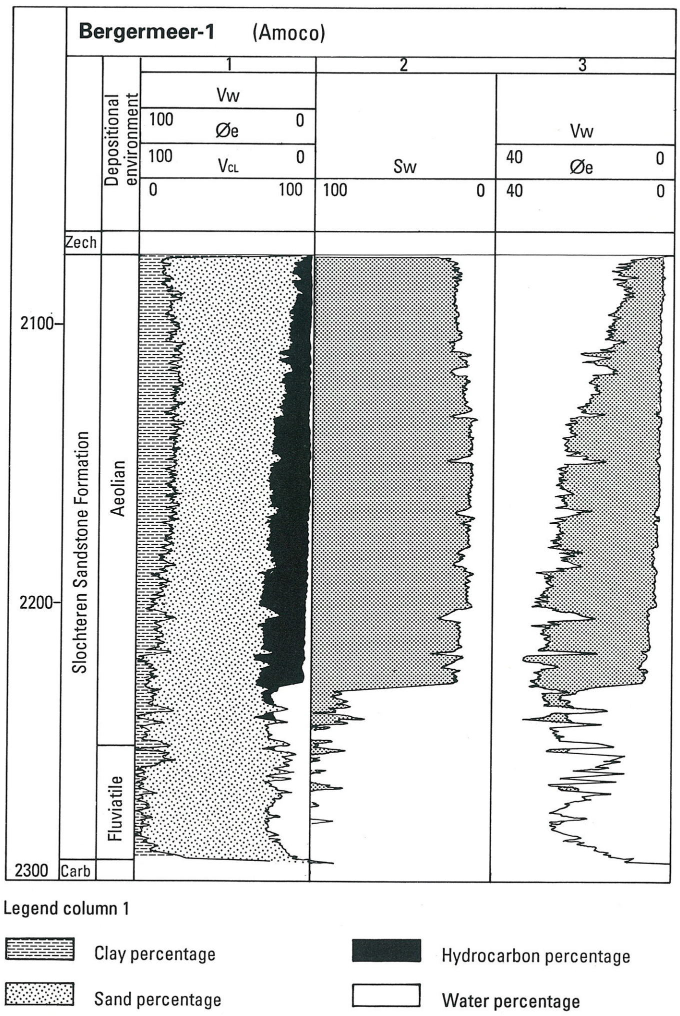


Figure 3.4. Petrophysical evaluation of the Upper Rotliegend Group in the Bergermeer-1 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained using the sonic logs (Raymer-Hunt comparison in single porosity model; Raymer et al., 1980) after correction for the clay content. Column 2: water saturation Sw. The Indonesia formula, which is suitable for argillaceous formations, was used to determine the water saturation (Fertl, 1987). Column 3: effective porosity Øe and the volume of water in the pores Vw. In the left-hand column, the boundaries of the formation and depositional environment are indicated. The depth is the actual depth.

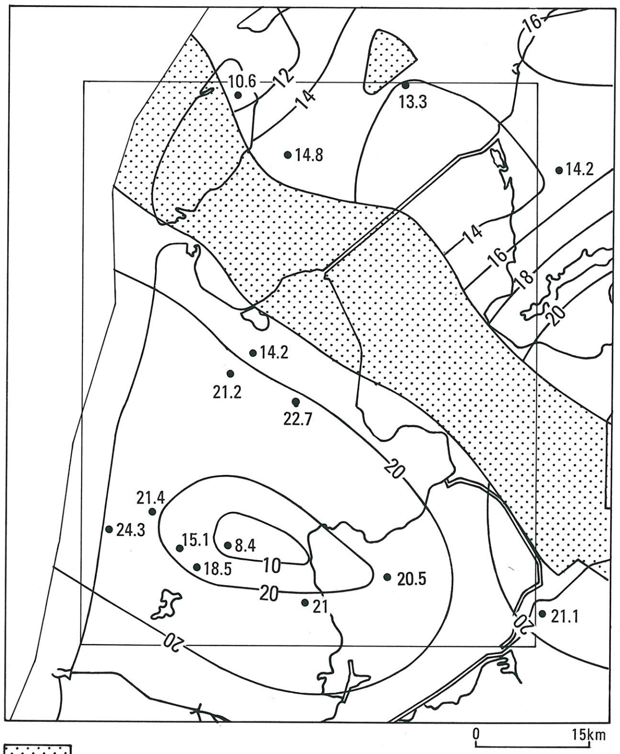
varies from 30 to 600 mD in the map sheet area (Geological Survey of The Netherlands, 1987; Geluk, 1988).

The highest porosity (>20%) in the Upper Rotliegend Group is found in the middle part in the aeolian sands. The basal part of the group has a more fluvial character, with a lower and more strongly fluctuating porosity (10<Øem<20). Locally, the top part of the group is strongly decolorised and/or reworked. These are still partly aeolian deposits. The cementation of this top part is also stronger than in the middle or basal parts, as evident from the acoustic log and the porosity (figs 3.2, 3.3 & 3.4). The calculated porosities agree closely with the published values for the 'Bergen' concession (Van Lith, 1983).

The presence of hydrocarbons in the reservoir rocks is mainly determined by the timing of the gas generation in relation to the development of adequate tectonic traps. The porosity and permeability of the Upper Rotliegend Group do not form any real barrier to exploration in this map sheet area.

N.B. The Depth map of the Base of the Upper Rotliegend Group (Map 1) erroneously does not show the occurrence of this group in the Wieringerwaard area in the vicinity of the Afsluitdijk, where, however, the deposits of the Zechstein Group are indicated (Maps 2 & 3).

Figure 3.5. Schematic contour map of the reservoir-average effective porosity Øem of the Upper Rotliegend Group (appendix C). In a large part of the map sheet area, the porosities are higher than 20%; exceptions are the area around the Texel-IJsselmeer High and an area in the Central Netherlands Basin. Further information can be found in the text.



Upper Rotliegend Group absent

—12— Isoporosity %

• 20.5 Well with porosity value

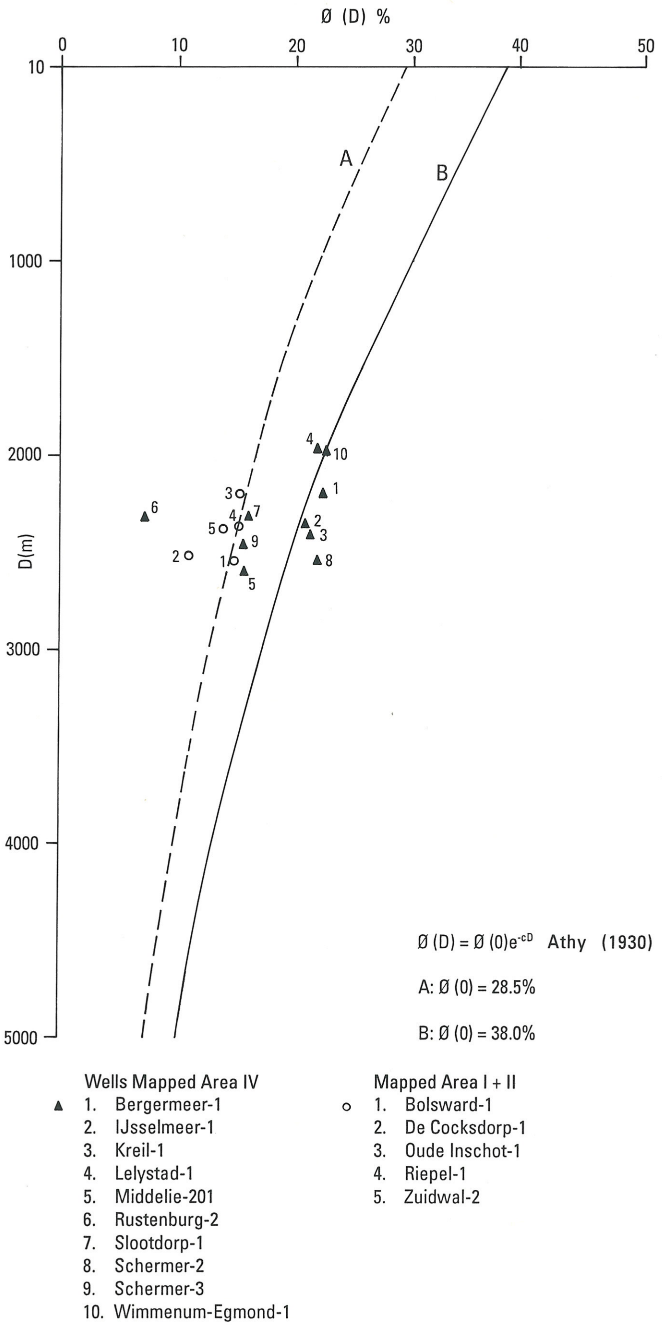


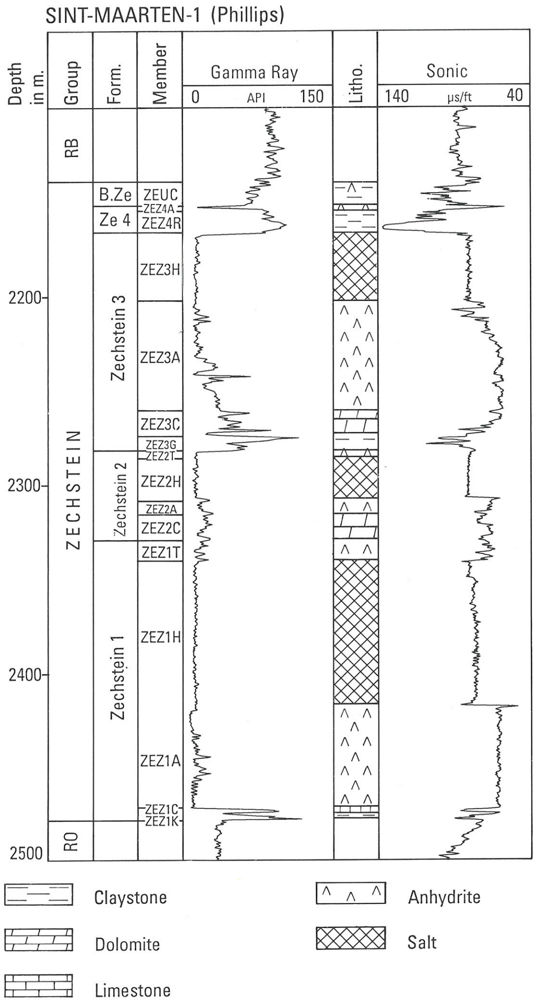
Figure 3.6. Porosity versus depth plot for the Upper Rotliegend Group for the evaluated relevant wells on map sheets I and II (open circles) and map sheet IV (closed triangles). Curve A is the compaction curve according to Athy's (1930) relation, with a surface porosity Ø(0) = 28.5%, as was selected for the wells on map sheet I. Curve B is the compaction curve for a surface porosity of 38.0 %. For the constant c a 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 (appendix C; RGD, 1991).

4 Zechstein Group

4.1 Stratigraphy

Within the map sheet area the Zechstein Group, of Late Permian age, is built up of clastic deposits and evaporites, with the percentage of clastic components decreasing from over 50% in the southwest to below 10% in the northeast (RGD, 1986f). The group, comprising four evaporite cycles, the Zechstein 1 to 4 Formation, overlain by a claystone, the Upper Zechstein Claystone Formation. The bases of the formations are characterised by transgressive deposits.

The Zechstein Group in the map sheet area is found on both sides of the Texel-IJsselmeer High (Maps 2 & 4), but is not, however, present on the high itself as a consequence of post-depositional



RB	Lower Germanic Trias Group	ZEZ2T	Zechstein 2 Roof Anhydrite
RO	Upper Rotliegend Group	ZEZ2H	Zechstein 2 Salt
B.Ze	Upper Zechstein Formation	ZEZ2A	Zechstein 2 Basal Anhydrite
ZEUC	Upper Zechstein Claystone	ZEZ2C	Zechstein 2 Carbonate
ZEZ4A	Zechstein 4 Pegmatite Anhydrite	ZEZ1T	Zechstein 1 Upper Anhydrite
ZEZ4R	Zechstein 4 Red Salt Clay	ZEZ1H	Zechstein 1 Salt
ZEZ3H	Zechstein 3 Salt	ZEZ1A	Zechstein 1 Lower Anhydrite
ZEZ3A	Zechstein 3 Main Anhydrite	ZEZ1C	Zechstein 1 Carbonate
ZEZ3C	Zechstein 3 Carbonate	ZEZ1K	Zechstein 1 Coppershale
ZEZ3G	Zechstein 3 Grey Salt Clay		

Figure 4.1. Lithostratigraphic composition of the Zechstein Group in the Sint Maarten-1 well. There is a fairly complete succession present in this well, with carbonate deposits in the Zechstein 1, 2 en 3 Formations and salt deposits in the Zechstein 1 to 4 Formations. The interpretation of lithologies has been made on the basis of gamma-ray and sonic log readings. The gamma-ray log is in API units, the sonic log in µs/ft.

erosion. The Zechstein Group is conformably overlain by the Lower Germanic Trias Group (Map 5), with the exception of a small area around the Texel-IJsselmeer High, where the Rijnland Group (Lower Cretaceous) covers the Zechstein Group unconformably (Map 17).

The Zechstein Group displays clear differences on both sides of the Texel-IJsselmeer High in terms of thickness as well as stratigraphic development. This is due to the presence of a precursor of the present high during the Permian. To the northeast of the high, thick salt members are found in the group, and the total thickness here sometimes exceeds 1000 m (Geological Survey of The Netherlands, 1991a). To the southwest of the high, the Zechstein Group consisting for the most part of clastics, anhydrite, carbonate and rock salt, has a thickness varying from less than 200 m to more than 400 m (Map 4). The occurrence of variations in thickness and facies in conjunction with the presence of faults indicates synsedimentary fault movements which are responsible for the complex character of the group. This is illustrated by both the Sint Maarten-1 well (fig. 4.1) and the north-south correlation diagram (fig. 4.2).

The formation is highly disrupted, and within the map sheet area the depth of the base increases from approximately 1500 to 2500 m around the Texel-IJsselmeer High to over 3000 m in the Vlieland Basin and nearly 4000 m in the Central Netherlands Basin (Map 2).

4.1.1 Zechstein 1 Formation

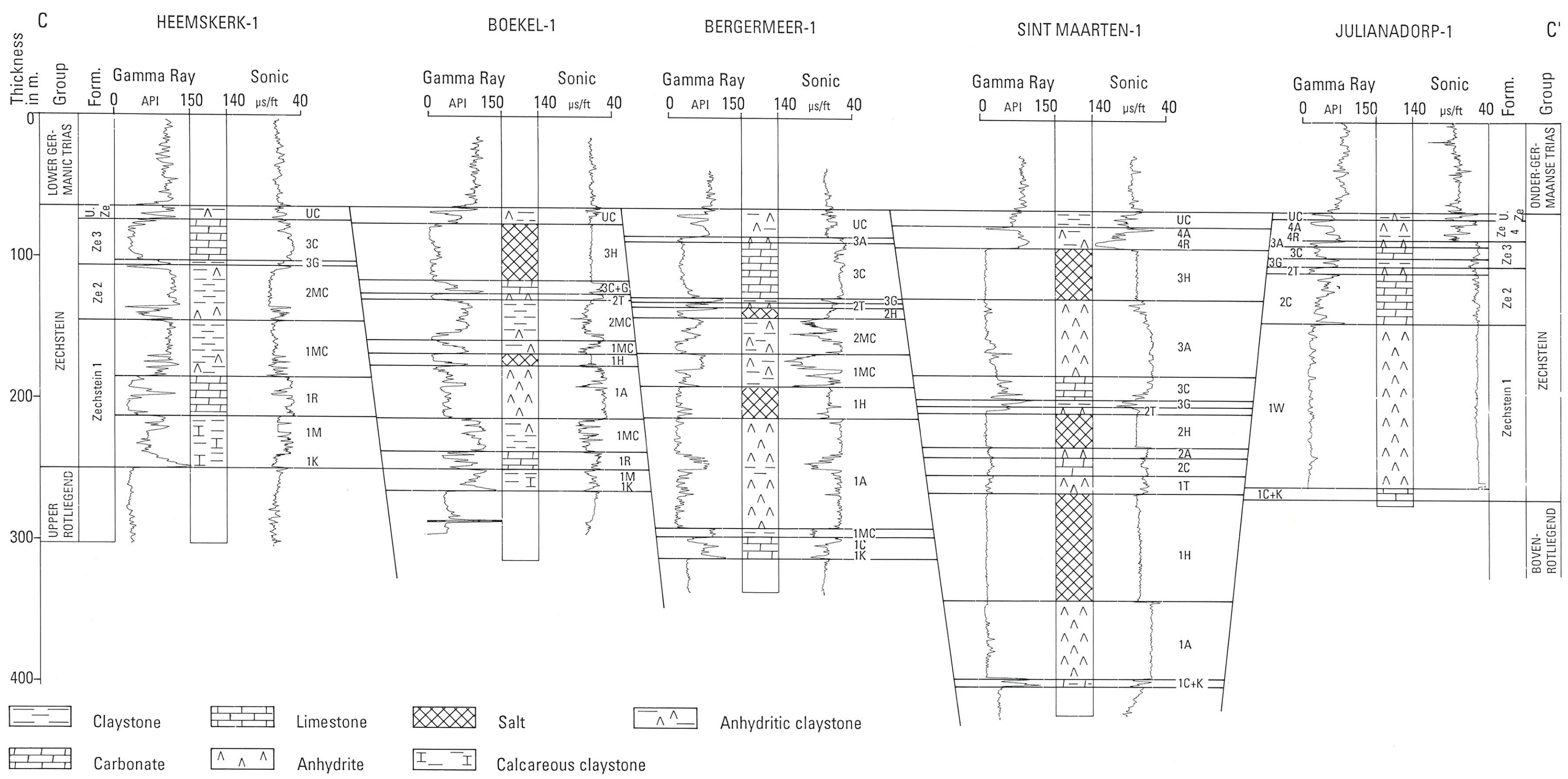
The Zechstein 1 Formation comprises the Coppershale, Zechstein 1 Carbonate, Zechstein 1 Halite, Zechstein 1 Middle Claystone and Zechstein 1 Anhydrite Members. A few additional members can also be identified which are the lateral equivalents of these and will, as far as possible, be discussed in combination with the above-mentioned members.

The formation to the northeast of the Texel-IJsselmeer High has a fairly constant depth of 35 m, whereas to the south of the high, it varies considerably, ranging from 50 to 350 m. On the flanks of the high, in the Riepel-1 and De Cocksdorp-1 wells, the thickness is less than 20 m. The greatest variations in the lithological succession of the formation occur to the south of the high, where this formation often accounts for over 50% of the total thickness of the Zechstein Group; this is less than 10% to its north.

The *Coppershale* forms the base of the formation deposits. The member consists of a dark, finely laminated claystone, rich in organic material. Although it is a mere 0.5 to 1 metre thick, the unit is clearly distinguishable by the high gamma-ray log reading and has a very large regional distribution.

The *Zechstein 1 Carbonate* consists of a grey-brown limestone or fine-crystalline dolomite and displays an upwardly decreasing clay content. In the southern half of the map sheet area a further, provisionally informal, subdivision can be made into the Zechstein 1 Lower Claystone and Zechstein 1 Rim Carbonate (fig. 4.3). This informal naming differs from the NAM & RGD (1980) nomenclature where the member is allocated to the Main Fringe Zechstein Member. In some places, only the Zechstein 1 Lower Claystone of the formation is present.

To the north of the Texel-IJsselmeer High the member is 2 to 20 m thick, whereas to the south of the high the thickness increases from less than 10 m to nearly 75 m in the extreme southwest (fig. 4.4). Alternating stratified carbonates and series of breccias, and intervals with holes of 0.5 to 1 cm in diameter, are characteristic of the dolomitic limestone unit on the north flank of the high, as identified in the Riepel-1 and De Cocksdorp-1 wells. Research by Van der Poel (1987) on the



U.ze	Upper Zechstein Claystone Formation	4R	Zechstein 4 Red Salt Clay	2H	Zechstein 2 Salt	1H	Zechstein 1 Salt
Ze 4	Zechstein 4 Formation	3H	Zechstein 3 Salt	2A	Zechstein 2 Basal Anhydrite	1A	Zechstein 1 Lower Anhydrite
Ze 3	Zechstein 3 Formation	3A	Zechstein 3 Main Anhydrite	2C	Zechstein 2 Carbonate	1C	Zechstein 1 Carbonate
Ze 2	Zechstein 2 Formation	3C	Zechstein 3 Carbonate	2MC	Zechstein 2 Middle Claystone	1R	Zechstein 1 Rim Carbonate
UC	Upper Zechstein Claystone	3G	Zechstein 3 Grey Salt Clay	1MC	Zechstein 1 Middle Claystone	1M	Zechstein 1 Lower Claystone
4A	Zechstein 4 Pegmatite Anhydrite	2T	Zechstein 2 Roof Anhydrite	1T	Zechstein 1 Upper Anhydrite	1K	Zechstein 1 Coppershale

Figure 4.2. Stratigraphic section CC' of the composition of the Zechstein Group. The location is shown in fig. 4.4. This section shows the great variation in the composition of the Zechstein Group. The indicated faults are tentative; their presence is presumed because of variations in thickness and composition. The correlations are based on gamma-ray (in API) and sonic log (in µs/ft) readings. The reference level of this section is the top of the Zechstein Group.

Zechstein Group in these wells led him to conclude that the breccias were caused by leaching during the Late Jurassic. The contrary conclusion is generally taken, namely that this process had already taken place during the Permian, in view of the frequent occurrences of breccias series in the Slootdorp-1 well for example, where the thick series of covering Permian and Triassic deposits make a Late Jurassic age for the leaching process unlikely. However, this well was not examined by Van der Poel (1987). Rebelle (1986) assumes a Permian age for the leaching.

The *Zechstein 1 Middle Claystone* occurs in the southwest of the area. The naming here adhered to differs from NAM & RGD (1980), where, like the carbonate, these clastics are allocated to the Main Fringe Zechstein Member. Detailed log correlation with the basin deposits enables the boundary between the Zechstein 1 and 2 Formations to be determined within the predominately claystone succession between the Zechstein 1 and 3 Carbonates. It lies at the base of a claystone succession which is taken as the equivalent of the reddish-brown salt clay in Germany as described by Teichmüller (1957; see Heemskerk-1 well in fig. 4.3). In some wells, however, the correlations present problems. The deposits consist of reddish-brown to greenish-grey claystone, with interbeds of anhydrite nodules. Northwardly, this succession grades into evaporites, the Zechstein 1 Anhydrite and the Zechstein 1 Rock Salt (see fig. 4.2).

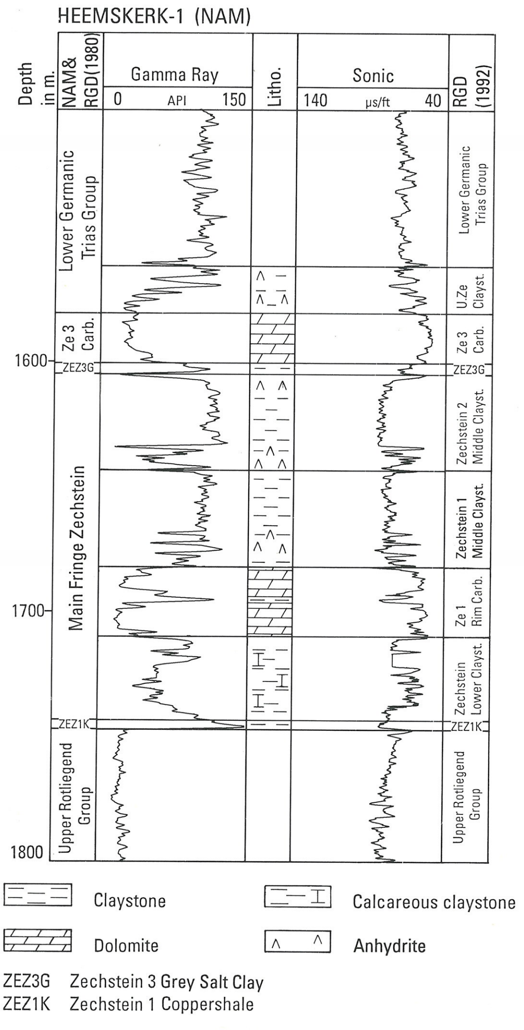
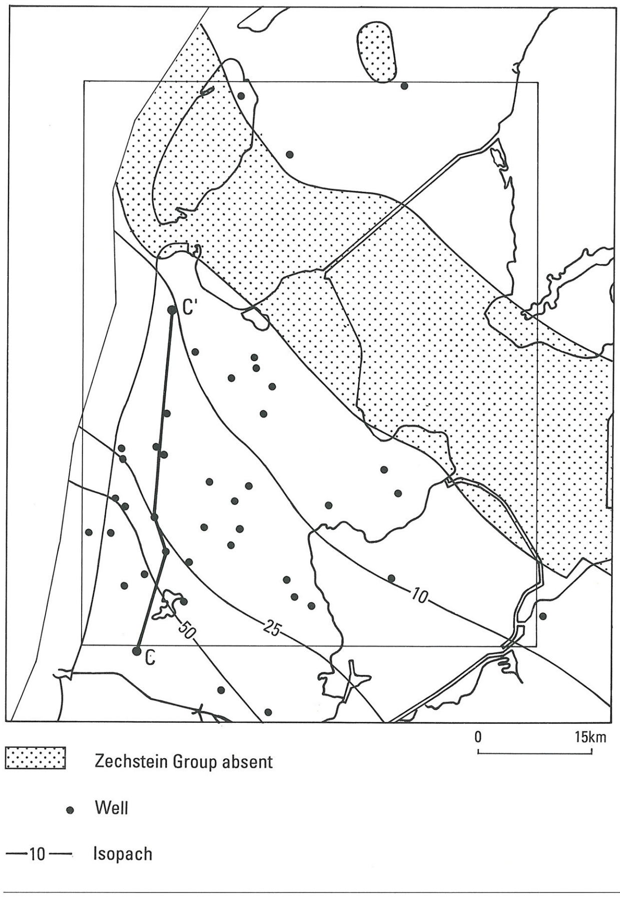


Figure 4.3. Stratigraphic division of the Zechstein Group in the Heemskerk-1 well, in the southern part of the map sheet area. On the one hand, the division in accordance with NAM & RGD (1980), and on the other hand the division applied here. The gamma-ray log is in API units, the sonic log in µs/ft.

The *Zechstein 1 Anhydrite* is present in almost the entire map sheet area, with the exception of the extreme southwest. Where the Zechstein 1 Salt occurs, the unit is subdivided into a Zechstein 1 Lower Anhydrite and a Zechstein 1 Upper Anhydrite (in the Sint Maarten-1 well, fig. 4.1 & 4.2). In the southwestern part, the unit is present as a several metre-thick anhydrite in the clastics. Towards the Texel-IJsselmeer High the thickness increases in a northerly direction to an average of 90 to 100 m. There may however be much thicker anhydrite successions present in places, sometimes as thick as 200 m. Great variations in thickness often occur between wells in close proximity. The depositional thickness pattern of the unit is usually in inverse proportion to the thickness of the rock salt. No anhydrite deposition took place at the top of the Texel-IJsselmeer High, as can be concluded from the absence of the unit in the Riepel-1 and De Cocksdorp-1 wells immediately to the north of the high. Further to the north, the anhydrite is 10 to 30 m thick.

The presence of the *Zechstein 1 Salt* is restricted to an area to the south of the Texel-IJsselmeer High (fig. 4.2 & 4.8), with the greatest thicknesses encountered in the Central Netherlands Basin. In this area intercalations of potassium-magnesium salts are found locally at two different levels. The salt thickness varies considerably and can sometimes exceed 100 m. Substantial differences in thickness occur at various points between wells in close proximity (see fig. 4.5). This is attributed to syndepositional differential fault movements and a certain amount of salt flow during subsequent geological history. The unit is not found in the Heerhugowaard-1 and Ursem-1 wells. In addition, the fact that a relatively thin Upper Rotliegend Group was encountered here leads to the conclusion that these wells have been positioned on a horst already present during deposition of the Zechstein Group.

Figure 4.4. Thickness map of the Zechstein 1 Carbonate. The thicknesses are in metres. C-C′ gives the location of the section shown in figure 4.2.



4.1.2 Zechstein 2 Formation

The Zechstein 2 Formation displays great variations in the map sheet area. In the southwest it is built up of only the Zechstein 2 Middle Claystone while in the middle and northeast it is composed of the Zechstein 2 Carbonate, Zechstein 2 Basal Anhydrite, Zechstein 2 Salt and Zechstein 2 Roof Anhydrite Members (fig. 4.2; the Heemskerk-1 and Julianadorp-1 wells, respectively). Between these two extremes, there is a complex transitional area.

The formation displays great variations in its composition to either side of the Texel-IJsselmeer High: to the northeast, the thickness of the formation reaches a maximum of 650 m and consists of more than 90% rock salt, the remainder being carbonate and anhydrite. To the southwest of the high, the thickness of the formation varies from 15 to 55 m and consists of clastics, carbonate and anhydrite. To the north of the high, the formation comprises 75% of the total thickness of the Zechstein Group. To the south of the high, this is 10 to 20%.

The *Zechstein 2 Middle Claystone* only occurs in the southwest and west of the map sheet area (fig. 4.6). The naming of the unit differs from NAM & RGD (1980). The base of the formation consists of a claystone horizon several metres thick which may be correlated with the red-brown salt clay in Germany as described by Teichmüller (1957). Above this an anhydrite horizon is present, which is considered to be the lateral equivalent of the bottommost part of the Zechstein 2 Carbonate. For the rest, the member is built up of red and grey coloured claystone, with interbedded anhydrite nodules. The unit is no more than 50 m thick and, northwards, grades laterally into the Zechstein 2 Carbonate and Zechstein 2 Basal Anhydrite.

The *Zechstein 2 Carbonate,* present in the area with the exception of the southern half, comprises dolomitic limestone which becomes upwardly more argillaceous, and in many of the wells around the Texel-IJsselmeer High there are breccias present (Riepel-1, De Cocksdorp-1, Slootdorp-1 and

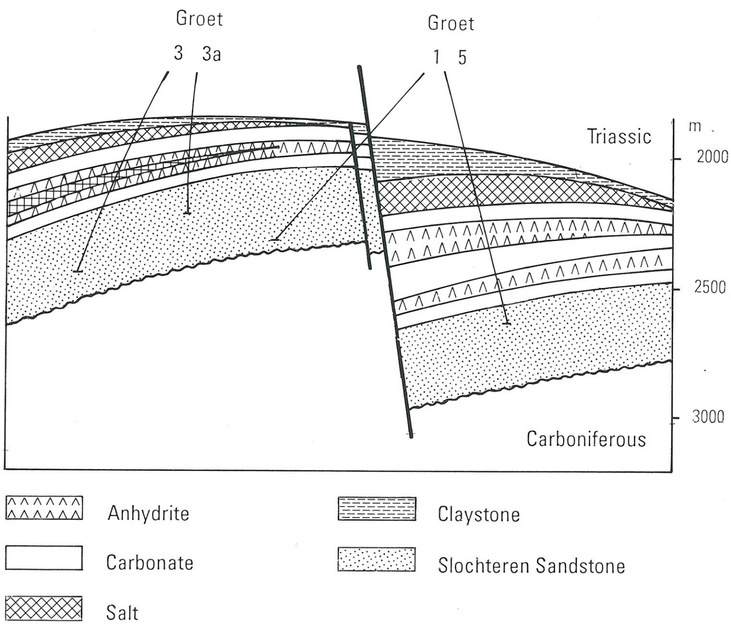


Figure 4.5. An example of lateral variations within the Zechstein Group in the Groet gas field. The thickness and facies variations shown are attributed to synsedimentary fault movements (from Van Lith, 1983).

Middenmeer-1). The unit varies in thickness from approximately 10 m to the north of the Texel-IJsselmeer High to over 30 m to the south. Towards the south, it grades laterally into the anhydrite level and the claystones of the Zechstein 2 Middle Claystone (fig. 4.2 & 4.6).

The *Zechstein 2 Basal Anhydrite* is found in the same area as the previous unit and consists of a massive white anhydrite, no more than 20 m thick.

Zechstein 2 Salt is found in great thicknesses to the north of the Texel-IJsselmeer High, but to the south of the high only occurring in places (fig. 4.2 & 4.8).

To the north of the Texel-IJsselmeer High three salt successions can be identified in the Zechstein 2 Salt (Geological Survey of The Netherlands, 1991a, b). These successions are separated from each other by polyhalite beds. This triple unit can be correlated in the north of The Netherlands and the adjacent section of the continental shelf.
The bottommost succession is characterised at the base by interbeds of anhydrite and, above this, by alternating beds of halite and clay. This gives the unit a strongly peaked character on the log readings. The clay content slowly decreases towards the top.
Three subcycles can be identified in the middle succession, each of which displays an increasingly greater potassium content towards the top.
The very low reading on the gamma-ray log shows that the uppermost salt succession consists of extremely pure rock salt. Salt beds rich in potassium-magnesium occur at the top, being the

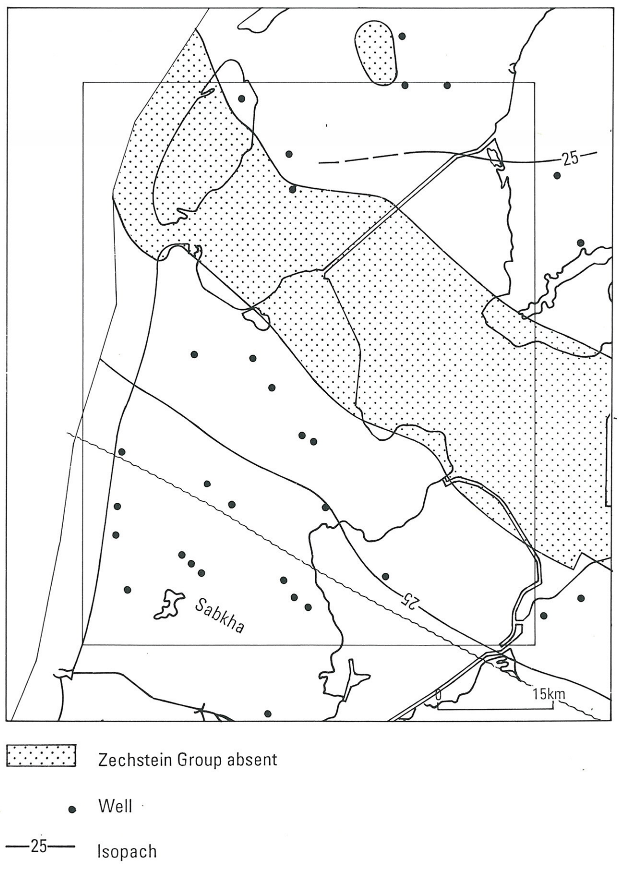


Figure 4.6. Thickness and distribution map of the Zechstein 2 Carbonate. The thickness is in metres. The equivalent deposits to the south of the limit of distribution are formed by the anhydrite at the bottom of the Zechstein 2 Middle Claystone. These are interpreted as sabkha deposits. The southern extension of the Zechstein 2 Carbonate was presumably tectonically determined; this corresponds to the area where the Upper Rotliegend Group shows a reduction in thickness (compare with fig. 3.1).

equivalent of the 'Kaliflöz Stassfurt' occurring at the top of the Zechstein 2 Salt in Germany (Kulick & Paul, 1987). The minerals embedded here are carnallite, kieserite, sylvine and halite.

To the south of the high the salt is only found in thicknesses of 5 to 25 m. and is sometimes interbedded in the claystone of the Zechstein 2 Middle Claystone. Thin beds of potassium-magnesium salts also occur. The salt occurrences are restricted to the Central Netherlands Basin and have approximately the same distribution as the Zechstein 1 Salt. The salt succession in this area is probably the equivalent of the middle salt succession occurring to the north of the Texel-IJsselmeer High.

At the top of the formation, the *Zechstein 2 Roof Anhydrite* is found at thicknesses of several metres.

4.1.3 Zechstein 3 Formation

This formation is composed of the Grey Salt Clay, Zechstein 3 Carbonate, Zechstein 3 Main Anhydrite and Zechstein 3 Salt Members. In comparison with the previously described units of the group, the differences in thickness and distribution of the formation on both sides of the Texel-IJsselmeer High are less pronounced. There are, on the other hand, considerable differences in respect of the composition of the formation within the map sheet area. To the northeast of the high the formation reaches a thickness of 200 m, and to the southwest, 150 m.

The *Grey Salt Clay* is a 3 to 10 m thick, grey claystone. This unit, with its characteristic appearance on the gamma-ray log reading, is highly appropriate for carrying out regional correlations.

The *Zechstein 3 Carbonate* (or Platy Dolomite) consists of a light-grey to brown dolomite or dolomitic limestone. Core studies indicate that the unit displays great differences in the area and that the original structures are sometimes unrecognisable owing to the strong diagenesis. Diagenesis included dolomitisation, leaching and cementation with halite and anhydrite. For a more complete overview, reference should be made to studies carried out by Clark (1980, 1986) and Van der Baan (1989). Although these studies relate in part to the Zechstein 2 Carbonate, the stratigraphy of these units in the east of The Netherlands lends itself particularly well to comparison with the Zechstein 3 Carbonate in the present study area. The lithological differences in the stratigraphy of the member apply not only to differences between the various wells, but also to the wells themselves.

The unit reaches its greatest thickness in the Central Netherlands Basin, namely over 40 m. Around the Texel-IJsselmeer High it is even less than 20 m thick, and immediately to the north of the high, in the Riepel-1 and De Cocksdorp-1 wells, the thickness is less than 10 m (fig. 4.7).
In the southern part of the map sheet area, the unit can be characterised as an alternation of micritic dolomite with coarse-grained layers, within which small incisions and current ripple marks may occur. The unit displays many small, open cracks and holes or cavities cemented with anhydrite. Desiccation cracks, root walls, layers of fossil debris and organic material are also observed. In a few wells there are indications of the presence of algal mats and oolites (Clark, 1986).

To the north of the Texel-IJsselmeer High the unit is composed of a laminated alternation of fine-grained and coarse-grained dolomite. In addition, in several wells around the Texel-IJsselmeer High, breccias occur, as for instance is the case in the Slootdorp-1, Riepel-1 and De Cocksdorp-1 wells.

The *Zechstein 3 Main Anhydrite* is a massive anhydrite occurring practically throughout the map sheet area, reaching its greatest thickness around the Texel-IJsselmeer High. To the north of the high the thickness exceeds 30 m, to the south it ranges from 20 to 30 m and in the Central Netherlands Basin the thickness varies between 2 and 10 m.

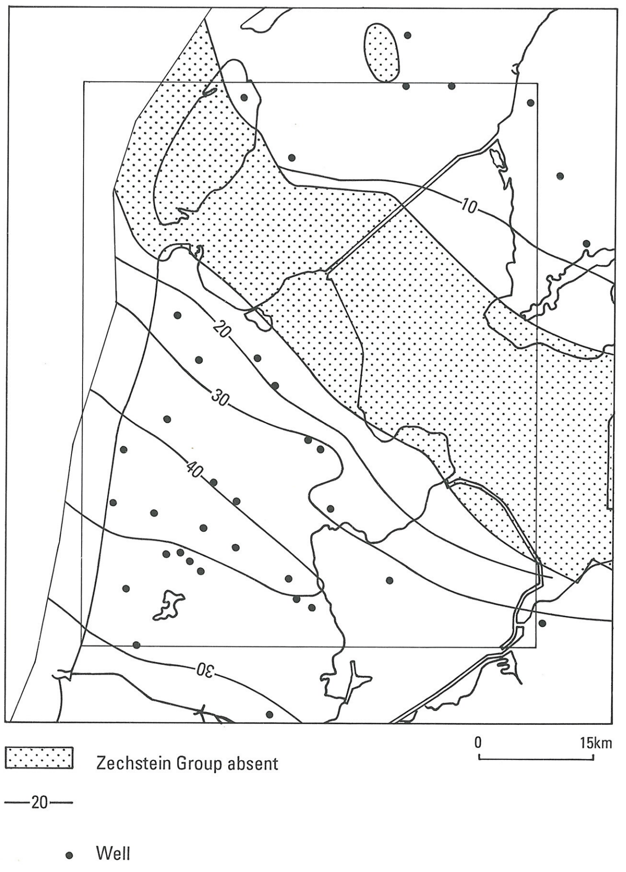
The *Zechstein 3 Salt* occurs on both sides of the Texel-IJsselmeer High. To the north of this high the thickness does not exceed 180 m. The salt consists of halite; potassium-magnesium salts are not found in the northeast of the map sheet area. To the south of the Texel-IJsselmeer High the Zechstein 3 Salt, mainly composed of halite accumulations with thicknesses ranging from only a few metres up to 100 m with interspersed potassium-magnesium salts, is found in the Central Netherlands Basin.

4.1.4 Zechstein 4 Formation

The Zechstein 4 Formation can be subdivided into the Red Salt Clay, Pegmatite-Anhydrite and Zechstein 4 Salt Members.

The *Red Salt Clay* and the *Pegmatite Anhydrite* within the map sheet area are uniformly distributed and have a combined thickness varying between 5 and 10 m only.

Figure 4.7. Thickness map Zechstein 3 Carbonate. The thicknesses are in metres. This composite map has been based on wells. The great thickness in the Central Netherlands Basin is notable.



The *Zechstein 4 Salt* only occurs in a small area in the Central Netherlands Basin, not exceeding 10 m thickness (fig. 4.2 & 4.8) and consists of halite.

4.1.5 Upper Zechstein Claystone Formation

The Upper Zechstein Claystone Formation is an anhydritic claystone succession between the top of the Zechstein 4 Formation and the easy-to-correlate base of the Lower Germanic Trias Group (see Chapter 5 for the definition of this base). Although NAM & RGD (1980) classified a part of the transition succession between the Zechstein Group and the Lower Germanic Trias Group as Permian, for practical reasons the succession was allocated to the Basal Buntsandstein Member of the Lower Germanic Trias Group. The equivalents of the higher Zechstein cycles, as are described in Germany in particular, have also been identified in The Netherlands (Best, 1989; RGD, 1989a; Geological Survey of The Netherlands, 1991a, b). In the present study, this succession is named the Upper Zechstein Claystone Formation.

The *Upper Zechstein Claystone Formation* has been identified almost everywhere in the map sheet area. It consists of a claystone succession varying from 5 m thick to no more than 20 m thick, with anhydrite interbeds in places. The claystone succession is characterised by low velocities on the acoustic log readings.

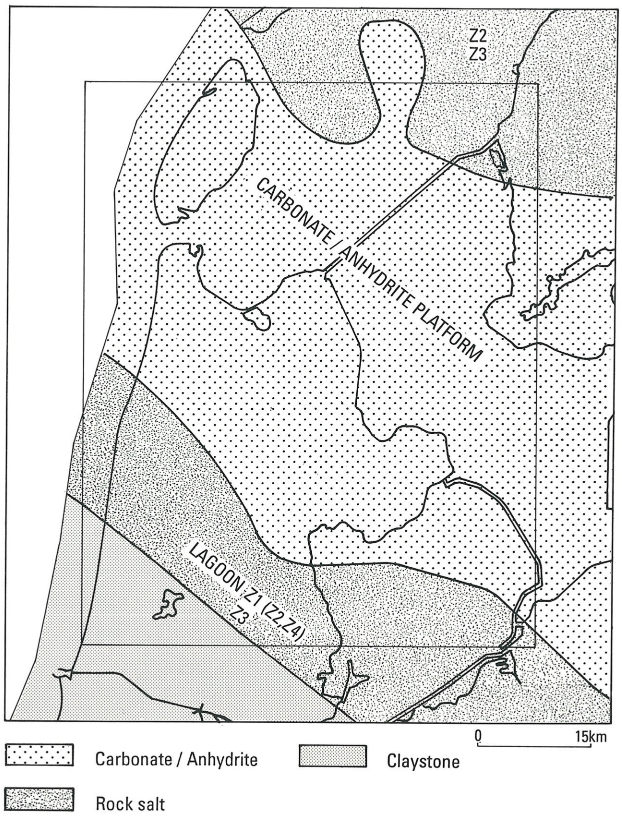


Figure 4.8. Reconstruction of the palaeogeography at the time of deposition of the Zechstein Group. In this map no account has been taken of later erosion on the Texel-IJsselmeer High. It has been indicated to which formation the salt belongs. Z1: Zechstein 1 Salt, Z2: Zechstein 2 Salt, (Z2): ditto, minimal thickness, Z3: Zechstein 3 Salt, (Z4): Zechstein 4 Salt, minimal thickness.

4.2 Sedimentary development and palaeogeography

During the deposition of the Zechstein Group the map sheet area was palaeogeographically speaking situated on the margin of the Permo-Triassic Basin. Sedimentation took place in a lagoon, which was separated from the more northerly main basin by the Texel-IJsselmeer High (fig. 4.8). In this area, the main deposits were carbonate, anhydrite and clastics. Only in isolated fault-bounded depressions did deposition of rock salt take place. During the deposition of the Zechstein 1 and 2 Formations the southwesterly part of the map sheet area was characterised by the vast plains which regularly dried up; here the depositions consisted predominantly of fine-grained sediments as well as a small amount of gypsum. This depositional environment is very comparable to that of the sabkhas along the marine border of the Persian Golf (Purser, 1973). The plains were situated around an island or tongue, originally projecting above sea level, to the south of the map sheet area, but were flooded by the sea as a result of the transgression of the third cycle. Between these plains and the Texel-IJsselmeer High there was a lagoon. During the maximum of the first three sea transgressions in the Permo-Triassic Basin, predominantly normal marine conditions prevailed in this lagoon, testified to by the carbonates present. After these transgressions the influx of seawater into the basin became restricted and, owing to the high evaporation resulting from the dry climate and the prevailing trade winds, the water level in the basin dropped and salinity increased. This had major consequences for the map sheet area. Owing to the fall in water level in the main basin, the Texel-IJsselmeer High dried up. It is generally assumed that during this period leaching and brecciation of the carbonates present on and around this high took place. The afore-mentioned lagoon was periodically cut off from the main basin, followed by the deposition of evaporites. On the southern margin of this high, these took the form of thick sulphate successions with the addition, in the Central Netherlands Basin, of halite and potassium-magnesium salts (Zechstein 1 Salt). The relief present at that time was for the most part filled up here during the first cycle. To the north of the high, in the main basin, insufficient evaporation took place during this cycle for salt sedimentation to occur.
The second Zechstein transgression did not extend as far south as the first and third (RGD, 1986f; Plomp & Geluk, 1988) and only extended halfway down the map sheet area. In the southern half of the map sheet area there is assumed to have been a sabkha with anhydrite accumulation. During the second Zechstein cycle sufficient evaporation took place in the main basin to enable rock salt to be precipitated. The great thicknesses of rock salt point to ongoing basin subsidence and a continuous influx of seawater into the basin. Changes in the extent of inflowing seawater in conjunction with climatological variations resulted in cyclicity, in particular in the middle salt succession of the Zechstein 2 Salt. The polyhalite layers indicate greater fluctuations and probably originated as a result of the influx of larger quantities of $CaSO_4$-bearing water in the basin (Braitsch, 1971). To the south of the Texel-IJsselmeer High the deposits of the Zechstein 2 Formation are relatively thin; this is the consequence of the fact that the relief was already partially filled in with the Zechstein 1 Formation. The deposits are also presumed to have been thin on the high. In the lagoon to the south of the Texel-IJsselmeer High, clays were deposited initially; only during deposition of the middle rock salt succession in the main basin did halite-precipitation take place here as well. The high itself projected above sea level during the evaporite deposition.

The third transgression extends the furthest to the south in the basin. During deposition of the carbonates, normal marine conditions prevailed again, and the influx of fine-grained sediments from the southwest was brought to an end. The depositional conditions of this cycle display considerable analogies with both the preceding ones. The cycles identified in the wells do however display clear internal differentiation, which is indicative of differences in the palaeorelief. Halite and potassium-magnesium salts were deposited in the deepest parts, while carbonate and anhydrite were formed on and around the highs. Carbonates were leached and brecciated on and around the highs as a result of meteoric water. This cycle levelled out the remaining differences in relief to a great extent; the higher Zechstein formations were deposited over the area like a blanket. After deposition of the Zechstein 3 Formation the map sheet area formed part of extensive plains where fine-grained sediments were deposited; salt was deposited only in small depressions.

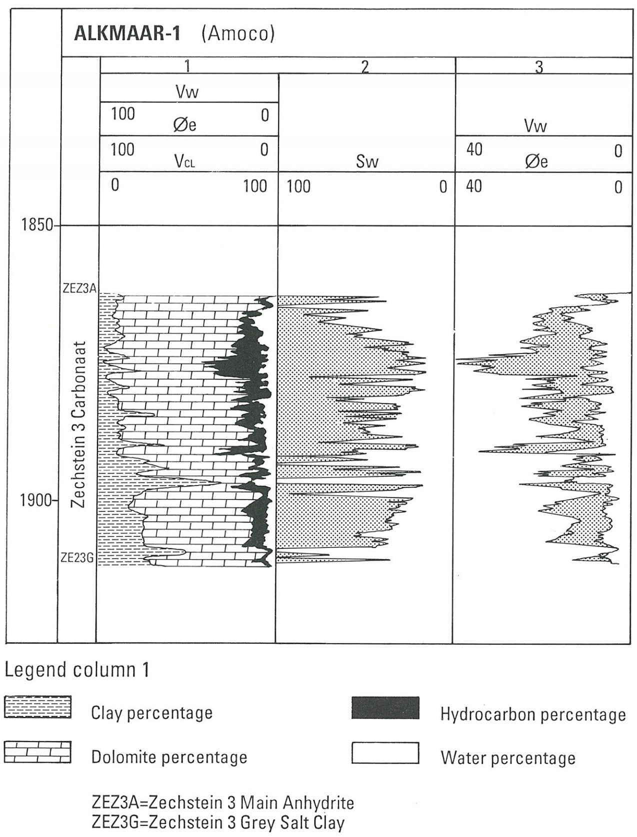
During deposition of the Zechstein 4 Formation and the Upper Zechstein Claystone Formation a slow regression took place towards the continental depositional conditions prevailing during deposition of the Lower Triassic. At the beginning of the fourth cycle normal marine conditions did not return to the basin which continued to be hypersaline. Salt sedimentation was restricted increasingly to the centre of the basin, with extensive plains bordering this area. The evaporites after the Zechstein 3 Formation were deposited in playas.

4.3 Petrophysical evaluation

The Zechstein Group is renowned above all for its good properties as a sealing layer above reservoir rocks. In particular, the low permeability and the plastic properties of the salts of this formation are an important factor here. In the map sheet area these properties are, however, of less importance, as the salt thicknesses here are minimal in comparison with those of the northeast of The Netherlands and on the Continental Shelf.

The carbonates from seven wells within the map sheet area have been petrophysically evaluated (RGD, 1991b). These carbonates often contain a certain amount of porosity. This porosity is

Figure 4.9. Petrophysical evaluation of the Zechstein 3 Carbonate in the Alkmaar-1 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw. The clay content was determined with the use of gamma-ray log readings. The effective porosity was obtained using sonic log readings (Raymer-Hunt comparison in single porosity model; Raymer et al., 1980) after correction for the clay content. Column 2: water saturation Sw. The Indonesia formula, suitable for argillaceous deposits, was used to determine the water saturation (Fertl, 1987). Column 3: effective porosity Øe and the volume of water in the pores Vw. The stratigraphic boundaries have been indicated in the right hand column. The depths are log depths.



virtually always of a secondary nature and it originated through selective leaching of less stable calcareous fragments. Leaching was determined by the depositional environment and the post-depositional history. The latter is determined predominantly tectonically.

The Zechstein 3 Carbonate (or Platy Dolomite) present in the map sheet area became strongly recrystallised, and usually dolomitised, throughout burial history (Van der Baan, 1990; Clark, 1986). The frequently occurring stylolites are a consequence of very intense chemical compaction. The secondary leaching indicates that a certain permeability must also have existed for the circulation of the dissolving liquids to have taken place. This initial permeability makes hydrocarbon production possible at relatively low porosities. As can be deduced from a comparison between Appendices C and E, the porosities of the gas-bearing reservoirs are often not even half those of the Slochteren Sandstone Formation. The average porosity of 4% and permeability of 10 mD of the Zechstein 3 Carbonate in the Rustenburg-1 well (Clark, 1986) correspond to this.

The Zechstein 3 Carbonate, in particular, contains a number of gas reservoirs (Alkmaar, Slootdorp, Schermer), which are characterised by a very irregularly varying, often layer-restricted porosity, which can be clearly seen from well logs. The highest readings are observed in bioclastic grainstones, namely an average porosity of 20% and a permeability of 110 mD in the Schermer-1 well (Van Adrichem Boogaert & Burgers, 1983). In the Slootdorp Concession the carbonate reservoir contains a combination of Zechstein 2 and 3 Carbonate, which developed as collapse-breccias. An example of the Zechstein reservoir in de Alkmaar-1 well is shown in figure 4.9. An isoporosity map based on well data has not been presented in view of the minimal density of the measuring points and the strong local variations in the carbonate deposits.

Reservoir properties of the Zechstein Group are highly dependent on the depositional environment. This was apparently not favourable to the positive development of the reservoir properties on a large scale; the reservoirs are limited in number and small in size.

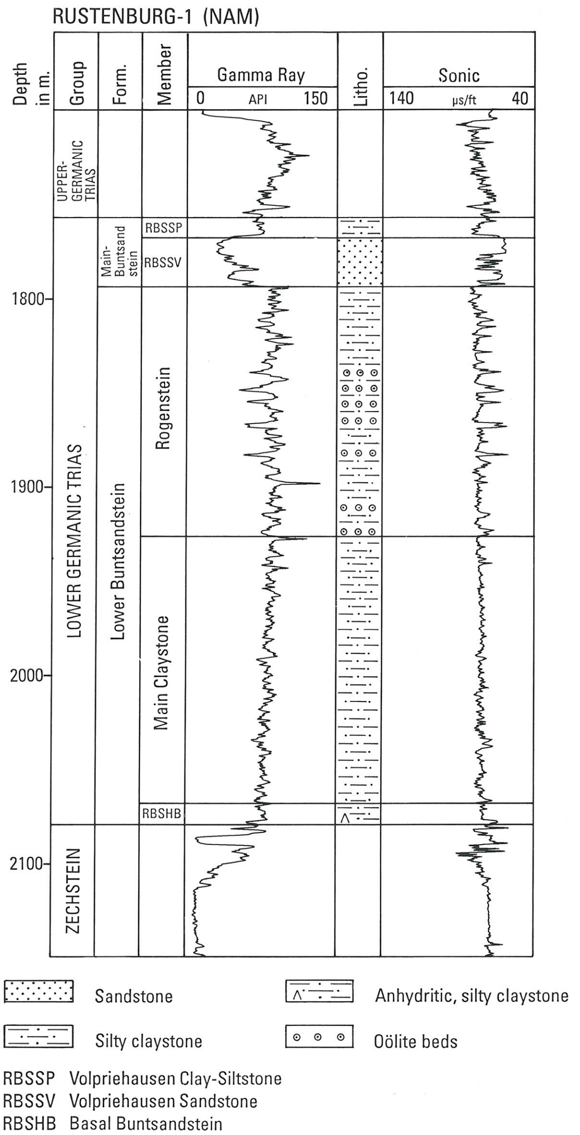
5 Lower and Upper Germanic Trias Group

5.1 General

The Triassic deposits consist of red and green coloured clastic sediments, grey coloured limestones as well as marls and evaporites. Within the Triassic deposits a Lower and Upper Germanic Trias Group are distinguished. Within the map sheet area deposits of a Late Permian, Early, Middle and Late Triassic age are present.

The Triassic deposits occur in the northeast, south and west of the map sheet area with the greatest thickness, well over 1100 m, being reached in the western part of the map sheet area (Map 6). On the flanks of the Texel-IJsselmeer High the thickness is drastically reduced as a result of post-depositional erosion. The deposits lie conformably on the Zechstein Group and are unconformably overlain by the Altena Group, Central Graben Group, Rijnland Group or North Sea Super Group (Maps 16, 17 & 18).

Figure 5.1. Composition of the Lower Germanic Trias Group in the Rustenburg-1 well. The interpretation of the lithologies has been based on gamma-ray log (in API) and sonic log (in µs/ft) readings. A line drawing of a seismic section over this well is shown in figure 11.7.



The base of the Triassic deposits is deepest in the Central Netherlands Basin, where depths of over 3000 m (Map 5) are achieved. In the remainder of the area the thickness is drastically reduced and the depth varies from around 1500 to 2500 m. The Triassic deposits are highly faulted.

The stratigraphic succession of the Triassic deposits is illustrated by means of the Rustenburg-1 well (fig. 5.1 & 5.5) and a log correlation section (fig. 5.2). Although the Rustenburg-1 well lies in a zone where there has been subterranean dissolution of the rock salt of the Muschelkalk Formation, the borehole nevertheless enables a good understanding of the composition of the Triassic deposits.

5.2 Lower Germanic Trias Group

5.2.1 Stratigraphy

The Lower Germanic Trias Group rests conformably on the Zechstein Group, and is overlain unconformably by the Upper Germanic Trias Group. The group is composed of a bottommost section consisting of predominantly claystone and siltstone and an uppermost section with alternating sandstones and claystones, and this bipartition is indicative of the Lower Buntsandstein Formation and the Main Buntsandstein Formation (fig. 5.1).

In the western part of the Central Netherlands Basin the group reaches a thickness of over 425 m. In the Vlieland Basin the thickness has been reduced by erosion to approximately 200 m. The deposits of the Lower Germanic Trias Group are characterised by a high degree of uniformity on both sides of the Texel-IJsselmeer High, in contrast to the deposits of the underlying Zechstein Group (see Chapter 4).

The age of the Lower Germanic Trias Group is Late Permian to Scythian.

5.2.1.1 Lower Buntsandstein Formation

This formation is built up of the Basal Buntsandstein, Main Claystone and Rogenstein Members (fig. 5.1). The formation is conformably overlain by the Main Buntsandstein Formation, or unconformably by Upper Jurassic or Lower Cretaceous deposits. In the Vlieland Basin only the first two members of this formation are represented. Within the map sheet area the complete formation reaches a thickness from at least 230 to 290 m in the Central Netherlands Basin; a slight increase in thickness is observed along the boundary faults of this basin.

A sedimentological study of the Basal Buntsandstein and the Main Claystone in Northwest Germany (Brüning, 1986; Röhling, 1991) has revealed that these are built up of a number of easy-to-correlate, fining-upward cycles. Log correlation within The Netherlands (Geluk & Röhling, in prep.) reveals similar cyclicity. However, the lithostratigraphic boundary in these members defined by NAM & RGD (1980) turn out to lie in the middle of just such a sedimentary cycle. What is more, according to the NAM & RGD (1980) definition, the Basal Buntsandstein comprises the equivalents of the higher Zechstein cycles. The equivalents of the high Zechstein cycles, are separately differentiated by the RGD informally as Upper Zechstein Claystone Formation (see chapter 4 and Geological Survey of The Netherlands, 1991a, b). The boundaries of the Basal Buntsandstein have been redefined so that this unit now corresponds to the 'Obere Bröckelschiefer' in Northwest Germany (Best, 1989; Geluk & Röhling, in prep.).

The *Basal Buntsandstein* consists of a fine-grained basal sandstone, quite possibly anhydrite-cemented, and of an overlying claystone succession. Within the map sheet area the unit reaches a thickness of 8 to 15 m. The claystone of the Basal Buntsandstein can generally be clearly distinguished from that of the overlying unit by higher gamma-ray readings and lower acoustic velocities.

The *Main Claystone* is composed of a cyclic succession, regionally well correlatable, of thin sandstone beds and (silty) claystone (fig. 5.2). The cyclic development within the map sheet area shows a remarkable analogy with that in Northwest Germany (Geluk & Röhling, in prep.) The composition of the Main Claystone is uniform throughout the northern Netherlands, from which it may be deduced that this unit was also deposited on the Texel-IJsselmeer High (RGD, 1989d). The thickness of the unit varies from 120 to 140 m.

The extremely uniform development and the great areal distribution makes this unit eminently suitable for burial history analysis. The restriction that should be made here is that the unit is not a pure claystone but a silty one; diagenetic processes have been active. The degree of compaction of the Main Claystone is considered to be an indication of the maximal burial depth of this unit during the geological history (Bulat & Stoker, 1987; Van Wijhe et al., 1980). The higher the interval velocity of the unit, the deeper the depth of burial was in the past. The burial history within the map sheet area has been analysed (see also section 2.3) and results (figure 5.3) display a clear difference between the inverted Central Netherlands Basin and the Noord-Holland Platform in respect of Bulat & Stoker's theoretical compaction curve (1987). In the basin, the Triassic deposits were buried 1000 to 2000 m deeper, while on the platform this lies in the order of a few hundred metres or less. It was also observed that this method is less reliable at places where the unit is relatively thin owing to later erosion. In two wells, the acoustic velocities were lower than might have been expected from their present depth. No clear explanation has as yet been found for this phenomenon. Major fracturing of the unit has been suggested, initiated during contemporaneous pressure reduction by erosion of the sediment overburden or alternatively from leaching of the cement present in the silts.

The *Rogenstein* comprises red and green coloured claystones, alternated by oolite layers. A core of the unit derived from the Bergermeer-1 well shows finely laminated claystone with sand lenses, disrupted by desiccation cracks and water escape structures. The oolites are cemented grainstones, with ooliths of up to a few millimetres in size. Five clear oolite beds can be distinguished, by well logging, in the middle part of the member (fig. 5.1) and can be correlated with the different wells within the map sheet area. In addition a number of less clear oolite beds are found. However, in contrast to the Main Claystone, the development of this unit is, strictly regionally, less uniform (RGD, 1989d); in the east of the country, more oolitic horizons are found. In the southern part of the map sheet area the Rogenstein unit, thickness 100-140 m, is overlain unconformably by the Volpriehausen Sandstone with a small hiatus (Geluk & Röhling, in prep.). This hiatus is the greatest in the eastern part of the map sheet area (fig. 5.2).

5.2.1.2 Main Buntsandstein Formation

The Main Buntsandstein Formation lies on the Lower Buntsandstein Formation with a small hiatus, and is also overlain unconformably by the Upper Germanic Trias Group or younger deposits. Within the map sheet area the formation is only present in the Central Netherlands Basin. In the northwestern part of this basin the thickness of the formation reaches a maximum of 75 m. This is caused by a combination of depositional differences in thickness and erosion. The Volpriehausen Sandstone and Volpriehausen Claystone and Siltstone Members subdivided the formation in this

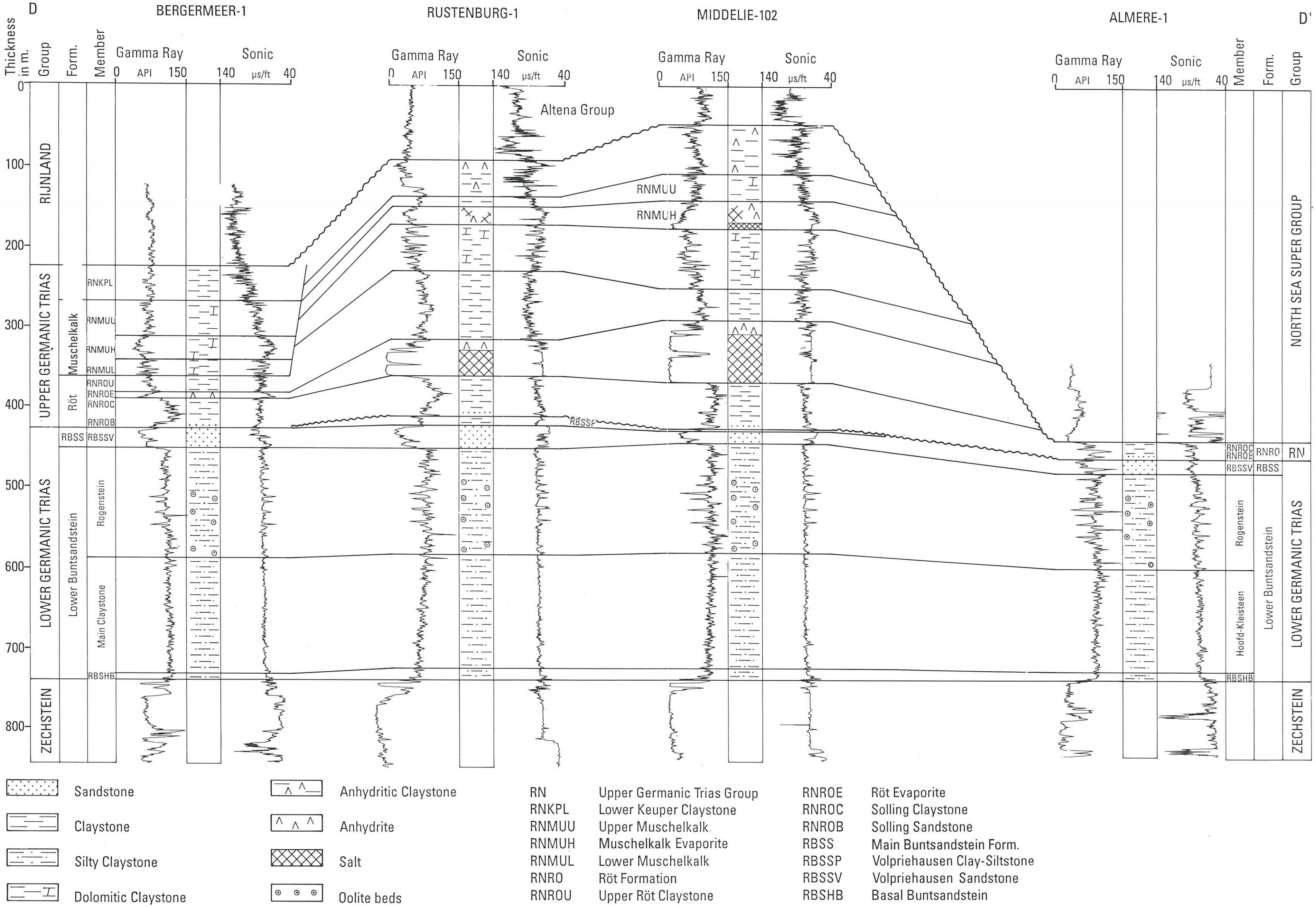


Figure 5.2. Stratigraphic section DD' of the Lower and Upper Germanic Trias Group. Observe the thinning of the Lower Buntsandstein, Main Buntsandstein and Röt Formations eastwards, caused by the influence of the Netherlands Swell. The reference level is the base of the Lower Germanic Trias Group. The correlations have been based on gamma-ray log (in API) and sonic log (in μs/ft) readings. The location of the section is indicated in figure 5.6.

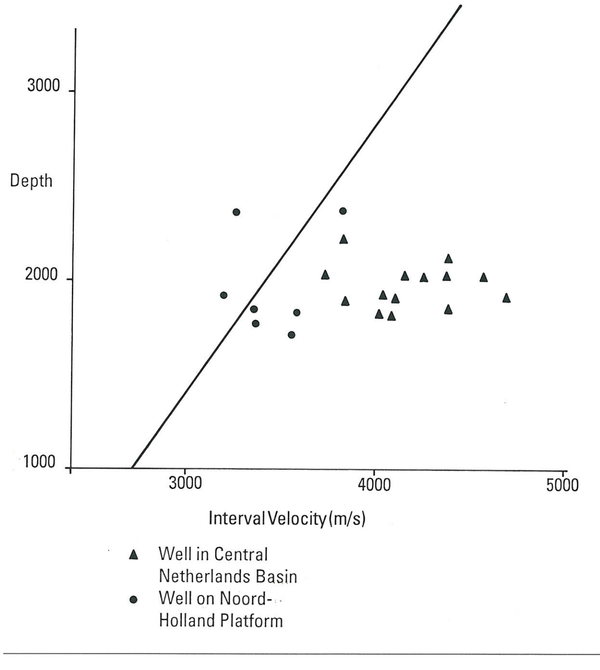
map sheet area from bottom to top. Contrary to Van Lith (1983) the Detfurth Sandstone is presumed not to be present in the area; this particular sandstone is taken to be on the base of the Röt Formation (Solling Sandstone).

The *Volpriehausen Sandstone* forms the basal sand succession of the formation. Cores show a stacking of light-coloured to light-red, medium to fine-grained sandstone beds. Erosion at the base of the sands is hardly observed. The sandstone beds comprise large, imbricated red claystone clasts at the base and display parallel or cross bedding. The sandstone is slightly cemented with calcite; anhydrite is also found in places. In the unit an interval occurs comprising an alternation of claystone and siltstone, highly disrupted by water-escape structures and desiccation cracks. The thickness of the complete unit increases in a westerly direction from a few metres to over 40 m (fig. 5.4). At the base of the unit there is a minor unconformity whose main effect within the map sheet area was in the eastern part. The upper boundary is sharp.

The Volpriehausen Sandstone is found throughout the map sheet area under the Röt Formation, except in the IJsselmeer-1 well. Its absence here is related to a salt pillow formed during the Triassic, and was caused by the deeper erosional incision at the base of the Röt Formation.

The *Volpriehausen Clay-Siltstone* consists of reddish-brown to green claystone and siltstone with small sand lenses and anhydrite nodules. Burrows, desiccation cracks and wave ripple marks also occur. The thickness of the member varies greatly, mainly as a result of erosion, and a maximum of 40 m in the western part of the Central Netherlands Basin. The unit is overlain unconformably by the Röt Formation.

Figure 5.3. Interval velocities versus present depth of the Main Claystone Member. The continuous line represents the compaction curve according to Bulat & Stoker (1987). The relative uplift in each well is determined by the vertical distance between the well and the continuous line. The two wells to the left of the line display a lower interval velocity than might be expected from the depth. Further information can be found in the text.



5.3 Upper Germanic Trias Group

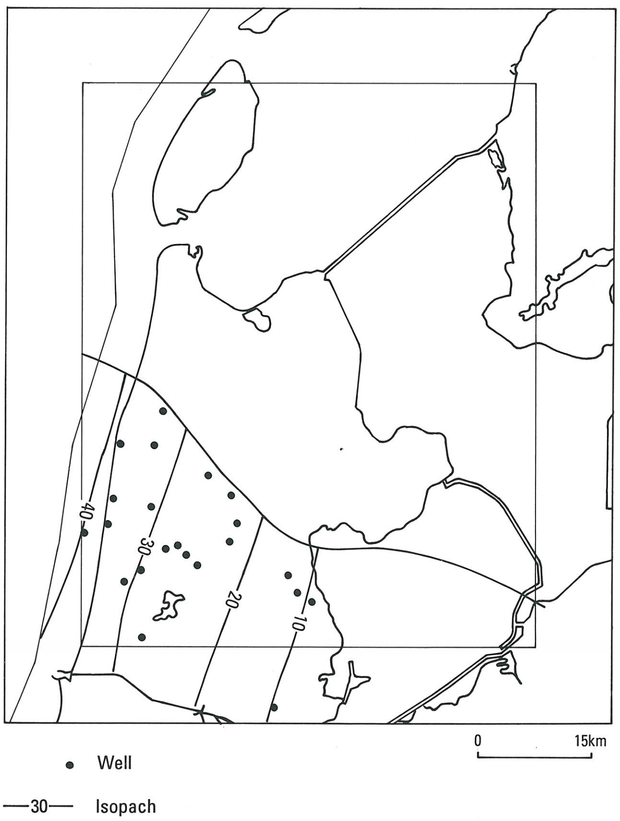
5.3.1 Stratigraphy

The Upper Germanic Trias Group is composed of clastic sediments, limestones and marls as well as evaporites. The group lies conformably on the Lower Germanic Trias Group and in turn is overlain unconformably by the Altena Group, Central Graben Group, Rijnland Group or North Sea Super Group. Within the group the Röt, Muschelkalk and Keuper Formation can be distinguished (fig. 5.5). Contrary to the stratigraphic nomenclature (NAM & RGD, 1980) the basal unconformity here is not referred to as the Hardegsen Unconformity, being stratigraphically incorrect to give an unconformity the name of a deposit lying below the erosion surface (see also: Röhling, 1991). The name 'Base Solling Unconformity' for the German 'H' unconformity is proposed.

As in the case of the Main Buntsandstein Formation, deposits of the Upper Germanic Trias Group only occur in the Central Netherlands Basin (fig. 5.6). Owing to erosion, they are not found in the remainder of the map sheet area. The greatest thickness of the group, over 500 m, is found in the western part of this basin.

A conspicuous characteristic of this group is that the enclosed evaporites can act as a disharmonious layer, uncoupling the structures above and below. At several places in the northern part of the Central Netherlands Basin the top of the Upper Germanic Trias Group is found to be strongly faulted, while its base displays little or no faults (fig. 11.7). A series of listric faults has

Figure 5.4. Thickness map of the Volpriehausen Sandstone Member. This unit displays a thickening towards the west, in the direction of the Off Holland Low. At the top of the Netherlands Swell the unit is less than than 10 m thick.



developed here, which peters out in the Muschelkalk Salt. Towards the basin, the fracture zone is bounded by a thickening of the Muschelkalk Salt. These fracture zones are seen as collapse structures of salt accumulations. Only in the Rustenburg-1 well (fig. 5.5) rock salt can still be found in the Röt Evaporite; in the Muschelkalk Evaporite no rock salt remains.

The Upper Germanic Trias Group is of Late Scythian to Carnian age.

5.3.1.1 Röt Formation

The Röt Formation is found throughout the extent of the area of the Upper Germanic Trias Group (fig. 5.6). The formation rests unconformably on the Main or Lower Buntsandstein Formation and is subdivided into the Solling Sandstone, Solling Claystone, Röt Evaporite and Upper Röt Claystone Members (fig. 5.2 & 5.5). The thickness of the formation varies from 110 m on the margin to over 200 m in the central part of the basin. The age of the formation is Scythian to Early Anisian.

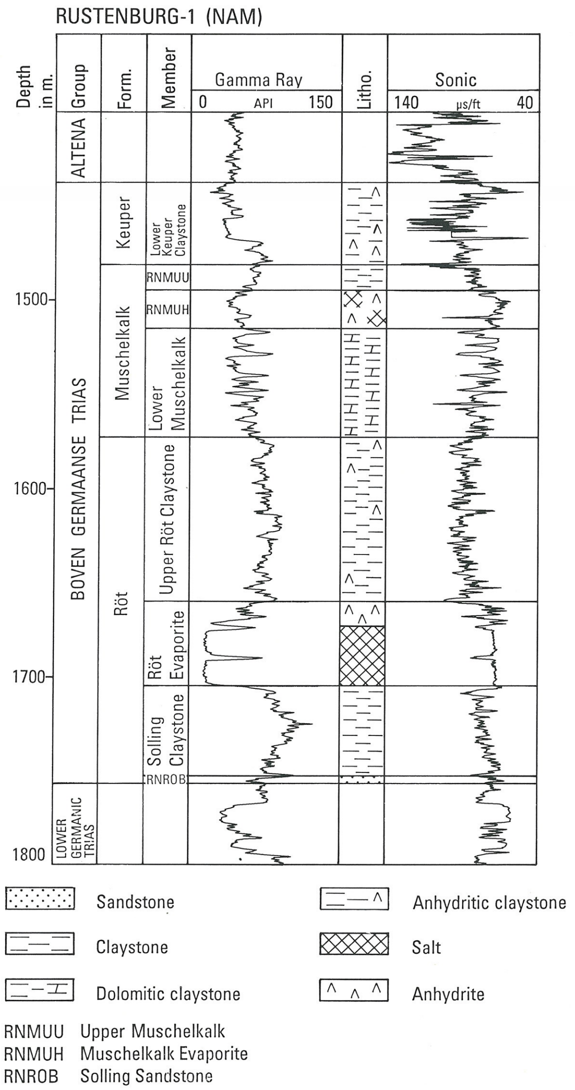


Figure 5.5. Composition of the Upper Germanic Trias Group in the Rustenburg-1 well. In this well the Muschelkalk Salt has disappeared owing to underground solution (subrosion). The interpretation of the lithology is based on gamma-ray log (in API) and sonic log (in µs/ft) readings. A line drawing of a seismic section over this well is shown in figure 11.7.

The basal deposits of the formation, the Solling Sandstone, comprise light-coloured, fine-grained sandstone. A claystone layer is found in the succession. A study of core material reveals that the bottommost part of the sandstone is structureless and that in the uppermost part small-scale cross bedding occurs. The unit ranges from less than one metre thick in the east to over 10 m in the west of the map sheet area. In comparison with the Volpriehausen Sandstone this unit displays a greater variation in composition.

The *Solling Claystone* is composed of grey-green and red claystone as well as fine-grained sandstone. Anhydrite nodules are found as well as beds with a high concentration of radio-active minerals. This member increases in thickness in a westerly direction from 20 to 40 m.

The *Röt Evaporite* rests conformably on the Solling Claystone, with a sharply defined boundary. Two cycles are distinguished in this evaporite, each consisting of claystone, a thin basal anhydrite and rock salt. Within the map sheet area, this unit is the thickest in the eastern part, reaching 80 m. Towards the margins of the Central Netherlands Basin and in a westerly direction, the thickness decreases.

The *Upper Röt Claystone* comprises a reddish-brown coloured claystone. In the bottommost part the unit developed anhydritically, while the uppermost part displays an increasing calcareous content. The bottommost anhydritic part of the succession forms the equivalent of the Upper Röt

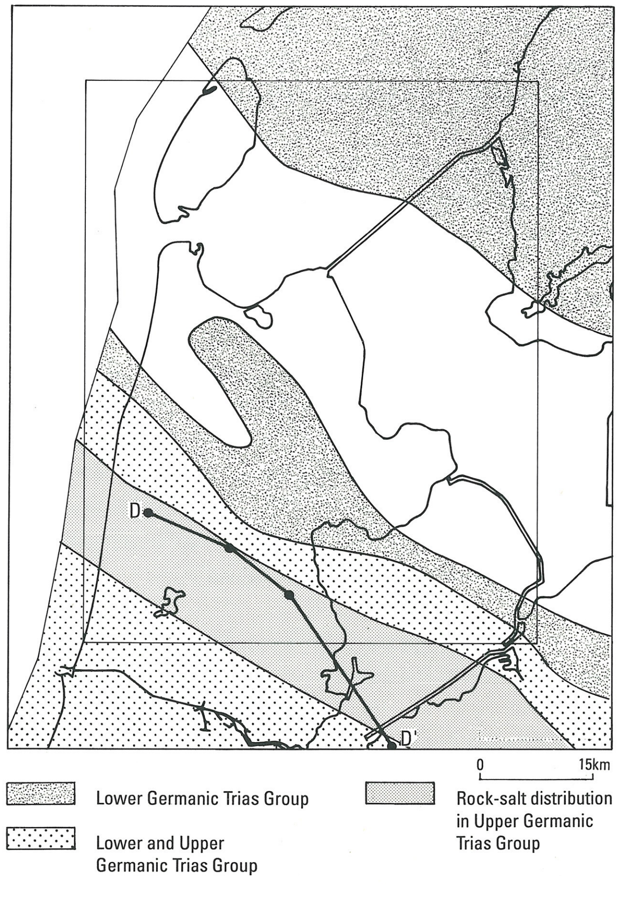


Figure 5.6. Distribution map of the Lower and Upper Germanic Trias Group. The occurrence of rock salt inside the Upper Germanic Trias Group is also shown. DD' is the location of the stratigraphic section shown in figure 5.2.

Evaporite present elsewhere. The boundary with the overlying Muschelkalk Formation is gradual. The thickness of the unit varies between 80 and 95 m.

5.3.1.2 Muschelkalk Formation

The Muschelkalk Formation rests conformably on the Röt Formation and is either overlain conformably by the Keuper Formation or else unconformably by the Altena Group, Central Graben Group, Rijnland Group or North Sea Super Group. The formation is built up of the Lower Muschelkalk, Muschelkalk Evaporite, Middle Muschelkalk Marl and Upper Muschelkalk Members. The present distribution of the formation is limited to the Central Netherlands Basin. The greatest thickness, 190 m, is found in the eastern part of the map sheet. The formation is the thinnest in the northwestern part of the Central Netherlands Basin, where the thickness is over 70 m. The Muschelkalk Formation is of Middle Anisian to Ladinian age.

The bottommost part of the *Lower Muschelkalk* consists mainly of grey marls together with a few claystone beds. Upwards, the member displays an increase in limestone and dolomite. This succession reaches a maximum thickness of 80 m and grades gradually into the overlying Muschelkalk Evaporite.

The *Muschelkalk Evaporite* consists of an alternation of claystone and anhydrite in the greater part of the Central Netherlands Basin, with halite in the central part of the basin. The thickness of this unit, 70 m, decreases towards the margins of the basin and in a westerly direction.

The *Middle Muschelkalk Marl* is a dolomitic marl with a maximum thickness of a few tens of metres. Combined with the Muschelkalk Evaporite this unit forms the Middle Muschelkalk. The upper boundary of the unit is formed by the base of the equivalent of the 'Trochitenkalk'.

The *Upper Muschelkalk* is a dark-grey coloured, calcareous to dolomitic claystone. This unit reaches a maximum thickness of 50 m. Upwards there is a gradual transition to the Keuper Formation.

5.3.1.3 Keuper Formation

Within the map sheet area the Keuper Formation only occurs in the central and western part of the Central Netherlands Basin. This present distribution has mainly been determined by erosion. Within the formation two members can be distinguished, namely the Lower Keuper Claystone and the Main Keuper Evaporite. The development of these members is reasonably comparable with the reference well L2-1 (NAM & RGD, 1980). Although the data is too scarce to make a well founded conclusion, this formation would appear to increase in thickness in a northwesterly direction. The formation in the map sheet area is of Carnian age.

The *Lower Keuper Claystone* is composed of green, reddish-brown and grey claystone with anhydrite interbeds. The thickness varies from 50 to 80 m.

The *Main Keuper Evaporite* is only identified in the western part of the Central Netherlands Basin where it is present in an anhydrite facies. The greatest thickness is nearly 60 m.

5.4 Sedimentary development and palaeogeography.

From the uniform development of the Lower Buntsandstein Formation within the northern part of The Netherlands it can be deduced that the map sheet area at that time formed part of an extensive plain. In view of the continental character of the deposits, the good correlation properties over extremely large distances and the fine-grained character of the sediments, sedimentation took place in a fluvio-lacustrine environment. The oolites were formed in brackish, lime-rich water during periods of low clastic influx and prominent current regime (Peryt, 1975; Brüning, 1986). The alternation of green and red staining and the desiccation cracks that are present point to a fluctuating water level and regular emerging, causing an alternation of redox conditions. During the deposition, the map sheet area formed a part of a NNE-SSW oriented high, which is known as the Netherlands Swell. The highest point of this high is presumed to have lain in the east of the map sheet area. To the west of this swell lay an area of subsidence, the Off Holland Low.

The Main Buntsandstein within the map sheet area represents the northern progradation of braided river systems, alternated with lake depositions. The cyclicity of the depositions is attributed by Brennand (1975) to fluctuations in the height of the water level of the lake in relation to pulsating tectonic activity in the hinterland. However, in contrast to what Brennand presumes to be the case, it is not the tectonic activity that is the initial driving force behind the cyclicity, but the fluctuations in the height of the water level of the lake. During periods of low water level the fluvial systems prograded northwards. Each progradation of the fluvial systems was ended by a rapid southward migration of the lake owing to a rising water level. There is also assumed to be a connection between the fluctuations of the water level of the lake and periodic changes in climate which also determine the sea level curve of Haq et al. (1987).

The sediments within the map sheet area were laid down in the transitional area between the Netherlands Swell in the map sheet area and the Off Holland Low to the west of it. The increase in thickness of the Volpriehausen Sandstone is, however, also partly caused by a lateral facies transition, in which the bottommost units of the Volpriehausen Clay-Siltstone become sandier in a westerly direction (Geluk & Röhling, in prep.). The sedimentation on the Netherlands Swell came to an end and erosion set in, presumably as a consequence of a water-level drop in the lake. The degree of erosion generally decreases in the direction of the Off Holland Low.

The deposits of the Upper Germanic Trias Group show the influence of several marine incursions. A striking fact is that during deposition of the Röt and the Muschelkalk Formation within the map sheet area, greater subsidence set in in the central and eastern part of the Central Netherlands Basin, whereas in the western part a swell was still present. During this process, the area of subsidence was fault-bounded. During the Triassic the depocentre of the Central Netherlands Basin was situated further to the north than during the Jurassic.

After a period of erosion on the Netherlands Swell, sedimentation once again extended over the entire map sheet area as a result of a transgression and the Solling Member was deposited. This was followed by evaporation and deposition of rock salt which was mainly accumulated in the Central Netherlands Basin. The claystones of the Röt Formation were formed in a playa. The high carbonate content of the sediments in the uppermost part of the Röt Formation is evidence of a new transgression, causing the areas of provenance of the clastic sediments to be largely flooded by the sea. This is how limestones and dolomites of the Muschelkalk Formation came to be deposited in the map sheet area. The deposition of the Lower Muschelkalk very likely took place in a shallow marine, wadden to sabkha-type environment, analogous with the depositional conditions in the east of The Netherlands (RGD, 1981). The Muschelkalk Evaporite was deposited during a phase in which the connection with the sea was interrupted. Only in the deepest part of the Central Netherlands Basin was halite deposited. During the deposition of the Middle Muschelkalk Marl the connection with the sea was re-established and during the Upper Muschelkalk, marine clays were laid down.

The Keuper Formation was deposited under predominantly continental conditions after a eustatic sea-level fall (Haq et al., 1987). The fine-grained sediments were laid down on a coastal plain, while anhydrite was subsequently formed. During deposition of the Keuper Formation a greater subsidence of the western part of the Central Netherlands Basin appears to have set in. This part of the basin in fact formed a high during the sedimentation of the preceding formations. As a result of the Early Kimmerian phase, only the oldest deposits of the Keuper Formation still remain.

5.5 Petrophysical evaluation.

The Volpriehausen Sandstone and the Solling Sandstone form, in comparison with those of the Upper Rotliegend Group, the second major gas reservoirs within the map sheet area. In the northern half of the map sheet area these sandstones are absent, and in the southern half, their thicknesses decrease eastwards. In consequence, the presence of potential reservoirs is restricted to the southwest. The claystones and evaporites of the Röt Formation form the sealing layer for these sandstone reservoirs.

Within the map sheet area two of the wells have been petrophysically evaluated (RGD, 1991b). The sandstone of the Volpriehausen and Solling Members within the map sheet area is fluvial in origin.

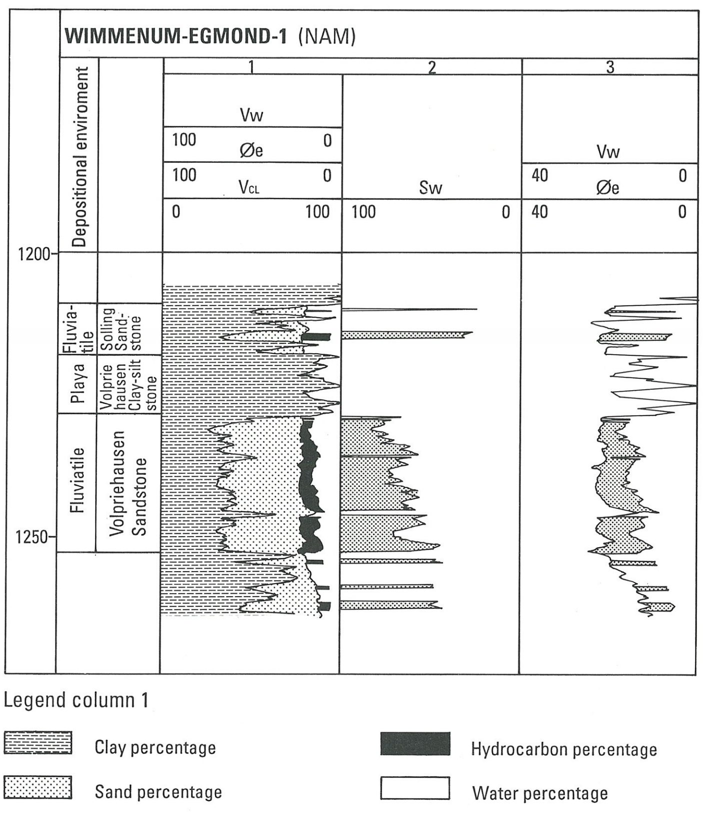


Figure 5.7. Petrophysical evaluation of the Volpriehausen and Solling Sandstone in the Wimmenum-Egmond-1 well. Column 1: clay content Vcl, effective porosity Øe and water volume in the pores Vw. The clay content was determined using gamma-ray log readings. The effective porosity was obtained using acoustic logs (Raymer-Hunt comparison in single porosity model; Raymer et al., 1980) after correction for the clay content. Column 2: water saturation Sw. The Indonesia formula, suitable for argillaceous deposits, was used to determine the water saturation (Fertl, 1987). Column 3: effective porosity Øe and the volume of water in the pores Vw. In the left-hand column, the stratigraphic boundaries and the deposition environment are indicated. Depths are log depths.

Permeability barriers do, however, occur internally in the form of clay beds and cemented horizons. In general, the sands are quite well sorted, but exhibits a small grain size. Carbonate cement and anhydrite cement are those most frequently found. Rims of clay and hematite around the quartz grains give the sandstones a soft-red colour. Feldspars are scarce, incorporated in mature, fine-grained quartz arenite.

The porosity of the Volpriehausen and Solling sandstone reservoirs varies between 12 and 25% (Appendix F and fig. 5.7). The highest porosities are associated with the coarser-grained cross-bedded riverbed deposits. The permeability varies from 50 to 500 millidarcy (Van Lith, 1983), but is in general low owing to the fine granularity and the occurrence of different kinds of cement. Occurrences of natural gas in the Triassic were found at Wimmenum, Heiloo and Middelie.

6 Altena Group

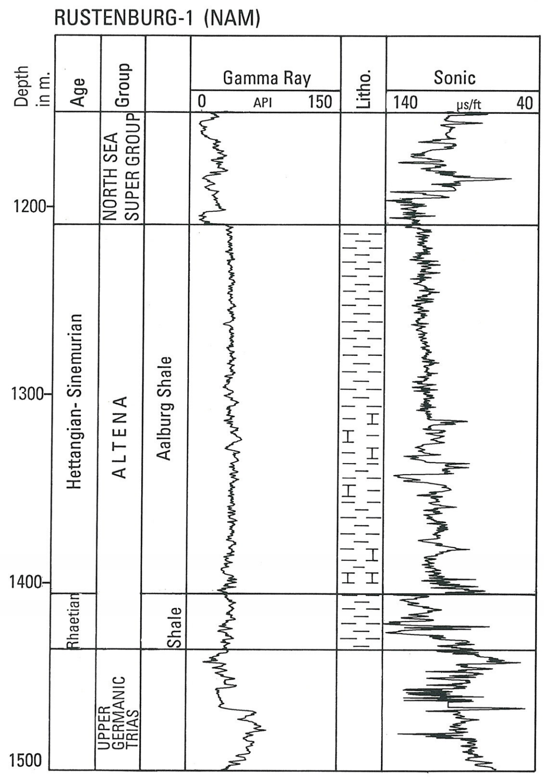
6.1 Stratigraphy

The Altena Group consists mainly of dark coloured claystones which were deposited in a marine environment. The group is subdivided in the Sleen Shale, the Aalburg Shale, the Werkendam Shale and the Brabant Formations. The presence of these formations in the map sheet area was mainly ascertained from seismic data. In well studies the presence of only the first two formations mentioned has been demonstrated. The Altena Group is latest Late Triassic to Middle Jurassic in age.

The deposits of the Altena Group rest on deposits of Triassic age, separated by the Early Kimmerian unconformity, and are covered both by the Central Graben Group and the Rijnland Group, separated by the Late Kimmerian unconformity (Map 16 & 17). In addition, in specific areas, the North Sea Super Group overlays the Altena Group, also unconformably (Map 18).

The deposits of the Altena Group occur only in the Central Netherlands Basin, in the southern half of the map sheet area (Map 7). The depth of the base of the group varies from less than 1000 m in the extreme southwest to over 2800 m in the Gouwzee Trough (Map 7). The greatest mapped thickness is over 1050 m and is also found in the Gouwzee Trough (Map 8). The thickness variations in the Altena Group are mainly determined by the extent of uplift and erosion which occurred later. The stratigraphic succession of the bottommost part of the Altena Group is illustrated by the Rustenburg-1 well (fig. 6.1).

Figure 6.1 Composition of the Altena Group in the Rustenburg-1 well. The interpretation of the lithology has been based on gamma-ray log (in API) and sonic log (in µs/ft) readings.



Claystone

Calcareous claystone

6.1.1 Sleen Shale Formation

The Sleen Shale Formation consists of a light-grey, non-calcareous claystone, with a fine-grained sandstone interbed (fig. 6.1). Thin intercalations of siltstone and lignite also occur. A lithological tripartition can be made on the basis of the interbedded sandy succession (NAM & RGD, 1980). Within the map sheet area, the thickness of the Sleen Shale Formation varies from 20 to 40 m. Within the formation itself, the thickness variations are restricted to the bottommost claystone succession; the sandstone succession and the uppermost claystone succession have a consistent thickness of around 20 m. The Middle Rhaetian age of the formation in the map sheet area has been confirmed by biostratigraphic studies (RGD, 1970).

6.1.2 Aalburg Shale Formation

The Aalburg Shale Formation rests conformably on the Sleen Shale Formation and is conformably overlain by the Werkendam Formation, or unconformably by the Central Graben Group, Rijnland Group or North Sea Super Group. The formation is built up of predominantly dark coloured claystone, with intercalations of calcareous, dolomitic, silty and fine sandy claystone. Pyrite, siderite, coal fragments and belemnites also occur in the formation. The lithological composition of the formation is conspicuously homogeneous throughout the North Sea area (Ziegler, 1982). Although the formation reaches great thicknesses, lithological variations vertically are not of such a nature to allow a useful subdivision (NAM & RGD, 1980). The various Lias stages can be differentiated, based on biostratigraphical characteristics. The thicknesses of these stages are comparable in the different wells within the map sheet area and immediately beyond it. The formation is not found in its entirety in wells, but from seismic data it can be deduced that the thickness of the complete formation is 450 to 500 m. This is supported by well data from adjacent areas.

6.1.3 Werkendam Shale Formation

In the southern part of the map sheet area, this formation rests conformably on the Aalburg Shale Formation (fig. 6.2). In the Gouwzee Trough the formation may well be conformably overlain by the Brabant Formation; for the rest, the formation is unconformably overlain by the Central Graben Group or the Rijnland Group. The Werkendam Shale Formation in the map sheet area has not been explored by drilling. In the Broad Fourteens and the West Netherlands Basin the formation is built up of four members, of which the bottommost member, the Posidonia Shale, has been identified within the map sheet area on seismic sections. This unit consists of a black bituminous claystone, whose thickness is presumed to be 30 m. Owing to the high content of marine organic constituent parts, this unit regionally forms a major oil-source rock. The remainder of the formation is presumed to consist of silty claystones with intercalations of sandstone and limestone, analogous with the development of the formation in the Broad Fourteens Basin to the west of the map sheet area and in the West Netherlands Basin (Bodenhausen & Ott, 1981). Where the formation has not been eroded, the thickness is estimated at a minimum of 400 m, deduced from the development of the formation in the adjacent Broad Fourteens Basin. The formation is of Toarcian to Bajocian age and reflects a marine depositional environment (NAM & RGD, 1980).

6.1.4 Brabant Formation

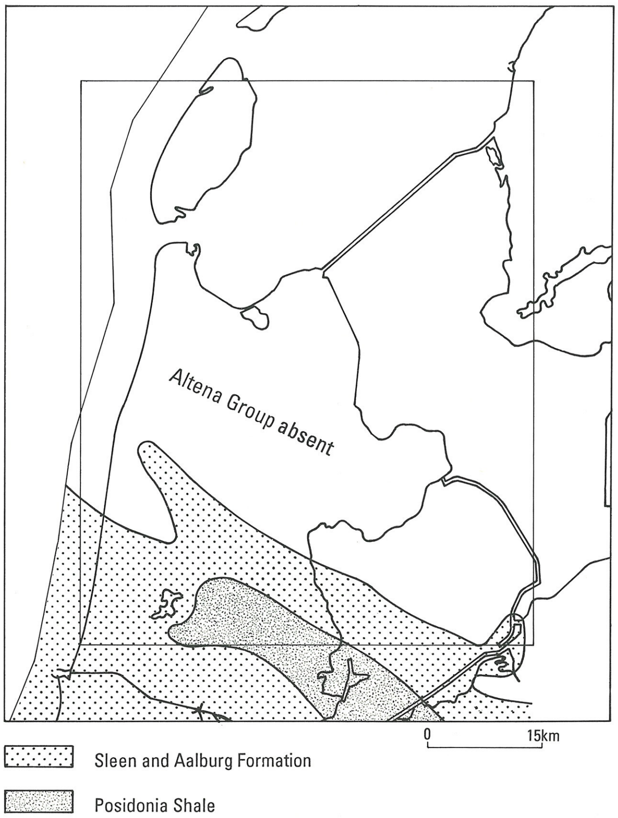
Like the Werkendam Shale Formation the presence of the Brabant Formation has not been demonstrated from wells within the map sheet area or the immediate surroundings. The presence of this formation in the Gouwzee Trough, is however, very likely, in view of the great thickness of the entire Altena Group and the seismic character of the uppermost part of this succession. The formation is presumed to be built up of an alternation of limestone layers with marls and claystone, analogous to the composition of the West Netherlands Basin (Bodenhausen & Ott, 1981) and of the Broad Fourteens Basin. The formation is held by NAM & RGD (1980) to be of Middle Jurassic age (Bajocian-Oxfordian) with an estimated thickness of a maximum of 150 m.

6.2 Sedimentary development and palaeogeography

As a consequence of a eustatic sea-level rise during the latest Late Triassic and Early Jurassic (Vail & Todd, 1981) the continental conditions of the Triassic came to an end. The claystones of the Aalburg Shale Formation were accumulated in a marine environment below the wave base. The fine-grained character of the deposits indicates the absence of landmasses in the immediate vicinity of the map sheet area. The thickness of the deposited successions and the gradual variations within them, indicate the minor influence of sea-level fluctuations and a less differentiated subsidence during the deposition of the Aalburg Shale Formation.

During the deposition of the Aalburg Shale the sea level gradually rose and the London-Brabant Massif and the Rhenish Massif were flooded by the sea. A connection developed between the Tethys and the Arctic Ocean, as is apparent from the mixture of the various faunas. In the area around the present North Sea the cold Arctic water blended with the warm water of the Tethys.

Figure 6.2. Distribution of the Posidonia Shale (Werkendam Formation) in the map sheet area. The presence of this formation is restricted to the Gouwzee Trough, the deepest part of the Central Netherlands Basin in the map sheet area.



This entire area is characterised by deposition of clays in an open marine environment (Ziegler, 1990).

The deposition of the Werkendam Shale Formation is characterised by an initially stagnating basin circulation, as a result of which the organic-rich Posidonia Shale was deposited in anoxic conditions. The presence of this oil-source rock is a specific feature of the area referred to in the previous paragraph during sea-level high stand. Its origin is attributed to a density inversion in the sea water, which limited the normal circulation and refreshment of the basins, leading in turn to an oxygen minimum on the sea floor (Ziegler, 1990). These anoxic conditions may only have been restricted to the basins. After deposition of the Posidonia Shale the circulation was restored and fine-grained sediments were laid down once again.

The reconstruction of the subsequent history of deposition of the Altena Group is seriously hampered by the absence of these deposits in large areas as a consequence of later tectonic phases. However, judging from the development of these sediments in the Broad Fourteens Basin, the West Netherlands Basin and the Roer Valley Graben (Haanstra, 1963; Van Wijhe, 1987a), sedimentation is presumed to have been mainly concentrated in the Central Netherlands Basin, while outside this basin non-deposition or erosion occurred. The latter very probably applies to the northern part of the map sheet area. The clays and sands of the Werkendam Shale Formation reflect the start of a regressive sequence contemporaneously deposited in the basin. Finally, the limestones and clays of the Brabant Formation are indicative of a shallow marine environment.

6.3 Geochemical evaluation

The major oil-source rock of The Netherlands, the Posidonia Shale, is found in the deposits of the Altena Group. In addition, a few clay layers, rich in organic material, are also found in the Aalburg Shale. Geochemical research on available samples from these last-mentioned rocks has not however produced any useful findings in most cases (RGD, 1989b). The Posidonia Shale is characterised by a high content of organic material mainly of marine origin; as such it is therefore allocated to a Type I or II kerogen (marine organic material). Geochemical analysis of a well to the west of the map sheet area displayed an organic carbon content of 5.0 % (Robertson Research International Ltd., 1984).

The generation of oil from the Posidonia Shale has been the subject of an extensive study in Germany (Binot et al., in press). It has been ascertained here that all oil-source rocks have a different oil window. In the case of the Posidonia Shale, oil formation takes place at a coal rank of 0.45 to 0.8 %Rm. Measurement of the coal rank of organic material in the Aalburg Shale in the map sheet area produced reliable results in one borehole only. In the Middelie-101 well a coal rank of 0.42 was recorded (RGD, 1989b). The Posidonia Shale does not lie so deep as the Aalburg Shale; the depth measurement at that place therefore can be taken as the maximum coal rank of the Posidonia Shale. In view of subsidence history of the Central Netherlands Basin, it is assumed that the coal rank of the Posidonia Shale is analogous to that of the Carboniferous (see fig. 3.4). It is therefore surmised that in the Gouwzee Trough in the extreme south of the map sheet area, the coal rank of the unit is higher. However this is not supported by measured data. The degree of maturity of the Posidonia Shale does not appear to be great in the map sheet area. Prior to the inversion of the basin during the Late Cretaceous, very little oil will have been generated in the centre of the basin. Within the map sheet area, up to the present time no economically exploitable accumulations of oil prove to be present; however, in the Groet-1 and IJsselmeer-1 wells, traces of oil have been observed in the carbonates of the Zechstein Group and sandstones in the Triassic (RGD, 1989b).

To the west of the map sheet area, the Posidonia Shale in the Broad Fourteens Basin (Van Wijhe, 1987b), is, however, a mature oil-source rock, as appears from the many exploitable accumulations of oil. This is also the case in the West Netherlands Basin to the south of the map sheet area (Bodenhausen & Ott, 1981; Van Doorn, 1991).

7 Central Graben Group

7.1 Stratigraphy

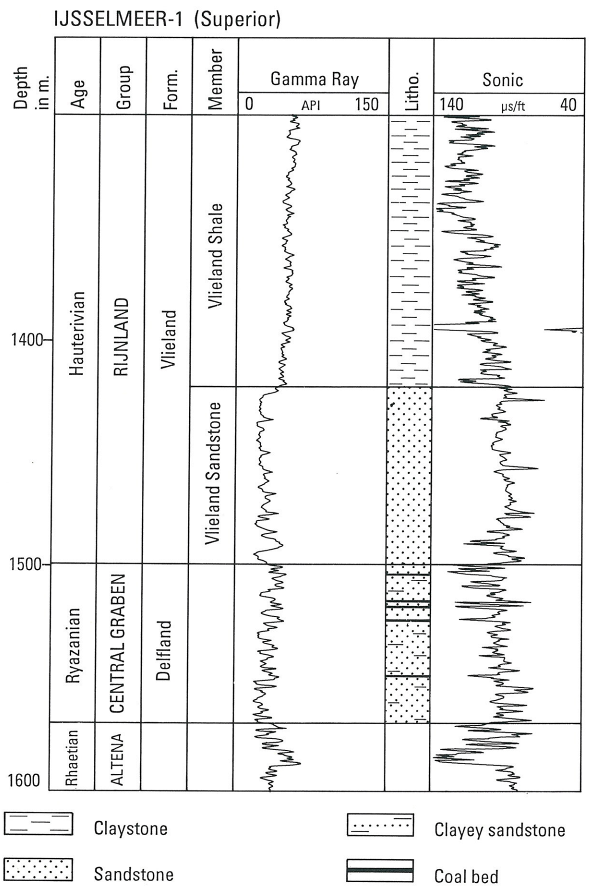
Deposits of the Central Graben Group are characterised by variegated clastic sediments with intercalated coal seams. Within the map sheet area, the group comprises only the Delfland Formation and is of Late Jurassic to earliest Cretaceous age.

The sediments of the Central Graben Group, present only in the southern Vlieland Subbasin and the Central Netherlands Basin (Map 9), rest unconformably on older sediments, separated by the Late Kimmerian unconformity (Map 16) and are overlain unconformably either by the Rijnland Group of Early Cretaceous age (Map 17) or by the North Sea Super Group of Tertiary age (Map 18).

The base of the Central Graben Group lies at a depth of 1950 to 2500 m in the Vlieland Basin, and at 1000 to 1750 m in the Central Netherlands Basin (Map 9). In the southern Vlieland Subbasin the deposits are 440 m thick whereas in the Central Netherlands Basin they are just over 250 m at the most (Map 10). The succession of the Central Graben Group is illustrated by the IJsselmeer-1 well (fig. 7.1) and a log correlation section (fig. 7.2).

Reference should be made to Herngreen et al. (1991) and Geological Survey of The Netherlands (1991a) for a more detailed description of the deposits in the Vlieland Basin.

Figure 7.1. Composition of the Central Graben Group in the IJsselmeer-1 well. The interpretation of the lithologies is based on gamma-ray log (in API) and sonic log (in µs/ft) readings. The indicated datings of the deposits have been taken from RGD (1975a).



7.1.1 Delfland Formation

The Delfland Formation is mainly composed of grey, green or brown siltstones, with intercalations of light-to-dark brown coloured sandstone. The rocks may occasionally have a red mottled appearance. There are also limestone occurrences as well as, particularly in the uppermost part, many plant debris and coal seams. In comparison with the Delfland Formation in the West Netherlands Basin (Nieuwerkerk-1; NAM & RGD, 1980) and the Broad Fourteens Basin (K15-1; NAM & RGD, 1980) the formation in this area is much more finely grained. The formation succession will be discussed separately for each basin.

The specific part of the formation in the Vlieland Basin within the map sheet area is characterised by silty claystones with occurrences of coal seams and sandstone in the uppermost part, and calcareous intercalations in the claystone at the base of the formation. Around the Zuidwal Volcanic Dome, sandstone is much more pronounced and intraformational vulcano-clastic deposits occur, consisting of fine-to-coarse angular green, red and brown clasts in a tuff-like matrix, which have been allocated to the Wadden Vulcaniclastic Member (Herngreen et al., 1991). Palynological studies have demonstrated that the Delfland Formation in this area is of Late Kimmeridgian to Ryazanian age, with the coal seams being Ryazanian (Herngreen et al., 1991; RGD, 1990d). The Delfland Formation is overlain by the Rijnland Group with a small hiatus.

Throughout the central part of the area within the Central Netherlands Basin the formation consists of a basal claystone unit followed by a coarsening-upwards succession. The claystone unit is brown-to-dark grey in colour and contains mica, pyrite, siderite, and layers of sandstone and limestone as well as coal seams, and shows characteristic peaks on well log readings (Middelie-201; fig. 7.2). The overlying succession is characterised by an upwardly increasing sand content and the fine-grained, light-grey to white siltstone and sandstone are poorly consolidated. This particular claystone unit represents a brackish water accumulation, while the overlying succession was partially laid down in freshwater (RGD, 1986d).

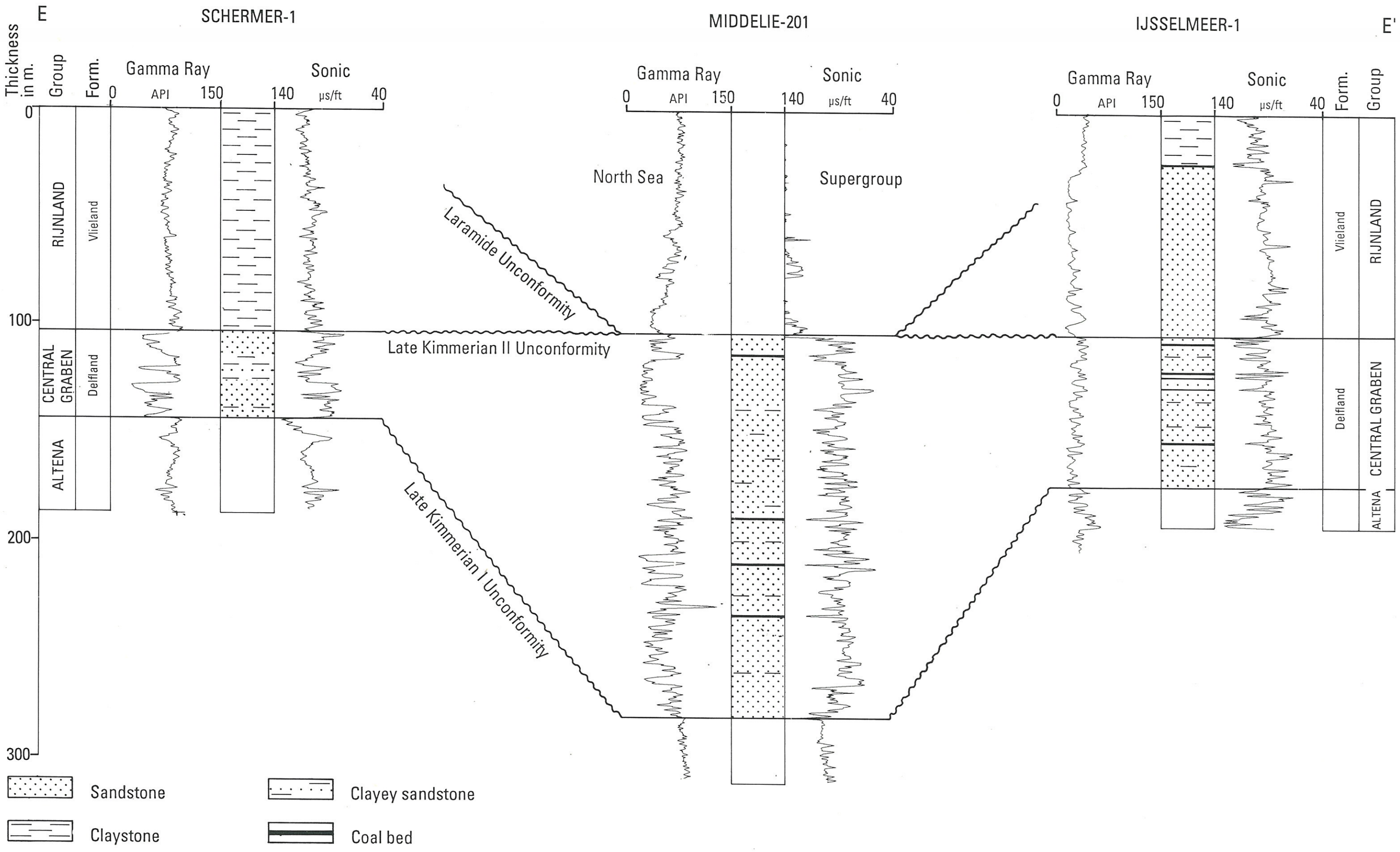
On the northeast margin of the Central Netherlands Basin the formation consists largely of the above-mentioned light coloured sandstones and siltstones with intercalated coal seams, related to fault-bounded depressions caused by subterranean solution of rock salt. In the Vlieland Formation, such structural configurations often contain a sand unit (see section 8.1.1).

In the Central Netherlands Basin the formation proved to be of Late Portlandian to Ryazanian in age (RGD 1971, 1975a, 1986a-d, 1990c,e).

7.2 Sedimentary development and paleogeography.

The Vlieland Basin was divided by the Zuidwal Volcano into a northern and a southern subbasin, only the latter being within the map sheet area. During the Kimmeridgian the Vlieland Basin was separated from the northerly marine basins by highs (Herngreen et al., 1991) and the products of erosion from these highs were deposited in the Delfland Formation. Deposition of the Delfland Formation began in the Late Kimmeridgian, during a period of relatively high sea level (Haq et al., 1987) and was laid down in this area in a predominantly lacustrine environment. As a result of a gradual drop in sea level (Haq et al., 1987) the fluvial influence of the sedimentation increased and there was, in fact, a clear fluvial influence around the Zuidwal Volcanic Dome during the entire depositional period. The barrier-effect of this dome prevented the brief transgressions during the Portlandian, as shown for the northern Vlieland Subbasin (Geological Survey of The Netherlands, 1991a), from reaching the southern subbasin and only marginal marine influences have been

Figure 7.2. Correlation section EE' of the Central Graben Group in the Central Netherlands Basin. The correlations are based on gamma-ray log (in API) and sonic log (in µs/ft) readings. The reference level is the top of the Central Graben Group. The location is shown in figure 8.3.



demonstrated in this subbasin (Herngreen et al., 1991). During the latest Early Cretaceous, extensive peat formation took place. This stagnation in drainage is attributed by Haq et al. (1987) to a minor sea-level rise. The Wadden Vulcaniclastic Member is built of erosion products from the Zuidwal Volcano (Herngreen et al., 1991).

The north margin of the Central Netherlands Basin was bounded by the Texel-IJsselmeer High. In this basin, deposition of the Delfland Formation began significantly later than in the Vlieland Basin, with the oldest sediments identified being of Late Portlandian age. The development of the Delfland Formation is also considered more likely to be related to the development in the southern West Netherlands Basin than to the development in the Vlieland Basin. Lagoonal clays accumulated in a brackish-water environment, determined by a transgression during the Portlandian. The overlying deposits reflect the regressive character and an increasing continental influence on the depositional environment during the Ryazanian.

7.3 Petrophysical evaluation

A petrophysical evaluation was carried out of the uppermost sandstone unit of the Delfland Formation from a number of wells in the study area, the reason being that this unit lies immediately under the gas-bearing sandstone at the base of the Rijnland Group. For a summary of the petrophysical data, reference should be made to appendix H.

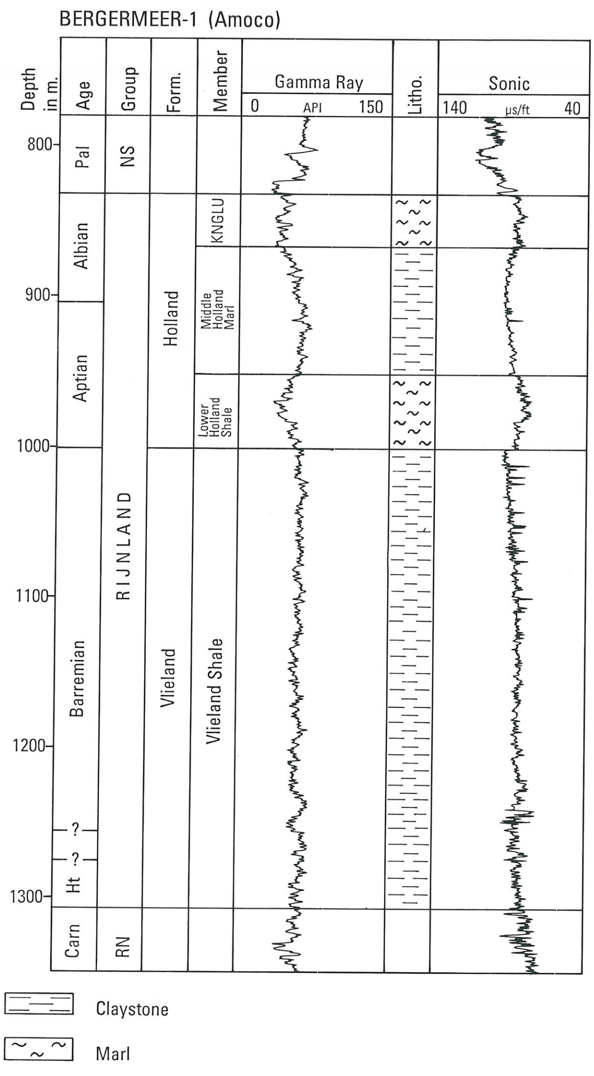
8 Rijnland Group

8.1 Stratigraphy

The Rijnland Group, of Valanginian to Albian age, was deposited in a gradually deepening open marine environment and comprises mainly siltstones, claystones and marls, with sandstone also occurring at the base in places.

Within the map sheet area the Rijnland Group rests predominantly unconformably on older deposits of the Limburg Group, Upper Rotliegend Group, Zechstein Group, Lower and Upper Germanic Trias Group, Altena Group or Central Graben Group (Map 17). In the northeast of the area, the group is separated in the Vlieland Basin from the Central Graben Group by a small hiatus only (Herngreen et al., 1991). In the north and middle of the area, the Rijnland Group is overlain

Figure 8.1. Composition of the Rijnland Group in the Bergermeer-1 well. The interpretation of the lithology is based on gamma-ray log (in API) and sonic log (in µs/ft) readings. The age of the deposits has been derived from RGD (1987b, 1990b).



Pal	Paleocene
Ht	Hauterivian
Carn	Carnian
NS	North Sea Supergroup
RN	Upper Germanic Trias Group
KNGLU	Upper Holland Marl

conformably by the Chalk Group (Map 13); in the south, however, the group is overlain unconformably by the North Sea Super Group (Map 18).

Deposits of the Rijnland Group occur throughout the map sheet area, with the exception of the extreme south where the group has been subjected to erosion in places. The base of the deposits lies nearest the surface in the Central Netherlands Basin, in places less than 1000 m, outside this basin increasing to more than 2700 m in a northwesterly direction (Map 11). The greatest thickness of the group is found in the Vlieland Basin, where it exceeds 700 m. On the Texel-IJsselmeer High thicknesses averaging 150 to 200 m are found, although in places even less than 100 m. South of this high, extreme variations in thickness occur as a result of subsequent erosion. However, thicknesses of over 500 m may occasionally occur (Map 12).

The Rijnland Group is subdivided into the Vlieland and the Holland Formation. The composition of the group is illustrated in the Bergermeer-1 well (fig. 8.1) and a correlation section (fig. 8.2).

8.1.1 Vlieland Formation

The Vlieland Formation, of Late Ryazanian to Barremian age (Herngreen et al., 1991; RGD, 1968, 1975a, 1990d), forms the base of the Rijnland Group in most of the area although it is completely absent on the Texel-IJsselmeer High, where the Holland Formation forms the base of the Rijnland Group (fig. 8.2 & Map 11). The Vlieland Formation comprises two members, namely the basal Vlieland Sandstone and the overlying Vlieland Shale Member; the Vlieland Sandstone is found in the Vlieland Basin and in some places in the Central Netherlands Basin. The contact with the overlying Holland Formation is conformable, although log correlation in the northern half of the map sheet area indicates the likelihood of a hiatus, with the probability of an disconformity. In the south of the area, the Vlieland Formation is overlain unconformably by deposits of the North Sea Super Group and rests unconformably on older deposits of the Limburg Group, Upper Rotliegend Group, Zechstein Group, Lower and Upper Germanic Trias Group, Altena Group and Central Graben Group. The thickness of the formation exceeds 500 m in the Vlieland Basin and 400 m in the Central Netherlands Basin. On the Noord-Holland Platform the thickness increases in a southerly direction from a few tens of metres to over 200 m. On the platform the contour pattern is influenced by the presence of a NW-SE oriented halfgraben near Slootdorp.

The *Vlieland Sandstone* is found in the Vlieland Basin at thicknesses exceeding 150 m in the central part, although decreasing towards the margins. The unit is absent on the Texel-IJsselmeer High while in the Central Netherlands Basin it is mainly confined to the fault-bounded depressions described in section 5.3.1 where the sandstone is over 20 to 80 m thick.

The Vlieland Sandstone comprises alternations of mostly well layered, lightly cemented, grey, grey-brown to green, fine to medium-fine quartz sandstones with darker siltstones and silty claystones. Coarse sandstone is also found in the Central Netherlands Basin, mostly displaying internal cross stratification which may, however, be absent owing to intensive bioturbation. The sandstone contains substantial amounts of glauconite in places. Well logging shows that within the Vlieland Sandstone, the sandstone passes upwards into siltstone and claystone intervals which are frequently laminated and rich in organic material. The siltstones and claystones are occasionally coarsening upwards into sandstone. Graded sequences contain intercalations of brown coloured sandstone layers cemented with siderite and calcite. The Vlieland Sandstone is characterised in general on well logs by a block-like reading. The transition to the Vlieland Shale is rather abrupt, and clearly recognisable on well logs (fig. 7.1 & 8.2).

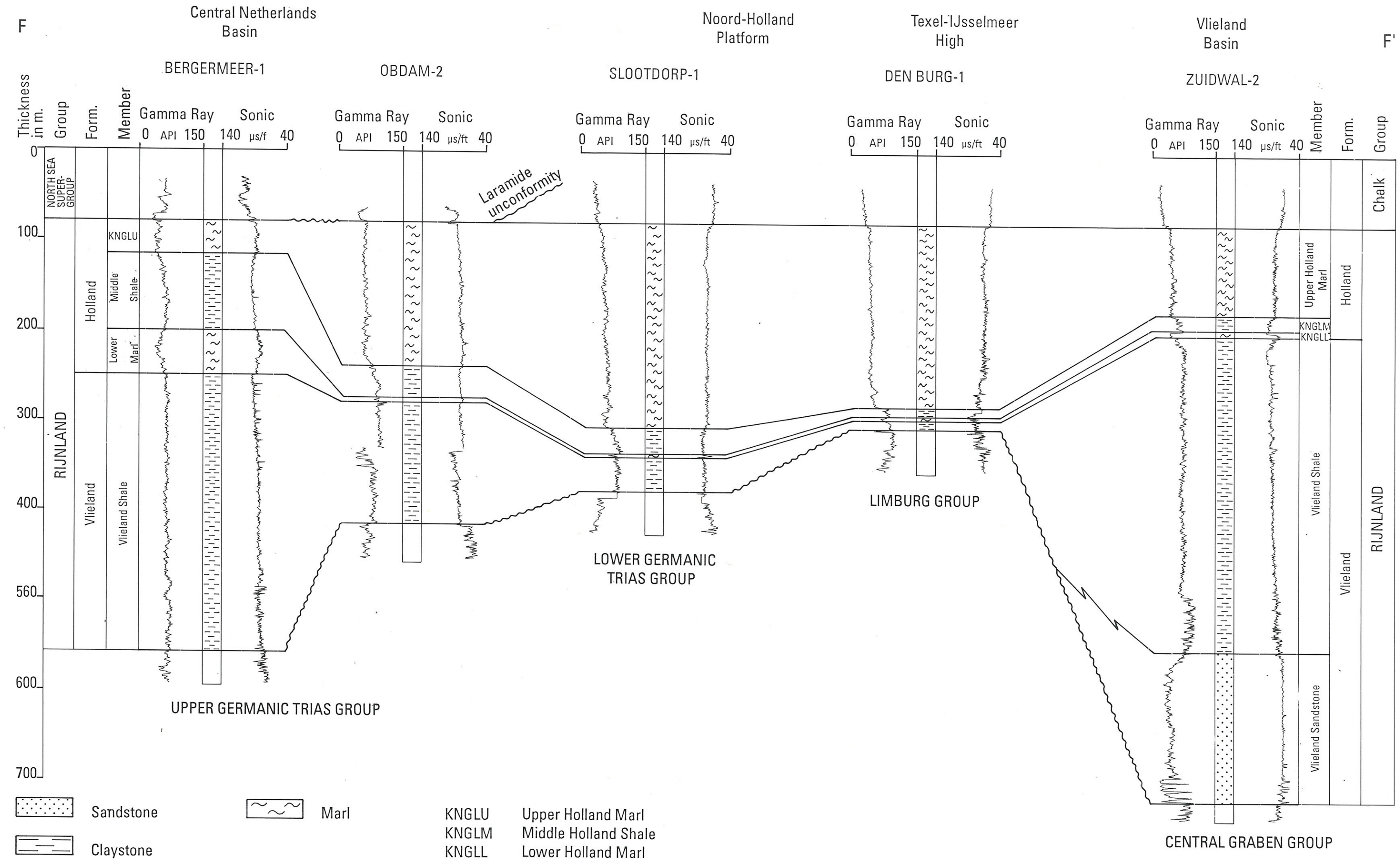


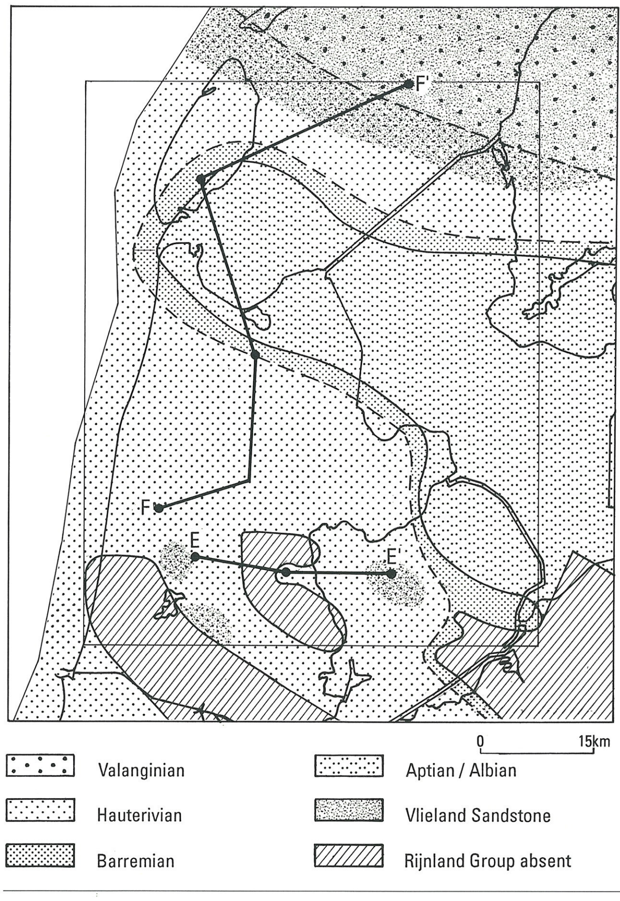
Figure 8.2. Stratigraphic section FF′ of the Rijnland Group from the Central Netherlands Basin to the Vlieland Basin over the Texel-IJsselmeer High. Observe the onlap of the Vlieland Shale on the high. The correlations are based on gamma-ray log (in API) and sonic log (in µs/ft) readings. The reference level is the top of the Rijnland Group. The location of the section is shown in Figure 8.3.

The age of the Vlieland Sandstone shows considerable differences between the two basins (fig. 8.3). In the Vlieland Basin the unit is of Valanginian age, with the bottommost part possibly of Late Ryazanian age (Herngreen et al., 1991; RGD, 1990d). In the Central Netherlands Basin the Vlieland Sandstone is clearly younger, Hauterivian of age (RGD, 1986a & 1990c).

The *Vlieland Shale,* which is marly at the top, consists of dark-brown to dark-grey, silty claystone. Thicknesses in the basins may reach over 350 m in the Vlieland Basin and 450 m in the Central Netherlands Basin, while on the platform around the high the thickness generally increases towards the basins from a few tens of metres to over 200 m. On the Noord-Holland Platform, however, variations in this pattern occur.

In the Vlieland Basin the age of the Vlieland Shale is Late Valanginian to Barremian (Herngreen et al., 1991; RGD, 1990d), whereas in the Central Netherlands Basin the base of the unit is Late Hauterivian (RGD, 1987b). Within the Vlieland Basin a condensed sequence is found on the base of the unit, and palynofacies analyses indicate sea-level fluctuations (Herngreen et al., 1991). From the basins towards the central part of the Texel-IJsselmeer High the base becomes younger, Barremian in age, near the outer limits of the Vlieland Shale (fig. 8.3) which is analogous with the top of the unit (well Den Burg-1; RGD, 1990a).

Figure 8.3. The age of the deposits at the base of the Rijnland Group. The distribution of the Vlieland Sandstone, where present at the base of the group, is indicated. EE' is the location of the section of figure 7.2; FF' is the location of the section of figure 8.2.



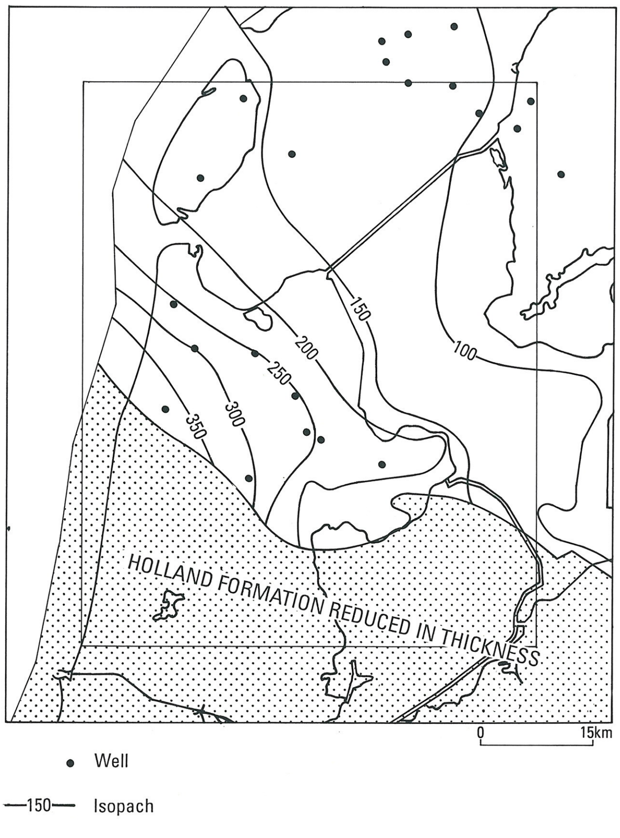
8.1.2 Holland Formation

The Holland Formation is the uppermost unit of the Rijnland Group and comprises a succession of light-grey to dark-grey, sometimes variegated marly claystones. The sediments of the Holland Formation, of Aptian/Albian age, were laid down in a marine environment with fluctuating water levels. The Holland Formation displays a continuous sedimentation pattern in the Central Netherlands Basin, whereas more to the north, hiatuses occur.

The Holland Formation Group is conformably overlain by the Chalk Group within its area of extent, although log correlations seem to point to a hiatus around the Texel-IJsselmeer High. Beyond the southern extent of the Chalk Group, in a small area, the deposits of the North Sea Super Group rest unconformably on the formation. In the Central Netherlands Basin the formation rests conformably on the Vlieland Formation without hiatuses (RGD 1990b), whereas in the Vlieland Basin and around the Texel-IJsselmeer High a hiatus occurs in the Early Aptian (Herngreen et al., 1991). On the Texel-IJsselmeer High the formation rests unconformably on the Limburg Group, Upper Rotliegend Group or Zechstein Group.

The Holland Formation has been reduced by erosion or is even completely absent in the Central Netherlands Basin. The thickness is the slightest on the Texel-IJsselmeer High, in places less than 100 m, and increases in a southwesterly direction to more than 300 m (fig. 8.4).

Figure 8.4. Thickness map of the Holland Formation. This map is based on well and seismic data. The thicknesses are in metres.



The Holland Formation is subdivided into the Lower Holland Marl, the Middle Holland Shale and the Upper Holland Marl Members. These three members can be clearly distinguished by borehole measurements (fig. 8.2) and the same tripartition can be identified in the subsurface virtually throughout The Netherlands.

The *Lower Holland Marl* comprises a light-grey to dark-grey, sometimes red, sometimes brown or yellowish coloured marly claystone. On the Noord-Holland Platform the unit developed as a limestone. The unit was deposited in a relatively shallow, open marine environment. Within the map sheet area, the age of this member is confined to Late Aptian in the Vlieland Basin, on the Texel-IJsselmeer High and in the northern part of the Noord-Holland Platform, but in the Central Netherlands Basin there are also Early Aptian deposits (RGD, 1990b).
The member is presumed not to have been deposited in the highest part of the Texel-IJsselmeer High. This, however, has not yet been confirmed by well data, but is nonetheless supported by the slight thickness of 1 to 2 m around this high (e.g. Slootdorp-1) and by the adjacent map sheets (Geological Survey of The Netherlands, 1991a, b). In the Vlieland Basin the thickness attains a maximum of 15 m, and from the Texel-IJsselmeer High the thickness increases in a southwesterly direction to over 60 m.

In the Vlieland Basin the Lower Holland Marl covers the Vlieland Shale, separated by a significant hiatus equivalent to the Early Aptian period (Herngreen et al., 1991). Immediately around the Texel-IJsselmeer High this hiatus reflects the duration of nearly the whole Aptian (RGD, 1986e). To the south of the high, however, this hiatus becomes shorter and in the Central Netherlands Basin it is no longer present (RGD, 1990b).

The *Middle Holland Shale,* Late Aptian to Middle Albian age, consists of a dark-grey to brownish claystone which is occasionally sandy at the base. The depositional environment is open marine (Herngreen et al., 1991).

The Middle Holland Shale lies in the Central Netherlands Basin on the Lower Holland Marl without any apparent hiatus (RGD, 1990b). Biostratigraphic investigations and log correlations show the bottommost part of the member to be Late Aptian (RGD, 1990b) contrary to NAM & RGD (1980) suppositions. This part is absent in the Vlieland Basin and around the Texel-IJsselmeer High and the boundary is represented by a hiatus (Herngreen et al., 1991). The uppermost part of the unit on the high is presumed to rest unconformably on the Limburg Group and the contact with the overlying unit is without a hiatus. The thickness of the member increases in a southerly direction from 20 m in the Vlieland Basin and around the Texel-IJsselmeer High to over 100 m in the Central Netherlands Basin.

The *Upper Holland Marl,* of Late Albian age, consists of light-grey and, in places, variegated marly and silty claystone (Herngreen et al., 1991). Several small hiatuses are presumed to occur, predominantly in the northern part of the area. Log correlations and the abrupt contact with the overlying Chalk Group would seem to indicate the local presence of a hiatus at the top of the unit (fig. 8.2 and 9.2, Den Burg-1 and De Cocksdorp-1 wells).

The thickness of this unit increases towards the southwest, from just over 40 m in the extreme northeast of the area to over 200 m immediately to the north of the Central Netherlands Basin. Owing to erosion the depositional thickness in the basin itself can no longer be ascertained.

8.2 Sedimentary development and paleogeography

The Rijnland Group forms a transgressive megasequence and was laid down in a marine environment, under the influence of a gradually rising sea level since the Ryazanian which gradually flooded the landmasses from the north.

In the map sheet area the deposits of Vlieland Sandstone resulting from this transgression, which were laid down in a shallow marine environment, are the oldest in the Vlieland Basin. At this stage, the thickness of Vlieland Sandstone was principally determined by the Vlieland Basin, but during the Hauterivian the extent of distribution of the Upper Jurassic sediments had already been exceeded. As a consequence of the progressive sea-level rise in the Vlieland Basin the clays of the Vlieland Shale were subsequently deposited during the Late Valanginian. During the Early Hauterivian the transgression also reached the part of the Central Netherlands Basin lying within the map sheet area, starting from the Broad Fourteens Basin. During the transgression in the Vlieland Basin, sands were sporadically deposited in fault-bounded depressions which originated as a result of the subterraneous solution of rock salt. Clay sedimentation gradually extended from the basins over the highs during the Hauterivian and Barremian and by the end of the Barremian only the central part of the Texel-IJsselmeer High projected above sea level (fig. 8.3). As the sea had flooded over the majority of the highs in the north of The Netherlands, the content of clastic components in the sediments diminished. This gave the sediments a more marly character, with the calcareous components mainly derived from planktonic organisms. During the deposition of the Vlieland Shale the differential subsidence of the basins continued. In addition, a striking feature during the deposition of the Vlieland Formation is a small halfgraben on the Noord-Holland Platform.

Finally, the last highs were covered by the sea during the deposition of the Holland Formation. This took place not during deposition of the Lower Holland Marl, but when the uppermost two members were being laid down, the flooding of the Texel-IJsselmeer High took place. The deposition of marine sediments continued and during deposition of the Holland Formation the Vlieland Basin no longer resembled a basin. Throughout the north of the map sheet area the little sedimentation that took place was punctuated by hiatuses and possibly emergence of immediately adjacent areas (RGD, 1990d). The Central Netherlands Basin, in contrast, displayed large subsidence and the most continuous sedimentation.

8.3 Petrophysical evaluation

To the north and northeast of this map sheet area, gas is produced from the Vlieland Sandstone. This unit is discussed in detail in the map sheets of areas situated further to the north (Geological Survey of The Netherlands, 1991a, b). In the Central Netherlands Basin the sandstone occurs locally in small collapse structures. A petrophysical evaluation was carried out in one well, the IJsselmeer-1 (RGD, 1991b). The porosity of 16.5% is similar to that found in the Vlieland Basin, although the high water saturation indicates the absence of gas (fig. 8.5).

The reduction in porosity in the Vlieland Sandstone in the Vlieland Basin is not only due to compaction but also to cementation, with calcite and siderite present as cements. Early diagenetic processes in particular, such as the precipitation of calcite, have played a part in reducing porosity. The presence of fibrous illite, comprising approximately 10% of the clay minerals (Perrot & Van der Poel, 1987), is of importance as it results in reduction in permeability (Seemann, 1979; Pallatt et al., 1984).

Based on lithological features in the Zuidwal gas field, Cottençon et al. (1975) identify five reservoir zones, which differ one from another by internally fining and coarsening sequences. As well as the lithological division, Perrot & Van der Poel (1987) also distinguish the quality of reservoir zones, based on porosity and permeability data. The reservoir characteristics display a regional tendency, in which an improvement in each layer is observed from the northwest to the southeast. From core studies, Perrot & Van der Poel (1987) described a number of permeability barriers from approximately 10 cm to approximately 1 m thick, consisting of sandstone beds cemented with siderite and calcite, dividing the Vlieland Sandstone into 18 thin units. The cemented zones only permit horizontal flow of gas in the reservoir rocks.

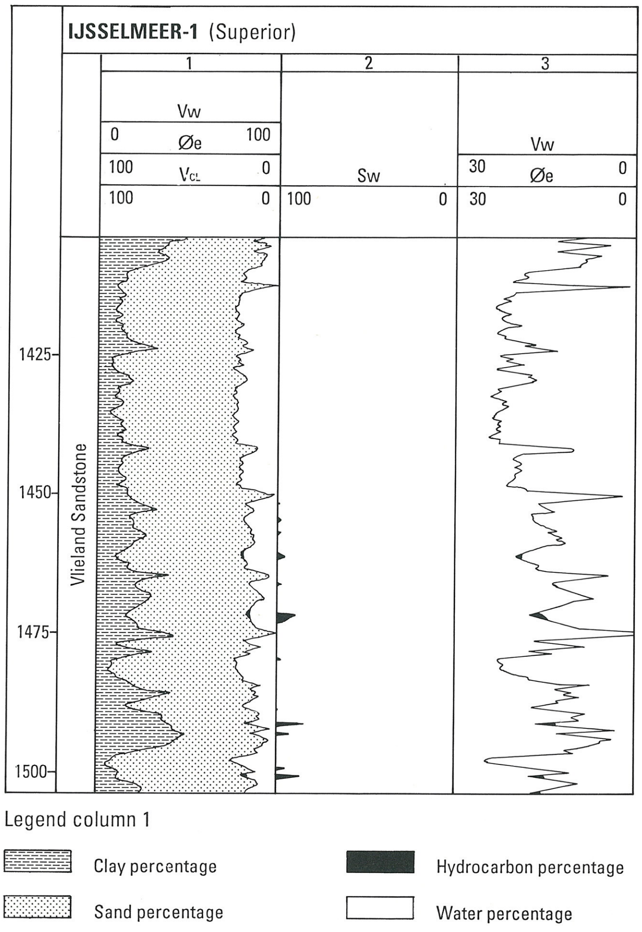


Figure 8.5. Petrophysical evaluation of the Vlieland Sandstone in the IJsselmeer-1 well. Column 1: clay content Vcl, effective porosity Øe and water volume in the pores Vw. Column 2: water saturation Sw. Column 3: effective porosity Øe and the volume of water in the pores Vw. The stratigraphic boundaries are indicated in the left-hand column. The depth is true depth.

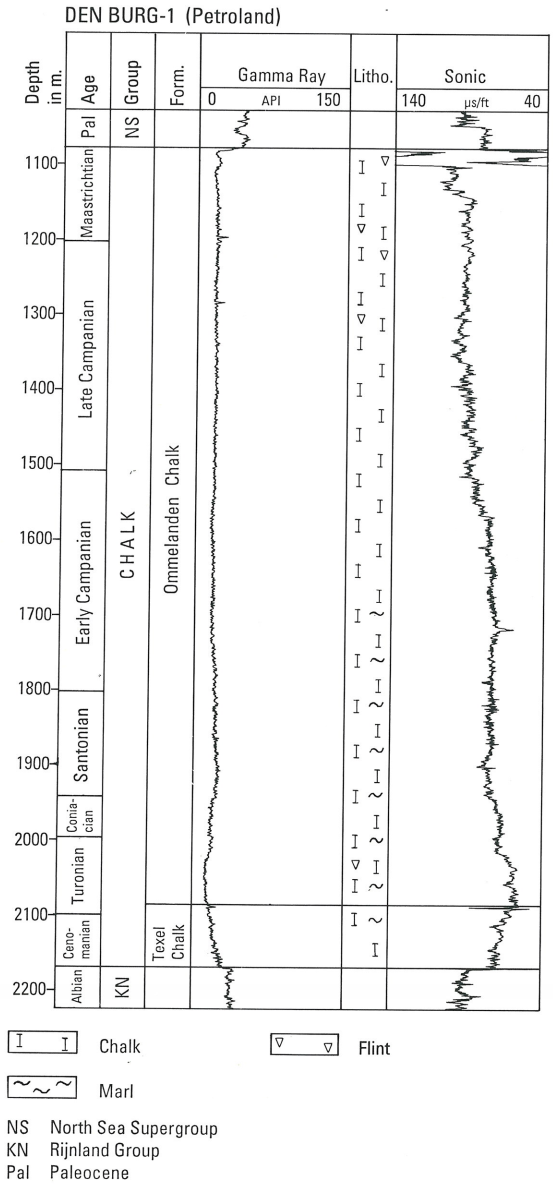
9 Chalk Group

9.1 Stratigraphy

The Chalk Group is composed of a succession of well cemented, light coloured fine-grained chalks and marly limestones. A prominent phenomenon is that calcareous skeletons of planktonic and benthonic organisms are the main constituents of the Chalk Group whilst a very small amount of terrigenous material is present (NAM & RGD, 1980).

The Chalk Group is subdivided into the Texel and Ommelanden Chalk Formations. The boundary between these two formations has been drawn at the top of the Plenus Marl, a black clay-rich marl layer, belonging to the Texel Chalk. The lower boundary of the group is placed at the base of the limestone succession which lies practically conformably on the marls of the Rijnland Group. The Chalk Group is overlain unconformably by the clastic sediments of the North Sea Super Group.

Figure 9.1. Composition of the Chalk Group in the Den Burg-1 well. The interpretation of the lithology has been based on gamma-ray log and sonic log readings. The age of the deposits has been obtained from RGD (1986e, 1991a).



The composition of the group is illustrated from the Den Burg-1 well (fig. 9.1) and a north-south correlation section (fig. 9.2).

As a consequence of inversion and erosion during the Upper Cretaceous, the Chalk Group is absent in the Central Netherlands Basin. The base of the formation is located at a depth of 1000 m on the northern flank of this basin to over 2500 m in the northwest (Map 13). The thickness of the group in the Vlieland Basin is at a minimum, as a result of inversion, and the greatest in the northwest part of the map sheet area, where it exceeds 1400 m (Map 14). The base of the Chalk Group within the map sheet area has a Cenomanian age; the top of the group is Maastrichtian in the north, becoming older towards the south as a result of erosion (fig. 9.2).

9.1.1 Texel Chalk Formation

The Texel Chalk Formation consists of marly limestone, which upwardly changes gradually into a light-grey chalk. The increase in the carbonate content is clearly manifested by well logging. The top of the formation is marked by the Plenus Marl which is a 1 to 2 m thick clay-rich black marl layer, with a regional, widespread extent and is characterised by a striking peak on the logs (fig. 9.1). Log correlation indicates the apparent presence of a slight unconformity immediately below this marl layer.

Within the map sheet area the thickness of the formation increases southwards from 70 m in the Vlieland Basin to 200 m on the northern margin of the Central Netherlands Basin (fig. 9.2), following the trend of the underlying Holland Formation (fig. 8.3).

The Texel Chalk Formation lies conformably on the Holland Formation; the abrupt transition on well logs indicates the presence of a hiatus between the above-mentioned formations in some places, but this has not however been demonstrated by biostratigraphic studies. Throughout most of the distribution area of the formation, which is of Cenomanian and earliest Turonian age (Herngreen et al., in prep.), it is overlain conformably by the Ommelanden Chalk Formation except for a strip to the north of the Central Netherlands Basin (Maps 13 & 14) where it is overlain unconformably by the North Sea Super Group.

9.1.2 Ommelanden Chalk Formation

The Ommelanden Chalk Formation consists of a white to light-grey chalk, chalky limestone and marly chalk with a few marl intercalations. In addition, the strongly peaked acoustic log pattern (fig. 9.1 & 9.2) indicates the occurrences of horizons of flint concretions, parallel to the bedding, immediately above the Texel Chalk and at the top of the formation. Cores and acoustic logs show the older deposits of the group to be harder than the younger deposits.

The monotonous lithological character of the section makes a mappable subdivision of the formation extremely difficult. On a local scale, however, a subdivision of the northern Netherlands proved to be feasible on a basis of well logs and seismics (RGD, 1988a; Geological Survey of The Netherlands, 1991b) which, however, revealed discrepancies with biostratigraphical dating (RGD, 1989c). Only the base of the Campanian can be indicated with any degree of certainty in the adjacent map sheet areas (Geological Survey of The Netherlands, 1991b). Since detailed biostratigraphical information on only four wells is available within the map sheet area (Den Burg-1, De Cocksdorp-1, Zuidwal-2, Slootdorp-1; RGD, 1968, 1975b, 1986e, 1987a, 1988b, 1990a, 1991a), the correlations made (fig. 9.2) may be subject to slight modification.

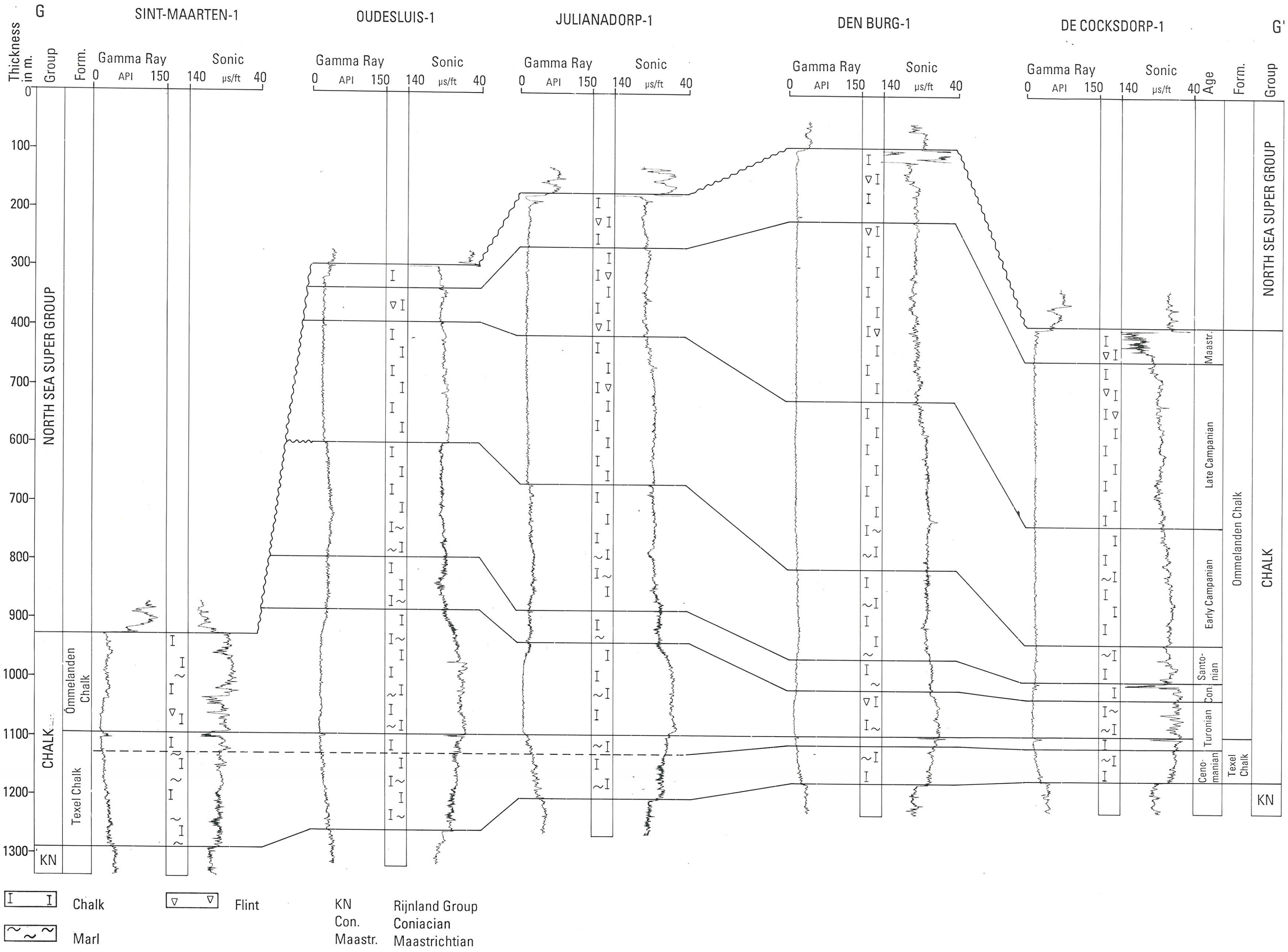


Figure 9.2 Stratigraphic section GG' of the Chalk Group. The reference level is the Plenus Marl. The correlations have been based on gamma-ray log (in API), sonic log (in µs/ft) readings and palaeontological datings. The progressive thickness of the bottommost part of the group towards the Central Netherlands Basin is notable; details of this can be found in the text.

The Ommelanden Chalk Formation rests conformably on the Texel Chalk Formation and is unconformably overlain by the North Sea Super Group. The erosive incision in the formation is clearly visible towards the south in figure 9.2. The hiatus between the Ommelanden Chalk Formation and the overlying group is the smallest in the north and northwest of the map sheet area; southwards the North Sea Super Group is found to rest on progressively older depositions of the formation (Map 19, section 1). Within the formation a few hiatuses and unconformities occur which are of particular significance in inverted areas (fig. 11.9).

In contrast to the underlying formation the greatest thickness, approximately 1300 m, of the Ommelanden Chalk Formation within the map sheet area is observed in the northwestern part. From there, the thickness decreases northeastwards to less than 100 m, and southwestwards to the limit of extent. A conspicuous thinning occurs in the central part of the map sheet area (Map 14). This structure, with a NW-SE oriented fold axis, will from now on be referred to as the Slootdorp - Middenmeer anticline.

From seismic information and the log correlation (fig. 9.2), the oldest deposits of the formation (Turonian-Santonian) would appear to become gradually thicker in a southerly direction. This part of the formation still follows the thickness tendency of the Texel Chalk Formation and the Holland Formation. The most extreme changes in thickness occur mainly in the Late Campanian (fig. 9.2), where the thickness increases from a few tens of metres in the Vlieland Basin to over 600 m in the northwest of the map sheet area, but elsewhere the thickness is dependent on the depth of erosion prior to deposition of the North Sea Super Group. In the greater part of the area of extent, Campanian deposits lie at the top of the formation. Only in a zone to the north of the Central Netherlands Basin are there any older deposits overlain unconformably by the North Sea Super Group, as a consequence of the increasing uplift. The youngest deposits, of a Maastrichtian age, only occur in the north and northwest and are a maximum of 100 m thick. It is striking that in the Vlieland Basin sediments of all stages are present within the Ommelanden Chalk, in spite of their thin succession (Geological Survey of The Netherlands, 1991a, b).

Within the formation, unconformities occur around inversion structures. These unconformities cannot always be precisely determined due to the lack of detailed biostratigraphical information, but would appear to occur in the Santonian and Campanian. An indication for this might be the thinning of older sediments (Turonian, Coniacian, Santonian) eastwards from the northwest. In the northwest (Den Burg-1) the Campanian deposits rest on 400 m of these older sediments, whereas in the Slootdorp-1 well this is only 140 m (RGD, 1975b). Seismically, these unconformities can be observed near the Vlieland Basin and the Slootdorp - Middenmeer anticline (fig. 11.9). Moreover, to both sides of the basin referred to, onlap structures towards the basin can be observed (Geological Survey of The Netherlands, 1991a, b), which indicate that the inverted basin was again covered by sediment even during deposition of the Chalk Group.

9.2 Sedimentary development and paleogeography.

The sea-level rise, which began during the Late Ryazanian, developed during the Late Cretaceous to become a global phenomenon (Pitman, 1978; Donovan & Jones, 1979). In the vicinity of the map sheet area, the latest 'former' landmasses were already flooded during the Albian and the area lay in the open sea, far away off coast. Flooding, by sea-level rise, of the source areas of clastic sediments caused upwardly a clear decrease in clastic material of the Holland Formation and the Texel Chalk Formation.

This high stand lasted for the entire Late Cretaceous, and during the Campanian reached 300 m above the present level (Haq et al., 1987), to be followed by a slight drop. The thickness development of the Texel Chalk and the bottommost part of the Ommelanden Chalk Formation are evidence of a progressive, greater subsidence of the Central Netherlands Basin, in which primary fault movements were no longer a factor.

The Chalk Group is built up of bioclastic components. The organisms are indicative of relatively cold water and pelagic depositional conditions. In the earliest Turonian the carbonate sedimentation was interrupted regionally, in conjunction with which there is a minimal unconformity present in the sediments. The Plenus Marl Member is presumed to have been laid down in a basin with euxinic conditions near the bottom, caused by a lack of vertical circulation in the water column (Ziegler, 1990).

During the deposition of the uppermost part of the Ommelanden Chalk Formation, mainly during the Campanian, the deposition was influenced by the tectonic inversion of the Mesozoic basins. The inversion of the Central Netherlands Basin was the most prominent within the map sheet area, with all the deposits of the Chalk Group being eroded. In the Vlieland Basin sedimentation was repeatedly interrupted, resulting in the deposition of a condensed sequence. As a consequence of the inversion the greatest subsidence took place in the region of the former Texel-IJsselmeer High and in the northwest of the map sheet area, where a prolongation of a marginal trough, the only one within the map sheet area, was formed to the north of the Broad Fourteens Basin. Another manifestation of the inversion is the formation of the Middenmeer - Slootdorp anticline during the deposition of the Ommelanden Chalk Formation. The development of this anticline is related to the inversion of a small halfgraben with a thickening of the Rijnland Group. Inversion movements at the end of the Cretaceous were only influential in the Central Netherlands Basin; the Vlieland Basin showed scarcely any further uplift.

The erosion linked to the inversion of the basins resulted in redeposition of the eroded bioclastic sediments. This resedimentation took place mainly in the area of subsidence to either side of the former basins. In the map sheet area this is to the south of the Vlieland Basin and in the northwest.

9.3 Petrophysical evaluation.

On the Dutch mainland, sustainable gas production, from the Chalk Formation occurs in only one place, namely the Harlingen gas field discovered in 1964, just within the limits of the map sheet area in the extreme northeast. The gas is exploited from the uppermost part of the Ommelanden Chalk Formation, of a Campanian to Early Maastrichtian age. Van den Bosch (1983) gives the following reservoir parameters for the field: the porosity consists on the one hand of matrix porosity (up to a maximum of 38% of the total rock volume) and on the other hand of fault porosity, caused by solution along joints (5% of the rock volume). The average porosity amounts to approximately 29%. Permeability ranges from 8 mD at the top to 0.7 mD at the bottom of the reservoir, with an average of 1.5 mD. The permeability is low in comparison with the porosity, which can be accounted for by the poor amount of interconnected pores.

Chalk Group reservoirs occupy a significant place amongst carbonate reservoirs. In contrast to reservoirs such as the Platy Dolomite for example, diagenetic changes in the Chalk Group seldom occur. As the bioclastic constituent parts are of stable low magnesium calcite, the reservoir parameters are largely determined by compaction (Hancock, 1984; Hancock & Scholle, 1975). Most other carbonates have aragonite as a compound, which becomes unstable during burial.

10 North Sea Super Group

10.1 Stratigraphy

The North Sea Super Group is mainly composed of clays, with a few sandy intercalations. The North Sea Super Group is subdivided into the Lower North Sea, Middle North Sea and Upper North Sea Groups separated by unconformities. In spite of displaying considerable lithological similarities, the units can be clearly differentiated on well logs. Within the map sheet area, the supergroup is laid down largely in a shallow marine environment and rests unconformably on the Chalk Group.

The North Sea Super Group is found throughout the map sheet area. The depth to base of the deposits corresponds with the thickness which ranges from just over 800 m in the southwestern part of the area to over 1400 m in the IJsselmeer area (Map 15). The greater part of the North Sea Super Group comprises deposits of the Upper North Sea Group. The stratification of the North Sea Super Group is illustrated from a north-south oriented section (fig. 10.1). During deposition of the group, not more than a few faults were still active, as is evident from the map pattern (Map 15; fig. 10.2 & 10.3).

The description of the North Sea Super Group deposits is mainly based on reports by the Geological Survey of The Netherlands (1984a; 1984b). The deposits are of both Tertiary and Quaternary age. The Quaternary deposits are only briefly referred to in this explanation; they are discussed in detail in the 'Explanation to the geological maps of The Netherlands 1:50.000'.

10.1.1 Lower North Sea Group

The Lower North Sea Group, which is found throughout the map sheet area, comprises the Landen Formation and the Dongen Formation, together deposited at the time of the Palaeocene and Eocene. The thickness pattern, increasing northwards from less than 100 m to over 400 m (fig. 10.1), is determined mainly by erosion.

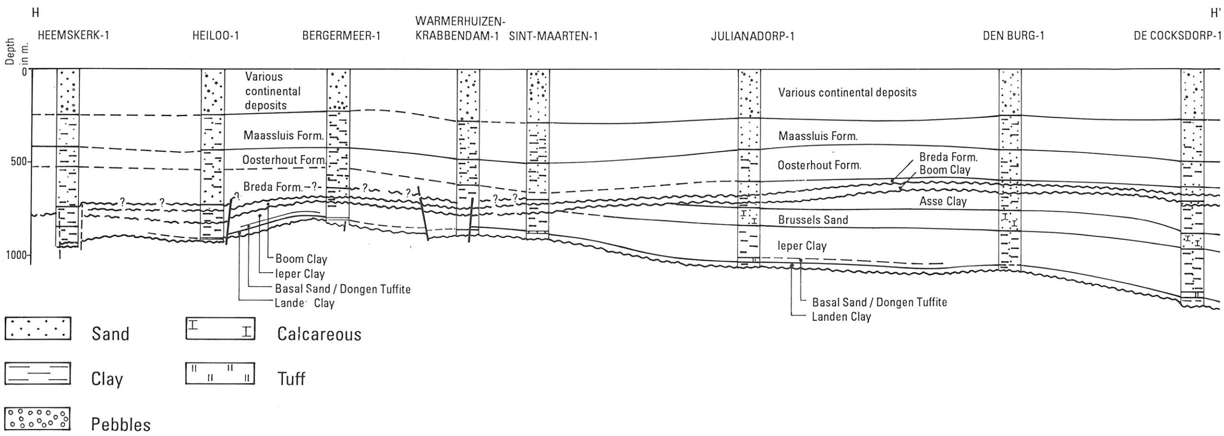


Figure 10.1. Schematic section HH' through the Cenozoic. Through uplift of the Central Netherlands Basin the deposits of the Lower North Sea Group have been greatly reduced in thickness (see Geological Survey of The Netherlands, 1984a). The location of the section is shown in figure 10.3.

Throughout the map sheet area the *Landen Formation* is represented by the Landen Clay Member comprising glauconite, mica and pyrite. A few metres of sand occur in places to the north and east on the base of the formation. Indurated horizons, cemented with calcite, are also found in the formation. The formation increases in thickness from 10 to 30 m in the western part to 50 m in the northern and eastern part and is of Paleocene age.

Within the *Dongen Formation,* the Dongen Tuffite, Ieper Clay, Brussels Marl and Asse Clay Members are differentiated. Owing to erosion, the formation decreases in thickness southwards and westwards from 350 to less than 100 m in places (fig. 10.1) and is of Eocene age.

The *Basal Dongen Tuffite* is encountered throughout the area at thicknesses from 5 to 15 m and consists of alternating glauconite-bearing clays with tephra layers.

In the *Ieper Clay* a rough bipartition can be made. The bottommost part of the formation consists of a brownish grey, non-calcareous clay and comprises claystone clasts, pyrite, shell debris and coal fragments. The uppermost part is greenish grey, somewhat sandy in places and contains glauconite and pyrite. Bioturbation is also observed. The formation occurs throughout the map sheet area, although it is only complete in the north and east where the thickness increases northwards from 175 to 350 m. Erosion is responsible for the reduction in thickness in some places to less than 75 m in the west and southwest of the map sheet area.

The *Brussels Marl* is found in the northern and eastern parts of the map sheet area, with the greatest thickness, exceeding 110 m, found in the east-northeast of the map sheet area. The unit is built up of glauconite-bearing fine-sand clays and marls, with beds of calcarenite, argillaceous sandstone and Nummulites. The carbonate and glauconite content increases upwards.

The *Asse Clay* has roughly the same extent as the Brussels Marl. The thickness of the formation is determined by erosion, and the greatest thickness, approximately 150 m, is observed in the north east of the map sheet area. The Asse Clay is built up of a plastic, grey-green to blue-grey clay and contains glauconite and pyrite.

10.1.2 Middle North Sea Group

The Middle North Sea Group, Oligocene in age, rests unconformably on the Lower North Sea Group and is overlain, also unconformably, by the Upper North Sea Group. Within this group the Rupel Formation and the Veldhoven Formation can be distinguished. The thickness of the group increases eastwards from less than 50 m in the western part of the map sheet area to over 125 m in the central part of the IJsselmeer. Outside these two areas the thickness ranges between 50 and 100 m (fig. 10.1).

The *Rupel Formation* consists of the Boom Clay Member practically throughout the area. Only locally in the eastern part, does the Berg Sand Member occur. The thickness of the formation is a maximum of 125 m in the extreme east of the map sheet area, and ranges from 50 to 75 m outside that area.

The *Berg Sand* is a dark-grey coloured, fine sand which occasionally also contains pyrite and glauconite. The member is approximately 5 m thick.

The *Boom Clay* consists of a fine-textured, brown to greenish grey fat clay. This unit contains pyrite and glauconite and is characterised by beds of septarian nodules (calcareous concretions).

Where the formation is overlain by the Veldhoven Formation, the uppermost part contains thin layers of sand and only a small amount of glauconite.

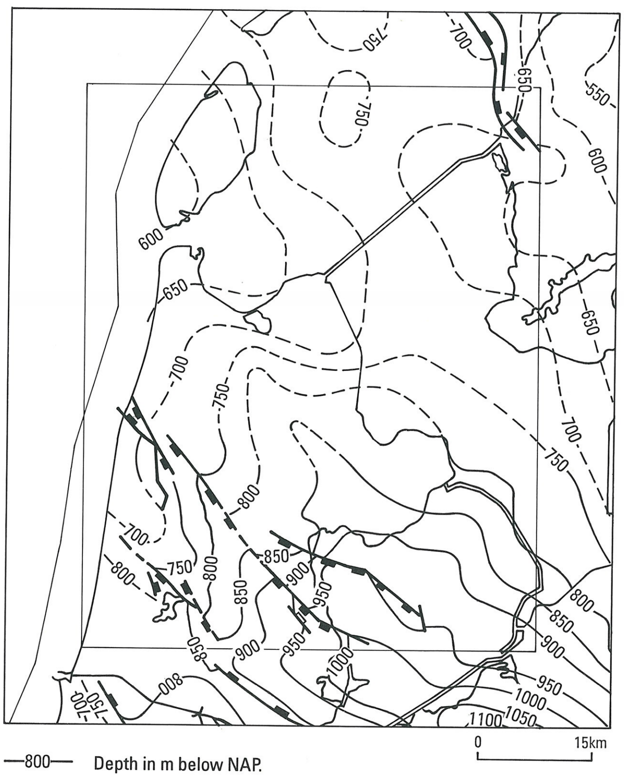
The *Veldhoven Formation* includes a green to brown coloured silty to sandy clay with a varying percentage of glauconite. Only in the southeastern part of the map sheet area did this formation escape erosion. The thickness is a maximum of 50 m.

10.1.3 Upper North Sea Group

The Upper North Sea Group rests unconformably on the Middle North Sea Group and is subdivided into the Breda and Oosterhout Formations, both of Late Tertiary age, as well as the Maassluis Formation and younger formations of a Quaternary age. The thickness of the group ranges from 600 m in the northwest to over 1000 m in the southeast. The depth of the base of this group is shown in figure 10.2.

The *Breda Formation,* Middle and Late Miocene, consists of a bottommost section of very glauconite-rich, green-grey to green-black clays, with a few sandy intercalations. Mica and plant remains are also found. The thickness of this clay-rich section may exceed 300 m in the southeast of the map sheet area. The uppermost part of the formation is predominantly composed of olive-green to green-grey sand, with thin layers of silt and clay. This sequence also contains glauconite,

Figure 10.2. Depth of the base of the Breda Formation (base Middle Miocene). The depth figures are in metres below Mean Sea Level. The base of this formation reaches a maximum depth in the Zuiderzee Low, in the southeast of the map sheet area.



—800— Depth in m below NAP.

--700-- uncertain

Normal fault

uncertain

mica and shell fragments. In the sandy deposits a coarsening-upwards sequence can be distinguished. As in the topmost part, the greatest thickness is found in the southeastern part of the map sheet area, reaching 250 m.

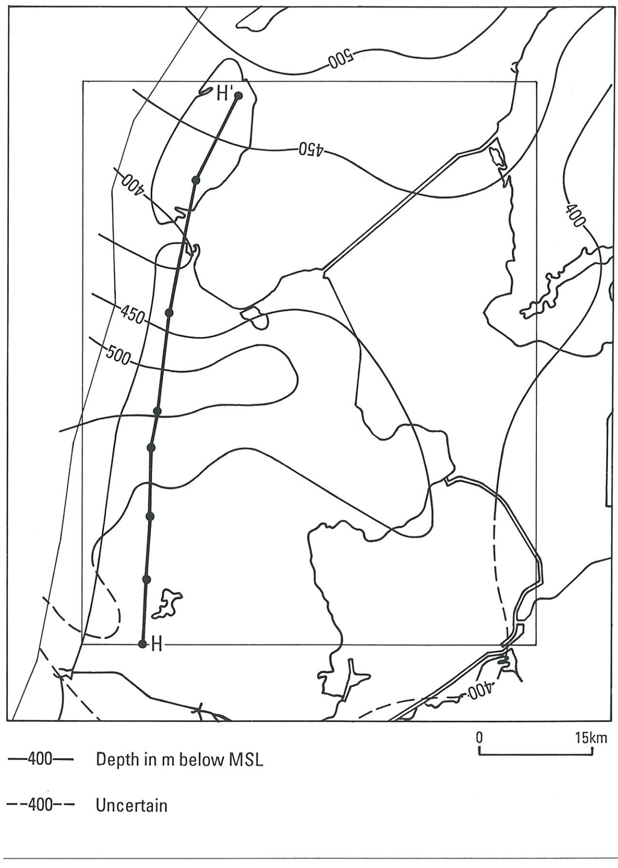
The total thickness of the formation ranges from 50 m in the northwest of the map sheet area to over 550 m in the southeast. These thickness discrepancies can be attributed to a greater basin subsidence in the southeast.

The *Oosterhout Formation,* Pliocene in age, contains light to dark (green-)grey argillaceous sand and sandy clays. In the most northerly part of the province of Noord-Holland the formation displays layers of shell debris at the top. The formation shows a primary decrease in thickness eastwards, from approximately 200 m in the western part of the map sheet area to around 50 m in the eastern part.

The *Maassluis Formation,* Early Pleistocene in age, consists of alternating sand and clay layers containing shell debris. In the eastern part of the map sheet area, coarser sands, rich in plant and wood remains, are found at the top. The formation thickness ranges from 150 to 200 m. The depth to the base of this formation is shown in Figure 10.3. The contour pattern also reflects the thickness of the Quaternary deposits.

The other formations of Quaternary age are composed of clays, sands and gravel.

Figure 10.3. Depth of the base of the Maassluis Formation (base Quaternary). The depth figures are in metres under Mean Sea Level. This map also serves as thickness map of the Quaternary deposits. HH' is the location of the section shown in figure 10.1.



10.2 Sedimentary development and paleogeography

During deposition of the North Sea Super Group the map sheet area formed part of the North Sea Basin. The deposition of the super group was strongly determined by eustatic sea-level changes. Periods of high stand were characterised by the sedimentation of clays predominantly, whereas periods of low stand were characterised either by deposition of sands or sandy clays, or by no deposition at all, or by erosion. A number of tectonic movements during the Tertiary combined with periods of low sea level resulted in uplift and erosion of the deposits (fig. 10.1). Furthermore, differentiated basin subsidence contributed to discrepancies in the thickness of the deposits. The sea-level changes are based on the curve of Haq et al. (1987).

The sediments of the Lower North Sea Group were laid down during a period of relatively high sea level, which was only interrupted by a brief drop during deposition of the Brussels Marl. Differentiated uplift of the area in combination with a sea-level drop brought an end to sedimentation during the Middle or Late Eocene and resulted in erosion.

The Middle North Sea Group shows a rapid sea-level rise, with high stand during deposition of the Rupel Formation. The Veldhoven Formation was laid down during a regressive phase, following which, in combination with renewed uplift of the area, the deposition of the Middle North Sea Group came to an end.

During the deposition of the Upper North Sea Group the sea level gradually dropped; this is reflected in an outbuilding of the land area during the Quaternary. This drop was of a clearly fluctuating nature, indicated by the alternating sands and clays in the sediments of the Breda, Oosterhout and Maassluis Formations. After deposition of the latter formation, continental conditions began to prevail.

11 Geological History

11.1 Introduction

This chapter outlines the geological history of the map sheet area from the Late Carboniferous to the Quaternary. Available data is insufficient to obtain a picture of the history of the area prior to the Late Carboniferous. The Quaternary is referred to in the explanation to the Geological Map of The Netherlands 1:50.000 and Zagwijn (1989).

The geological history of the map sheet area is divisible into a number of periods which pass gradually one into another. They can be distinguished and are characterised by tectonic-induced features.

1. Late Carboniferous and earliest Permian. The Variscan Orogeny, whereby the structural framework of the map sheet area was formed.
2. Early Permian - Early Jurassic. A mainly regional subsidence, in response to the Variscan Orogeny.
3. Middle Jurassic - Early Cretaceous. Kimmerian extensional tectonic phases, whereby strong differential movements occurred.
4. Late Cretaceous - Early Tertiary. Reversal of the forces and inversion of the Mesozoic basins.
5. Middle Tertiary - Quaternary. Gradual subsidence, subsequently becoming stronger, as a component of the North Sea Basin.

11.2 Geological history and development.

11.2.1 Late Carboniferous

The formation of the Variscan mountain chain to the south of what is now The Netherlands had a clear influence on the geological history of the map sheet area despite the great distance. The Variscan Orogeny took place during the Late Carboniferous and the earliest Permian and has three phases of deformation: the Sudetic, Asturian and Saalian. The deformation front progressed gradually northwards during these phases. The orogeny marks the ending of the Proto-Tethys and the incipient formation of the supercontinent Pangaea.

The Sudetic phase, at the start of the Late Carboniferous, reflects the collision between Gondwana in the south and Laurussia in the north. The north-south compression led to the formation of an east-west trending mountain chain which extended right across Europe. To the north of this mountain chain, as a result of isostatic compensation a foreland basin was formed in which erosion products from the mountains were deposited as a thick sediment succession under paralic conditions. The map sheet area covers part of the basin interior. During the Westphalian A, predominantly lacustrine clays were laid down, alternating with deltaic and fluvial sands and peat. Episodically, brief transgressions flooded large areas of the basin owing to the very flat relief. These transgressions are the expressions of glacio-eustatic sea-level rises (Ziegler, 1990). During the latest Westphalian A and the Westphalian B the fluvial influence on the sedimentation became greater and there was widespread peat formation in marshes between the rivers. This was more extensive in the southern part of the map sheet area than in the north and east, and points to slightly greater subsidence in the south.

The Asturian phase of deformation initiated the northward migration of the Variscan orogenic front at the end of the Westphalian (Lorentz & Nicholls, 1976), which caused the deposits in the foreland basin to become strongly folded and emplaced northwards by slightly inclined overthrust planes. In the map sheet area, the sediment succession was transformed into open folds as a result of block movements in the subsurface (Read & Watson, 1975; Ziegler, 1988) and the northern part of the map sheet area was presumably uplifted during this phase (Bless et al., 1977). Sedimentation concentrated increasingly in basins such as the Roer Valley Graben, Off Holland Low and the Ems Low.

The Saalian phase of deformation during the Stephanian and the earliest Permian is the last phase of the Variscan Orogeny. The north-south compressional stressfield during this phase were followed by an east-west extension tendency. To the north of the Variscan mountain chain, NW-SE trending, mainly dextral, transverse fault systems developed. Whereas this was accompanied by volcanic activity and differential subsidence elsewhere in the foreland basin (Chadwick, 1986; Lorentz & Nicholls, 1976; Ziegler, 1990), in the map sheet area transtensional movements led to uplifts, tilting and erosion.

Within the map sheet area, the Asturian and in particular the Saalian phase had major consequences. During the latter phase, the NW-SE tendency developed which was to have such a great effect on subsequent geological history. The subcrop map of the Saalian unconformity (fig. 2.3) shows that in the north and middle of the map sheet area, the erosion was the most deeply incised, down into the Westphalian A. The uplift and subsidence areas during the Carboniferous are seen as precursors of structural elements which are presumed to have also manifested themselves during the Permian, Triassic and Jurassic. Although the orientation and boundaries of these structural elements differed in the various geological periods, they were nevertheless bounded by more or less the same fault systems.

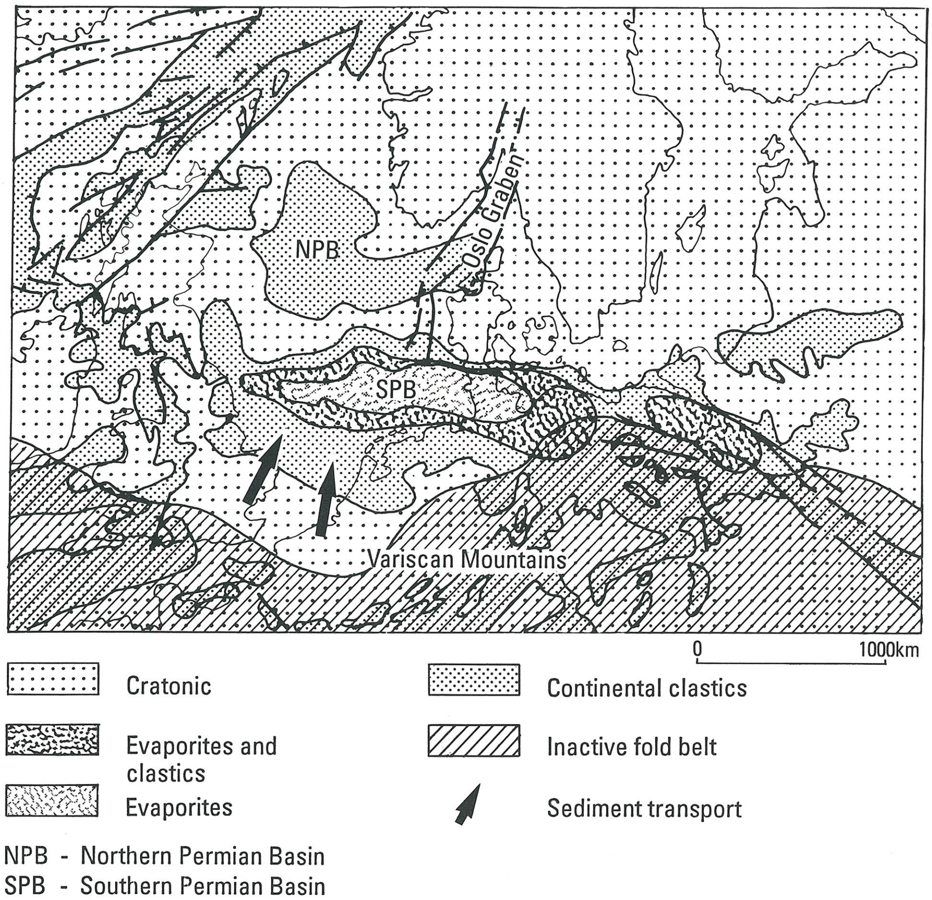


Figure 11.1. Palaeogeographic map with the location of the Southern Permian Basin and the Variscan mountains at the time of the Early Permian. (From Ziegler, 1982).

11.2.2 Permian

The Saalian phase of the Variscan Orogeny ultimately resulted, during the Early Permian, in an exceptionally extensive landmass. The Permian was, tectonically speaking, a relatively calm period characterised by minimum extension in the map sheet area. The cause of the change in the tectonic stress regime in comparison with the Carboniferous must be sought in the processes in the asthenosphere under the super continent Pangaea (Ziegler, 1990).

Subsequent cooling of the lithosphere caused subsidence, especially in areas of Early Permian volcanic activity. This led to the formation of an extensive intracratonic basin which is known as the Permo-Triassic Basin. The basin was separated by the Mid North Sea - Ringkøbing-Fyn High into a Northern and a Southern Permian Basin (fig. 11.1). During the Permian and Triassic, the area which was uplifted during the ultimate phase of the Variscan Orogeny to the south of The Netherlands formed a source area for clastic sediments.

The large-scale cooling-induced subsidence with a slight east-west oriented superimposed extension, resulted in a number of north-south oriented, fault-bounded depressions perpendicular to the basin axis, such as the Off Holland Low and the Ems Trough in which drainage from the Variscan hinterland lying further to the south accumulated. (fig. 11.1). The map sheet area was situated on the eastern margin of the Off Holland Low. Beyond these depressions, in response to the extensive forces, the reactivated northwest-southeast trending Variscan fault systems which influenced the sedimentation during the Permian and the Triassic are of particular importance in the map sheet area. The Off Holland Low had a southeastern prolongation, bordered by the Zandvoort Ridge to the south of the map sheet area and the Texel-IJsselmeer High to its northeast (fig. 3.1), which is considered as the incipient Central Netherlands Basin.

After the Saalian tectonic phase, incipient Early Permian sedimentation is characterised by fluvial deposition in the central part of the basin, to the north of the present-day Netherlands mainland. Owing to the decrease in tectonic instability, differential subsidence changed to regional subsidence and the sedimentation area gradually extended over the highs in the basin and the basin flanks. A fluvial system developed in the map sheet area, draining to the north into the central part of the basin via the Off Holland Low, and resulting in a playa, where fine-grained sediments and evaporites were deposited (Geological Survey of The Netherlands, 1991a). The cyclical sea-level rise caused the playa to extend up to the Texel-IJsselmeer High. The differences in relief of the basin interior became slighter and extensive sand flats formed along the borders of the playa, where the sands accumulated in the form of dunes, through the effect of the prevailing trade winds. The map sheet area formed part of a widespread area of sand dunes (fig. 11.2). The river systems occurred only in the Off Holland Low lying further to the west. Aeolian sedimentation continued up to the end of the Early Permian in the map sheet area. Owing to the slow rate of sedimentation compared with basin subsidence, the Permo-Triassic Basin sank below sea level by the end of the Early Permian (Glennie, 1986).

An important change occurred at the beginning of the Late Permian. Rifting in the North Atlantic/Arctic area, together with eustatic sea-level rises, initiated the development of an open connection between the Barentsz Sea in the north and the Permo-Triassic Basin. As the basin had subsided below sea level in the Early Permian, the transgression in the basin was rapid, indicated principally by reworked sediments at the top of the Upper Rotliegend Group (Glennie & Buller, 1983). Basin subsidence was even further intensified by the weight of the large water masses and the thick rock salt successions accumulated over a short period of time. Although synsedimentary faults had a clear influence on the facies distribution in the map sheet area (fig. 4.2), the limited extension forces, responsible for the reactivation of fault systems, decreased during the Late Permian. The Late Permian sediments were deposited under the influence of glacio-eustatic sea-level fluctuations (Ziegler, 1990), resulting in a number of large transgressions in the basin.

Pronounced differences in basin subsidence caused great variations in facies within the map sheet area (fig. 4.2). In the northeast, the increase in thickness (Map 4) points to stronger synsedimentary fault movements than in the Early Permian. Thick successions of rock salt were deposited (Map 4 & fig. 4.8).

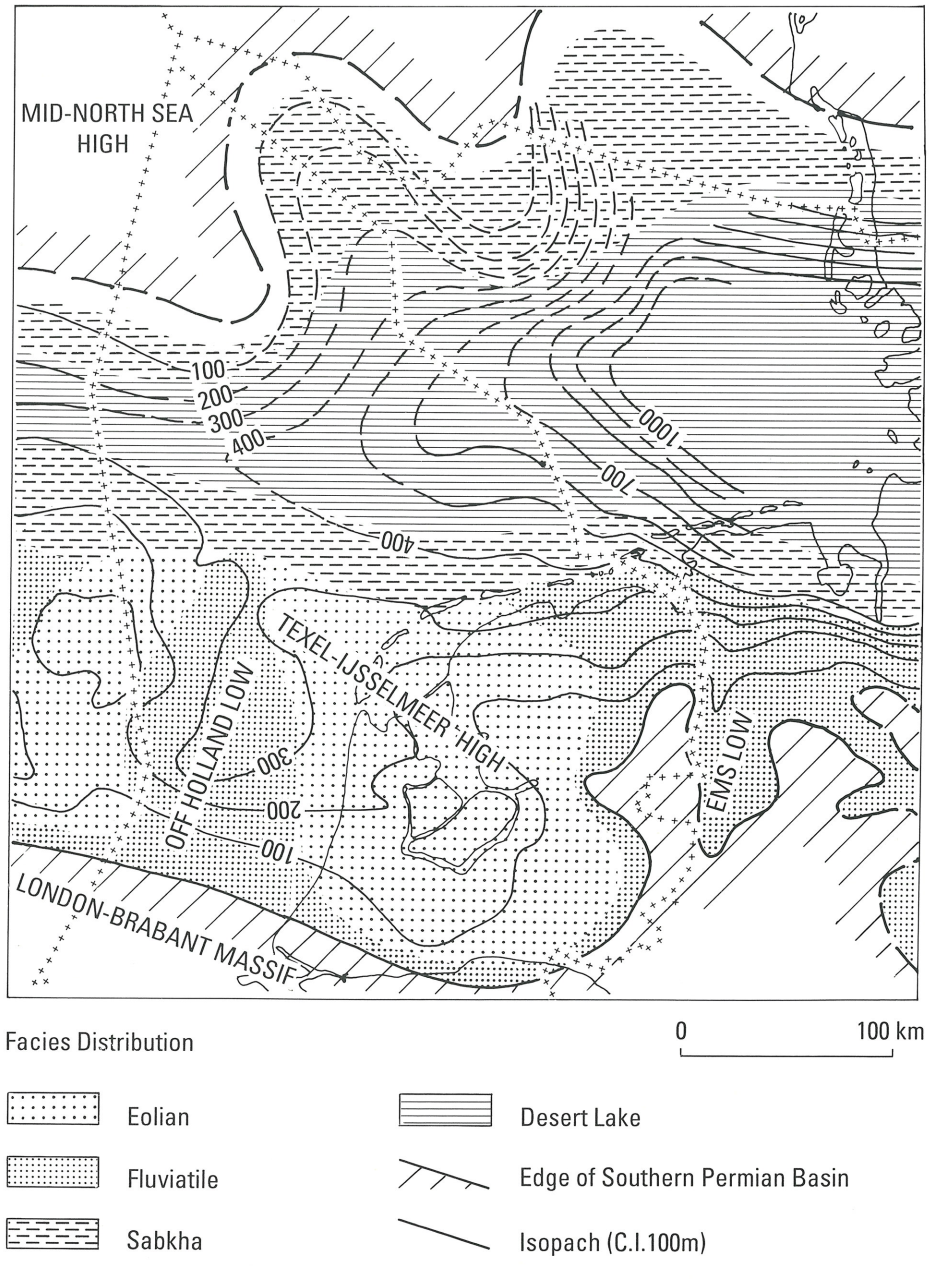


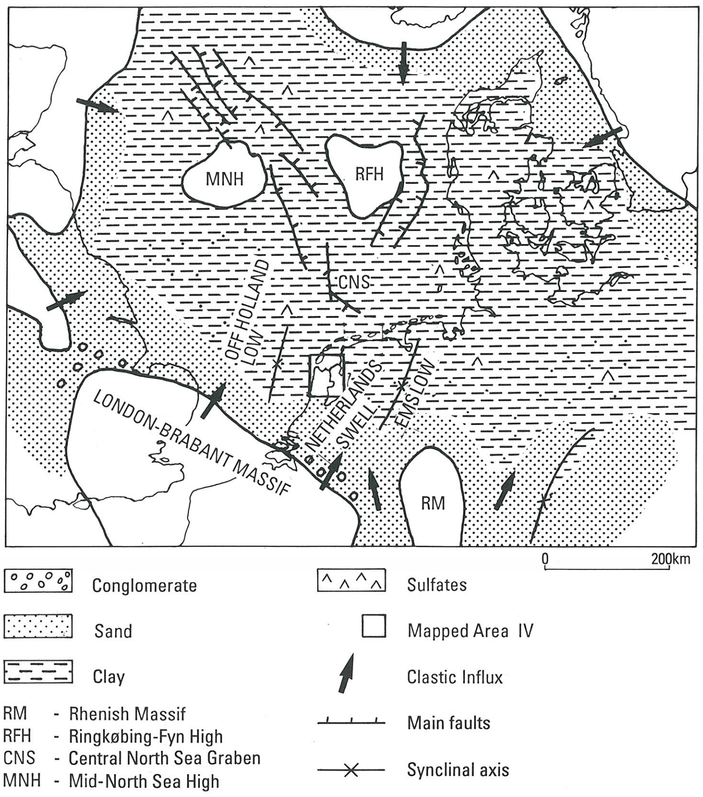
Figure 11.2. Schematic isopachs of the Upper Rotliegend Group and the schematic distribution of the various facies. The thicknesses are in metres. From Van Wijhe et al. (1980).

The Texel-IJsselmeer High subsided to a lesser extent and sedimentation only took place during episodes of relative high stand, mainly as carbonates and sulphates (fig. 4.7). During periods of salt precipitation in the basin, the high formed an effective barrier separating the Central Netherlands Basin from the main basin and became exposed to meteoric influences, which underwent leaching and brecciation.

The subsidence of the area to the south of the Texel-IJsselmeer High was concentrated in the Central Netherlands Basin which enlarged with respect to the Early Permian and now formed a connection between the Off Holland Low and the Ems Low (compare fig. 3.1 and Map 3). During the Late Permian, the Central Netherlands Basin was transformed into a marginal basin with lagoonal depositional conditions and cut off from the main basin at low stand, which resulted in deposition of rock salt and potassium-magnesium salts. The southern margin of the Central Netherlands Basin exhibits a sabkha.

The first three transgressions during the Late Permian resulted in normal marine conditions. The third transgression was the most pronounced (Plomp & Geluk, 1988) and flooded over the remaining highs in the vicinity of the map sheet area. Subsequently, the marine influence diminished and the last remaining relief of the Permo-Triassic Basin was filled up. At the end of the Permian and in the earliest Triassic, tectonic elements such as the Texel-IJsselmeer High and the Central Netherlands Basin were no longer effective. At this time the area was characterised by highly uniform subsidence and coeval development of a continental sedimentary environment.

Figure 11.3. Palaeogeographic map of the Permo-Triassic Basin in the Early Triassic. The map sheet area is situated in the southern part of the basin. Clastic sediments came in from the south and were derived from the London-Brabant Massif and areas more to the south (from Ziegler, 1982).



11.2.3 Triassic

The Triassic is characterised by gradually increasing tectonic instability with intensification of the extension leading to the development of a multidirectional rift system in North West Europe (Ziegler, 1990). During the Triassic the way was paved for the breaking up of Pangaea during the Jurassic. Frequent sea-level fluctuations occurred, as well as a eustatic sea-level rise during the latest Early and Middle Triassic. Rifting caused the breaking up of the old highs and a connection developed between the Permo-Triassic Basin and the Tethys (Ziegler, 1990). Transgressions entered the basin initially from the east, but later from a southerly direction as well.

The subsidence pattern during the Triassic was influenced by extensional forces, which accentuated the N-S trending structural elements such as the Off Holland Low and the Ems Low. Between these two subsidence areas the Netherlands Swell developed as a high with a NNE-SSW trend (fig. 11.4). The map sheet area is located to the west of this swell. Movements of the Netherlands Swell coincided with older structural units such as the Texel-IJsselmeer High.

During the Scythian, the map sheet area was situated within a vast flood plain which had originated after the extensive levelling of the topography at the end of the Permian. The development of the Lower Triassic deposits over a very wide area indicates highly uniform basin subsidence. There was an influx of clastic material from the south and the sediments were deposited in a lacustrine environment (fig. 11.3) The sediments display a cyclical stratification which can most probably be attributed to variations in precipitation. In connection with this, periodical changes occurred in the quantity of sand transported into the basin and the lake dried up.

During deposition of the Main Buntsandstein Formation, sedimentation concentrated mainly on the Off Holland Low and the Ems Low, while on the Netherlands Swell only a thin more argillaceous succession was deposited. The stratification of the formation was determined by tectonic uplift of the hinterland and variations in the water level of the lake in the Permo-Triassic Basin. During a water-level fall in the lake, braided fluvial systems extended in the map sheet area and laid down sands. During periods of water-level rise, the lake extended southwards and deposition of playa clays and silts occurred. In the sequence on the high, several hiatuses are presumed to have occurred, whereas in the depressions, sedimentation was probably continuous. Erosion, caused by a combination of a drop in the water level in the lake and an epeirogenic uplift, resulted in a regional unconformity during the latest Scythian, which further accentuated the already existing differences in subsidence (Base Solling Unconformity; fig. 11.4).

At the end of the Scythian a new phase in the development of the Permo-Triassic Basin began. An increase in extensional stress reactivated the NW-SE trending Variscan fault systems within the map sheet area and somewhat greater subsidence occurred in the Central Netherlands Basin, which also comprised the southern part of the previously formed Netherlands Swell (compare fig. 5.4 and 5.6). After a eustatic sea-level rise, sedimentation increased, spreading from the Off Holland Low right over the map sheet area. During this process, sands were deposited in the western part, later to be overlain by clays (Solling Member). The latest part of this member also covered the Netherlands Swell. During the Early Anisian, clays and sulphates were deposited in a sabkha environment within the map sheet area and clays and rock salt in the Central Netherlands Basin (Röt Formation).

A new transgression during the Middle Anisian brought normal marine conditions to the map sheet area. This transgression, linked to the decrease in the influx of clastics, resulted in the deposition of the shallow-water carbonates of the Muschelkalk. During the Early Ladinian the Permo-Triassic Basin was again cut off from the sea, resulting in the deposition of rock salt in the Central Netherlands Basin (Middle Muschelkalk Evaporite Member). During the Late Ladinian the influx of clastic sediments again increased, of which deposition of marl and clays in the map sheet area were the consequence.

A regression at the beginning of the Late Triassic (Carnian) brought an end to marine sedimentation in the Permo-Triassic Basin as well as a reversal in the direction of influx of sediment. Whereas during the Permian and the Early Triassic this was mainly from a southerly direction, the uplift of the Fennoscandia High caused sediment transport mainly from the north and east during the Late Triassic (Ziegler, 1990). The map sheet area was at a considerable distance from this uplifted area and the Late Triassic sediments are consequently fine-grained. In and

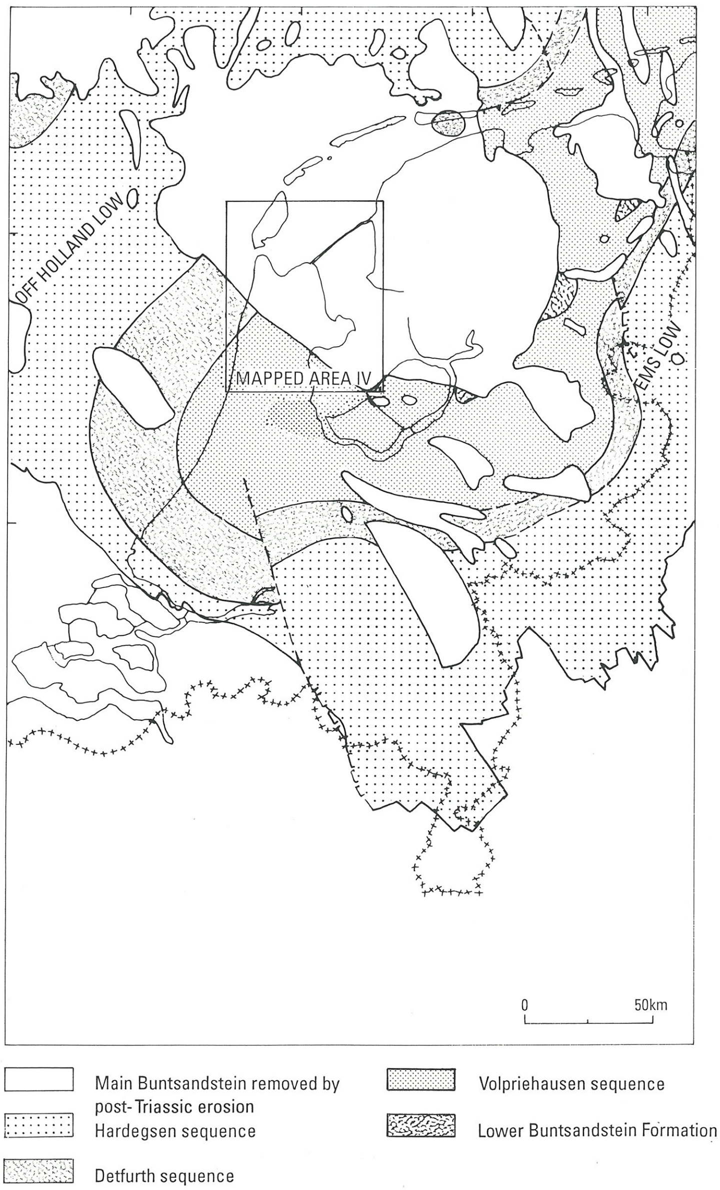


Figure 11.4. Subcrop map of the Base Solling Unconformity indicating the main structural units. The map sheet area lies along the western margin of the Netherlands Swell (from NAM & RGD, 1980).

around the map sheet area, a complex of tidal-flat areas, lagoons and sabkhas was formed, where sulphates as well as fine-grained sediments were deposited. During the Carnian and Norian the increase in intraplate stresses caused uplift and erosion on the basin margins and highs within the basins (Wolburg, 1967, 1969; Ziegler, 1990). This, in combination with a eustatic low stand, resulted in the Early Kimmerian unconformity at the end of the Norian. In the greatest part of the map sheet area the hiatus resulting from the erosion comprises the latest part of the Carnian and the whole of the Norian, but in the southeast of the area, the hiatus also encompasses the whole of the Carnian and part of the Ladinian.

In view of the facies changes proceeding from the Central Netherlands Basin and the Off Holland Low down to the Netherlands Swell, the greatest part of the map sheet area is assumed to have been part of a slowly subsiding area during the Triassic, with less sedimentation than in the aforementioned areas of subsidence. The uniform development of the Triassic around the high indicates that all the Triassic units were deposited throughout the map sheet area, but in places disappeared entirely or partially owing to the later uplift and erosion. Salt movements on a small scale developed in the Central Netherlands Basin during the Triassic, resulting in the formation of salt pillows.

11.2.4 Jurassic

The Jurassic and the earliest Cretaceous together form a tectonically highly active period. In this period, the formation of the Atlantic Ocean was completed as well as the disintegration of the supercontinent Pangaea. In northwestern Europe, the Permo-Triassic Basin ceased to exist in its original form during the Middle Jurassic and, under the influence of extension, basins developed which were separated by highs.

The strong tectonic activity can be subdivided into the Mid-Kimmerian and the Late Kimmerian phases. Within the map sheet area the erosion coincidental with these phases was the slightest in the Central Netherlands Basin. However, the Jurassic deposits are not found beyond this basin, and on the Texel-IJsselmeer High erosion cut deep down into the Carboniferous deposits (Map 16 & 17). The thickness map of the Lower and Middle Jurassic deposits (Map 8) therefore displays mainly the later uplift and erosion and, to a lesser extent, the differences in thickness. For practical reasons, the Kimmerian phases have been related to stratigraphic unconformities, but in reality correspond with more or less continuous tectonic phases (Ziegler, 1990).

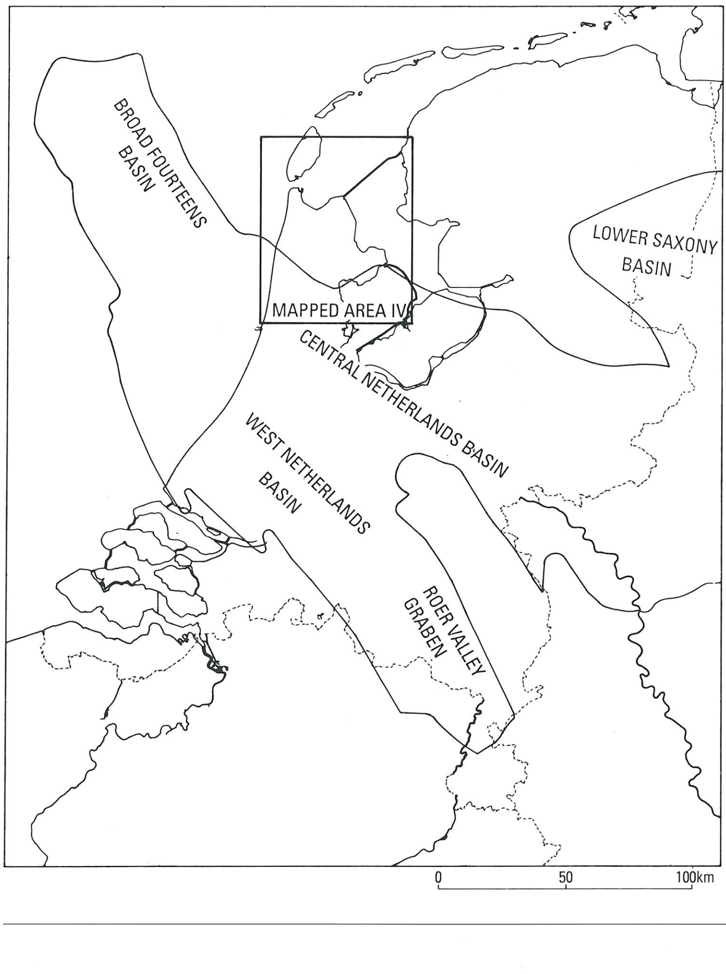
During the Early Jurassic, the Triassic pattern of subsidence progressed, under the influence of regional extension. Actual deposition of the characteristic marine sediments commenced with the transgression during the Middle Rhaetic (latest Triassic) which formed the beginning of a long period of marine sedimentation throughout northwestern Europe (Ziegler, 1990). Although the present areal extent of these Early Jurassic marine sediments is restricted to the various Jurassic basins in and around the map sheet area (fig. 11.5), the striking uniformity in the lithological stratification of these sediments indicates that they have been deposited in a single large marine basin. The predominantly argillaceous character of these sediments provides no grounds for assuming the presence of highs elevated above sea level during the Early Jurassic.

Within the map sheet area, during the Early Jurassic, the greatest subsidence took place in the Central Netherlands Basin. In comparison with the Permian and the Triassic the axis of the basin shifted in a southerly direction during the Jurassic, which is apparent from a comparison of the thickness maps of these periods (Maps 4, 6 & 8). This is presumed to have been partly the consequence of later tectonic phases, during which the northern part of the basin was uplifted more strongly, while the remainder of the map sheet area presumably subsided less strongly. The sediments were deposited in an open marine environment. Several times, anoxic conditions prevailed, apparent from organic-rich clay deposits. A regional anoxic event, presumably related to a (relative) high stand (Haq et al., 1987), led probably only in the basin to the development of the Posidonia Shale, an important oil-source rock at the beginning of the Toarcian.

During the Middle Jurassic, the opening of the central Atlantic Ocean began, accompanied by great regional uplifts (Van Wijhe, 1987a; Ziegler, 1990). The uplift of the North Netherlands High and the Texel-IJsselmeer High both of which extended across the north and east of the map sheet area had a significant effect on it (Geological Survey of The Netherlands, 1991a,b). This tectonic pulse is known as the Mid-Kimmerian phase. Its effect on the area within the map sheet can no longer be precisely determined, as virtually all the Middle Jurassic sediments during the Late Kimmerian phases were removed by erosion.

It may be assumed that the sedimentation in the Central Netherlands Basin continued into the Middle Jurassic. Sediments from the Middle Jurassic have only been identified in wells in the Roer Valley Graben, the West Netherlands Basin and the Broad Fourteens Basin where they consist of alternating carbonates and fine-grained clastic deposits. This combination indicates a low relief in and around these basins, with relatively little influx of sediment from the highs, which could indicate a relatively minor effect of the Mid-Kimmerian phase. At the end of the Middle Jurassic,

Figure 11.5. Basins in the vicinity of the map sheet area at the time of the Early Jurassic.



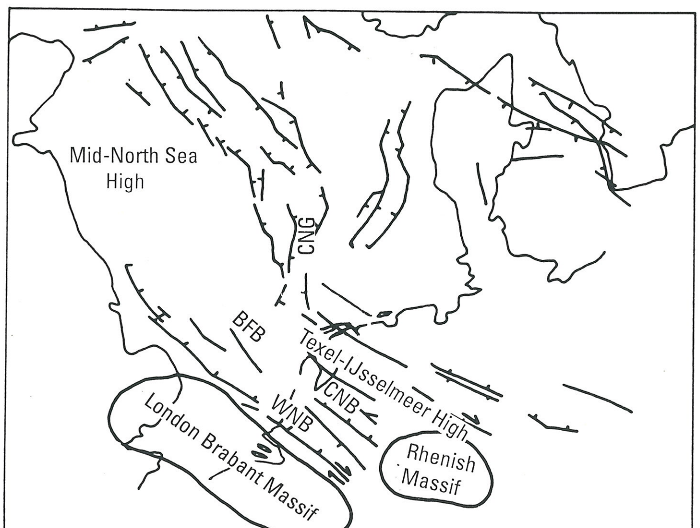
sedimentation ended, owing to the combined effects of a drop in sea level and tectonic uplift. This uplift is interpreted as being the first impulse of the Late Kimmerian phase ('t Hart, 1969; Ziegler, 1990). During the first phase, the North Netherlands High was uplifted, tilted, eroded and broken up into different tectonic elements (Geological Survey of The Netherlands, 1991b).

Two main impulses can be distinguished within the Late Kimmerian phase. The first impulse, the Late Kimmerian I, is related to the hiatus at the base of the Upper Jurassic deposits during the Oxfordian. It was during this impulse that the Vlieland Basin came into being. The second impulse, the Late Kimmerian II during the Early Cretaceous, is related to the unconformity at the base of the Rijnland Group and was expressed in a strong accentuation of the basin configuration.

During the Late Jurassic, the east-west trending extension resulted in the southwards prolongation of the Central North Sea Graben. On the southern extremity of this graben, the stress in the crust was accommodated by dextral divergent strike-slip along NW-SE fault systems (fig. 11.6). This happened on the one hand because the presence of the rigid London-Brabant Massif impeded the southward progradation and on the other hand by the presence of brittle zones in the form of the Variscan fault system. Indications put forward by Harding (1985, 1990) for the occurrence of strike-slip movements in the map sheet area are the en echelon character of faults and the development of changes in thickness, offset and direction of movement along faults (see for example Maps 5 & 6). The current fault configuration indicates left-lateral movements along the faults. The identification of transverse movements in conjunction with the Late Kimmerian phases is, however, hampered by the occurrence of convergent strike-slip movements during the later tectonic phases.

The divergent strike-slip movements led to the occurrence of NW-SE trending halfgrabens, superimposed on the Central Netherlands Basin to the southeast of the map sheet area. From the time of the Kimmeridgian, continental and marine sediments were laid down in these halfgrabens

Figure 11.6. Structural units during the Jurassic. Immediately to the north of The Netherlands the N-S trending rift structure passes into NW-SE trending transtensional strike-slip movements along reactivated Variscan faults (from Ziegler, 1982).



CNB Central Netherlands Basin
WNB West Netherlands Basin
CNG Central North Sea Graben
BFB Broad Fourteens Basin

and the character of these sediments indicates the existence of a connection with the Lower Saxony Basin. Under the influence of extension and local volcanic activity the Vlieland Basin started to develop in the extreme northeast of the map sheet area during the Oxfordian-Kimmeridgian (Herngreen et al., 1991). In the remainder of the map sheet area, uplift and erosion took place, characterised by an increase in intensity of the uplift in a northeasterly direction as far as the Texel-IJsselmeer High.

The Vlieland Basin was filled up by fine-grained erosion products from the surrounding highs, deposited under lacustrine conditions. The Vlieland Basin is separated by the Zuidwal Volcanic Dome into a northerly and a southerly Vlieland Subbasin. Although transgressions from the Central North Sea Graben reached the northern subbasin, further southward aggradation was restricted by the presence of this Volcanic Dome (Herngreen et al., 1991; Geological Survey of The Netherlands, 1991a).

During the Portlandian the differential subsidence decreased and sedimentation extended from the halfgrabens across parts of the Central Netherlands Basin in the south of the map sheet area. In this basin, a few notable depressions confined by complex fault structures developed in the northern part which are regarded as collapse-structures. Their development is related to the subsurface solution of rock salt of Triassic or Zechstein age (fig. 11.7), and they are sometimes connected with deep seated faults. The sea-level fall towards the end of the Ryazanian caused the deposition of a regressive sequence in sedimentation areas. It is presumed that the original distribution of these sediments was greater than the present one and that, in view of similarities in the deposits, the Central Netherlands Basin and the Broad Fourteens Basin were connected.

In the Vlieland Basin and the Central Netherlands Basin sedimentation ended as a result of the Late Kimmerian II phase during the earliest Cretaceous. This impulse did not have a great effect in the basins, but the basin margins and highs became more pronounced during this phase and erosion occurred on a wide scale. Evidence for this is to be found in the great quantity of sand in the Lower Cretaceous deposits which are encountered in the Vlieland Basin and the Broad Fourteens Basin.

11.2.5 Cretaceous

At the beginning of this period, a reversal in the tectonic regime took place. Because the sea-floor spreading during the Early Cretaceous became increasingly concentrated in the northern part of the Atlantic Ocean and the Bay of Biscay (Hancock, 1984; Ziegler, 1990), the rift activity in the North Sea diminished even further. In the Late Cretaceous, an end came to the regime of extensional tectonics which had determined the geological history since the Carboniferous. During the Cretaceous the differential basin subsidence, characterising the Late Jurassic, changed over to an isostatic subsidence which occurred as a reaction to the resumption of the thermal disturbance of the crust. Influenced by the gradually rising sea level, the basins extended again, leading to the disappearance of the highs. During the Late Cretaceous this culminated in an open marine environment which extended over a large part of northwestern Europe. After a period of relative tectonic rest the area came under the influence of a compressive stress regime in the Late Cretaceous.

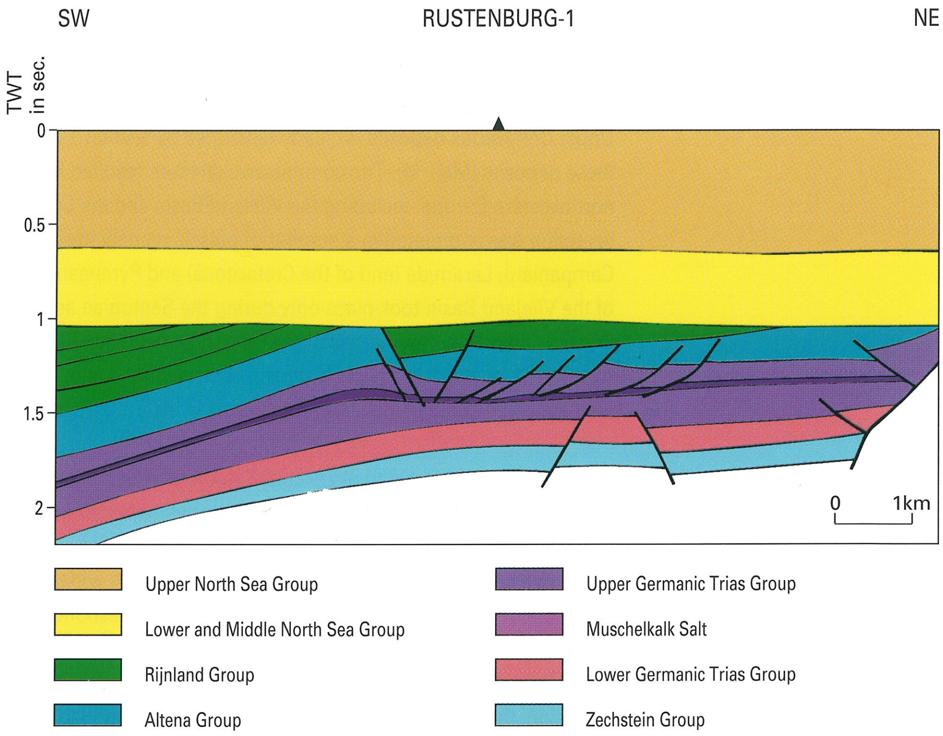
The slow rise in sea level was not a continuous event but was interrupted by a number of brief regressions. These regressions are identified in the form of unconformities and hiatuses in the stratigraphic sequences on the highs (Haq et al., 1987) and are tectonically induced (Kooi et al., 1989). The transgressions during the Albian are of particular importance, as they led to the flooding of many of the highs (Crittenden, 1987). The Cretaceous transgression was the result of a global sea-level rise, probably in response to an increase in sea-floor spreading rate and the proportional enlargement in volume of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979).

After the Late Kimmerian II phase, sedimentation in the map sheet area recommenced during the Early Cretaceous. The transgression took place from the Central North Sea Graben southwards, reaching the Vlieland Basin during the Valanginian and the Central Netherlands Basin during the Hauterivian. During the Barremian and Aptian the sedimentation extended over the Noord-Holland Platform and parts of the Texel-IJsselmeer High. During the Albian this high became completely submerged by the sea (fig. 8.3).

During the Early Cretaceous and the earliest Late Cretaceous, there were still great differences in subsidence within the map sheet area (Map 19, section 1). The role of the Vlieland Basin as depocentre ended during the Hauterivian-Barremian, but in the Central Netherlands Basin greater subsidence was manifested until during the Santonian (fig. 9.2). Owing to the fact that the Vlieland Basin became inactive, the entire north of the map sheet area formed a stable, relatively high area (fig. 8.2).

The transgression resulted in the deposition of a thick sand unit in a shallow marine environment in the Vlieland Basin (Perrot & Van der Poel, 1987). In the Central Netherlands Basin, however, the transgression only led to sand deposition in a limited area. These deposits are found mainly in fault-bounded depressions in the northern part of this basin, originating during the Late Jurassic. The restricted occurrence of sand can be accounted for by the fact that the outcropping formation in this basin was the Lower Jurassic claystone (Map 17). Reworking and erosion of the claystone could not have had sandy deposits as a result.

Figure 11.7. Line drawing of a seismic section. The highly fractured character of the top of the Trias, Jurassic and Lower Cretaceous is shown here in the northern part of the Central Netherlands Basin, whereas the underlying deposits show virtually no faults. Such fault zones are regarded as collapse structures, originating as a consequence of the underground solution of rock salt. This phenomenon is found in various places within the map sheet area.



During the Early Cretaceous, the Central Netherlands Basin formed virtually a single entity with the more southerly situated West Netherlands Basin. A few major fault systems were still being reactivated in certain places, but in general the fault systems were inactive during this period (Map 19, section 1). The presence of a small NW-SE trending halfgraben on the Noord-Holland Platform during the Hauterivian-Barremian is notable (fig. 11.9).

During the Aptian and Albian the sedimentation of clay and marl continued. Several hiatuses in these deposits are presumed to occur in the northern part of the map sheet area (Geological Survey of The Netherlands, 1991a). In the more rapidly subsiding Central and West Netherlands Basins, in contrast, the sedimentation was probably fairly continuous. During this period, the area of sedimentation extended over the Texel-IJsselmeer High, under the influence of a rising sea level. The distance between the map sheet area and the source areas of clastic sediments thus became increasingly greater, while the source themselves areas became increasingly smaller. Because of this, the proportion of the terrigeneous clastic material gradually decreased, as a result of which the Late Cretaceous deposits consist mainly of marine, bioclastic components.

During the Late Cretaceous there came an end to the relative tectonic rest and regional subsidence. The generated compressive regime, a consequence of the collision between Europe and Africa, was intensified and extended gradually over northwestern Europe (Ziegler, 1982). The orogenic front lay more than 1000 km further south, but the contemporaneous tectonic phases in northwestern Europe and the Alpine-Mediterranean domain are sufficient grounds for assuming a relation between them (Ziegler, 1990). Baldschuhn et al. (1991) ascribe compressive stress in the crust of Northwest Europe more to local processes than to the orogeny active at a great distance, whereas Coward (1991) sees a relation between the inversion and phases in the opening of the Atlantic Ocean. Owing to compressive stress, pre-existing fault systems were reactivated by means of sinistral shear. As far as the inversion movements in the map sheet area are concerned, the Alpine tectonic phases appear to be coeval. The inversion movements, however, can certainly not be attributed to these tectonic phases alone, but local processes have also been taken into account.

Preceding the inversion, the Cenomanian, Turonian and Coniacian periods were characterised by continuing strong subsidence of the Central Netherlands Basin. The increase in thickness of the Upper Cretaceous deposits is clearly illustrated by section 1 (Map 19) and on the thickness map of these deposits (Map 14). The compressive stresses resulted in the uplift of a number of basins in northwestern Europe, including the Vlieland Basin and the Central Netherlands Basin. This inversion was completed in a number of pulses, namely the Sub-Hercynian (Santonian and Campanian), Laramide (end of the Cretaceous) and Pyrenean phase (Eocene-Oligocene). Inversion of the Vlieland Basin took place only during the Santonian and Campanian (Sub-Hercynian phase), whereas inversion movements of the Central Netherlands Basin occurred in all three of the phases mentioned, of which the Sub-Hercynian phase is presumed to have been the most effective. This is also observed in inversion structures in northwestern Germany (Baldschuhn et al., 1991).

The first inversion movements occurred during the Santonian and Campanian. A clear reversal of the relief took place, with the most intense movements occurring in the Late Campanian (fig. 9.2).

In the two subsidence areas the inversion took place in widely differing manners. In the Vlieland Basin the original subsidence area is observed to correspond with the inverted area (Map 19; section 2). The inverse relief is evident from onlap against the flanks of this basin and from angular unconformities in the inverted areas (Geological Survey of The Netherlands, 1991b). Despite the inversion, the sedimentation in the inverted basin continued. During the Late Cretaceous this resulted in a 100-150 m condensed sequence above the inversion axis, in contrast to 600 to 700 m at the margin of the basin. In the Central Netherlands Basin the inverted area does not correspond to the original area of subsidence. The greatest uplift took place here, through convergent transverse movements along the boundary faults and other fault zones, whereas the area of subsidence (the Gouwzee Trough) has retained its original shape. On the northern border, the principal movements took place along three faults (Maps 13 & 14). In the case of the northern boundary fault, this resulted locally in overthrusts of the basin over the Noord-Holland Platform (fig. 11.8) and this boundary fault is characterised as a flower structure on seismic records. Harding (1990) gives this as a clear indication of convergent transverse movement, which is supported by alterations in the direction of movement along the fault (Map 11). In addition, strong alterations in the rate of uplift along the faults are indications of convergent transverse movements, in the opinion of Harding (1985, 1990) and can be seen in the south of the map sheet area on the subcrop base of the Tertiary map (Map 18). The compressive stresses caused fold structures in the basin as well as the reactivation of faults (Map 19: section 1). The uplift in the Central Netherlands Basin is much greater than in the Vlieland Basin; virtually all the deposits from the Cretaceous were eroded (Map 18; Map 19: section 1, 2 and 3).

The different reaction of the two basins to the compressive stresses is attributed to the fact that a rock salt member a few hundred metres thick is found under the Vlieland Basin, which has accommodated a certain number of the faults. In the Central Netherlands Basin, however, the rock salt was too thin to accommodate the fault movements. A further fact of significance is that in the afore-mentioned basin the differential fault movements before the inversion were much greater than in the Vlieland Basin.

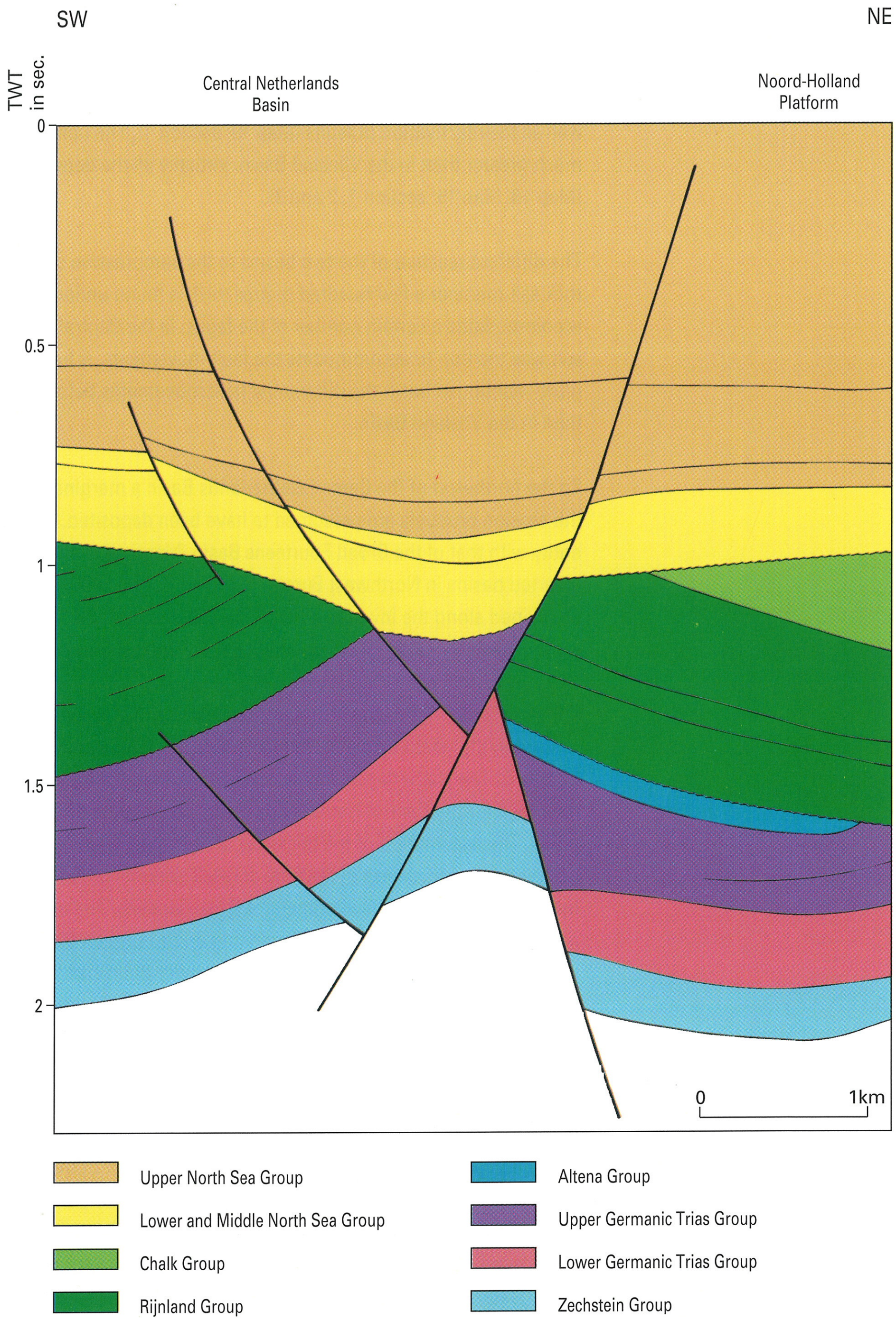
To the northwest of the Central Netherlands Basin a marginal trough developed, in which some of the erosion products are presumed to have been deposited. This marginal trough forms a single entity with that of the Broad Fourteens Basin. Marginal troughs have also been observed in other inverted basins in Northwest Europe (e.g. Van Hoorn, 1987; Betz et al., 1987). No marginal troughs developed along the inverted zone of the Vlieland Basin, presumably related to the fact that this is a comparatively small inversion structure (Geological Survey of The Netherlands, 1991a,b).

If the thickness of the Upper Cretaceous deposits in Friesland from 700 to 800 m is taken as reference, the relative uplift of the basin axis of the Vlieland Basin is 600 to 700 m (Geological Survey of The Netherlands, 1991a, 1991b). Taking the afore-mentioned values from Friesland as reference for the Central Netherlands Basin, an estimate of the relative uplift of this basin can be made. The assumption of the thickness of the Lower Cretaceous in the basin is 600 to 700 m and the cumulative thickness of the total Jurassic sediments, 800 to 900 m. These assumptions are based on the regional development of these deposits. The uplift of the Central Netherlands Basin is a maximum of 1000 to 2000 m, depending on the structural position. This is supported by the analysis of the compaction data set of the Lower Buntsandstein Formation (section 5.2.1.1; fig. 5.3). This uplift was much greater than that of the Vlieland Basin, but less than the uplift of the Broad Fourteens Basin, which exceeds the 3000 m (Van Wijhe, 1987b).

In spite of the fact that the compressive stresses had a minor effect outside the inverted basins, they were nonetheless the cause of the inversion of a NW-SE striking halfgraben. The Sub-Hercynian phase was responsible for the development of the Slootdorp-Middenmeer anticline (fig. 11.9). which is a continuation of the reactivated boundary fault of the Central Netherlands Basin in the southeast of the map sheet area and is clearly visible on the thickness map of the Upper Cretaceous deposits (Map 14). Although no further upward movement of this anticline took place during later compressive phases, there was nonetheless a SW-NE trending dextral transverse movement during the Laramide phase, which cuts through the anticline formed previously (Map 13

& 14). This fault is normal to the direction of the main fault. During the Laramide phase, a large area outside the basins was uplifted slightly; because of this, sediments of the Maastrichtian and part of the Campanian are missing in the middle and east of the map sheet area.

Figure 11.8. Line drawing of a seismic section through the overthrust fault, which separates the Central Netherlands Basin from the Noord-Holland Platform. During the inversion the basin was thrust over the platform. The flower-structure leads to the assumption that strike-slip movements also played a part here.



11.2.6 Cenozoic

After the Laramide compressive phase, a new basin formed in northwestern Europe, the North Sea Basin, which has influenced sedimentation up to the present day. During the Tertiary and particularly the Quaternary the rate of subsidence of the North Sea Basin increased spectacularly and in the centre of the basin over 3000 m sediment was deposited during the course of 65 million years. These sediments consist principally of erosion products from the Alpine uplifted area. The Netherlands is situated on the southern margin of this basin.

The change in the sedimentary facies in the Tertiary reflects the transition to a new phase in the collision between the African and European plates (Ziegler, 1990), during which large areas of the hinterland were uplifted and eroded. Throughout the North Sea area the accumulation of bioclastic material came to an end through the influx of large quantities of terrigenous detritus. Sea-level fluctuations (Haq et al., 1987) continued to exert a strong influence on the depositional process right into the Tertiary. During periods of relative high stand clays were deposited, while at relative low stand deposition of sands predominated or hiatuses in the succession developed. Some major tectonic phases are also related to periods of low sea level. This can be seen as a confirmation of the tectono-eustatic model of sea-level changes put forward by Cloetingh (1986). These tectonic phases occurred during the Late Eocene to Early Oligocene (related to the Pyrenean phase) and during the Early Miocene (in conjunction with the Savian phase). Under the influence of extensive forces during the Tertiary, a few older faults were reactivated (fig. 11.8).

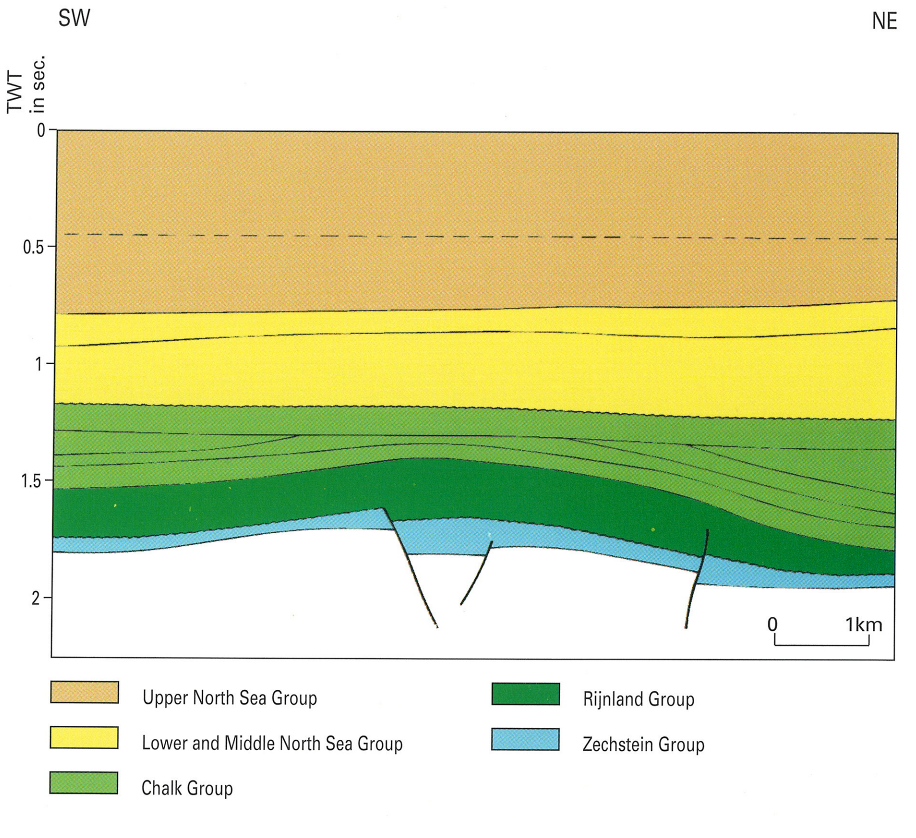


Figure 11.9. Line drawing of a seismic section over the Slootdorp-Middenmeer anticline. This anticline is an inversion structure of a small halfgraben with deposits of the Rijnland Group. Above the unconformity within the Chalk Group there are sediments of Campanian age. The formation of this structure is related to the Sub-Hercynian phase.

In the Paleocene, the marine sedimentation in the map sheet area resumed. During the Paleocene and Eocene, the map sheet area initially formed part of the uniformly subsiding North Sea Basin. Volcanic activity in northwestern Europe at the beginning of the Eocene, particularly in the nearby Skagerrak area, resulted in the deposition, within the map sheet area, of a tuffite allowing widespread regional correlation (Basal Dongen Tuffite). As a reaction to a compressive tectonic phase at the end of the Eocene (Pyrenean phase) a large anticlinorium formed in the central Netherlands, the axis of which partly followed the basin axis of the West Netherlands Basin. The Central Netherlands Basin was on the northern margin of this anticlinorium. The rate of uplift in the extreme southwest of the map sheet area did not exceed 300 m and decreased northwards. Erosion cut down into the oldest Tertiary deposits.

During the Oligocene, at first uniform subsidence of the area took place, at the end of which the area was once again uplifted as a result of the Savian tectonic phase which interrupted sedimentation. The associated erosion was of minor significance in the map sheet area.

During the Late Oligocene and Miocene a new area of subsidence developed in the map sheet area, the Zuiderzee Low, the depocentre of which lay in the extreme southeast of the mapped area. This depression is taken to be part of the large North Sea Basin. The area subsided substantially, in particular during the Middle and Late Miocene (Zagwijn, 1989). During the Miocene, Pliocene and the Early Pleistocene, sediments were deposited in a marine environment. The map sheet area did not emerge until after the Early Pleistocene. The greater influx of sediments as a consequence of the uplift of the Rhenish Massif, the Eifel and the Ardennes (Ziegler, 1990) played an important role in this emerging. During the Quaternary the map sheet area is characterised by rapid basin subsidence: during the course of 2 million years, sedimentation here exceeded 400 m in places (fig. 10.3). This rapid subsidence is observed over wide extents of the North Sea Basin (Kooi et al., 1989).

Appendices

Appendix A

Overview of seismic data used

Survey/line	*Year*	*Owner*
1**	1965	Amoco
22**	1961	NAM
42**	1968	NAM
7**	1965	NAM
71**	1971	Amoco
7110**	1972	NAM
7210**	1972	NAM
7240**	1972	NAM
73-0**	1973	Amoco
7410**	1975	NAM
7510**	1975	NAM
7604**	1976	NAM
7710**	1977	NAM
7820**	1978	NAM
7840**	1979	NAM
7890**	1978	NAM
8091**	1980	NAM
9030**	1973	NAM
69W-**	1969	Elf Petroland
71W-**	1971	Elf Petroland
72W-**	1972	Elf Petroland
72Y-**	1972	Amoco
80-W-**	1980	Elf Petroland
ANE72**	1972	Amoco
ANE73**	1973	Amoco
ANE-78-2**	1978	Amoco
ANE-79-1**	1979	Amoco
ANE792**	1979	Amoco
ANE-80-202	1980	Amoco
ANE-80-207	1980	Amoco
FR-1**	1978	Elf Petroland
FR75-**	1975	Elf Petroland
FR77-32	1977	Elf Petroland
FR78-**	1978	Elf Petroland
FR79-**	1979	Elf Petroland
L-**	1965	Placid
NSW-**	1985	Western Geophysical
PL-**	1971	Placid
S69-**	1969	NAM
SL-76**	1976	Elf Petroland
SL78-0**	1978	Elf Petroland
SL78-18	1978	Elf Petroland

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Continuation of Appendix A

Survey/line	*Year*	*Owner*
SL78-28	1978	Elf Petroland
SL79-34	1979	Elf Petroland
SL79-38	1979	Elf Petroland
T3**	1969	NAM
T6**	1969	NAM
TX-111	1964	Elf Petroland
TX-3	1964	Elf Petroland
TX-8	1964	Elf Petroland
Y-5**	1968	Chevron

* Arbitrary figure

Appendix B

Overview of wells used

Well	*Code*	*Owner*	*Final depth log depth in metres*	*Year completed*
Almere-1	ALE-1	Amoco	1877	1976
Alkmaar-1	ALK-1	Amoco	2588	1975
Bakkum-Castricum-1	BAC-1	NAM	2282	1964
Bergen-1	BER-1	Amoco	2857	1965
Bergen-2	BER-2	Amoco	2633	1976
Bergen-3	BER-3	Amoco	3023	1976
Bergen-4	BER-4	Amoco	2752	1976
Bergermeer-1	BGM-1	Amoco	2314	1969
Bergermeer-2	BGM-2	Amoco	2661	1970
Bergermeer-3	BGM-3	Amoco	2960	1972
Bergermeer-4	BGM-4	Amoco	3338	1972
Bergermeer-5	BGM-5	Amoco	2420	1972
Bergermeer-6	BGM-6	Amoco	2397	1972
Bergermeer-7	BGM-7	Amoco	3255	1980
Boekel-1	BKL-1	Amoco	3131	1975
Den Burg-1	BRG-1	Elf Petr.	2864	1964
Bolsward-1	BWD-1	NAM	2679	1971
De Cocksdorp-1	COC-1	Elf Petr.	2798	1964
Egmond Zee-1	EGZ-1	NAM	2004	1984
Franeker-1	FRA-1	Elf Petr.	1837	1978
Groet-1	GRT-1	Amoco	2850	1965
Groet-2	GRT-2	Amoco	3843	1970
Groet-3	GRT-3	Amoco	2708	1970
Groet-4	GRT-4	Amoco	2850	1971
Groet-5	GRT-5	Amoco	2728	1971
Groet-6	GRT-6	Amoco	2475	1971
Groet-7	GRT-7	Amoco	2935	1980
Harlingen-West-1	HAW-1	Placid	3348	1965
Heemskerk-1	HEK-1	NAM	1966	1965
Heerhugowaard-1	HEW-1	NAM	2220	1964
Heegermeer-1	HGM-1	Chevron	2144	1973
Heiloo-1	HLO-1	Amoco	2271	1965
Heiloo-2	HLO-2	Amoco	2458	1982
Hoogkarspel-1	HOK-1	NAM	2061	1950
Hoogkarspel-2	HOK-2	NAM	1821	1964
Hoorn-1	HOO-1	Elf Petr.	2894	1984
Harlingen-1	HRL-1	Elf Petr.	3103	1965
Harlingen-2	HRL-2	Elf Petr.	1870	1965
Harlingen-3	HRL-3	Elf Petr.	2003	1965
IJsselmeer-1	IJM-1	Superior	2892	1966
Ilpendam-1	ILP-1	NAM	1064	1948

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Continuation of Appendix B

Well	*Code*	*Owner*	*Final depth log depth in metres*	*Year completed*
Julianadorp-1	JLD-1	Phillips	2953	1965
Knardijk-1	KRD-1	Amoco	1524	1978
Kreil	KRL-1	Elf Petr.	2731	1981
Langedijk-1	LAD-1	NAM	1974	1964
Leekermeer-1	LKM-1	Elf Petr.	2116	1982
Lelystad-1	LEL-1	Conoco	2057	1970
Lambertschaag-1	LMB-1	Elf Petr.	2491	1973
Landsmeer-1	LSM-1	NAM	1703	1977
Middenmeer-1	MDM-1	Elf Petr.	2046	1975
Middenmeer-2	MDM-2	Elf Petr.	2295	1979
Meep-1	MEE-1	NAM	3240	1969
Middelie-101	MID-101	NAM	2625	1964
Middelie-102	MID-102	NAM	2877	1975
Middelie-103	MID-103	NAM	2810	1975
Middelie-104	MID-104	NAM	2722	1975
Middelie-201	MID-201	NAM	2913	1980
Middelie-301	MID-301	NAM	2812	1985
Nagele-1	NGA-1	Elf Petr.	4304	1970
Obdam-1	OBD-1	BP	2117	1964
Obdam-2	OBD-2	BP	2471	1965
Oudesluis-1	ODS-1	Elf Petr.	2934	1966
Oude Inschot-1	OIS-1	Elf Petr.	2350	1972
Oostzaan-1	OZN-1	NAM	2767	1951
Peins-1	PEI-1	Elf Petr.	1884	1982
Ried-1	RID-1	NAM	3039	1952
Ried-2	RID-2	Elf Petr.	1806	1980
Riepel-1	RPL-1	Elf Petr.	2509	1972
Rustenburg-1	RST-1	NAM	2684	1977
Rustenburg-2	RST-2	NAM	2770	1981
Slootdorp-1	SLD-1	Elf Petr.	2508	1965
Slootdorp-2	SLD-2	Elf Petr.	2277	1965
Slootdorp-3	SLD-3	Elf Petr.	2044	1976
Slenk-1	SLK-1	Elf Petr.	2482	1971
Sint-Maarten-1	SMA-1	Phillips	3006	1964
Spaarnwoude-1	SPW-1	NAM	923	1949
Schermer-1	SRM-1	Amoco	2139	1964
Schermer-1-deep	SRM-1-VE	Amoco	2505	1976
Schermer-2	SRM-2	Amoco	2703	1965
Schermer-3	SRM-3	Amoco	2681	1965
Starnmeer-1	STM-1	Amoco	2884	1975
Twisk-1	TWI-1	Elf Petr.	2657	1981

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Continuation of Appendix B

Well	*Code*	*Owner*	*Final depth log depth in metres*	*Year completed*
Ursem-1	URS-1	NAM	2184	1965
Warmenhuizen-1	WAH-1	NAM	1345	1950
Warmenhuizen-Krabbendam-1	WAK-1	Amoco	2447	1964
Wieringerwaard-1	WRW-1	Elf Petr.	2645	1986
Wimmenum-Egmond-1	WIM-1	NAM	2116	1964
Weesp-1	WSP-1	Amoco	2259	1970
Zaandam-1	ZAD-1	NAM	950	1948
Zuidwal-1	ZDW-1	Elf Petr.	3002	1970
Zuidwal-2	ZDW-2	Elf Petr.	2632	1971
Zuidwal-3	ZDW-3	Elf Petr.	2060	1971
Zeewolde-1	ZEW-1	Conoco	2000	1966
Zurich-Waddenzee-1	ZUR-1	Placid	2164	1965
Zwaag-1	ZWA-1	Phillips	2175	1964
Q8-1	Q8-1	BP	2550	1976

Reservoir calculations Upper-Rotliegend Group and sandstone units

Cut-off values applied: clay content Vcl(co) = 50%; effective porosity Øe(co) = 6%; water saturation Sw(co) = 90%. Øem average effective porosity; Vclm average clay content; Swm average water saturation. Gross, Net in metres; Øem, Vclm and Swm in percentages. Wells in which only a part of the Upper Rotliegend sequence was evaluated are marked with an *.
In the oil industry zones, for which Swm > 80, are not considered as part of the pay zone.

Upper-Rotliegend Group

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
BGM-1	217.0	215.6	21.4	14.0	168.4	21.7	15.9	24.2
BWD-1	128.0	116.7	14.2	21.1	1.7	14.8	17.5	88.1
COC-1	218.0	144.4	10.6	36.0	68.7	12.6	34.3	80.0
*HRL-1	79.5	17.5	8.0	33.4	5.6	9.7	32.7	83.9
JM-1	180.0	180.0	20.5	13.1	0.3	20.1	12.6	80.6
KRL-1	173.7	172.3	21.2	21.6	114.1	20.9	23.0	82.0
LEL-1	144.0	143.2	21.1	8.6	16.9	21.6	9.5	79.6
*MDM-1	27.2	27.1	22.7	20.2	27.1	22.7	20.2	8.2
MID-201	193.8	191.4	21.0	10.7	59.3	15.4	12.1	75.0
RPL-1	162.5	160.5	14.8	24.9	159.1	14.8	24.9	75.5
RST-2	178.7	104.9	8.4	7.7	10.9	7.0	5.9	52.0
SLD-1	161.0	149.6	14.2	18.8	120.0	15.3	18.2	76.2
SRM-2	209.0	189.0	18.5	16.7	119.4	21.2	16.6	69.8
SRM-3	232.0	175.7	15.1	21.3	175.7	15.1	21.3	46.1
WIM-1	191.0	137.2	24.3	30.0	33.8	21.8	35.9	83.2
*ZDW-2	163.1	112.5	13.3	27.4	31.8	12.9	28.0	81.0

Slochteren Sandstone Formation

Well	Gross	Reservoir			Pay			
		Net	Øem	Vclm	Net	Øem	Vclm	Swm
BGM-1	217.0	215.6	21.4	14.0	168.4	21.7	15.9	24.2
BWD-1	119.0	116.0	14.3	21.0	1.7	14.8	17.5	88.1
IJM-1	180.0	180.0	20.5	13.1	0.3	20.1	12.6	80.6
KRL-1	173.7	172.3	21.2	21.6	114.1	20.9	23.0	82.0
LEL-1	144.0	143.2	21.1	8.6	16.9	21.6	9.5	79.6
*MDM-1	27.2	27.1	22.7	20.2	27.1	22.7	20.2	8.2
MID-201	193.8	191.4	21.0	10.7	59.3	15.4	12.1	75.0
RPL-1	162.5	160.5	14.8	24.9	159.1	14.8	24.9	75.5
RST-2	178.7	104.9	8.4	7.7	10.9	7.0	5.9	52.0
SLD-1	161.0	149.6	14.2	18.8	120.0	15.3	18.2	76.2
SRM-2	209.0	189.0	18.5	16.7	119.4	21.2	16.6	69.8
SRM-3	232.0	175.7	15.1	21.3	175.7	15.1	21.3	46.1
WIM-1	191.0	137.2	24.3	30.0	33.8	21.8	35.9	83.2

Upper Slochteren Sandstone

Well	Gross	Reservoir			Pay			
		Net	Øem	Vclm	Net	Øem	Vclm	Swm
COC-1	122.0	97.4	10.1	37.6	45.1	11.8	36.6	84.0
*HRL-1	57.0	17.5	8.0	33.4	5.6	9.7	32.7	83.9
ZDW-2	110.0	102.2	13.7	27.6	24.4	13.8	29.2	81.4

Show, status and testdata Upper Rotliegend Group

D&A dry and abandoned; RFT repeat formation tester (test interval in metres log depth; quantities in litres); PRP production test (flow gas, Q50, in 1000 m^3/day; flow water and condensate in m^3/day); FIT formation interval test (quantities in litres); DST drill stem test (quantities in litres); SW salt water; GCW gas cut water; MF mud filtrate; G gas; FW formation water; W water; C condensate; M mud; GCM gas cut mud; WCM water cut mud; u upper chamber; l lower chamber; Rw electrical resistance of the formation water in ohms m^2/m (temperature, °C); Unit formation or member; ZEZ1 Zechstein 1; ROSL Slochteren Sandstone; ROSLU Upper Slochteren Sandstone; ROCLT Ten Boer Claystone;

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*	*Unit*
BGM-1	gas	GAS	PRP	2130-2150	G	> 735		ROSL
					C			
			DST 4	2085-2106	G			ROSL
BWD-1	–	D&A	FIT 1	2500	W	10		ROSL
COC-1	–	D&A	DST 3	2413-2431	W	7000		ROCLT
HRL-1	gas	D&A	DST 5	3013-3031	GCW	160		ZEZ1,
								ROCLT
			DST 6	3081-3103	GCW	2000		ROSLU
IJM-1	gas	D&A	–					
KRL-1	gas	D&A	PRP 1	2450-2456	GCW	82		ROSL
			PRP 2	2658-2694	GCW	73		ROSL
LEL-1	–	D&A	DST 1	1850-1950	W			ZEZ1,
								ROSL
MDM-1	gas	GAS	PRP	1893-1903	G			ROSL
			DST 5	1886-1892	G			ZEZ1,
								ROSL
MID-201	–	D&A	RFT	2685	FW+MF(u)	3.5		ROSL
					FW+MF(l)	5.5		
			PRP	2750-2850	FW		0.0445(24)	ROSL
RPL-1	–	D&A	DST 2	2304-2324	W	11900		ROSL
RST-2	gas	GAS	PRP	2464-2515	G	51		ROSL
			RFT	2527	G			ROSL
SLD-1	–	D&A	DST 4	2225-2243	GCW	7500		ZEZ1,
								ROSL
SRM-2	gas	D&A	DST 2	2457-2480	W	2600		ROSL
								GCM
			DST 3	2485-2611	W	1800		ROSL
					GCM	4600		
					FW	8400	0.042 (24)	
SRM-3	gas	D&A	DST 2	2350-2418	WCM			ROSL
WIM-1	–	D&A	–					
ZDW-2	–	D&A	DST 2	2372-2393	W		0.0424(24)	ROSLU

Reservoir calculations Zechstein Group

Cut-off values applied: clay content Vcl(co) = 50%; effective porosity Øe(co) = 6%; water saturation Sw(co) = 90%. For an explanation of the other symbols see Appendix C.

Zechstein 3 Carbonate (Platy Dolomite)

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
ALK-1	48.8	44.9	18.2	17.1	43.3	18.6	16.8	41.5
BGM-1	39.0	20.8	10.4	4.3	18.9	10.6	4.1	56.3
IJM-1	35.0	18.0	9.7	19.7	17.4	9.9	20.1	54.1
LEL-1	5.0	0.0	–	–	0.0	–	–	–
SRM-2	38.0	17.6	12.8	9.9	15.4	13.3	9.7	41.8
SRM-3	37.0	20.7	13.0	18.8	18.1	13.6	19.0	49.3
WIM-1	40.5	27.6	12.6	16.0	8.5	13.1	20.0	64.1

Zechstein 2 Carbonate and Zechstein 3 Carbonate

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
MDM-1	37.0	25.0	16.8	30.5	25.0	16.8	30.5	16.2
SLD-3	6.5	0.3	6.9	32.8	0.3	6.9	32.8	70.5

Show, status and test data Zechstein Group

PRP (flow gas, Q50, in 1000 m³/day; flow water and condensate in m³/day). Flow: pra pre-acid; pa post-acid. Unit formation or member; ZEZ3A Zechstein 3 Anhydrite; ZEZ3C Zechstein 3 Carbonate (Platy Dolomite); ZEZ2C Zechstein 2 Carbonate. For an explanation of the other symbols see appendix D.

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*	*Unit*
ALK-1	gas	GAS	PRP 1	2099-2115	G	340 pra		ZEZ3C
					G	870 pa		
			PRP 2	2068-2092	G	1200 pa		
						(pa zone		
						2099-2115)		ZEZ3C
					G	1800 pa		
BGM-1	gas	D&A	DST 3	1855-1878	GCW			ZEZ3A,
								ZEZ3C
IJM-1	–	D&A	–					
LEL-1	–	D&A	–					
MDM-1	gas	GAS	DST 1	1797-1805	G			ZEZ2C,
								ZEZ3C
			DST 2	1811-1821	G			ZEZ2C,
								ZEZ3C
			PRP	1793-1812	G			ZEZ2C,
								ZEZ3C
					C		2	
SLD-3	–	D&A	–					
SRM-2	gas	D&A	DST 1	2183-2222	GCM			ZEZ3A,
								ZEZ3C
					FW		0.041 (24)	
SRM-3	gas	GAS	PRP	2079-2088	G			ZEZ3A,
								ZEZ3C
					C			
WIM-1	–	D&A	–					

Reservoir calculations Lower and Upper Germanic Trias Group

Cut-off values applied: clay content Vcl(co) = 50%; effective porosity Øe(co) = 6%; water saturation Sw(co) = 90%. For an explanation of the other symbols see appendix C.

Volpriehausen Sandstone

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
HLO-2	30.1	16.7	13.8	29.8	16.7	13.8	29.8	19.9

Solling Sandstone and Volpriehausen Sandstone

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
WIM-1	59.0	26.7	20.7	38.1	26.7	20.7	38.1	63.2

Show, status and test data Lower and Upper Germanic Trias Group.

PRP (flow gas, Q50, in 1000 m^3/day; flow water and condensate in m^3/day); RFT (quantities in litres). Flow: pra pre-acid; pa post-acid. Unit formation or member; RBSSV Volpriehausen Sandstone; RNROS Solling Sandstone. For an explanation of the other symbols see appendix D.

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*	*Unit*
HLO-2	gas	GAS	PRP	1774-1784	G			RBSSV
					C	0.4		
					W	0.8		
WIM-1	gas	GAS	PRP	1222-1228	G	95 pra		RNROS
					G	190 pa		
			RFT	1228	G	2500		RNROS
					W			

Reservoir calculations uppermost Delfland Formation

Cut-off values applied: clay content Vlc(co) = 50%; effective porosity Øe(co) = 8%; water saturation Sw(co) = 90%. The choice of cut-off value for the effective porosity was deduced from core data. For an explanation of the other symbols see appendix C.

Uppermost Sandstone unit Delfland Formation

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
HRL-1	4.0	1.8	35.2	30.4	1.8	35.2	30.4	40.7
ZDW-2	26.0	16.2	16.3	19.0	1.5	16.8	23.0	79.6

Reservoir calculations Vlieland Sandstone

Cut-off values applied: clay content Vlc(co) = 50%; effective porosity Øe(co) = 8%; water saturation Sw(co) = 90%. The choice of cut-off value for the effective porosity was deduced from core data. For an explanation of the other symbols see appendix C.

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
BWD-1	8.0	2.5	13.6	42.9	2.5	13.6	42.9	73.2
FRA-1	58.8	40.7	15.0	32.7	17.6	17.5	30.8	74.5
HAW-1	169.5	115.5	12.7	35.7	23.2	16.5	32.5	84.5
HRL-1	98.5	83.3	18.5	31.7	80.3	18.8	31.4	58.6
IJM-1	80.0	72.7	17.0	18.9	0.3	16.5	29.8	87.8
PEI-1	20.0	16.6	11.7	31.2	2.4	10.0	40.9	87.5
RPL-1	24.0	15.8	14.9	21.2	8.2	15.9	32.7	75.0
ZDW-1	81.0	78.8	17.9	17.8	78.6	17.9	17.8	49.5

Show, status and test data Vlieland Sandstone

PRP (flow gas, Q50, in 1000 m³/day; flow water in m³/day); DST (quantities in litres). KNNCZ Vlieland Sandstone. For an explanation of the other symbols see appendix D.

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*	*Unit*
BWD-1	–	D&A	–					KNNCZ
FRA-1	gas	GAS	DST 2	1776-1779	W	57	0.0590(20)	KNNCZ
			PRP 1	1741-1747	G	52		KNNCZ
					W	0.4		
			PRP 2	1750-1765	W			KNNCZ
HAW-1	–	D&A	–					
HRL-1	gas	GAS	DST 2	1691-1702	G&W			KNNCZ
			DST 3	1680-1702	G&W			KNNCZ
			FIT	1695-1700	W			KNNCZ
			PRP	1680-1702	G	200		KNNCZ
IJM-1	–	D&A	–					
PEI-1	–	D&A	–					
RPL-1	–	D&A	DST 1	2220-2238	–			KNNCZ
ZDW-1	gas	GAS	PRP 1	1938-1944	G			KNNCZ
			PRP 2	1872-1944	G	530		KNNCZ

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