Rijks Geologische Dienst **RGD**

Explanation to map sheet I
Vlieland-Terschelling

Geological Atlas of the Subsurface of The Netherlands

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Explanation to map I Vlieland-Terschelling

Contents

Maps and Sections:

Geological Survey of The Netherlands, Haarlem 1991

One of the main tasks of the Geological Survey of The Netherlands (Rijks Geologische Dienst) is to collate knowledge about the geology of The Netherlands, including the compilation of maps and explanations to map sheets. Up to now the Geological Survey has only published maps and explanations on the shallow subsurface geology of The Netherlands and the North Sea.
The situation for the deeper subsurface geology is different. The data are nearly exclusively collected by oil companies and made available to the Geological Survey on terms laid down in the mining legislation. Data collected on the Dutch continental shelf are released after ten years, so that everyone can gain insight into the subsurface geology of the North Sea and interested parties can make their own interpretations of the information. However, the existing mining legislation that applies to the mainland does not cover the general release of information. The Geological Survey has made special agreements with the companies about using the mainland data that allow the Geological Survey to process the data and publish the results, once the data is more than ten years old. Data from concession areas form an exception, with a limit of five years. This agreement enables the Geological Survey to bring the geological framework of the subsurface of The Netherlands to wider attention.

The Vlieland-Terschelling map sheet of the Geological Atlas of the Subsurface of The Netherlands is the first map to be published in the framework of the systematic mapping of the subsurface of The Netherlands based on these data. The Netherlands has been divided into 15 map sheet areas, to be compiled on a scale of 1:250,000 (see map 1, the division is shown in the bottom righthand corner). The Annual Report of the Geological Survey of The Netherlands gives an overview of the progress of this mapping. Each map sheet is accompanied by an explanation and consists of a number of depth and thickness maps of the most important lithostratigraphically defined geological units, with some sections and subcrop maps.

The Geological Survey hopes that this series of maps 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, local authorities, state and semi-government institutions, and various other groups in the community. These are all increasingly confronted with questions about the possibilities which the subsurface has to offer in The Netherlands. For example, these may concern waste disposal problems, energy storage, and thermal energy as an alternative source of energy. 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 amateur geologists.

The mapping of The Netherlands' subsurface started in 1985, under the leadership of H.M. van Montfrans. Between 1986 and 1990 the work was supervised by A. Lokhorst and, since 1991, it has been guided by Th. E. Wong. The actual mapping of the Vlieland-Terschelling map sheet started in 1986. As well as those acknowledged for their contributions in the credit column, many other employees of the Geological Survey have been involved in the compilation of this map sheet. These include J. Breeuwer, C.E. Elmers-Kathman, J. Klijn, N. Parker-Witmans, C.C. de Ruyter and R.A. Wermuth, who all deserve special mention for their efforts, which I greatly appreciate. The pertinent and constructive criticism from the reviewers contributed much to the quality of the explanation. We also owe special thanks to Chevron, Elf Petroland, NAM, Mobil, Phillips, Placid, Shell and Western Geophysical, who all provided data used for this map sheet.

C. Staudt, *director*

1 Introduction

1.1 Extent of area studied

The map sheet for Vlieland-Terschelling is the first map sheet to be published within the framework of the systematic mapping of the subsurface of The Netherlands. The map sheet covers the extreme northwestern part of The Netherlands and extends to the territorial water boundary. Its location is given in figure 1.1.

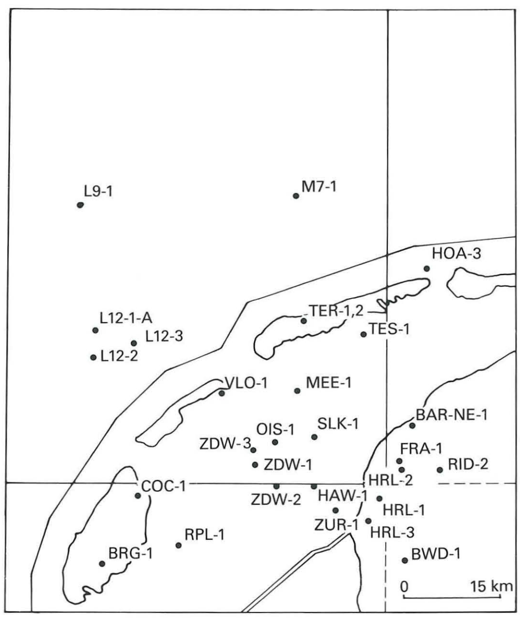
1.2 Data base

The data on which the knowledge of the subsurface is based come primarily from oil companies. The discovery of the Groningen gasfield in 1959 was part of the stimulation to further exploration within the area of the map sheet. Since then different companies have been active in the regions of Friesland, North Holland and the Wadden Sea. Many kilometres of seismic profiles have been shot and various wells drilled to locate possible hydrocarbon occurrences.

The exploration target in the first instance was the Slochteren Sandstone, the Permian gas reservoir unit of the Groningen field. However, in 1964 Petroland discovered gas in the Vlieland Sandstone (Harlingen-1), followed by another gas find in the Ommelanden Chalk (Harlingen-2, 1965) in the direct vicinity of the area covered by the map sheet. Since these gas finds, the exploration has been directed towards various targets.

After the Act on Mineral Resources Exploration became law in 1967, drilling licences, which lay partly or wholly inside the area mapped, were granted to Petroland, the Nederlandse Aardolie Maatschappij (NAM) and to the partnership NAM/Mobil Producing Netherlands Inc. (MPNI). Petroland found gas in the Vlieland Sandstone (Zuidwal-1) in 1970, within the boundaries of the map sheet area. The great vulnerability of the Wadden Sea environment led to the temporary halting of exploration activity. Consequently, there is only an old and limited data base on this area to use in this study. In 1984 Petroland was granted a concession for the Zuidwal gasfield

Figure 1.1 Location of the Vlieland-Terschelling map sheet and of wells drilled in the map sheet area and its immediate vicinity.



and gas has been produced since 1988. Concessions and drilling licences have also been granted in this region, partly within the map sheet area, to NAM, NAM/MPNI and Placid (see figure 1.2).

The mapping of the subsurface of The Netherlands is based to a large extent on the interpretation of the data acquired for the companies mentioned. The chapter on the geological history of the map sheet area is also based on data from published literature. The regional geological framework has been taken from publications such as Ziegler (1982), Glennie (1984) and Heybroek (1974).

1.3 Research set up

Seismic mapping

The research was directed towards systematic structural geological mapping based on seismic data. A seismic line grid of approximately 4 x 4 km was chosen for the regional mapping. This line density could not be achieved in a number of areas because seismic recording was made difficult by the type of terrain or prevented by the limitations on exploration already mentioned. An overview of the seismic lines used is shown in figure 1.3. Non-migrated seismic lines were used, acquired in the period 1965-1980 (see appendix A).

The picked reflectors form the boundaries between the large lithostratigraphic units (groups). Acoustic logs and well-shot data were used to calibrate the seismic data with respect to the 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 relation between the interval velocity and the depth of the layer was assumed ($Vz = Vo + kz$). An exception is the Zechstein Group; because of its specific lithological composition, a hyperbolic relation between the interval velocity and time interval was chosen ($Vint = a + [d/(\Delta t\text{-}b)]^c$). To obtain a consistent fit for depth maps from adjoining map sheets, a regional velocity distribution was determined that could be applied to

Figure 1.2 Concessions granted for the exploitation of hydrocarbons in and near the map sheet area.

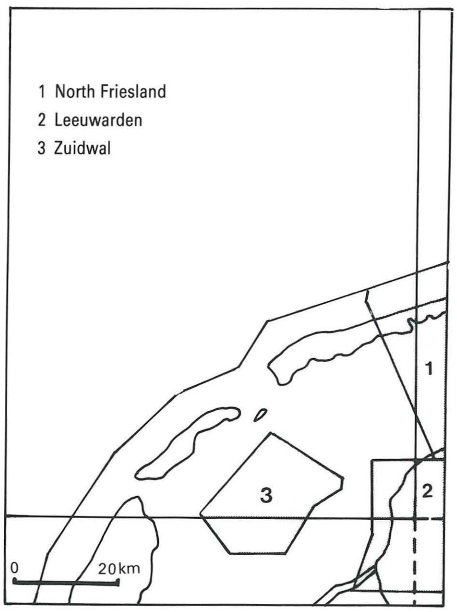
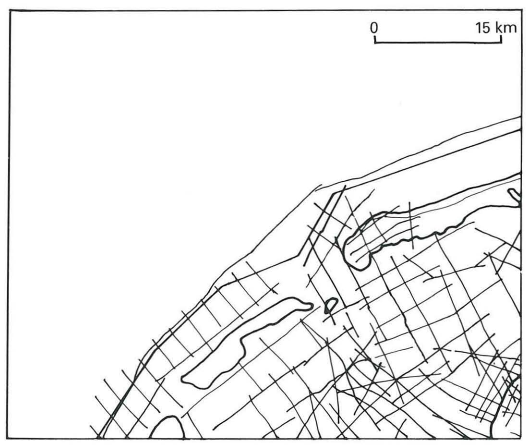


Figure 1.3 Location of the seismic line grids used.



all the map 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 depths from the wells and the seismic interpretations was considered acceptable. Table 1 lists the parameters which were used for the linear velocity distribution.

Geological research

The geological research was directed towards the lithostratigraphic composition of the rocks present in the map sheet area (see figure 1.4), and their geological history with respect to the regional geological framework. 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.

There were only nine wells available for study in the mapped part of the map sheet. Since there was not a representative section present for each formation on the map sheet in these wells, use was also made of wells outside the immediate surroundings for the lithological descriptions. The locations of all the wells used in the study are shown in figure 1.3.

Petrophysical research

As well as the geological research, the characteristics of the reservoir rocks in the map sheet area were also studied. Well measurements and core analysis data were processed to calculate porosities.

Table 1 Applied velocity distribution

based on $V_z = V_o + kz$

Unit	***Vo m/s***	***k***
North Sea Super Group	1696	0.40
Chalk Group	2092	1.08
Holland Formation	2020	0.63
Vlieland Formation	2051	0.41
'Upper Jurassic' deposits	1507	0.82
Lower Germanic Trias Group	2293	0.69
Upper Rotliegend Group	3535	0.18

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

Unit	***a***	***b***	***c***	***d***
Zechstein Group	4410	0.047	− 0.018	1

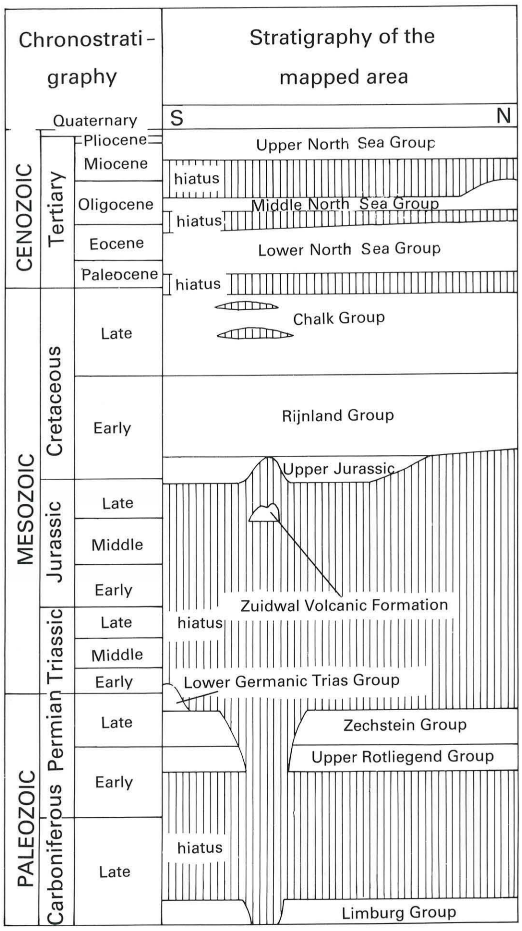
Δt = time interval Zechstein
a = asymptote interval velocity (m/s)
b = asymptote Δt (s)
c,d = constants

1.4 Maps and Sections

The results of the seismic mapping are shown in a series of maps and two sections. Depth and thickness maps have been made per group (as figure 1.4). Subcrop maps have been constructed of the two important unconformities, at the bases of the Rijnland Group and the 'Upper Jurassic' deposits. Depth maps have been made of the base of the Upper Rotliegend Group, the Zechstein Group, the Lower Germanic Trias Group, the 'Upper Jurassic' deposits, the Rijnland Group, the Chalk Group and the base of the North Sea Super Group. A depth map to the top of the Zechstein Group has also been made. The depth maps are based on seismic data. Because the conversion of time to depth was carried out with a regionally determined velocity distribution, as mentioned already, local deviations from the depths determined in the wells may occur. The depth maps have not been corrected for these deviations.

The seismic lines used for mapping the map sheet were generally of rather poor quality. For example, the base of the Upper Rotliegend could not be determined from the seismic records, so that the depth map of this group was compiled from the depth map of the base of the Zechstein Group and a regional map of the thickness of the Upper Rotliegend Group constructed from drilling data.

Figure 1.4 Stratigraphic diagram of the deposits present in the map sheet area.



Thickness maps were also made of all the stratigraphic units mentioned except for the North Sea Super Group, for which the depth map suffices as a thickness map. The thickness map of the Upper Rotliegend Group is based on well data because of the limited quality of the seismic data (fig. 3.2).

The quality of the maps depends on the quality and density of the data available. In the area of the Wadden Sea and Vlieland the mapping quality is limited. The seismic coverage was rather restricted and, moreover, the seismic lines available dated from the 1960s.

The subcrop maps of the base of the Rijnland and the base of the 'Upper Jurassic' deposits, show the stratigraphic units which occur under the unconformities and thus give an impression of the degree of erosion. Only the Chalk Group occurs under the North Sea Super Group within the area mapped so no subcrop map is given.

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

1.5 Explanation

The explanation, with the different maps, attempts to portray the geology of the map sheet area. The text is divided into two parts. Firstly, the lithostratigraphic groups present in the map sheet area are described. Thereafter, in the last chapter, an overview of the geological history of the study area within the framework of the regional geology is given.

In chapters 2-9, the lithostratigraphic composition and development is described per group, starting with the oldest. The emphasis lies on the distribution and variation of the rock units within the area mapped. The description closes with a paragraph on the sedimentary environment and the palaeogeography during the deposition of the group. Finally, extra attention is paid to two economically important reservoir rocks, with features being illustrated from log correlations. In a number of cases, units mapped at formation or member level are included in the explanation as figures.

The 'Upper Jurassic' comprises the Scruff Group and the Central Graben Group. The groups are partly lateral equivalents of each other so that no sharp boundary can be delimited. Because the distribution and sedimentary environments of both groups are closely related they are dealt with as the 'Upper Jurassic' in the information.

Cenozoic sediments are not dealt with at group level but as a whole as the North Sea Super Group. The description is limited to Tertiary sediments, while for Quaternary deposits you are referred to 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.

In chapter 10, the structural setting and development of the map sheet area is described. The Texel-IJsselmeer High and the Vlieland Basin, which contains the Zuidwal High, are important structural units in the study area.

The depth maps of the Upper Rotliegend Group and the Zechstein Group (maps 1 and 2) indicate the structural trend of the area. This is oriented northwest-southeast and superimposed on a more east-west trend from the Carboniferous.

The presence of a thick sequence of rock salt in the Zechstein Group has been important in the structural development of the area. The relatively plastic behaviour of this rock has enabled it to function as a detachment zone. This has resulted in salt ridges and disharmonic structures under and above the Zechstein Group. These phenomena are clearly visible on the thickness map of the Zechstein Group and in a comparison of the depth maps of the top and base of this Group (maps 2, 3 and 4). Most of the faults that cut the base of the group are accommodated by the plastic behaviour of the salt and do not occur in the top of the group. Those faults that do occur in the top are nearly all related to collapse structures above salt ridges.

Important phases of uplift and their related erosion occurred during the Early Permian (Saalian phase; fig. 2.4), during the Jurassic (Kimmerian phase; maps 14 and 15) and during the Late Cretaceous (sub-Hercynian phase and Laramide phases). During this last phase the Vlieland Basin was inverted. This can be clearly seen in the sections (map 16) and is evident from a comparison of the thickness of the Rijnland Group and the Chalk Group (maps 10 and 12).

A special geological phenomenon in the map sheet area is the Zuidwal volcano. The influence of this Jurassic volcano on the sedimentation is evident from the isopach maps of the Zechstein Group, the 'Upper Jurassic' deposits and the Rijnland Group.

Finally, the depth map of the base of the North Sea Super Group (map 13) reveals the subsidence since the beginning of the Tertiary.

2 Limburg Group

2.1 Stratigraphy

The sediments of the Limburg Group form the oldest deposits drilled within the area of the map sheet. They comprise alternations of claystones with fine to very fine sandstones, siltstones and coal layers. The sediments are of Late Carboniferous (Westphalian) age.

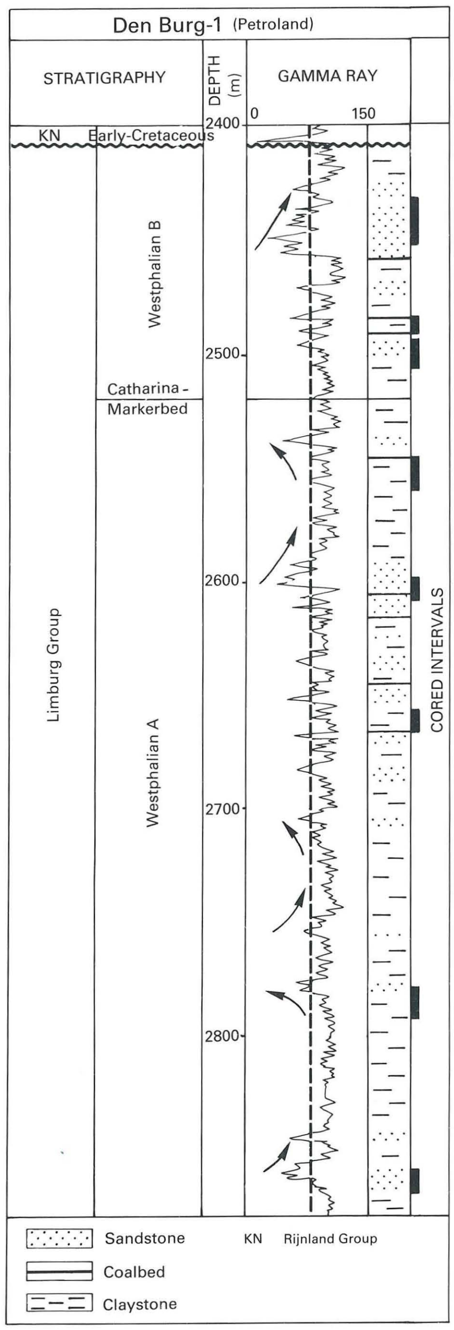


Figure 2.1 Composition of the Limburg Group in the Den Burg-1 well. Graded sequences are marked with an arrow: coarsening upward to the left, fining upward to the right. C: coal seam.

In general the Limburg Group is overlain unconformably in the map sheet area by the Upper Rotliegend Group of Early Permian age (map 1). The southern part of the map sheet area, where sediments from the Central Graben and the Rijnland Groups (Late Jurassic and Early Cretaceous, respectively) lie on the Limburg Group, is an exception (maps 14 and 15). The group is missing from the centre of the Zuidwal area as a result of Jurassic volcanic activity (Zuidwal-1 well).

None of the wells reached the base of the Limburg Group. Since the seismic information was also inadequate to determine the base, the thickness of this group is unknown. It is probable that marine deposits of Early Carboniferous age occur under the continental deposits of the Limburg Group.

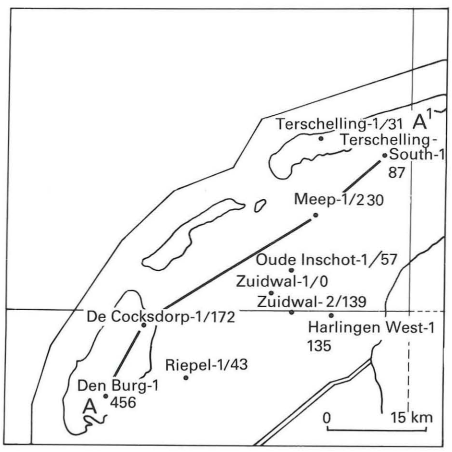
Only one formation, the *Coal Measures*, is distinguished within the Limburg Group here. This term, which is taken from the English Carboniferous stratigraphy, was introduced by NAM & RGD (1980) as the formation name for the Upper Carboniferous coal-bearing deposits.

Well Den Burg-1 (fig. 2.1), lying directly south of the map sheet, is used as reference well for the lithological description of the Limburg Group deposits. The Limburg Group sequence in this well is relatively thick (approximately 455 m) and there are ten cores available, distributed evenly throughout the sequence. The wells which have penetrated the Limburg Group are shown in figure 2.2 with the thicknesses logged.

2.1.1 Coal Measures

The Coal Measures comprise mainly dark grey to violet coloured silty claystones, in which sandstones and coal seams occur (figs 2.1 and 2.3). The claystones are micaceous and contain finely distributed plant remains; beds with roots or bioturbations, hardened by siderite, occur locally. The sandstones occur in coarsening-upwards and fining-upwards sequences. They are rich in micas and are fine to very fine sandy to silty. Based on log characteristics, the top of the Coal Measures is the sandiest in this area (figs 2.1 and 2.3). The thicknesses of the individual sandstone bodies vary widely and reaches an observed maximum thickness of more than 9 m in the Den Burg-1 well. Coal seams or coal-containing layers occur in nearly all the sequences of the Coal Measures studied. They are often only a few millimetres to several centimetres thick, but they can also reach a thickness of approximately 2 m (Terschelling South-1). Coal seams

Figure 2.2 Thickness map of the sequences drilled in the Limburg Group and the location of the stratigraphic section A-A'.



occur both at the tops of coarsening-upwards and fining-upwards sequences. Coal seams or coal-bearing sediments also occur in silty claystones that are not part of these sequences.
The recently published map of the top of the Carboniferous (Van Wijhe, 1987) gives a Westphalian A age to most of the map sheet area (fig. 2.4). Our own biostratigraphic research in fact indicates the presence of Westphalian B at the top of the Limburg Group in a number of wells (RGD, 1964; 1965; 1973; 1985b, 1985c; 1987; 1988b, 1988c). The presence of Westphalian B is also suspected from log correlations, because the Catharina Bed, the boundary between Westphalian A and B, is present in a number of wells (RGD, 1989b; fig. 2.3). The relatively sparse data does not, however, justify modification to Van Wijhe's (1987) map of the top of the Carboniferous at the moment.
The Coal Measures in the map sheet area were deposited in a sequence of varying fluvial, deltaic and lacustrine environments, with thin marine intercalations (RGD, 1989b).

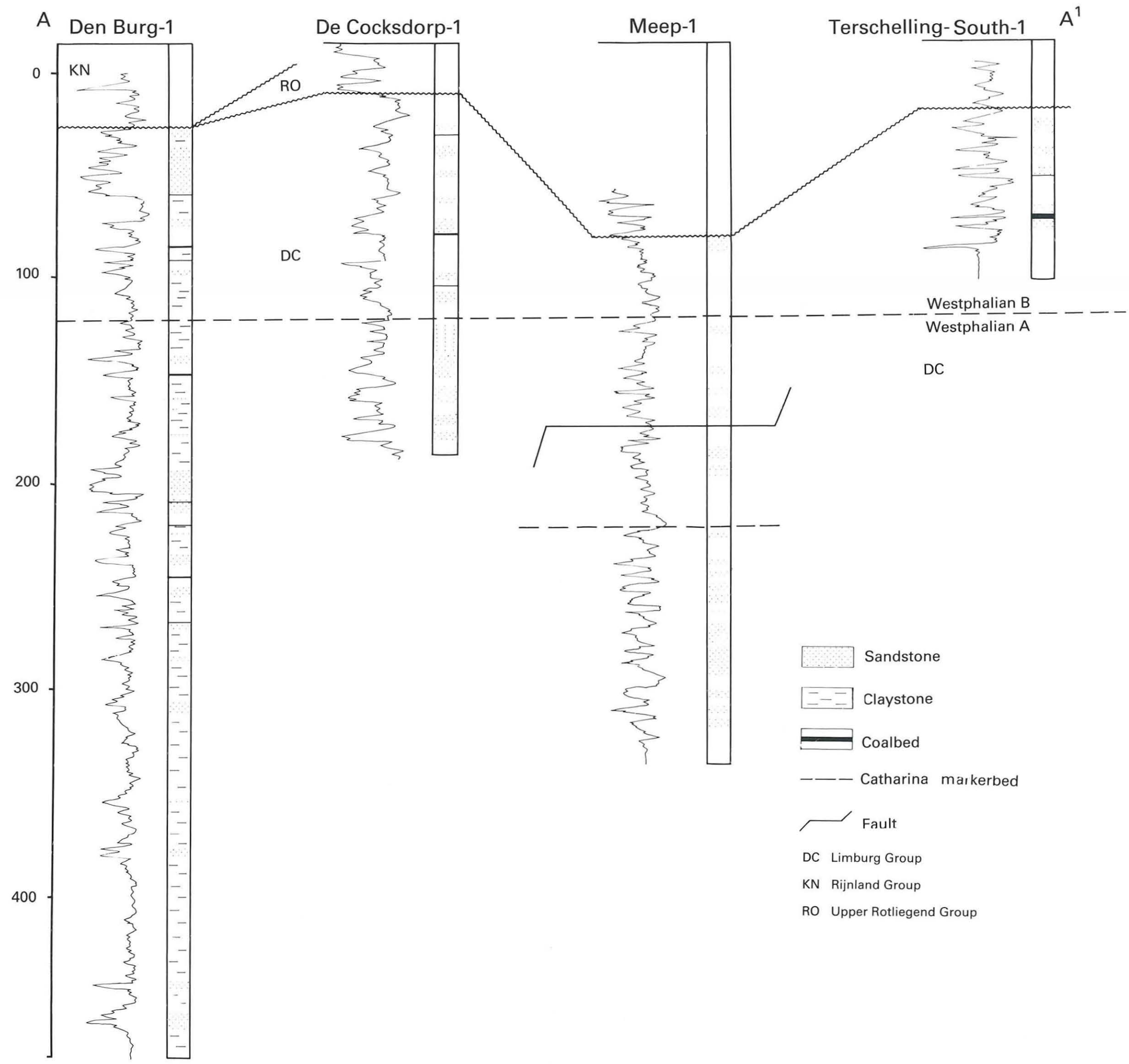


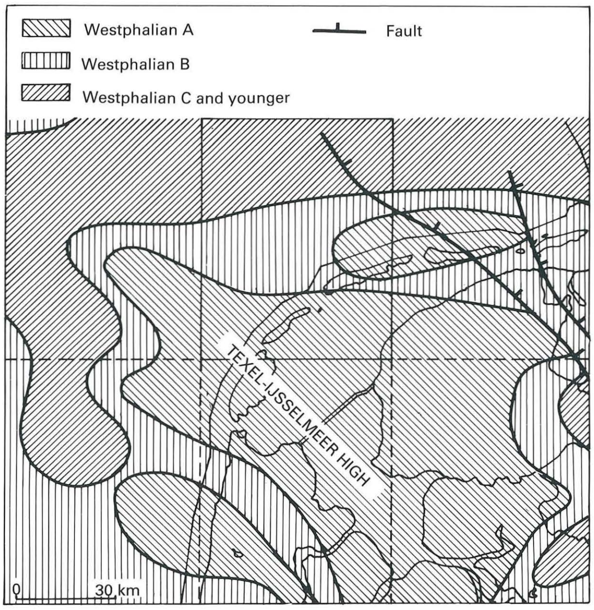
Figure 2.3 Stratigraphic section A-A', with the Catharina Bed as reference level. Gamma ray logs were made in all wells. After RGD, 1989b. The location of this section is shown in figure 2.2.

The Coal Measures were not fully drilled through in any of the wells within the map sheet area or in its direct surroundings.

2.2 Sedimentary development and palaeogeography

The clayey character of the continental deposits of the Limburg Group as well as the large geographical extent of the intercalated marine sediments indicate a landscape that must have been very flat during the deposition of the Limburg Group and that was only just above sea level. Both the tropical climate with its abundant plant growth and the very flat landscape, in which the surface water was often stagnant, contributed to the formation of lakes and marshes in which fine-grained sediments were deposited. Fining-upwards sequences are generally interpreted as being deposits from meandering rivers (Moody Stuart, 1966). This type of river originated in an area with little relief and where such river systems flowed into lakes, coarsening-upwards sequences were formed. Peat was formed both in the marshes and in cutoff channels. Coal was eventually formed by coalification of the peat consequent to its deep burial.

Figure 2.4 Subcrop map of the top of the Carboniferous. Adapted from Van Wijhe (1987).



3 Upper Rotliegend Group

3.1 Stratigraphy

The Upper Rotliegend Group comprises clastic sediments and evaporites. The sediments generally have a characteristic reddish or reddish-brown colour and were deposited under continental conditions. The group is split into two formations, the Slochteren Sandstone Formation and the Silverpit Claystone Formation, which grade laterally into each other within the map sheet area (fig. 3.1). The Upper Rotliegend Group is of Early Permian age.

The sediments of the Upper Rotliegend Group lie unconformably on the Carboniferous deposits of the Limburg Group, separated by the Saalian unconformity (map 1). The Late Permian Zechstein Group deposits lie directly on the Upper Rotliegend Group in most of the area (map 2). The contact between these two groups is conformable. However, in the southwest and south of the map sheet area, where the Upper Rotliegend Group is overlain by the Rijnland Group, the contact is unconformable (map 15).

The thickness of the Upper Rotliegend increases towards the north, from more than 200 m in De Cocksdorp-1 to more than 350 m in the offshore area to the north of the map sheet. Around the Zuidwal area in the south of the map sheet the thickness is 160-180 m. This is a result of the presence of the Zuidwal High during the deposition of the Upper Rotliegend Group (fig. 3.2).

Except for the Silverpit Evaporites, all the members of the Slochteren Sandstone and Silverpit Claystone Formations defined in NAM & RGD (1980) occur within the map sheet (fig. 3.1). The stratigraphic sequence of the Upper Rotliegend Group is illustrated by the De Cocksdorp-1 well, which lies directly to the south of the map sheet area (fig. 3.3) and in which all the members occur. The location of this and other relevant wells is given in figure 3.4.

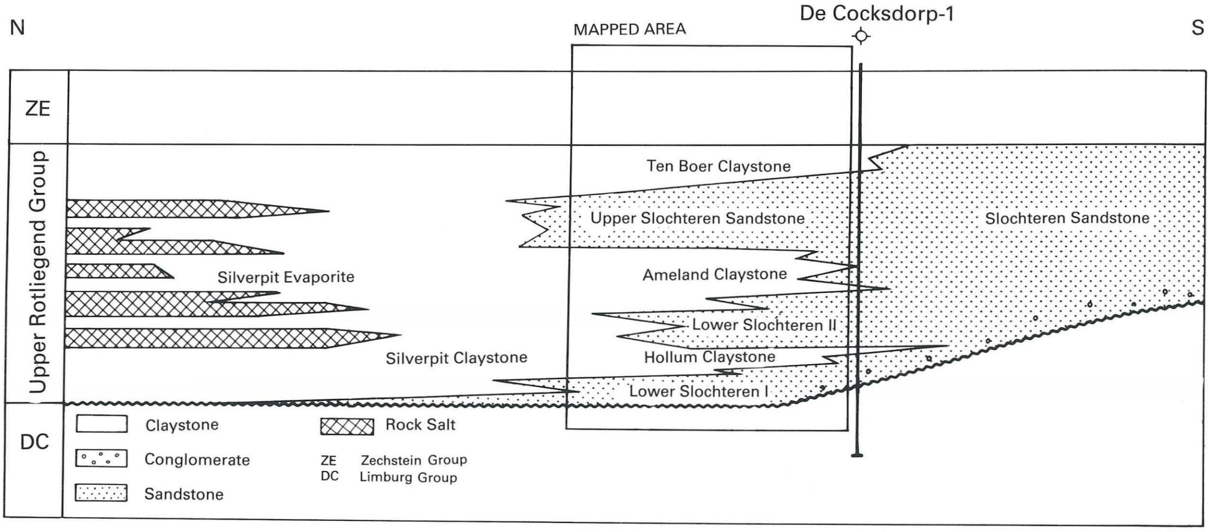


Figure 3.1 Schematic stratigraphic diagram of the Upper Rotliegend Group. The position of the map sheet area is shown and also the location of the De Cocksdorp-1 well (fig. 3.3), directly to the south of the map sheet area. Adapted from NAM & RGD (1980).

3.1.1 Slochteren Sandstone Formation

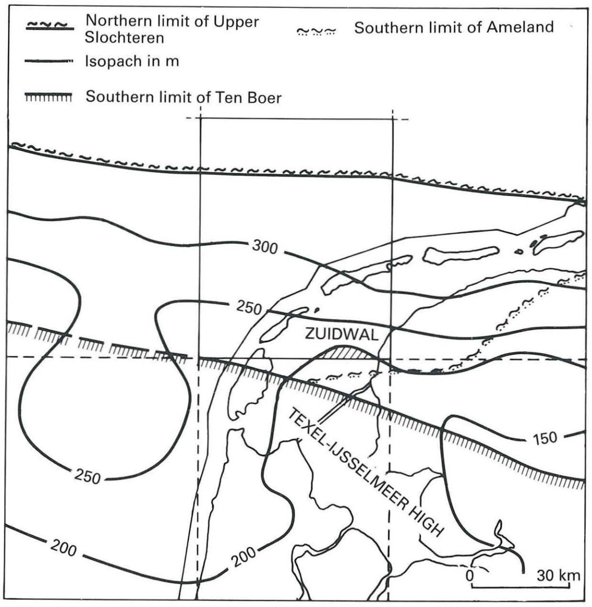
Three sandstone units can be distinguished in the south of the map sheet area from wells in the Slochteren Sandstone Formation. They are separated stratigraphically by tongues of claystone of the Silverpit Claystone Formation (fig. 3.1). The uppermost sand unit is the Upper Slochteren Sandstone. The middle and lower units form the Lower Slochteren Sandstone. This division of the Lower Slochteren Sandstone into two parts can be recognised over a large area of the northern Netherlands but the claystones are missing to the south of the map sheet so that no division can be made (figs 3.1 and 3.5).

The *Lower Slochteren Sandstone* only occurs in the southern part of the map sheet and is split into two parts by interfingering with the Silverpit Claystone Formation (fig. 3.1). The basal part is informally called the Lower Slochteren I and comprises sandstone beds with intercalated layers of conglomerate and claystone. The sandstone banks have an erosive base with a basal conglomerate. Further fining-upwards is observed in the sandstone, as well as small-scale cross-stratification. The conglomerates have a fine sandy to clayey matrix.

The upper part of the Lower Slochteren Sandstone, informally called Lower Slochteren II, comprises fine to coarse, red to reddish-brown coloured quartz sandstones, in which the grains are generally well rounded. The gamma-ray log pattern of the Lower Slochteren II in De Cocksdorp-1 indicates the relatively clean nature of this sandstone (fig. 3.3).

A much thinned Lower Slochteren Sandstone lies unconformably on the Limburg Group in the Zuidwal-2 and Oude Inschot-1 wells (fig. 3.6). The reason for this thinning is thought to be the presence of a depositional high, the Zuidwal High. To the north the unit becomes the Silverpit Claystone Formation (fig. 3.6). At the same time it is evident that the thickness of the lowest part of the unit increases to the northwest of the map sheet area (fig. 3.5).

Figure 3.2 Reconstructed thickness map of the Upper Rotliegend Group. The northern limit of distribution of the Upper Slochteren Sandstone is marked, as well as the southern limits of the Ameland Claystone and the Ten Boer Claystone.



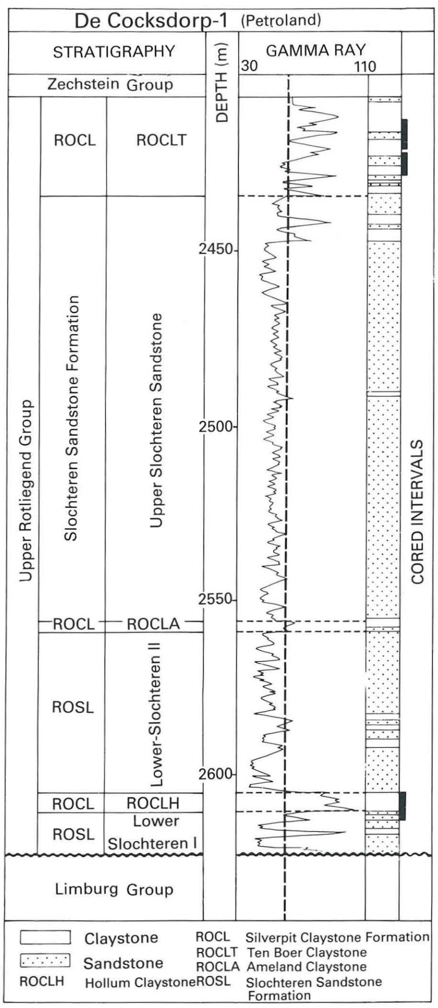
Within the map sheet area the association of lithofacies indicates a fluvial and possibly aeolian environment of deposition. The basal part of the unit, Lower Slochteren I, appears to have been completely deposited by braided river systems, while in the Lower Slochteren II aeolian deposits also occur. This is in agreement with data from the literature (Van Wijhe et al., 1980; Van Lith, 1983; Glennie, 1984). It is assumed that the sediments lying in the transitional area between the Lower Slochteren Sandstone and the Silverpit Claystone Formation were deposited in a sabkha-type environment.

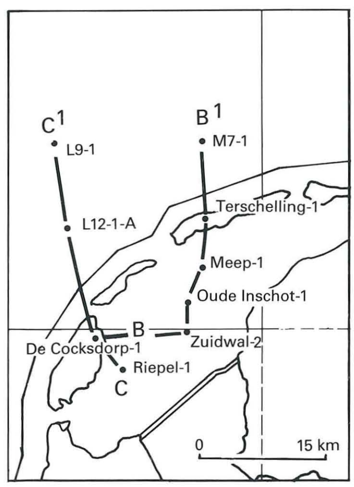
The *Upper Slochteren Sandstone* can be recognised in all the wells in the map sheet area. In the southern part of this area it comprises a relatively clean sandstone. Towards the north the unit grades laterally into the Silverpit Claystone Formation. This is evident as intercalated sandy and silty claystones (Terschelling-1). The thickness of the member varies from 105 m in Zuidwal-1 to approximately 135 m in Meep-1.

The Upper Slochteren Sandstone comprises mainly reddish-brown, well sorted, fine sandstones in the map sheet area. Further south very coarse-grained sandstones occur locally (De Cocksdorp-1, Riepel-1). The sandstones are poorly cemented and comprise mainly quartz. Small

Figure 3.3 Composition of the Upper Rotliegend Group in the De Cocksdorp-1 well (Petroland).

Figure 3.4 Overview map of the wells used for the description of the Upper Rotliegend Group and the locations of the sections B-B' and C-C' (figures 3.5 and 3.6, respectively).





quantities of feldspar, volcanic material and shale fragments are also found (De Cocksdorp-1, Oude Inschot-1). The red colouring mostly grades into beige in the top tens of metres.

The well-sorted sandstones of the Upper Slochteren Sandstone are described as aeolian deposits, formed in a desert-type environment (Blanche, 1973; Glennie, 1972, 1983; Marie, 1975; Van Adrichem Boogaert, 1976; Van Wijhe et al., 1980). The slightly coarser and less well-sorted sandstones are interpreted as deposits from wadis and braided rivers. Just as in the case of the Lower Slochteren Sandstone, it is assumed that sediments in the transitional area with the Silverpit Claystone Formation were deposited in a sabkha-type environment.

3.1.2 Silverpit Claystone Formation

The Silverpit Claystone Formation is the distal equivalent of the Slochteren Sandstone Formation and is mainly composed of alternations of red, reddish-brown and brown coloured silty claystones and siltstones. The Silverpit Claystone Formation contains local intercalations of thin layers of dolomite and anhydrite, and fine sandstones in the transitional area with the Slochteren Sandstone Formation. Within the map sheet area this formation reaches a thickness of 150 m (Terschelling-1, fig. 3.5). The thickness of the Silverpit Claystone Formation increases further northwards.

In the transitional area with the Slochteren Sandstone Formation, the Silverpit Formation is divided up as follows: (from bottom to top) the Hollum Claystone, the Ameland Claystone and the Ten Boer Claystone (fig. 3.1). They are all interpreted as playa lake deposits (Glennie, 1984).

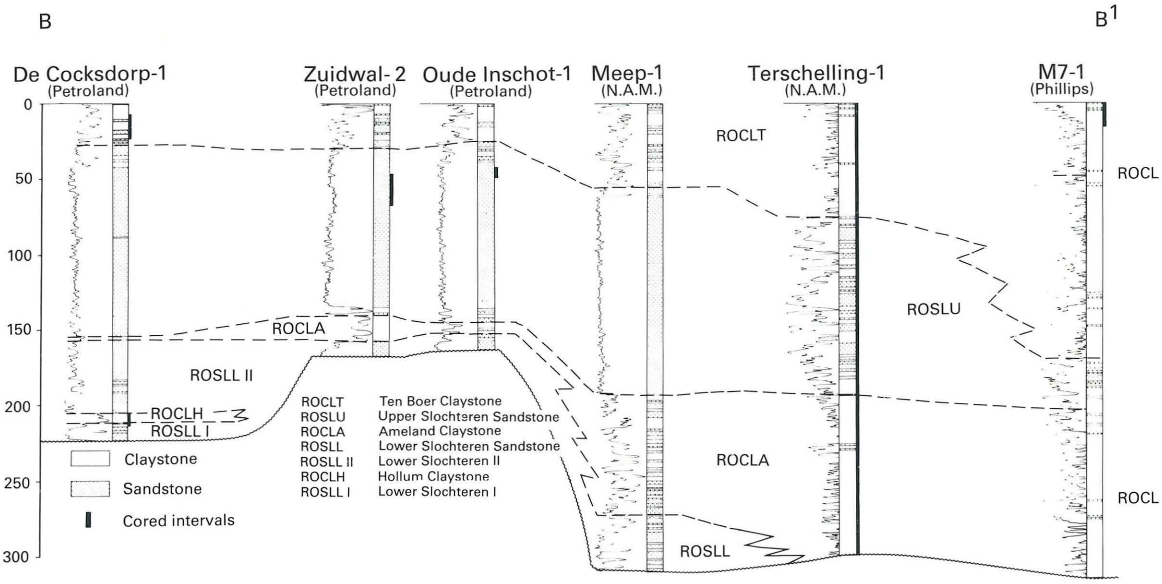


Figure 3.5 Stratigraphic section B-B', with the base of the Zechstein Group as reference level. This section shows the influence of the Zuidwal High during the deposition of the Upper Rotliegend Group. The location of this section is given in figure 3.4.

The *Hollum Claystone* is only distinguished in the southern part of the map sheet. This unit has a thickness of 5 m in De Cocksdorp-1. In contrast to the example given by NAM & RGD (1980), sandy deposits were also found in the Hollum Claystone in De Cocksdorp-1 (fig. 3.3).

The *Ameland Claystone* is found throughout the map sheet area. In De Cocksdorp-1 the claystone is only a few metres thick (fig. 3.3). The thickness increases further northwards. In the northeast of the map sheet, where there is no Lower Slochteren Sandstone, the Ameland Claystone directly overlies the Limburg Group (figs 3.5 and 3.6).

The *Ten Boer Claystone* is the uppermost unit of the Silverpit Claystone Formation and is overlain by the Coppershale of the Zechstein Group. The thickness of the Ten Boer Claystone increases northwards, from approximately 25 m in De Cocksdorp-1 to more than 70 m in Terschelling-1 (fig. 3.5). Southwards the unit becomes sandier (De Cocksdorp-1) and south of the map sheet area it grades laterally into the Slochteren Sandstone (fig. 3.6).

3.2 Sedimentary development and palaeogeography

The Upper Rotliegend Group was deposited under continental conditions in the intra-cratonic Southern Permian Basin (fig. 10.1). During the deposition of the Lower Slochteren Sandstone

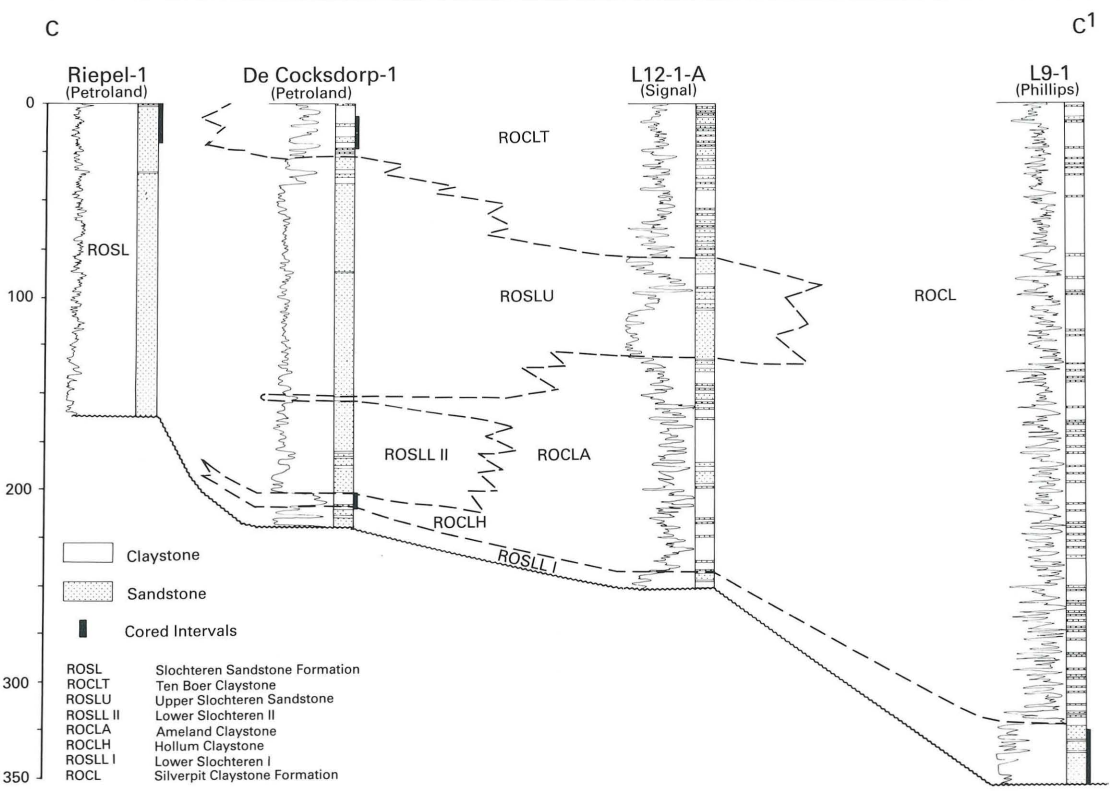


Figure 3.6 Stratigraphic section C-C′, with the base of the Zechstein Group as reference level. This section shows the transition of the Texel-IJsselmeer High to the Southern Permian Basin. The location of this section is given in figure 3.4.

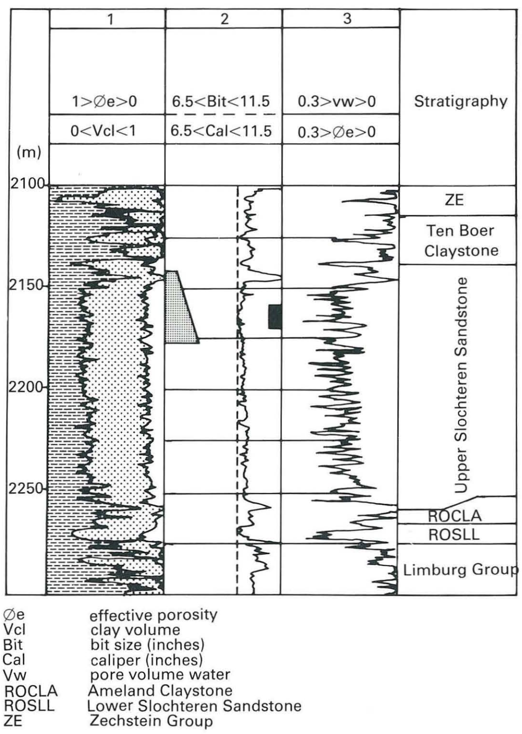
the map sheet area lay within the influence of a braided river system. During the deposition of the lowest part of this unit, the Zuidwal High and possibly, initially, the Texel-IJsselmeer High were exposed to erosion.

A lake formed in the centre of the basin with a desert area, under the influence of the arid climate, on its southern shore. The deposits within the map sheet area show the interaction between the northern expansion of the desert area and the southern expansion of the lake. The Hollum, Ameland and Ten Boer Claystones represent the lacustrine deposits, while the Lower and Upper Slochteren Sandstones are the aeolian and fluvial deposits of the desert area. The shifting of the facies boundary between these areas during the deposition of the Upper Rotliegend Group was influenced by variations in the water level of the lake, on the one hand, and the sediment influx, on the other.

During the deposition of the Hollum Claystone, the lake expanded to cover most of the area of the map sheet. Only on the Zuidwal High was there no deposition; some erosion may even have taken place. This high was only covered by sediment at a depositional later stage of the Lower Slochteren Sandstone.

The deposits of the Upper Slochteren Sandstone represent a new period of northwards expansion of the desert area. Sedimentation took place under aeolian and fluvial conditions. Thereafter the lake grew southwards again over the map sheet area and the Ten Boer Claystone was deposited as the uppermost unit of the Upper Rotliegend Group.

Figure 3.7 Petrophysical evaluation of the Upper Rotliegend sequence in Oude Inschot-1. Column 1: clay content Vcl, determined from the gamma ray log, and effective porosity øe. The effective porosity was determined with the use of acoustic logs (Raymer-Hunt comparison in single porosity model; Raymer et al., 1980) after correction for the clay content. Column 2: wellhole diameter (Cal) and drillbit diameter (Bit), both in inches; tested and cored intervals are also marked (appendix D). Column 3: effective porosity øe and the water volume in the pores Vw. The last two curves are nearly the same because of the high water saturation (Sw). The Indonesian formula, which is suitable for clayey formations was used to determine the water saturation (Fertl, 1987). Depths are actual depths.



The extended boundary of the lacustrine deposits lies just to the south of the map sheet area; to the south of which the Upper Rotliegend Group consists entirely of fluvial and aeolian deposits (figs 3.5 and 3.6). This extended boundary of the lacustrine deposits is prescribed to the influence of the Texel-IJsselmeer High, which subsided slightly less than the areas lying further to the north.

The source areas for the Slochteren Sandstones probably lay to the south and east of the map sheet area. The coarser sands and conglomerates of the Lower Slochteren Sandstone mainly originate from the southern source area and were transported northwards via wadis from the Variscan mountains (Stäuble & Milius, 1970; Van Wijhe et al., 1980). The aeolian deposits of the Upper Rotliegend probably originated from a much larger area, which stretched far to the east of the map sheet area. Possibly deflation of the sediments deposited by the degraded rivers and in the wadis played an important role (Glennie, 1972). During the deposition of the Upper Rotliegend Group, the basin subsidence exceeded the sedimentation rate and, by the beginning of the Late Permian, a large depression below sea level had developed (Glennie, 1984).

3.3 Petrophysical evaluation

The sandstones of the Upper Rotliegend Group form one of the principal targets for exploration in The Netherlands' territory and on the continental shelf. The petrophysical features of the deposits of this group were evaluated from eleven wells in the map sheet area and direct surroundings (appendix C; RGD, 1990b). The sandstones of the Upper Rotliegend Group are water-saturated in all of these wells (appendix D). The results from the Oude Inschot-1 well are shown in figure 3.7 as an example of a log evaluation of the Upper Rotliegend reservoir sequence. Figure 3.8 shows schematically the distribution of the average effective porosity (Øem) of the Upper Rotliegend Group in the map sheet area and surroundings. This porosity distribution conforms with the facies distribution of the Slochteren Sandstone Formation.

The average effective porosities of the Upper Rotliegend reservoir sequences are lower than one would expect on the basis of the present depth of burial. The compaction curve in figure 3.9 was used as the basis for calculating the reduction of porosity as a consequence of burial for the Upper Rotliegend sandstones. The value of the surface porosity (28.5%) falls within the limits of

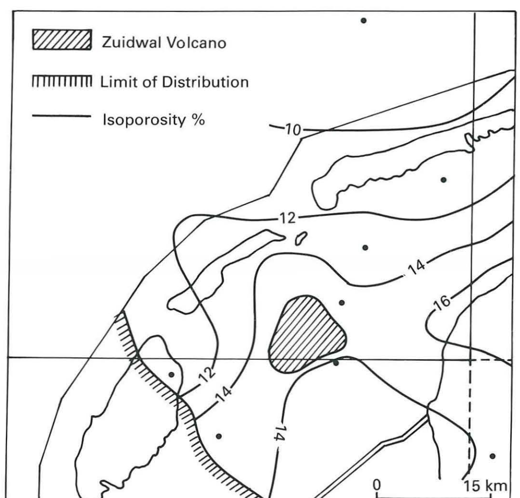


Figure 3.8 Schematic contour map of the reservoir-average effective porosity øem of the Upper Rotliegend Group (appendix C).

surface porosity given by Nagtegaal (1979), i.e. 26% (wadi facies) to 40% (dune top facies). Burial history studies indicate in fact that the Upper Rotliegend Group in the map sheet area has never been buried any deeper than its present position (Perrot & Van der Poel, 1987). The porosity reduction was caused by cementation as well as by physical compaction. To a slight extent quartz, anhydrite, calcite and dolomite are present as cements. The quartz grains also appear to have a coating of hematite. Especially the early diagenetic cementation probably played a role in reducing the porosity. Given the low depth of burial, it is unlikely that formation of the authigenic clay mineral, illite, contributed to reduction of the reservoir quality.

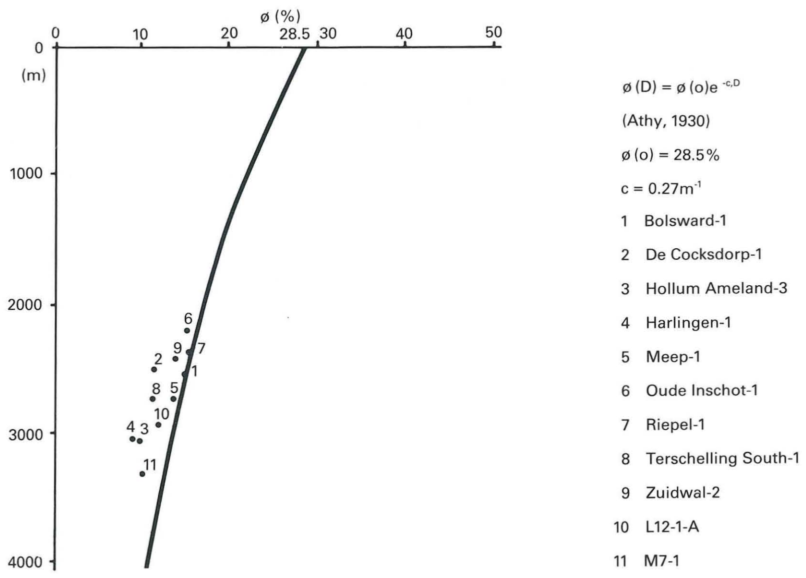


Figure 3.9 Porosity versus depth plot for the Upper Rotliegend Group. The curve drawn is the compaction curve according to Athy's (1930) relation, with a surface porosity for sandstone ø(0) = 28.5%. A value of 0.27 was adopted for the constant c (Sclater & Christie, 1980). The data points represent the reservoir-average effective porosity of the Upper Rotliegend Group as a whole (appendix C).

4 Zechstein Group

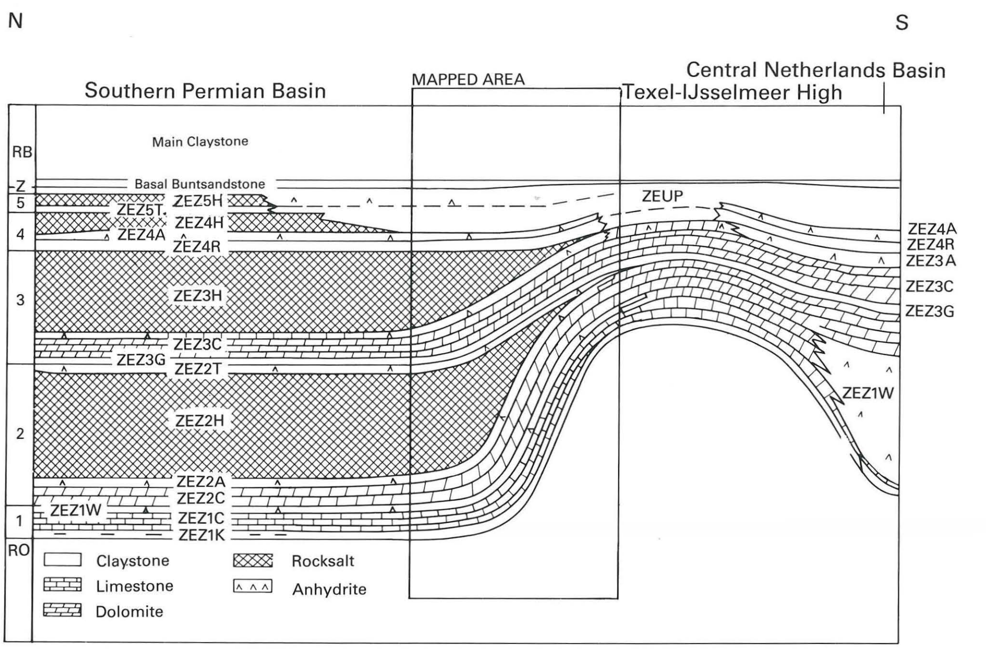
4.1 Stratigraphy

The Zechstein Group comprises mainly evaporites formed by the periodic flooding and subsequent evaporation of sea water. A complete evaporite cycle comprises carbonate/dolomite – anhydrite – halite – potassium and magnesium salts – halite and anhydrite, from bottom to top (Herrmann, 1981).

The Zechstein Group lies conformably on the Rotliegend Group (map 2) and in most of the area is overlain unconformably by the Central Graben and Rijnland Groups, of Late Jurassic and Early Cretaceous age respectively (maps 14 and 15). In the Harlingen Sub-basin in the southeastern part of the map sheet area, and in the extreme northwest, the Zechstein Group is overlain conformably by the Lower Germanic Trias Group (map 5). The age of the Zechstein Group is Late Permian (NAM & RGD, 1980; Van Adrichem Boogaert & Burgers, 1983).

The deposits of the Zechstein Group occur in most of the map sheet area. The greatest thickness mapped is more than 1100 m. The group is not present on the Zuidwal High or on the Texel-IJsselmeer High in the extreme southwest of the map sheet (map 4).

Five evaporite cycles can be recognised in the map sheet area in the Zechstein Group; the Zechstein 1 up to and including Zechstein 4 Formations and the Upper Zechstein (fig. 4.1). The Upper Zechstein is an informal unit at the top of the Zechstein Group. This deviates from the



ZEUP	Upper Zechstein	ZEZ 2 T	Zechstein 2 Roof Anhydrite
ZEZ 5 H	Zechstein 5 Salt	ZEZ 2 H	Zechstein 2 Salt
ZEZ 5 T	Zechstein 5 Salt Clay	ZEZ 2 A	Zechstein 2 Anhydrite
ZEZ 4 H	Zechstein 4 Salt	ZEZ 2 C	Zechstein 2 Carbonate
ZEZ 4 A	Zechstein 4 Pegmatite-Anhydrite	ZEZ 1 W	Zechstein 1 Anhydrite
ZEZ 4 R	Zechstein 4 Salt	ZEZ 1 C	Zechstein 1 Carbonate
ZEZ 3 A	Zechstein 3 Main Anhydrite	ZEZ 1 K	Zechstein 1 Coppershale
ZEZ 3 H	Zechstein 3 Salt	RB	Lower Germanic Trias Group
ZEZ 3 C	Zechstein 3 Carbonate	RO	Upper Rotliegend Group
ZEZ 3 G	Zechstein 3 Grey Salt Clay		

Figure 4.1 Schematic stratigraphic diagram showing the composition of the Zechstein Group in the map sheet area and its immediate vicinity. Adapted from NAM & RGD (1980) and Plomp & Geluk (1988).

NAM & RGD (1980) definition of the Zechstein Group and the transition to the Lower Germanic Trias Group. The composition of the Zechstein Group is illustrated by the Harlingen-1 well, which lies just outside the map sheet area, where a complete section was drilled (fig. 4.2).

4.1.1 Zechstein 1 Formation

The Zechstein 1 Formation is composed of the Coppershale, the Zechstein 1 Carbonate and the Zechstein 1 Anhydrite layers. In the map sheet area the thickness of this formation varies from 6 m in the Oude Inschot-1 well to 48 m in Terschelling-1.

The *Coppershale* is a black claystone, rich in organic material and about 1 m thick. This unit lies at the base of the Zechstein Group and is found over nearly all the Southern Permian Basin. It is characterised by a high gamma-ray log recording, caused by a high content of radioactive minerals.

The *Zechstein 1 Carbonate* (fig. 4.3A) is a grey-brown dolomitic calcareous rock. The lowest part of this unit contains some clay, but the clay content decreases upwards.

The *Zechstein 1 Anhydrite* (fig. 4.3B) comprises anhydrite with some interbedded dolomite. In the Zuidwal-2, Riepel-1 and De Cocksdorp-1 wells, on the Texel-IJsselmeer High and the Zuidwal High, these dolomite interbeds become so thick with respect to the anhydrite that this unit can

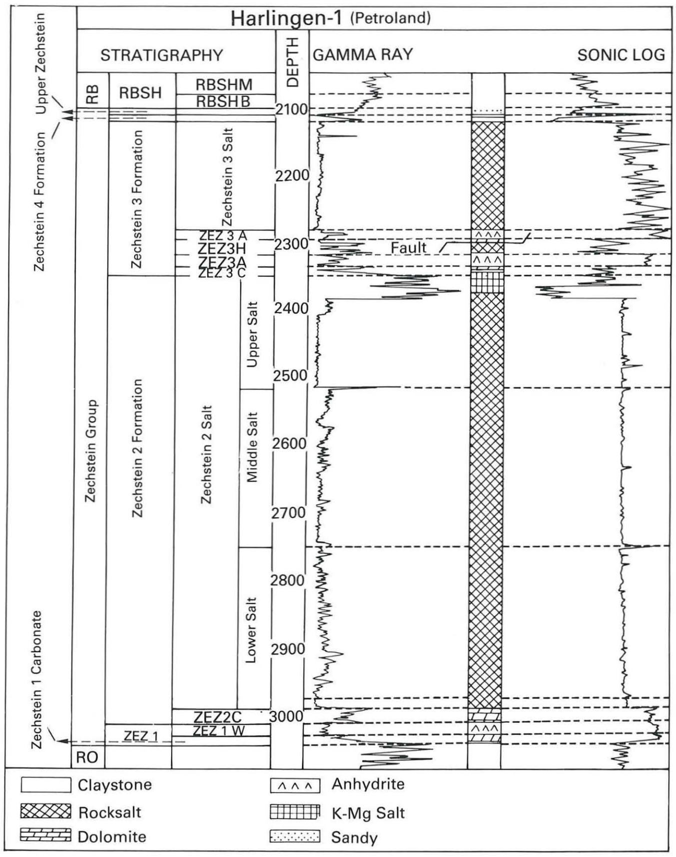


Figure 4.2 The composition of the Zechstein Group in the Harlingen-1 well. There is a fault in the section at approximately 2300 m, which causes a repetition of the sequence. The quality of the sonic log in the Zechstein 3 Salt is poor.

no longer be distinguished lithologically from the underlying Zechstein 1 Carbonate (fig. 4.7). In the De Cocksdorp-1 and Riepel-1 wells, intraformational breccia strata also occur in the carbonates.

4.1.2 Zechstein 2 Formation

The Zechstein 2 Formation consists of the Zechstein 2 Carbonate, the Zechstein 2 Basal Anhydrite, the Zechstein 2 Salt and the Zechstein 2 Roof Anhydrite Members. This is the only formation which represents a complete evaporation cycle.

The thickness of this formation varies from a few metres near the Zuidwal High and the Texel-IJsselmeer High to more than 800 m in the southeastern corner of the map sheet (fig. 4.2). As well as variation in depositional thickness, this is primarily due to variations in the thickness of the salt as a consequence of salt flow.

The *Zechstein 2 Carbonate* (Main Dolomite) is composed of a brown compact limestone and dolomite, with increasing clay content towards the top. The thickness of the Zechstein 2 Carbonate is least on the Zuidwal High and the Texel-IJsselmeer High (fig. 4.3C).

The *Zechstein 2 Basal Anhydrite* (fig. 4.3D) is composed of a white to beige coloured anhydrite. On the Zuidwal High, this unit is much reduced in thickness and it is completely missing on the Texel-IJsselmeer High.

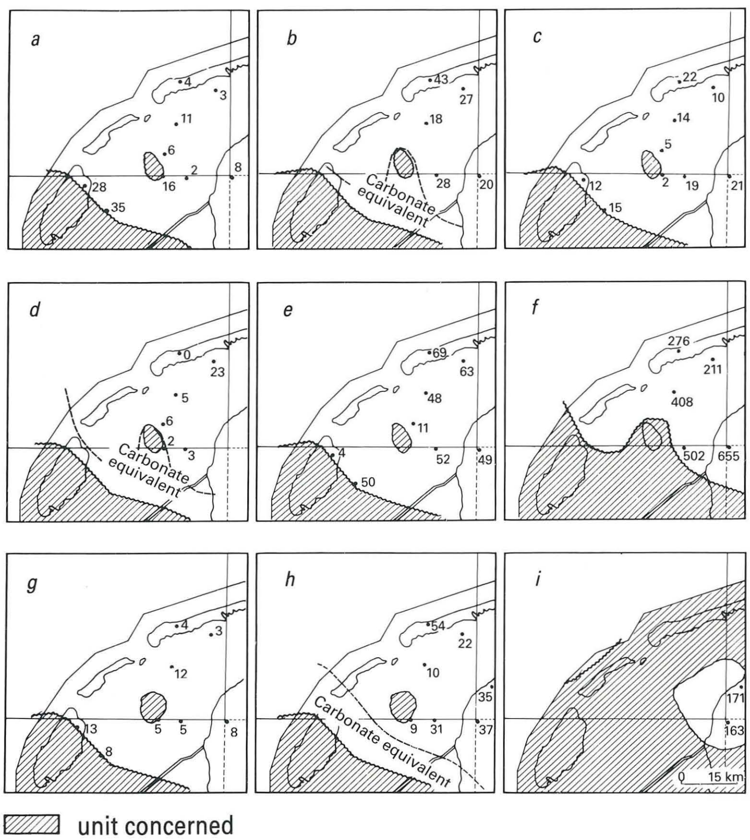


Figure 4.3 The distributions and thicknesses of the different members of the Zechstein Group within the map sheet area.

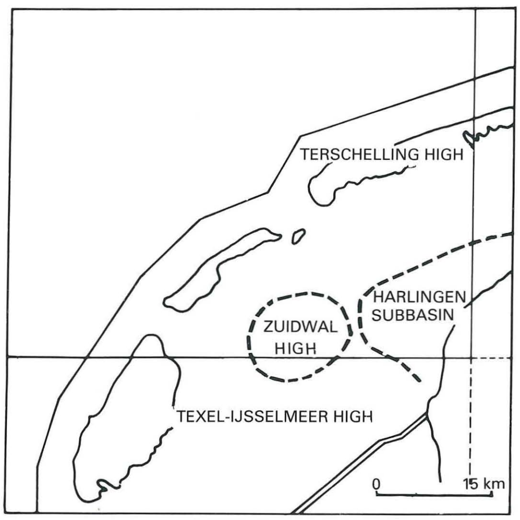
a Zechstein 1 Carbonate
b Zechstein 1 Anhydrite
c Zechstein 2 Carbonate
d Zechstein 2 Basal Anhydrite
e Pre-saline sequence (Zechstein 1 Formation together with the Zechstein 2 Carbonate and the Zechstein 2 Basal Anhydrite)
f Zechstein 2 Salt
g Zechstein 3 Carbonate
h Zechstein 3 Anhydrite
i Zechstein 3 Salt

The Zechstein 1 Formation, the Zechstein 2 Carbonate and the Zechstein 2 Basal Anhydrite together form the pre-saline substratum on which the Zechstein 2 Salt was deposited. Thickness variations in this substratum indicate the relief present before the salt was precipitated. The thickness of this pre-saline sequence was approximately 50 m in the Harlingen Sub-basin, and 45-60 m in the offshore area to the north of the map sheet. The thickness was 11 m on the Zuidwal High and 20-24 m on the Texel-IJsselmeer High (fig. 4.3E). The great thickness of this unit near Terschelling (65 m), together with the negligible thickness of the Zechstein 2 Salt in this area, indicates a depositional high, the Terschelling High (fig. 4.4). This high was less pronounced than either the Texel-IJsselmeer High or the Zuidwal High and provided favourable conditions for carbonate and anhydrite deposition.

The *Zechstein 2 Salt* (fig. 4.3F) is white to translucent, mostly coarsely but sometimes finely crystalline. Within the map sheet area, this unit reaches a maximum thickness of approximately 800 m in the Harlingen Sub-basin. The Zechstein 2 Salt was not deposited on the Zuidwal High or the Texel-IJsselmeer High. Three salt members can be distinguished in the Zechstein 2 Salt (fig. 4.2). The members are separated by polyhalite layers. This triple sequence can be correlated regionally in The Netherlands and on the adjacent continental shelf (fig. 4.6). The lowest member is characterised at the base by interbedded anhydrite layers and above those by interbedded layers of potassium-magnesium salts in the halite. This gives it a strongly peaked character on the gamma-ray log. The potassium content decreases slowly towards the top. Subcycles, each with an upwards-increasing potassium content, can be recognised in the middle one of the three salt members.

In the top salt member, which is characterised by very pure rock salt, potassium-magnesium rich salt layers are present. These form the equivalent of the 'Kaliflöz Stassfurt', which occurs at the same stratigraphic level in West Germany (Kulick & Paul, 1987). The thickness of these potassium-magnesium salts is 40 m in the Harlingen-1 well. They achieve a greater thickness in the Harlingen Sub-basin than the average over the northern Netherlands. Carnallite, kieserite, sylvite and halite are present in these layers.

Figure 4.4 Palaeogeographic map at the time of deposition of the Zechstein Group.



The Zechstein 2 cycle ended with the deposition of the *Zechstein 2 Roof Anhydrite.* This is a pure anhydrite with a thickness of a few metres.

4.1.3 Zechstein 3 Formation

The Zechstein 3 Formation is divided into four members: the Grey Salt Clay, the Zechstein 3 Carbonate, the Zechstein 3 Main Anhydrite and the Zechstein 3 Salt (fig. 4.2). The thickness of this formation varies from a few metres on the edge of the Texel-IJsselmeer High to 200 m in the Harlingen Sub-basin. The Zechstein 3 Main Anhydrite is unconformably overlain by Upper Jurassic or Lower Cretaceous deposits outside the area of the Harlingen Sub-basin (fig. 4.6).

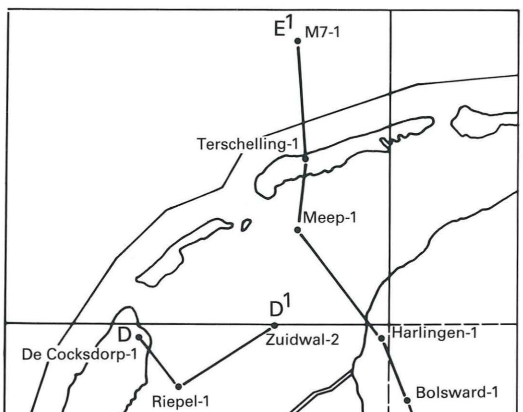
The *Grey Salt Clay* is a 2-4 m thick, grey claystone. This unit has a characteristically high gamma-ray log record and is very useful for regional correlations.

The *Zechstein 3 Carbonate* (Platy dolomite or Plattendolomite) comprises finely crystalline, beige to light brown dolomite. The thickness of this unit within the map sheet area is 2-5 m, with a remarkable thickness of 12 m in Meep-1 (fig. 4.3G). In the Riepel-1 and De Cocksdorp-1 wells, there are intercalated breccias in the Zechstein 3 Carbonate (fig. 4.7).

The *Zechstein 3 Main Anhydrite* comprises white anhydrite, with carbonate interbedding and claystone layers in the lowest part. The thickness of this unit varies greatly within the map sheet area (fig. 4.3H). The unit is missing from the Texel-IJsselmeer High and only carbonate and claystone interbeds are found; these are assigned to the Zechstein 3 Carbonate.

The *Zechstein 3 Salt* comprises orange to red coloured rock salt. Potassium-magnesium salt layers are not found in this unit within the map sheet area. The Zechstein 3 Salt reaches a maximal thickness of 163 m in the Harlingen-1 well (figs 4.2 and 4.3I).

Figure 4.5 Location of the stratigraphic sections D-D′ and E-E′ with respect to the map sheet area.



4.1.4 Zechstein 4 Formation

The Zechstein 4 Formation comprises the *Red Salt Clay* with a maximal thickness of 3 m and the 1 m thick *Zechstein 4 Pegmatite-Anhydrite*. The formation is only found in the southeastern part of the map sheet area and on the Texel-IJsselmeer High, although the Pegmatite-Anhydrite is missing on the high. No rock salt was deposited in this formation in the area studied.

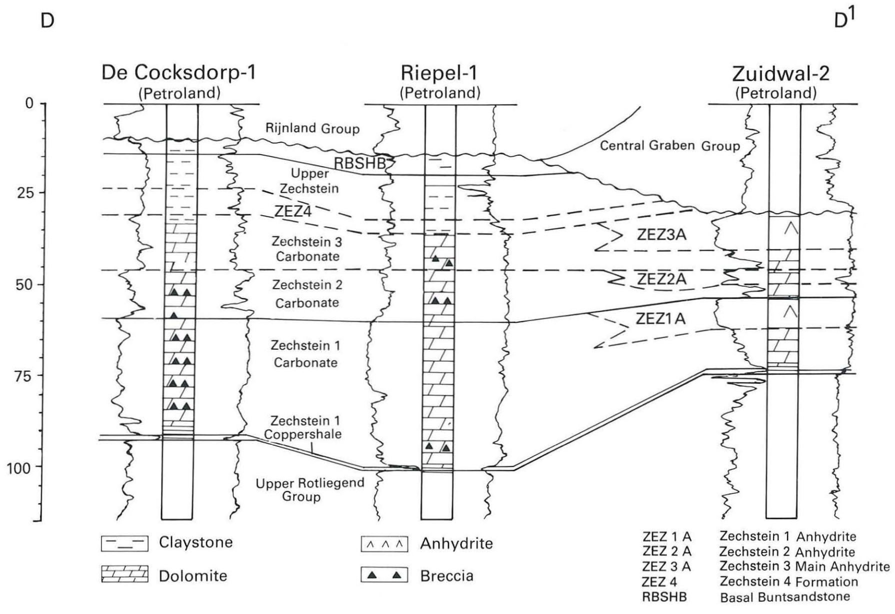
4.1.5 Upper Zechstein *(informal)*

The Upper Zechstein is an anhydritic claystone succession between the Pegmatite-Anhydrite and the basal part of an easy to correlate, fine sandy sequence at the base of the Lower Germanic Trias Group (see also chapter 5). Although NAM & RGD (1980) assigned a Permian age to part of the transition succession between the Zechstein Group and the Lower Buntsandstein Group, the succession was grouped with the Basal Buntsandstein of the Lower Germanic Trias group for practical reasons.

The equivalents of the higher Zechstein cycles, especially as described in Germany (Best, 1989), can also be distinguished in The Netherlands (RGD, 1989d). This succession has been informally named the Upper Zechstein in the present study (see figure 4.8 for the difference in stratigraphic interpretations).

The Upper Zechstein is preserved locally and consists of claystones with thin anhydrite layers. The claystones of this formation are characterised by low acoustic velocities. The equivalent of the fifth evaporite cycle can still be recognised in this succession. The formation is approximately 10 m thick.

Figure 4.6 Stratigraphic section D-D', with the base of the Lower Germanic Trias Group as reference level. The section runs from the Texel-IJsselmeer High (Heegermeer-1) towards the centre of the basin (M7-1). It shows the palaeo-relief during the deposition of the Zechstein Group. The location is given in figure 4.5.



4.2 Sedimentary development and palaeogeography

During the deposition of the Zechstein Group the study area was still part of the Southern Permian Basin. A large topographic depression was formed below sea level at the end of the Early Permian (Glennie, 1972, 1984). At the beginning of the Late Permian a rapid transgression invaded this depression, possibly under catastrophic circumstances (Glennie & Buller, 1983). This transgression heralded the deposition of several evaporite cycles.

The evaporite cycles of the Zechstein Group began with an influx of sea water. Then the salinity of the water increased because the sea level fell putting of the connection with the open ocean and because of the dominant arid climate. The more easily dissolved salts were deposited because of the increase in salinity. The closing of the connection to the open ocean was ascribed to changes in sea level, possibly related to alternating glacial and interglacial periods (Ziegler, 1988).

Variations in the extent of basin subsidence can be seen in the map sheet area (map 4). In the southwestern part there were a few pronounced highs during deposition of the Zechstein Group, namely the Texel-IJsselmeer High and the Zuidwal High (fig. 4.4). Carbonate-anhydrite platforms developed on the sides of these highs; evaporation largely exposed the highs and increased the salinity so much that salts were deposited in the deeper areas. Thick salt successions were deposited especially in the Harlingen Sub-basin. The influence of the basins and highs on sedimentation was limited mainly to the Zechstein 1, 2 and 3 Formations. The primarily clastic composition of the Zechstein 4 Formation and the Upper Zechstein reflect the transition to

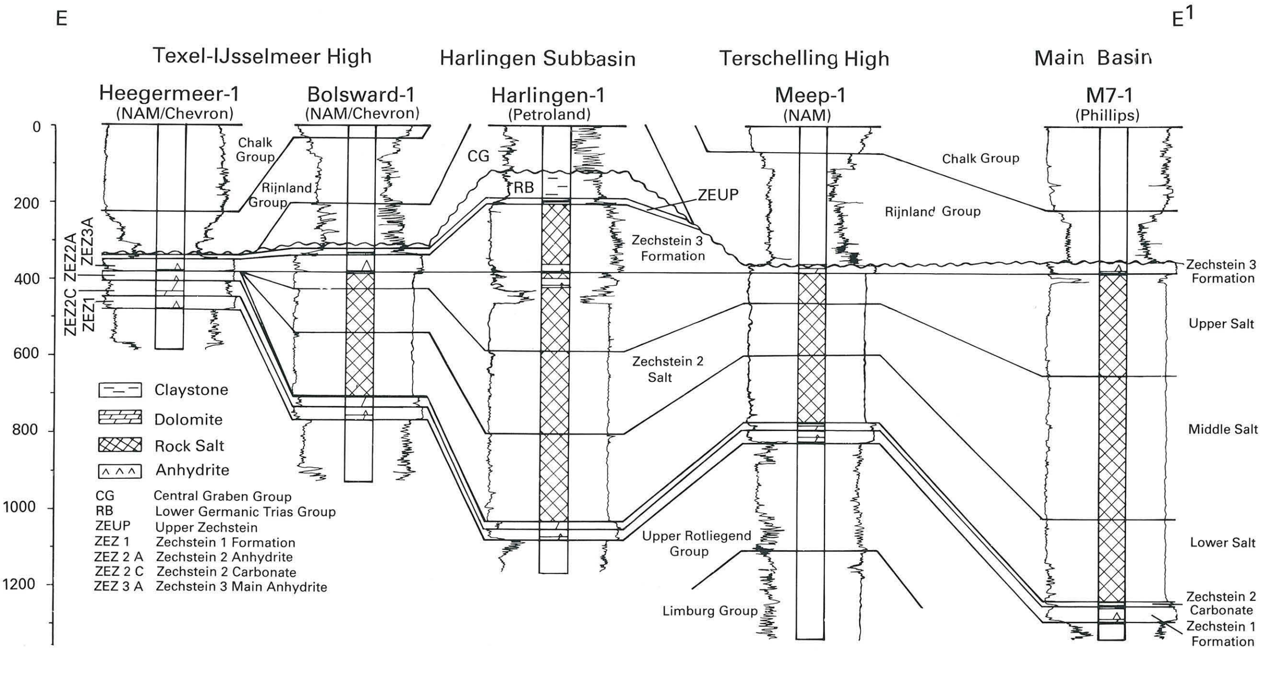


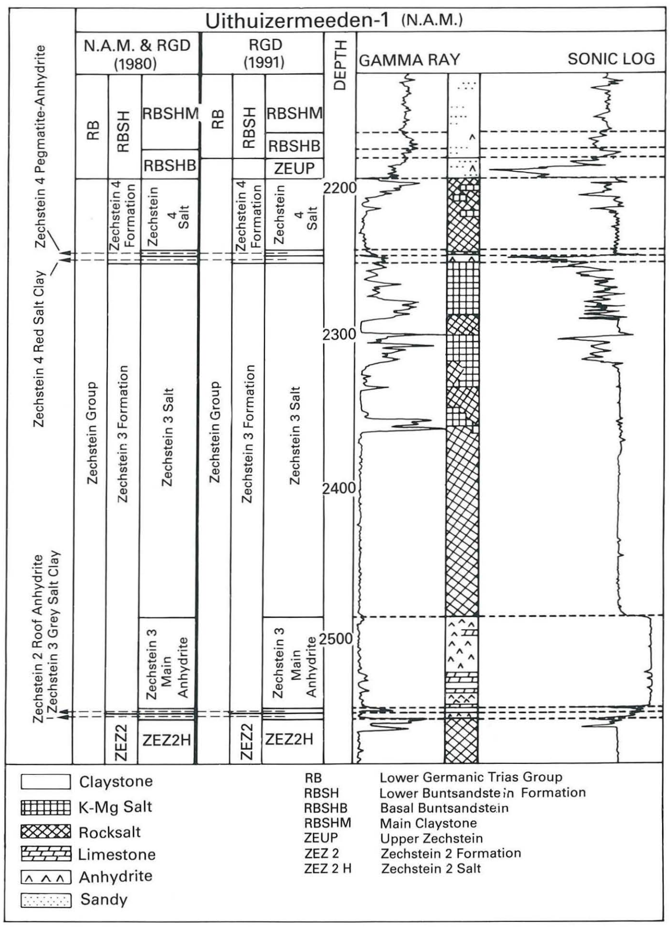
Figure 4.7 Stratigraphic section E-E', with the base of the Zechstein 3 Formation as reference level. The wells are located on the Texel-IJsselmeer High and the Zuidwal High and they show the condensed sequence which was laid down on these highs. The location of this section is given in figure 4.5.

playa-type conditions. The whole map sheet area showed little variation in subsidence and sedimentary development during the deposition of these units.

The sedimentary sequence of the Zechstein Group begins with the Coppershale, which was deposited in an anaerobic environment (Taylor, 1986). Only partial evaporation of the sea water occurred during the deposition of the Zechstein 1 Formation and the salinity was not sufficiently high for the precipitation of rock salt. Interbedded carbonates in the anhydrites indicate fluctuations in the quantity of inflowing sea water. It is thought that the Texel-IJsselmeer High was nearly completely exposed during the deposition of the sulphates because of the breccias found in the carbonates there. These are interpreted as leached breccias, under the influence of meteoric water (Rebelle, 1986).

The Zechstein 2 Formation represents a complete evaporite cycle. After the carbonates and anhydrite, salt was also deposited here. During the formation of the lowest and middle salt members of the Zechstein 2 Salt, the salinity in the basin varied slightly under the influence of periodic influxes of sea water and possibly meteoric water. Larger fluctuations led to the formation of two polyhalite layers, which possibly reflect sudden drops in salinity as a result of influxes of sea water. The topmost salt member contains very pure rock salt, with potassium-magnesium salt layers at the top. The pure composition of the topmost salt member

Figure 4.8 The stratigraphic names used in the reference well Uithuizermeeden-1 for the transition layers of the Zechstein Group and the Lower Germanic Trias Group, with the nomenclature according to NAM & RGD (1980) and that adopted in this explanation (RGD, 1991).



may be indicative of reworked salt. The potassium-magnesium salts were formed during the highest salt concentrations of the brine present in the basin. The minerals present and the large regional extent of these salts indicate that the basin was not completely exposed.

The third, large transgression heralded a new evaporite cycle. The reconstruction of the course of sedimentation of both the Zechstein 3 Formation as well as the younger Zechstein Formations is hindered by the fact that these units have only been preserved in the Harlingen Sub-basin (and locally on the Texel-IJsselmeer High). The absence of potassium-magnesium salts within the map sheet area, indicates that the edge of the evaporite basin had moved further to the north.

After the transgression of the fourth cycle the Red Salt Clay and Pegmatite-Anhydrite were deposited under prolonged hypersaline conditions, as shown by the absence of carbonates in this and higher cycles. It is thought that the Zechstein 4 Formation and the Upper Zechstein deposition took place over a large area on the edge of the basin, under playa-type conditions.

5 Lower Germanic Trias Group

5.1 Stratigraphy

The deposits of the Lower Germanic Trias Group are only represented in this area by the Lower Buntsandstein Formation. The deposits consist of alternations of thin sandstones and claystones, deposited in a continental environment.

The Lower Germanic Trias Group lies conformably on the Zechstein Group (map 5) and is unconformably overlain by the Central Graben Group (Upper Jurassic; map 15) and the Rijnland Group (Lower Cretaceous; map 14). The Lower Germanic Trias Group dates from the Early Triassic (NAM & RGD, 1980).

The Lower Germanic Trias Group is present in the southeast, the northwest and the west of the map sheet area, with a maximum mapped thickness of more than 200 m (map 6).

5.1.1 Lower Buntsandstein Formation

The Lower Buntsandstein Formation is not complete in the map sheet area. The formation is built up from the Basal Buntsandstein and the Main Claystone Members; the Rogenstein Member has been removed by erosion. The deposits have a characteristic red colour.

A sedimentological study of the Basal Buntsandstein and the Main Claystone in northwest Germany has shown that these are built up from fining-upwards cycles (Brüning, 1986). The lithostratigraphic boundary between these members defined by NAM & RGD (1980) in fact appears to lie in the middle of one such sedimentary cycle. At the same time the Basal Buntsandstein, as defined by NAM & RGD (1980), includes the equivalents of the higher Zechstein cycles. In the present description, the equivalents of the higher Zechstein cycles are informally called the Upper Zechstein (see § 4.1.5 and figure 4.8). The boundaries of the Basal Buntsandstein are set so that the unit correlates with the lowest clastic cycle of the Trias. According to this description the Basal Buntsandstein can be correlated with the 'Obere Bröckelschiefer' in West Germany (Best, 1989).

The *Basal Buntsandstein* comprises a basal fine-grained sandstone and an overlying claystone sequence. The unit reaches a thickness of 10 to 15 m in the map sheet area. The basal sandstone is cemented with anhydrite. The claystone in the Basal Buntsandstein is easily distinguished from the claystone of the overlying Main Claystone by its higher gamma-ray values and lower acoustic velocities.

The *Main Claystone* is built up from a cyclic sequence of thin sandstone banks and thick claystone sequences. The cyclic composition can be correlated well on a regional scale and the development in the map sheet area is exceptionally easy to compare with that in the north of Germany, as described by Brüning (1986). The thickness and composition of the first three cycles is very uniform in the north and northwest of The Netherlands (RGD, 1989a). The Main Claystone reaches a thickness of approximately 190 m within the map sheet area.

5.2 Sedimentary development and palaeogeography

During the deposition of the Lower Buntsandstein Formation, the map sheet area was an extensive, flat area. Given the continental environment of deposition (Brüning, 1986; Paul, 1982) and the very good correlations that are possible for the individual cycles of the Early Triassic deposits, it seems likely that the sedimentation took place in a very extensive lake. Evidence that the lake must have dried up at times under the influence of a fluctuating groundwater table and the arid climate, is found in the red colour caused by the oxidation and reworking of the iron present in the sediments (Walker, 1967).

The Basal Buntsandstein represents the last phase of infilling of a relief present since the Early Permian. The identical development of the Main Claystone to the north and to the south of the Texel-IJsselmeer High shows that the high played no role as a tectonic element during the Early Triassic. This indicates uniform subsidence, which had probably already started in the beginning of the Late Permian.

6 'Upper Jurassic' Deposits

6.1 Stratigraphy

In contrast to the other chapters, two lithostratigraphic groups and a formation are described in this chapter under the name of the 'Upper Jurassic'. This is because these facies-connected groups were deposited at the same time and grade laterally into each other. Moreover, they cannot be differentiated seismically. The rocks date from the Middle Jurassic to the oldest period of the Early Cretaceous.

The 'Upper Jurassic' deposits which occur in the map sheet area are limited to the Vlieland Basin (map 7). This basin was divided into northern and southern sub-basins (fig. 6.1) by the Zuidwal Volcanic Dome. The stratigraphy of these 'Upper Jurassic' deposits is relatively complex and differs from that in the nearby Central North Sea Graben (fig. 6.2).

Marine claystones and sandstones are present in the northern Vlieland Sub-basin, which have been allocated to the Scruff Group (NAM & RGD, 1980; Herngreen & Wong, 1989). These are overlain in the sub-basin by mainly continental sandstones, siltstones and claystones of the Central Graben Group. There are only continental deposits of the Central Graben Group in the southern Vlieland Sub-basin. Around the Zuidwal-1 well, in the south of the map sheet area, there is a volcanic breccia, the Zuidwal Volcanic Formation. This unit forms a separate, independent formation, not allocated to any group.

The 'Upper Jurassic' deposits lie unconformably on the Lower Germanic Trias, Zechstein, Upper Rotliegend and Limburg Groups (map 15). The deposits are conformably overlain by the Rijnland Group, separated by a small hiatus (map 14).

The 'Upper Jurassic' deposits in the map sheet area reach a thickness of more than 400 m in the northern sub-basin (map 8), while in the southern sub-basin their thickness is more than 440 m (fig. 6.3). The thickness of the 'Upper Jurassic' diminishes rapidly towards the edges of the basin and the deposits are not present in the direct surroundings outside the limits of the Vlieland

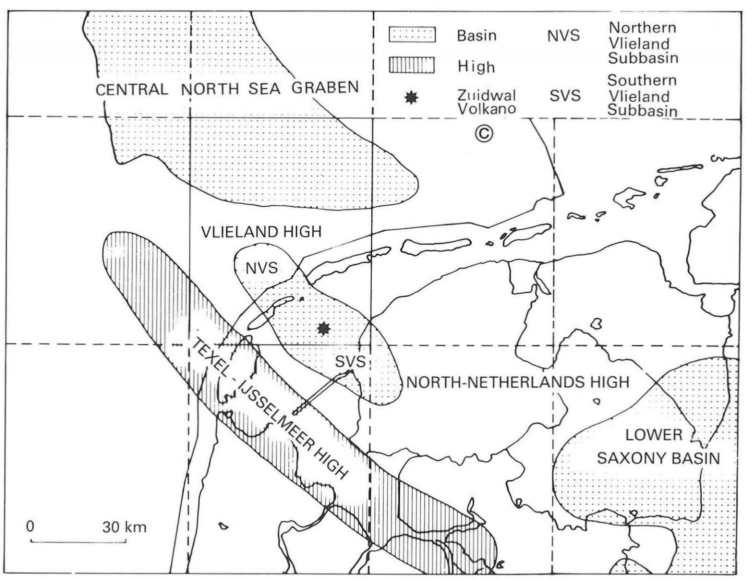


Figure 6.1 The most important structural elements in the northern Netherlands during the Late Jurassic.

Basin. It is assumed that they were never deposited there. To the north of the basin, on the Vlieland High, a thin sequence of sediments was probably deposited during the Late Jurassic and later eroded.

6.1.1 Zuidwal Volcanic Formation

The Zuidwal Volcanic Formation (Herngreen et al., in press) was only encountered in the Zuidwal-1 well (figs 6.2 and 6.5). The rock consists of a breccia of grey, dark brown or green coloured, very angular, fragments of 0.5 to 5 cm diameter, and a pink to light brown coloured matrix of sandy to silty, strongly petrified, volcanic ash. The components of the breccia are chemically weathered to a high degree and have a basaltic – phonolitic, leucitic and trachytic – composition (Dixon et al., 1981). Based on trace elements, the components of the breccia belong to 'alkaline intra-plate' volcanic rocks (Perrot & Van der Poel, 1987).

In the Zuidwal-1 well more than 1050 m of volcanic breccia were drilled through, leading to the conclusion that the well penetrated the pipe of the former Zuidwal Volcano (fig. 6.5). The Zuidwal Volcanic Formation is unconformably overlain by deposits of the Rijnland Group in the Zuidwal-1 well. The eastern extension of the volcanic breccia is probably unconformably overlain by deposits of the Central Graben Group (map 15).

Radiometric ages of the volcanic breccia range from late Middle Jurassic (Callovian) to early Late Jurassic (Oxfordian) (Dixon et al., 1981; Perrot & Van der Poel, 1987; fig. 6.2).

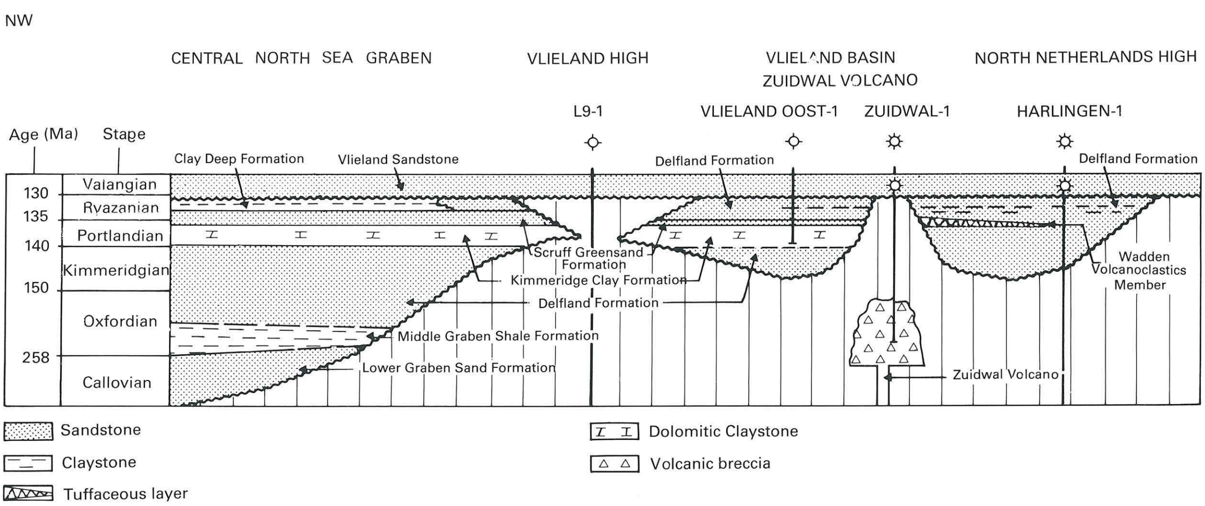


Figure 6.2 An approximately northwest-southeast oriented lithostratigraphic diagram of the 'Upper Jurassic' deposits in the area of the Vlieland Basin, the Vlieland High and the southern Central North Sea Graben (not to scale). Absolute ages (in millions of years, Ma) according to Kennedy & Odin (1982). The age of the Zuidwal Volcanic Formation according to Dixon et al. (1981) and Perrot & Van der Poel (1987). Adapted from Herngreen & Wong (1989) and Herngreen et al. (in press).

6.1.2 Central Graben Group

Within the map sheet area the Central Graben Group is represented by the Delfland Formation. The latter formation occurs in the Vlieland Basin (figs 6.2 and 6.4). The Delfland Formation lies unconformably on the Lower Germanic Trias and Zechstein Groups in the southern sub-basin; in the northern sub-basin it lies conformably on the Scruff Group. In the vicinity of the Zuidwal Volcano the formation lies unconformably on the Zechstein, Upper Rotliegend and Limburg Groups. The Delfland Formation is itself conformably overlain by the Rijnland Group (map 15).

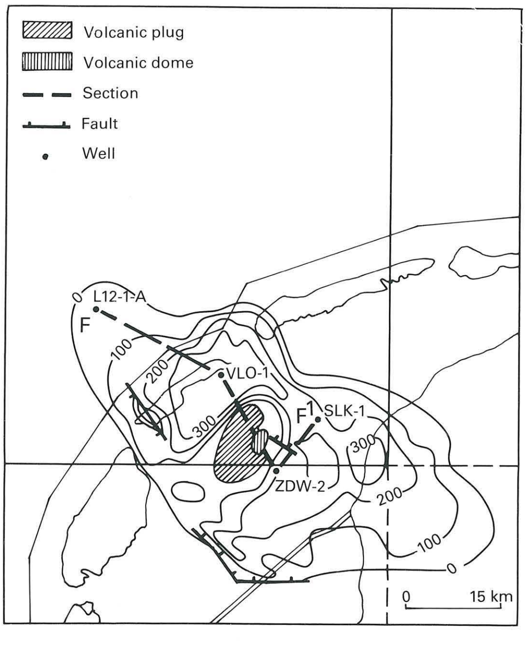
6.1.2.1 Delfland Formation

The Delfland Formation (NAM & RGD, 1980; Herngreen & Wong, 1989) consists of alternating light to dark brown coloured sandstones and grey, green or brown siltstones and claystones, sometimes with red spots. The upper part of the formation contains many plant remains and a few coal and limestone beds. Clastic deposits of volcanic origin are intercalated in the Delfland Formation in both sub-basins. These are allocated to the Wadden Volcano-Clastic Member (figs 6.2 and 6.4).

The Delfland Formation was primarily deposited in a fluvial or lacustrine environment. A brackish water to marine ostracod fauna is present in the limestone beds already mentioned. Palynological data also indicate that the Delfland Formation was subjected to marine influence in both sub-basins, although only to a very slight extent in the southern sub-basin.

Palynological research has shown that the Delfland Formation in the Vlieland Basin is of Late Kimmeridge to Ryazanian age (Herngreen et al., in press). Based on that age, it is probable that the youngest deposits of this formation in the northern Vlieland Sub-basin are the lateral continental equivalent of the marine clays of the Clay Deep Formation (Scruff Group), which are found further to the north in the Central North Sea Graben.

Figure 6.3 Isopach map (contour interval 100 m) of the 'Upper Jurassic' sediments in the Vlieland Basin. The map is based on seismic and well data. The location of the stratigraphic correlation section F-F' is also given.



The greatest observed thickness (440 m; fig. 6.3) of the Delfland Formation occurs in the Harlingen West-1 well, which lies directly to the south of the map sheet area. The greatest thickness of the Delfland Formation found on top of the Scruff Group in the northern Vlieland Sub-basin is approximately 150 m (fig. 6.4). Based on the total thickness of the 'Upper Jurassic' (map 8), it is assumed that this unit also occurs under the Scruff Group. The thickness of the Delfland Formation under the Scruff Group is estimated at 50 m in the centre of the sub-basin. The thickness diminishes rapidly towards the edges of the basin.

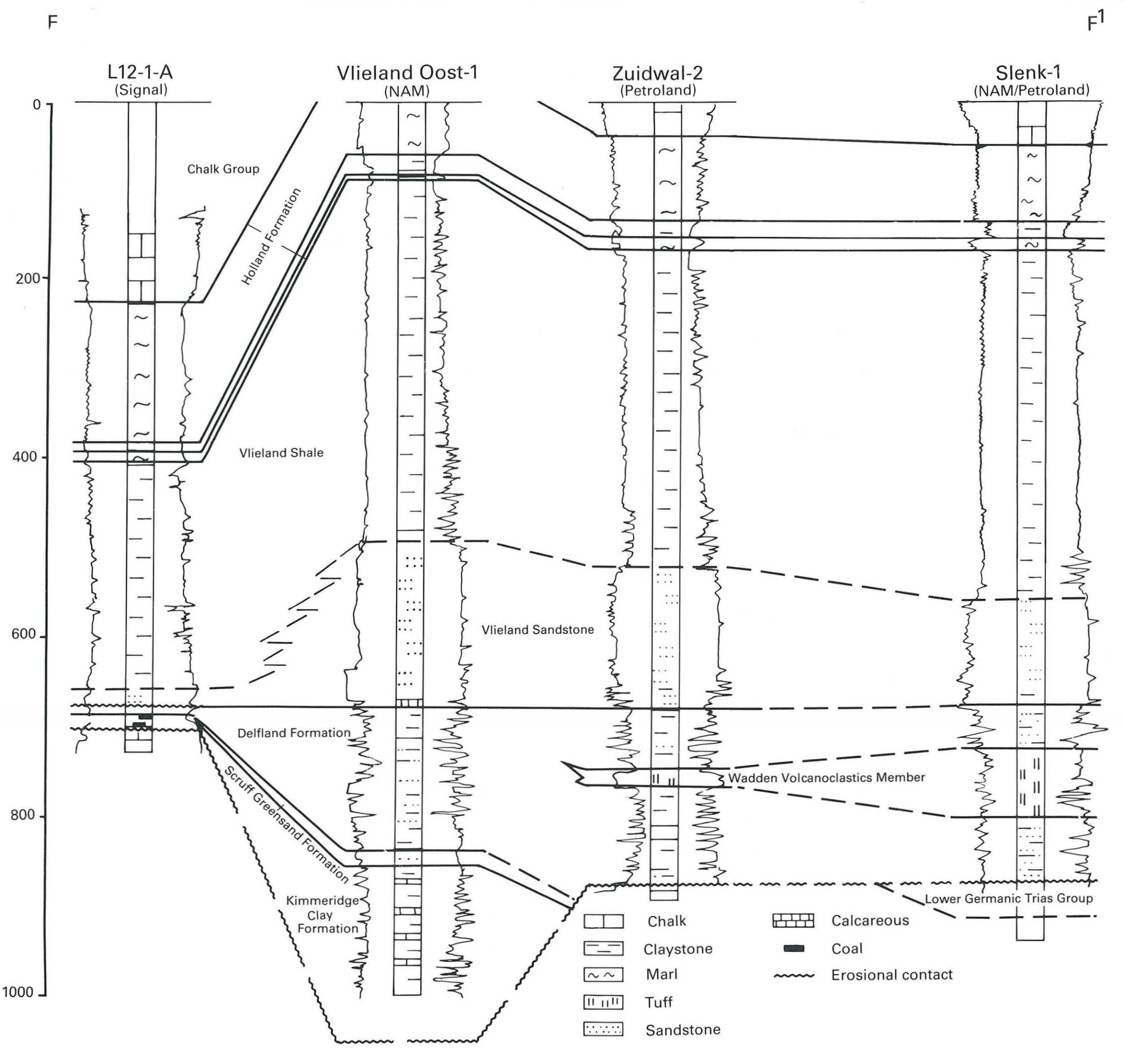


Figure 6.4 Stratigraphic correlation section F-F', with the base of the Rijnland Group (base Vlieland Sandstone) as reference level. See figure 6.3 for the location of section F-F'.

The *Wadden Volcano-Clastic Member* (Herngreen et al., in press) consists of fine to coarse, angular, opaque, green, red and brown clasts in a grey, tuffaceous matrix. These deposits are thought to be the products of erosion of the lavas that made up the Zuidwal Volcano. They occur in several layers, intercalated in deposits of the Delfland Formation in the direct vicinity of the Zuidwal Volcanic Dome (fig. 6.4). The thickness of the individual layers is only a few tens of centimetres. Where several layers occur together, alternating with sandstones and claystones, a total thickness of 78 m is reached (Slenk-1; fig. 6.4).

Palynological dating of this unit in the Slenk-1 well gives it a Portlandian age. The significant difference in the ages of the volcanic pipe and the Delfland Formation make it likely that there was renewed activity of the Zuidwal Volcano.

6.1.3 Scruff Group

The claystones of the Scruff Group are allocated to the Kimmeridge Clay Formation, while the sandstones at the top of the group possibly belong to the Scruff Greensand Formation. The deposits of the Scruff Group were laid down in a marine environment and they form a regressive sequence. The Scruff Group in the northern Vlieland Sub-basin is probably intercalated in the Delfland Formation (fig. 6.2). This is a stratigraphic sequence which varies from that in the Central North Sea Graben, where the Scruff Group was deposited on top of the Central Graben Group. Based on seismic data, the thickness of the Scruff Group in the centre of the northern sub-basin is estimated at approximately 200 m.

6.1.3.1 Kimmeridge Clay Formation

The Kimmeridge Clay Formation (NAM & RGD, 1980; Herngreen & Wong, 1989) consists of light to dark grey claystone, with intercalations of thin limestone and dolomite beds. In the Vlieland Oost-1 well the top of the Kimmerdige Clay is slightly sandier and studies of wall cores have revealed that sedimentation took place in a fairly deep, open marine environment below the wave base. However, the dolomite beds which are present indicate that there were also probably short periods when the marine environment was more enclosed.

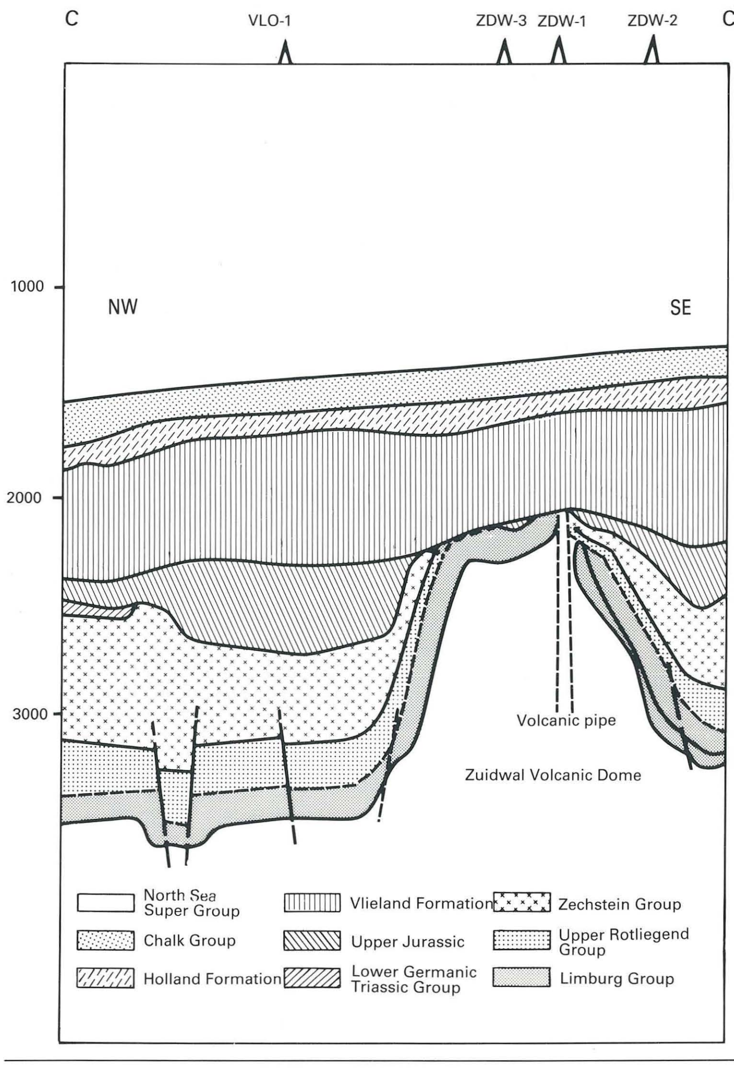
The Kimmeridge Clay Formation is overlain by deposits probably from the Scruff Greensand Formation. The Kimmeridge Clay Formation in Vlieland Oost-1 is of Portlandian age (Herngreen et al., in press). This date, based on palynological research, shows that the top of this formation in the northern Vlieland Sub-basin is slightly younger than the Kimmeridge Clay Formation in the southern part of the Central North Sea Graben.
The maximum thickness of the Kimmeridge Clay Formation in the centre of the northern Vlieland Sub-basin is estimated at approximately 175 m, based on a combination of seismic and well data. The Vlieland Oost-1 well penetrated more than 140 m of this formation (fig. 6.4). The formation thins towards the edges of the northern sub-basin and it pinches out to the south against the Zuidwal Volcanic Dome. Southeastwards the Kimmeridge Clay Formation grades laterally into the Delfland Formation (figs 6.2 and 6.4).

6.1.3.2 Scruff Greensand Formation

A sandstone succession directly overlies the Kimmeridge Clay Formation in the Vlieland Oost-1 well in the northern sub-basin. Based on its sponge spiculae and glauconite, it is possible that this succession belongs to the Scruff Greensand Formation. However, there are also indications, such as a coal layer and a terrestrial/deltaic facies (RGD, 1990a), that part of this succession could belong to the Delfland Formation.

Different levels in these grey-brown to green-brown coloured sandstones are rich in glauconite and sponge spiculae. These are characteristic components of the Scruff Greensand Formation in the Central North Sea Graben and indicate a marine environment of deposition. The basal part of the Scruff Greensand Formation contains dinocyst associations, the composition of which indicates that these were possibly residual from the underlying Kimmeridge Clay Formation (RGD, 1990a). The transitions between the Scruff Greensand Formation and both the overlying Delfland Formation and underlying Kimmeridge Clay are gradual. A Late Portlandian age is assumed for the Scruff Greensand Formation from its stratigraphic position (fig. 6.2). In the Vlieland Oost-1 well the formation is approximately 25 m thick (fig. 6.4).

Figure 6.5 Section over the Zuidwal Volcanic Dome. The section is based on seismic and well data.



6.2 Sedimentary development and palaeogeography

During the Kimmeridgian the Vlieland Basin was separated from the surrounding marine basins by the North Netherlands High, the Texel-IJsselmeer High and the Vlieland High (fig. 6.1). In this period continental sediments of the Delfland Formation were deposited over the whole of the Vlieland Basin. The sediments were produced by erosion of the above-mentioned highs.

During the Portlandian a transgression flooded over the Vlieland High from the Central North Sea Graben and thereby reached the northern Vlieland Sub-basin. The Kimmeridge Clay Formation was deposited under marine conditions in this northern sub-basin while continental conditions prevailed in the southern sub-basin, where the youngest sediments of the Delfland Formation were laid down. This facies transition can be explained by the presence of the Zuidwal Volcanic Dome, which reasonably effectively protected the southern sub-basin from marine ingressions from the north. The infilling of the northern Vlieland Basin, in combination with an eustatic fall in sea level (Vail & Todd, 1981; Haq et al., 1987), led to a regressive sequence and the deposition of the Scruff Greensand Formation.

After the deposition of the Scruff Greensand Formation, the northern Vlieland Sub-basin was again closed off from marine influence for a long time. The Delfland Formation was then deposited in both sub-basins in a fluvial and lacustrine environment, with intercalations of erosion products from the Zuidwal Volcano in both sub-basins in the direct surroundings of the volcano. Poor drainage in the Vlieland Basin led to the formation of peat, which was later subjected to further coalification.

6.3 Petrophysical evaluation

The uppermost sandstone unit of the Delfland Formation was evaluated petrophysically from a number of wells in the study area. It is of interest because it occurs directly under the gas-containing sandstone at the base of the Rijnland Group. See appendix E for a summary of the petrophysical data (RGD, 1990c).

7 Rijnland Group

7.1 Stratigraphy

The Rijnland Group (NAM & RGD, 1980) consists of a sequence of grey-brown to greenish coloured sandstones and grey to brown coloured silts and claystones and marls. These sediments were deposited in an originally shallow but gradually deepening, open marine environment. The Rijnland Group dates from the Early Cretaceous.

In the Vlieland Basin the Rijnland Group lies with a slight hiatus conformably on deposits of the 'Upper Jurassic'. Outside the Vlieland Basin this group lies unconformably on the Lower Germanic Trias, Zechstein, Upper Rotliegend and Limburg Groups (map 14). The Rijnland Group is overlain conformably by deposits of the Chalk Group.

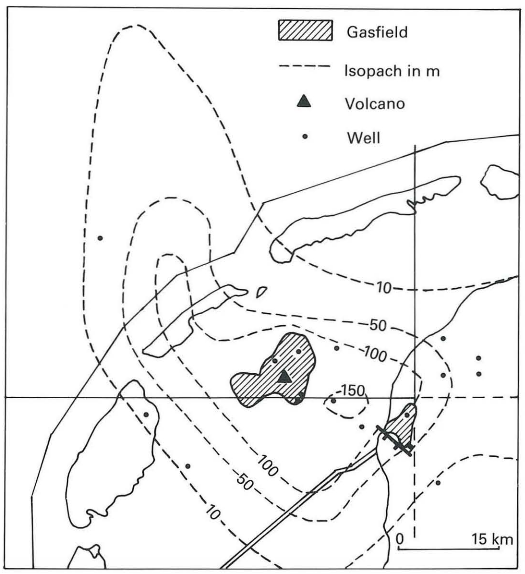
Rijnland Group deposits occur throughout the map sheet area. They are more than 750 m thick in the northern and southern Vlieland Sub-basins (map 10) but diminish away from these depocentres to less than 200 m both southwestwards and northeastwards. The sandstones at the base of the Rijnland Group may contain exploitable amounts of natural gas in this area and are, therefore, of economic importance.

The type section of the Rijnland Group is present in the Vlieland Oost-1 well (NAM & RGD, 1980; fig. 6.5). It can be divided into two formations, the Vlieland Formation at the base, overlain by the Holland Formation.

7.1.1 Vlieland Formation

The Vlieland Formation (NAM & RGD, 1980) consists of the basal Vlieland Sandstone and the overlying Vlieland Shale Member. The definition of the Vlieland Sandstone, sensu lato, differs from that of NAM & RGD (1980) where only the lowest sand layer is called Vlieland Sandstone, senso stricto. This wider definition of the Vlieland Sandstone was adopted because of the correlation with the reservoir sandstone of the Zuidwal gasfield (fig. 7.4) and based on

Figure 7.1 Simplified isopach map of the Vlieland Sandstone (based on well data).



sedimentological studies. In this definition the Vlieland Shales contain only siltstone and claystone. The Vlieland Formation was originally deposited in a shallow, open marine environment, which got deeper with time. The formation is Late Ryazanian up to and including Barremian in age.

Because the Vlieland Formation is the lowest formation in the Rijnland Group, the subcrop map of the basis of the group corresponds with that of the formation (map 14). The formation is separated by a hiatus from and overlain by deposits of the Holland Formation.

The Vlieland Formation occurs throughout the area and its thickness varies from more than 650 m in the centre to 200 m in the northwestern part of the map sheet.

The *Vlieland Sandstone*, sensu lato, consists of an alternation of mainly well-layered, little lithified, grey-brown to green coloured, fine to medium-fine quartz sandstones, dark coloured siltstones and silty claystones. The sandstones generally show internal cross-bedding. Intensive bioturbation has also resulted in some structureless sandstones. The sandstones grade gradually upwards into siltstones and claystones. The silty and clayey intervals are often laminated and rich in organic material. The opposite also occurs in which siltstones and claystones grade gradually upwards into sandstones. Layers of brown coloured sandstones, cemented with calcite and siderite, are interbedded in these graded sequences.

The Vlieland Sandstone, sensu lato, was deposited in a shallow marine environment. The strongly bioturbated sands were laid down close to the coast; the coarse, poorly sorted sands reflect deposition in a bank front facies. The transition of the Vlieland Sandstone, sensu lato, to the Vlieland Shale is rather abrupt and can be easily identified on gamma-ray and sonic logs (fig. 6.4). The Vlieland Sandstone is Late Ryazanian up to and including Early Valanginian in age (Herngreen et al., in press).

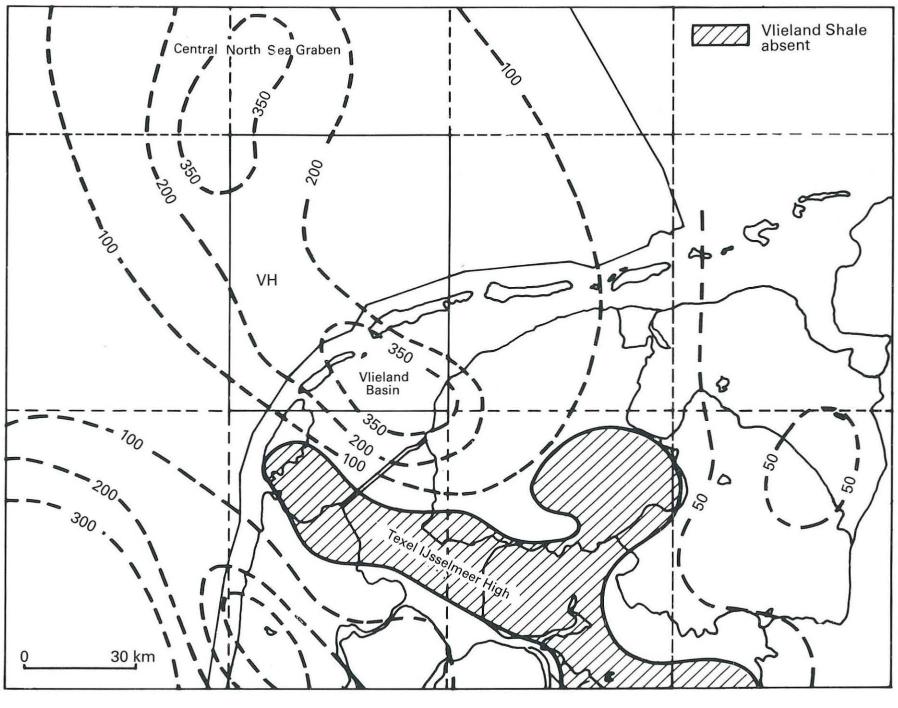


Figure 7.2 Simplified isopach map of the Vlieland Shale. The map is based on both well and seismic data. VH is the Vlieland High.

The thickness of the Vlieland Sandstone observed in wells varies from more than 150 m, in the southern Vlieland Sub-basin in the south of the map sheet area, to less than 10 m outside the boundaries of the Vlieland Basin (fig. 7.1).

The *Vlieland Shale* (NAM & RGD, 1980) is the uppermost unit of the Vlieland Formation. The member consists of dark brown to dark grey, silty claystones. At the top of the unit the claystone is slightly marly. The Vlieland Shale was deposited in an originally shallow, open marine environment which gradually became deeper. It is Late Valanginian up to and including Barremian in age.

The Vlieland Shale occurs throughout the map sheet area. Its thickness varies from 350 m in the Vlieland Oost-1 well to less than 200 m outside the boundaries of the Vlieland Basin (fig. 7.2). The relatively thick claystone deposits of the Vlieland Shale form an effective cap on the Vlieland Sandstone reservoirs of the Zuidwal gasfield.

7.1.2 Holland Formation

The Holland Formation (NAM & RGD, 1980) is the topmost unit of the Rijnland Group. It consists of successive light to dark grey, sometimes colourful, marly claystone, dark grey claystones and light grey marly claystone. The sediments of the Holland Formation were laid down in a marine environment alternating from shallow to fairly deep and are of Late Aptian to Albian age.

The Holland Formation overlies the Vlieland Formation with a hiatus between, which encompasses nearly all the Early Aptian (Herngreen et al., in press). The Holland Formation is overlain conformably by deposits of the Chalk Group. The Formation occurs throughout the map sheet area. Its thickness varies greatly, from less than 50 m in the northeast of the map sheet to more than 150 m in the southwest (fig. 7.3).

The Holland Formation is divided into the Lower Holland Marl, the Middle Holland Shale and the Upper Holland Marl Members. This three-fold division can be recognised in the subsurface over nearly the whole of The Netherlands (fig. 6.5). The members can be easily distinguished from each other by well measurements.

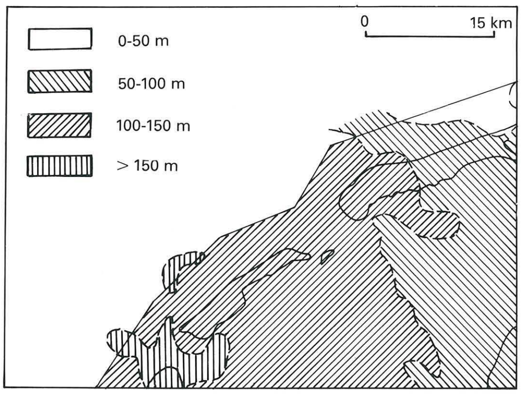


Figure 7.3 Simplified isopach map of the Holland Formation. The map is based on seismic information.

The *Lower Holland Marl* (NAM & RGD, 1980) comprises a light to dark grey, sometimes red, brown or yellow coloured marly claystone. The Lower Holland Marl was laid down in a relatively shallow, open marine environment and it is Late Aptian to earliest Early Albian in age.

The Lower Holland Marl overlies the Vlieland Shale, separated by an important hiatus of regional significance. This hiatus encompasses nearly all the Early Aptian. There is another hiatus between the Lower Holland Marl and the Middle Holland Shale. The thickness of this unit varies from 5 m in the centre to 15 m in the south and southwest of the map sheet area.

The *Middle Holland Shale* (NAM & RGD, 1980) consists of dark grey claystone with a sandy character at its base. Its depositional environment was open marine. The Middle Holland Shale dates from the late Early Albian up to and including the Middle Albian.

The Middle Holland Shale overlies the Lower Holland Marl, separated by a hiatus. The hiatus between these units encompasses a part of the Early Albian. The hiatus is probably slightly greater in the southeast of the map sheet area, where it contains part of the early Middle Albian as well (Herngreen et al., in press). The contact with the Upper Holland Marl is conformable. The greatest thickness is found in the centre and southwest of the map sheet area (20 m in Vlieland Oost-1; fig. 6.5). In the north and northeast of the map sheet area, the unit is only a few metres thick.

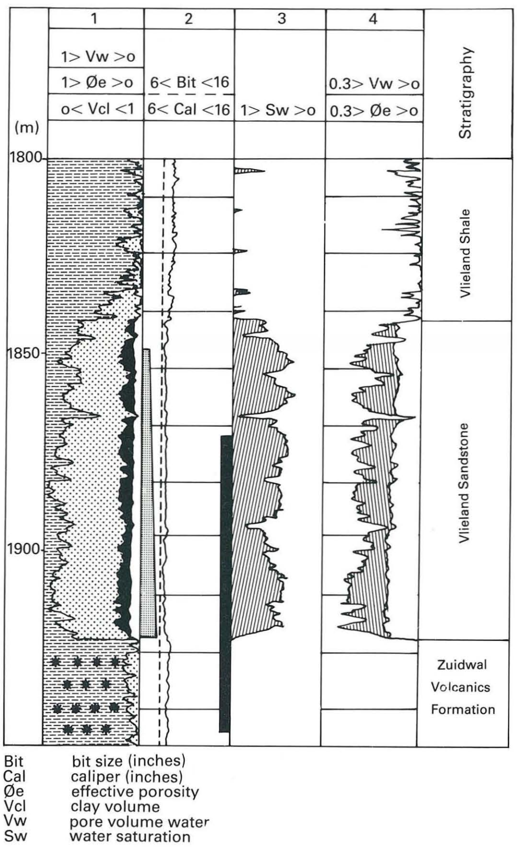


Figure 7.4 Petrophysical evaluation of the Vlieland Sandstone sequence in the Zuidwal-1 well. See figure 3.9 for an explanation of columns 1 and 2, and the symbols used. Tested (appendix G) and cored intervals are also marked. Column 3 gives the water saturation Sw. Column 4 gives the effective porosity øe and the water volume in the pores (Vw). The gamma ray log cannot be used as a clay indicator because the Vlieland Sandstone locally contains 5-10 % glauconite. The clay content (Vcl) was determined from the density-sonic clay indicator. The effective porosity was determined from the sonic (density) porosity (Wyllie comparison in single porosity model; Wyllie et al., 1956, Wyllie et al., 1958) after correction for the clay and hydrocarbon contents. The Indonesian formula, which is suitable for clayey formations, was used to determine the water saturation (Fertl, 1987). Depths are actual depths.

The *Upper Holland Marl* (NAM & RGD, 1980) consists of light grey, marly claystone. It was deposited in an open marine environment and it is of Late Albian age. Several hiatuses probably occur in the Upper Holland Marl, although they are of too short a duration to prove biostratigraphically (Herngreen et al., in press). The contacts with both the Middle Holland Shale and the overlying Chalk Group are conformable. The unit varies in thickness from more than 100 m in the southwest to approximately 30 m in the northeast of the map sheet area.

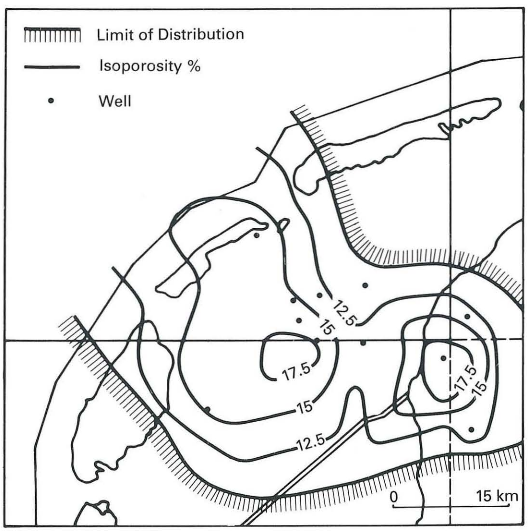
7.2 Sedimentary development and palaeogeography

The continental phase of the 'Upper Jurassic' deposits ended with a transgression from the north, as a result of a rise in sea level during the Late Ryazanian. At the beginning of this transgression the sands at the base of the Vlieland Formation were deposited in a shallow marine environment. The depocentres of the Vlieland Sandstone were still mainly determined by the configuration of the northern and southern Vlieland Sub-basins. The regional distribution of the Vlieland Sandstone reveals that the original Late Jurassic boundaries of the Vlieland Basin had already been transgressed during the deposition of the Vlieland Sandstone (fig. 7.1).

More fine-clastic sedimentation took place as a result of the continuing rise in sea level and the Vlieland Shale was laid down. Palyno-facies analyses indicate that there were probably fluctuations in water depth during this period (Herngreen et al., in press). In the beginning the distribution of the Vlieland Shale within the map sheet area was still determined by the Vlieland Basin, which was connected with the southern part of the Central North Sea Graben (fig. 7.2) over the interlying Vlieland High. The input of clastic sediment gradually decreased during the Barremian and more marly claystones were deposited, the calcareous component of which came mainly from planktonic organisms.

Sedimentation in a marine environment also took place during the Aptian and Albian. Palaeontological and sedimentological data indicate different periods of short stillstands in the sedimentation, small tectonic movements, and transgressions and regressions (Crittenden, 1987;

Figure 7.5 Schematic contour map of the reservoir-average effective porosity øem of the Vlieland Sandstone (appendix F). The limits of the Vlieland Basin during the deposition of the Vlieland Sandstone are given. The frame shows the boundaries of the map sheet area.



RGD, 1990a). The more marly character of the Lower Holland Marl deposits compared with those of the Vlieland Shale probably means that the source areas of clastic sediments were even further removed as a result of a transgression extending further towards the south. The sandy character of the Middle Holland Shale reflects the Albian transgression (NAM & RGD, 1980; Crittenden, 1987). During the deposition of the Holland Formation, the Vlieland Basin no longer exerted any influence on the thickness distribution (compare figure 7.1 and figure 7.3).

7.3 Petrophysical evaluation

The Vlieland Sandstone was evaluated petrophysically from ten wells in the map sheet area and direct surroundings (appendix F; RGD, 1990c). It contains gas in three of these wells (appendix G). The result of a log evaluation of the Vlieland Sandstone for the Zuidwal-1 well (fig. 7.4) is given as an example. A schematic distribution of average effective porosity of the Vlieland Sandstone over the map sheet area is shown in fig. 7.5, from which it is evident that the average effective porosity decreases towards the edges of the sub-basins.

The reduction in porosity is not only due to compaction but also to cementation (fig. 7.6), with calcite and siderite present as cements. Mainly early diagenetic processes, such as the precipitation of calcite, have played a role in reducing the porosity. With respect to the permeability it is important that illite makes up 10% of the clay minerals present (Perrot & Van der Poel, 1987), as the existence of illite fibres results in a reduction in permeability (Seemann, 1979; Pallatt et al., 1984).

Cottençon et al. (1975) recognised five reservoir zones in the Zuidwal gasfield based on lithological features The zones are distinguished from each other by internal fining- and coarsening-upwards sequences. As well as the lithological division, Perrot & Van der Poel (1987) also distinguished the quality of reservoir zones based on porosity and permeability data. The reservoir characteristics show a regional trend, in which improvement in each layer is observed

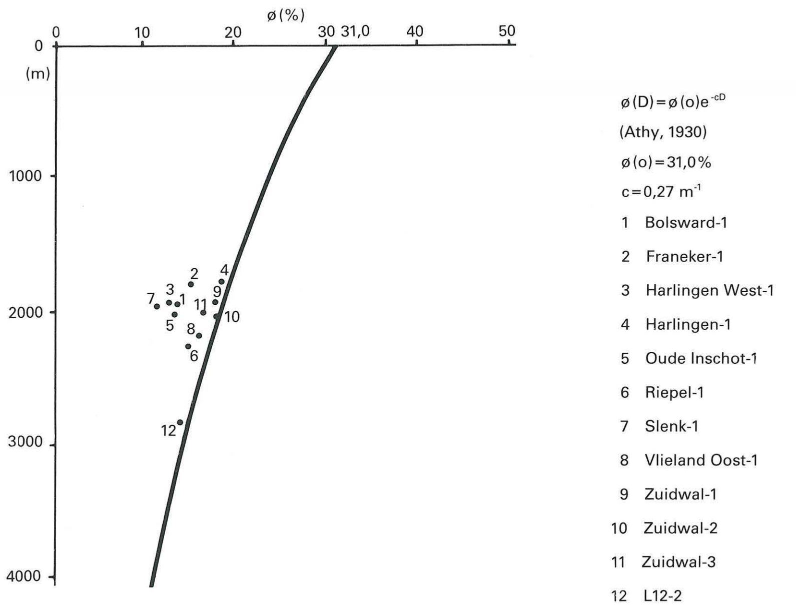


Figure 7.6 Porosity versus depth plot for the Vlieland Sandstone: the compaction curve according to Athy's (1930) exponential relation with a surface porosity for sandstone of ø(0) = 31.0%. A value of 0.27 was used for the constant c (Sclater & Christie, 1980). The data points represent the reservoir-average effective porosity of the Vlieland Sandstone (appendix F).

from the northwest of the map sheet area towards 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 calcite and siderite. These sandstone beds divide the Vlieland Sandstone into a total of 18 thin units. The cemented zones permit only a horizontal flow of gas in the reservoir rock. Since November 1988 Elf Petroland B.V. have been producing gas from the Zuidwal gasfield, which has an initial reserve of 26 billion cubic metres of gas (Perrot & Van der Poel, 1987).

8 Chalk Group

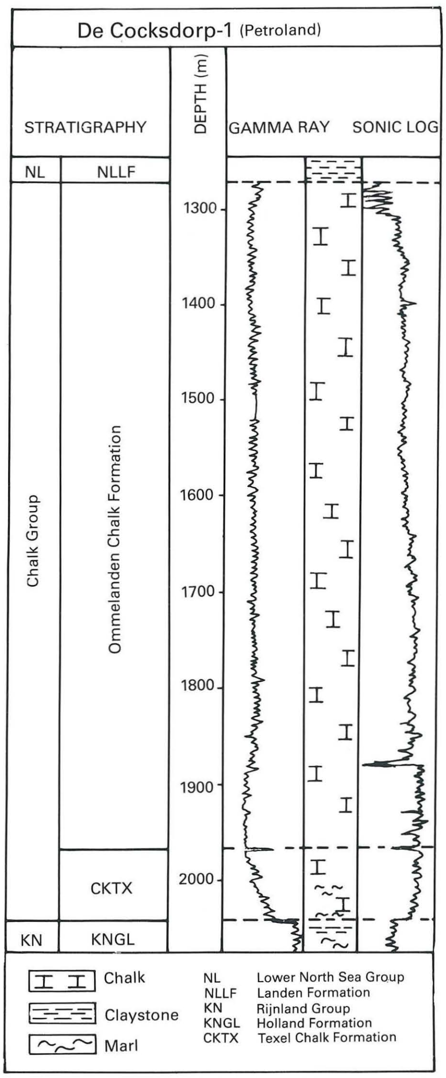
8.1 Stratigraphy

The Chalk Group consists of a sequence of well-cemented, light coloured, fine-grained chalks and marly limestones. These sediments are characteristically composed of mainly calcareous skeletons of planktonic and benthonic organisms (coccoliths, foraminifera, sponges, bryozoa, etc.) and a low content of terrigenous material (NAM & RGD, 1980).

The lower boundary of the Chalk Group is set at the base of the limestone succession which follows conformably on top of the marls of the Rijnland Group. The top boundary is set where the limestones are unconformably overlain by clastic sediments of the Lower North Sea Group (NAM & RGD, 1980).

The Chalk Group is divided into the Texel Chalk Formation and the Ommelanden Chalk Formation. This division is shown in figure 8.1 using the measurements from De Cocksdorp-1 well. The boundary between these formations is set at the top of the Plenus Marl, a prominent, dark, shale-rich marl layer, belonging to the Texel Chalk.

Figure 8.1 Composition of the Chalk Group in the Cocksdorp-1 well (Petroland).



The Chalk Group deposits are of Late Cretaceous age (RGD, 1989d). They occur throughout the area and their thickness varies from 100 m to 1400 m in the southwest of the map sheet area (map 12).

8.1.1 Texel Chalk Formation

The Texel Chalk Formation in the map sheet area consists of light grey chalk and marly limestone with a number of marl intercalations and the Plenus Marl, a prominent marl layer at the top, which can be traced over large distances. This layer takes its name from the English equivalent, a marl bed in which the belemnite *Actinocamax plenus* is abundant. Within the map sheet area, the Plenus Marl consists of a marl layer only a few metres thick, identifiable by a conspicuous peak on the gamma-ray log (fig. 8.1).
The composition and structure of the Texel Chalk is uniform over the map sheet area. It is 60 to 70 m thick with little variation and is Cenomanian in age (RGD, 1989d).

8.1.2 Ommelanden Chalk Formation

The Ommelanden Chalk Formation consists of white to light grey chalk, chalky limestone and marly chalk with some marl intercalations. There are also several levels of nearly parallel, sorted, flint concretions.

The formation overlies the Texel Chalk Formation and itself is overlain unconformably by Tertiary clastics. The age of the formation has been determined as Turonian up to and including Maastrichtian, based on biostratigraphic data. There are also some intraformational hiatuses (RGD, 1989d), some of which can be determined from log correlations as well (RGD, 1988a).

The thickness of the formation varies greatly within the map sheet area. Erosion cut deeply into the deposits of the Ommelanden Chalk as a result of the tectonic upheaval (inversion) of the Vlieland Basin. The thickness is approximately 25 m (Vlieland Oost-1) above the inversion axis of the basin, whereas it increases to more than 1000 m towards the southwest.

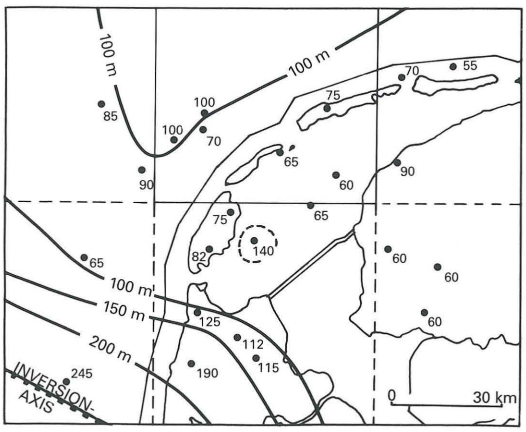


Figure 8.2 Isopach map of the Texel Formation, based on well data. The increase in thickness towards the Central Netherlands Basin reveals the progressive subsidence of this Jurassic basin during the beginning of the Late Cretaceous.

The monotonous character of the sequence makes further division on a regional scale difficult. Distinctions based on seismic data and well measurements are sometimes possible for local applications (RGD, 1988a; Baldschuhn & Jaritz, 1977).

8.2 Sedimentary development and palaeogeography

The transgression which began in the Albian developed into a worldwide phenomenon in the Late Cretaceous (Pitman, 1978; Donovan & Jones, 1979), flooding the last land masses in the map sheet area, and making it into an open sea a long way from any coastline. The flooding of the source areas for clastic sediments led to the Late Cretaceous deposits consisting mainly of bioclastic components, in contrast to the Holland Formation which was still built up of claystone and marls. The transition between the two formations is gradual and the sedimentation was more or less continuous. This is clearly shown in the well measurements (fig.8.1).

Initially there was a period of tectonic rest during the deposition of the Texel and the beginning of the Ommelanden Chalks (Cenomanian and Turonian). The sequences drilled within the map sheet area show a reasonably constant thickness. Outside the map sheet area, the thicknesses of these deposits increase towards the Mesozoic Central Netherlands Basin (fig. 8.2). The former Vlieland Basin was inverted after the Turonian, under the influence of a compressive regime. This had important consequences for the deposition and erosion of the Ommelanden Chalk Formation. In the most strongly inverted part of the Vlieland Basin, the total thickness of the Chalk Group is only 100 m, while a sequence of 750 m, on average, was deposited on the more or less stable North Netherlands High in Friesland. More than 1000 m of Ommelanden Chalk Formation was deposited on the Texel-IJsselmeer High and the part of the Central Netherlands Basin which immediately borders it, an area which underwent subsidence during the inversion. Map 12 shows the total thickness of the Chalk Group; the variations in thickness occur only in the Ommelanden Chalk Formation.

Biostratigraphic (Oude Inschot-1, Zuidwal-2 and other wells; RGD, 1985a; RGD, 1989c) and seismological investigations have shown that the sedimentation of the Ommelanden Chalk was interrupted for short periods or reduced several times during the inversion of the Vlieland Basin. This led to a condensed sequence with intraformational hiatuses in which the Santonian and Campanian sediments are clearly the least thickly developed. This implies that the tectonic activity of the sub-Hercynian tectonic phase was strongest during these periods.

It is evident that the products of erosion originating from the uplifted areas were deposited in the areas of subsidence. Especially the border troughs, which flanked the inverted basins, would have received a lot of material. The uplift and erosion linked with the Laramide tectonic phase had relatively little influence in the map sheet area, so that the Maastrichtian has been preserved over a part of it.

The present thickness of the deposits of the Chalk Group (map 12) is mainly structurally determined. The thickness of the deposits decreases perpendicularly away from the inversion axis of the Vlieland Basin on both sides.

9 North Sea Super Group

9.1 Stratigraphy

The North Sea Super Group (NAM & RGD, 1980) is built up of clays, with some sandy intercalations. The Super Group is divided into the Lower, Middle and Upper North Sea Groups, which are separated from each other by unconformities. The North Sea Super Group lies unconformably on the Chalk Group and the deposits are of Tertiary and Quaternary age. The description of these deposits is mainly based on reports by the Geological Survey of The Netherlands (Rijks Geologische Dienst) (RGD 1984a, 1984b). Quaternary sediments are only mentioned briefly here but are considered fully in the information to the Geological Survey's 1:50,000 map of the shallow subsurface. In the map sheet area the sediments of the North Sea Super Group were largely laid down in a marine environment.

The North Sea Super Group is found throughout the area, with a thickness varying from 1250 to 1500 m. The thickness increases towards the northwest (map 13).

9.1.1 Lower North Sea Group

The Lower North Sea Group comprises the Landen Formation and the Dongen Formation.

The *Landen Formation* comprises the Heers Sand at the base and the Landen Clay. The formation is of Palaeocene age and lies unconformably on the Chalk Group. The *Heers Sand* is a green-grey, very fine-grained glauconitic sand, locally bound with a calcareous cement. The sand varies from 10 to 20 m in thickness. The *Landen Clay* is a green-grey clay or claystone, which contains glauconite, mica and pyrite. There are a few levels bound by calcite cement. The Landen Clay reaches a thickness of 30 to 40 m.

The *Dongen Formation* comprises the Basal Dongen Tuffite, Ieper Clay, Brussels Marl and the Asse Clay. The thickness of the Dongen Formation increases towards the northeast within the map sheet area, from 440 m in the Zuidwal-2 well to 640 m in the Terschelling South-1 well. This trend is due to both a greater basin subsidence and erosion. Large thicknesses are also encountered in the Meep Graben, a graben structure which runs from the western part of Terschelling towards the southwest just up to west of the Friesian coast (map 13). The Dongen Formation is of Eocene age. The *Basal Dongen Tuffite* comprises glauconitic clays with intercalations of tuff. The unit is 10 to 15 m thick and this is fairly constant in the area. The *Ieper Clay* is composed of a clayey base and a sandy upper part. The clayey basal part is characterised by the brown-grey colour and may contain pyrite, shell remains and carbon fragments. The uppermost part is green-grey to grey and contains silty to sandy intercalations with pyrite and glauconite. The thickness of the unit varies from approximately 270 m in the southwestern part of the map sheet area up to 330 m in the northeast. It is more than 380 m thick in the Meep Graben (Slenk-1 well). The *Brussels Marl* comprises glauconitic, green-grey to light grey, fine-sandy clays, marls, calcareous sandstones and clayey sandstones. The thickness of this unit increases towards the north, from 80 m in the De Cocksdorp-1 well to more than 120 m in the Terschelling-1 well. The *Asse Clay* is a plastic, green-grey to blue-grey clay, containing glauconite and pyrite. Apart from deposition, the thickness of this unit is primarily determined by erosion. The greatest thickness, of more than 190 m, was observed in the Terschelling South-1 well. The thickness is least in the southeastern part of the map sheet area, where it is less than 50 m.

9.1.2 Middle North Sea Group

The Middle North Sea Group lies unconformably on the Lower North Sea Group and is overlain, also unconformably, by the Upper North Sea Group. The group comprises the Rupel Formation and the Veldhoven Formation.

The *Rupel Formation* is divided into the Berg Sand and the Boom Clay. The formation is overlain unconformably by the Breda Formation in most of the area and its thickness has been reduced by erosion. The formation is overlain conformably by the Veldhoven Formation only near Terschelling. The greatest thickness, of 105 m, is found there and locally to the south of Vlieland. In the rest of the area, the formation is 45 m thick. It is Oligocene in age.
The *Berg Sand* is a fine sandy unit, with a green-grey to dark grey colour, locally containing pyrite and glauconite. The unit has a constant thickness of approximately 5 m.
The *Boom Clay* comprises a stiff, greasy, brown to dark green-grey clay, characterised by the occurrence of pyrite, glauconite and mica. Septarian nodules (calcareous concretions) also occur in several levels. Where the clay is overlain by the Veldhoven Formation and is most complete, some fine sandy intercalations may occur in the uppermost part.

The *Veldhoven Formation* comprises grey-green, silty clays. The formation is only present in the Terschelling-1 well, with a thickness of 25 m. It is assumed that this formation was deposited throughout the area but was later eroded for the greater part. The formation is Late Oligocene to Early Miocene in age.

9.1.3 Upper North Sea Group

The Upper North Sea Group lies unconformably over the Middle North Sea Group. It is divided into the Tertiary Breda and Oosterhout Formations, and the Quaternary formations of Maassluis and others.

The *Breda Formation* comprises a lower part of very glauconite-rich, green-black clays and an upper part containing less glauconite. The upper part comprises grey-green clays with a few sandy and/or silty intercalations. The Breda Formation is unconformably overlain by the Oosterhout Formation. The formation has been eroded from the western part of Terschelling. The thickness of the formation varies over the rest of the area, from 30 m in the west to 85 m in the east, in the Meep Graben. This variation in thickness is probably the result of later erosion. The Breda Formation was deposited during the Middle to Late Miocene.

The *Oosterhout Formation* comprises light to dark grey, sandy clays with an occasional single, sand intercalation. The top of the formation contains many shell remains. Well data reveal a remarkable variation in thickness in the Oosterhout Formation. The thickness increases from 100 to 140 m in the southeastern and northwestern corners of the map sheet, to more than 300 m in the Zuidwal area (360 m in the Oude Inschot-1 well). The Oosterhout Formation is of Pliocene age.

The *Maassluis Formation* comprises sands and clays, with shell remains and micas. Coarse sands and many plant remains are found at the top of the formation. The formation thickness varies from 150 m in the southwestern part of the map sheet to 200 m in the northeastern part. The formation is of Quaternary age (Early Pleistocene).

The other Quaternary formations comprise clays, sands and gravels, deposited in continental and shallow marine conditions.

9.2 Geological developments and palaeogeography

Changes in sea level had a large effect on the extent of Tertiary and Quaternary sediments in the map sheet area. Mainly clays were deposited during periods of high sea level, while during periods of low sea level, mainly sands were laid down. Some tectonic movements during the Tertiary led to uplift of the area and erosion, which affected the extent and thickness of the deposits present (Letsch & Sissingh, 1983).

The thickness of Tertiary deposits is also determined by salt movements which occurred in the Zechstein rock salt during the Tertiary, causing associated collapse structures in the overlying rocks. In the Meep Graben, thicker successions of sediment were laid down on the one hand while, on the other, more sediments were also left after erosion.

10 Geological History

This chapter describes the geological history of the Vlieland-Terschelling map sheet area. It is restricted to the period from the Late Carboniferous (Variscan orogeny) to the Quaternary, since there are no data concerning the period prior to the Late Carboniferous for this area. For a broader description of this period, see publications by Ziegler (1982, 1989), Glennie (1984) and others.

Pre-Permian

Although the Variscan orogeny took place far to the south of the map sheet area, it still had a significant effect on the geological history. Its development will therefore be described briefly. During the Late Carboniferous, the Variscan orogeny marked the ending of the Proto Tethys. The orogenic front progressed gradually northwards and was manifest in three phases of deformation in the Late Carboniferous: the Sudetic, the Asturian and the Saalic.

The Sudetic phase is evidence of the collision between the Gondwana landmass from the south and Laurasia to the north. The north-south compression caused by this collision resulted in the formation of a mountain chain running east-west across Europe, from Central Europe to Portugal. A foreland basin developed along the northern edge of the mountain chain because of the tectonic forces in the Earth's crust arising from the stacking of Variscan overthrusts. This basin was initially characterised by a relatively rapid accumulation of erosion products originating from the Variscan mountains and laid down under paralic conditions. The large amount of sedimentation increased the amount and rate of isostatic subsidence that the tectonic conditions generated in the basin.

The Variscan orogenic front migrated northwards during the Asturian phase of deformation, at the end of the Westphalian (Lorentz & Nicholls, 1976). The deposits in the foreland basin were strongly folded and transported northwards over slightly inclined thrust planes during this phase. Further north, open folds formed in the Carboniferous sediments in response to movements of fault blocks in the basement (Read & Watson, 1975; Ziegler, 1988). There was also a slow change from a damp, tropical climate during the Late Carboniferous to a desert climate in the Permian.

The Saalic deformation phase, the last of the Variscan orogeny, was an expression of a change in the relative directions of movement between Gondwana and Laurasia during the Stephanian. The north-south compression was replaced by an east-west oriented stretching. This gave rise to an approximately northwest-southeast oriented fault system to the north of the Variscan orogeny, which was characterised by dextral side thrusts. Movements in this fault system led to various horsts and grabens appearing in the Variscan foreland (Ziegler, 1982, 1989; Chadwick, 1985). The fault movements were associated with volcanic activity, especially in northern Germany, Poland and the North Sea (Lorentz & Nicholls, 1976). This suggests very deep rooted faults associated with an important lithospheric thermal rise and accompanying regional uplift (Ziegler, 1988). The Saalic deformation phase lasted from the Stephanian to the Early Permian. In the map sheet area, the related erosion resulted in a hiatus in the sedimentary sequence from about, or close to, the transition from Westphalian A to Westphalian B up to and including the earliest Permian. The uplift of the Variscan mountain chain and its accompanying foreland created the source area for the clastic sediments of the Permian and Triassic.

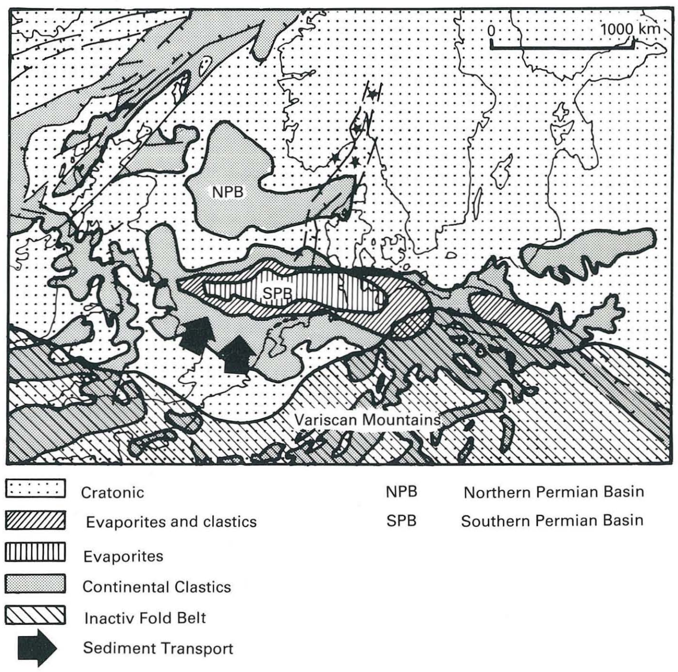
The structures that were formed at the end of the Carboniferous are shown by the subcrop map of the pre-Permian (Van Wijhe, 1987). Since this map is based on well data, it only gives a general structural picture (fig. 2.4). It shows that there were already a few large-scale structures that would be reactivated in later phases of the geological development. For example, the northwest-southeast lying synclinal structure in the south of The Netherlands can be seen as the precursor to the Jurassic basins. Moreover, the presence of a Late Carboniferous high over a large part of the northern Netherlands is deduced from the deeply incised erosion. This original Asturian/Saalic high was a precursor to the Texel-IJsselmeer High, which was evident again particularly during the Triassic and Late Jurassic.

Permian

In the Early Permian, faults, volcanic activity and the regional uplift, which accompanied the last phase of the Variscan orogeny, resulted in an exceptionally extensive landmass. Subsidence of the crust followed the cooling down of the lithosphere, especially in areas of Early Permian volcanic activity. This resulted in an extensive, mountain-ringed, intra-cratonic continental basin known as the Southern Permian Basin (fig. 10.1). Since this basin existed, in more or less the same form, into the Triassic, it is also known as the Permo-Triassic Basin. Superimposed on the large-scale subsidence, the east-west stretching, which was already evident during the Late Carboniferous/Early Permian, resulted in the formation of a number of north-south lying depressions. Two of these depressions, the Off-Holland Low, lying to the west of the map sheet area, and the Ems Trough, to the east, had particular influence on the development of the area.

The southern part of the basin comprised the Variscan mountain chain as hinterland, with a desert area at its foot. A salt lake formed in the central part of the basin and the drainage was concentrated in river systems which arose in the north-south depressions already mentioned. The map sheet area lay in the transition zone between the desert and the salt lake. The northern limit of the desert area lay approximately along the fault-bounded north side of the Texel-IJsselmeer High, suggesting that the limits of sedimentary environments are influenced by tectonic elements.

Figure 10.1 Palaeogeographic map of the Southern Permian Basin (ZPB) during the Early Permian. After Ziegler (1988, plate 7).



The Zuidwal High lay directly to the north of the Texel-IJsselmeer High. This suggests that it is an erosion remnant from a dome-like structure, which was formed as a result of an intrusion during the Late Carboniferous or Early Permian. A history of formation, in which a magmatic process played a role (with or without accompanying volcanic activity), not only agrees well with the extensive Early Permian magmatism seen elsewhere in the Southern Permian Basin, but also seems to fit with the Jurassic volcanic activity evident in this location (Herngreen et al., in press).

In the map sheet area, the sedimentary development during the Early Permian reflects, on the one hand, a number of fluctuations in the level of the salt lake and, on the other hand, the tectonically determined topography. A three-fold rise in the water level resulted in the southwards extension of the lacustrine sediments (Hollum, Ameland and Ten Boer Claystones). The topographic influence can be assumed from the increase in thickness of the sedimentary sequence in the Off-Holland Low with respect to that laid down on the Texel-IJsselmeer High. The extent of aeolian sandstones in the central part of The Netherlands and the occurrence of fluvial sands in the flanking depressions (Van Wijhe et al., 1980, fig. 3) lend further support to the relief described.

Originally the Texel-IJsselmeer High and the Zuidwal High acted as sources of coarse clastic sediments. From the development of the Lower Slochteren Sandstone on the Zuidwal High and on the Texel-IJsselmeer High (De Cocksdorp-1), it would seem likely that the Zuidwal High retained its positive relief longer (fig. 3.5).

Rift formation in the North Atlantic/Arctic area, together with eustatic sea-level changes resulting from the deglaciation of Gondwana, led to the development of an open connection between the Barents Sea in the north and the Northern and Southern Permian Basins. This connection probably lay to the west of Norway, in the vicinity of the present Viking Graben and of the Rockall Trough, which lies further west (Ziegler, 1988). The transgression probably occurred very quickly, under catastrophic circumstances, since the Southern Permian Basin had subsided below sea level at the end of the Rotliegend, because the rate of sedimentation was less than the rate of subsidence of the basin (Glennie & Buller, 1983).

The Zechstein evaporites comprise a number of cycles, which were probably due to fluctuations in sea level as a result of glacial periods during the Late Permian. The loading from large amounts of salt deposited over a short period would probably also have played a role in the subsidence of the Southern Permian Basin, along with the cooling down of the lithosphere.

The Late Permian was a relatively quiet tectonic period. Carbonate-anhydrite platforms were formed on the various high-lying areas: the Terschelling High in the northeast, and the Zuidwal High and the Texel-IJsselmeer High in the south of the map sheet area (fig. 4.4). Mainly salts were deposited in the northern part of the basin, and in the Harlingen sub-basin (in the southeastern part of the map sheet area). The large differences in thickness point to synsedimentary tectonics. The influence of the depositional highs remained primarily limited to the Zechstein 1, 2 and 3 Formations.

The composition of the higher Zechstein cycles reflects the fact that the map sheet area became progressively terrestrial and that the relief was filled in. The extent of the fourth cycle is much less than that of the previous cycles and there is only a clastic equivalent of the fifth. With the equalisation of the relief, the influence of the structural units still present during the Permian came to an end, including the Texel-IJsselmeer High, the Zuidwal High, the Off-Holland Low and the Ems Trough. A fall in sea level at the end of the Zechstein finally resulted in the definite transition from a marine to a continental environment (Vail et al., 1977; Fisher, 1984).

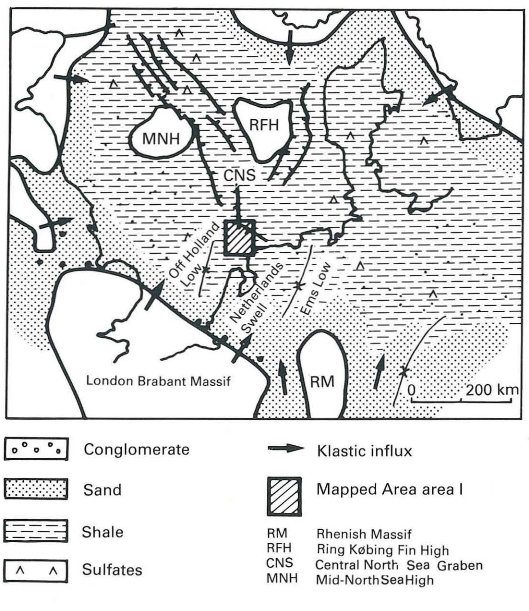
Triassic

The map sheet area was part of an extensive, flat flood plain during the Early Triassic (fig. 10.2). The clastic sediments were transported by river systems mainly from the London-Brabant Massif and from the west. Sediments were laid down under fluvial and lacustrine conditions.

During the Triassic, there was a change in the forces which determined the structural development of Northwest Europe. Intensification of the extension in the mega-rifts in the Arctic/North Atlantic and the Tethys/Central Atlantic domains led to an increasing degree of regional stretching. This led to the development of a complex rift system. Its southern most feature, the Central North Sea Graben, extended almost into the map sheet area. All this resulted in even more changes in the Southern Permian (or Permo-Triassic) Basin (Ziegler, 1982).

After an initially uniform development of sedimentation during the beginning of the Early Triassic, the Permian structural units, such as the Off-Holland Low, the Ems Trough and to a certain extent, the Texel-IJsselmeer High, were again emphasised in the first instance. For example, during the deposition of the Rogenstein, a more or less NNE-SSW oriented high began to develop, the Netherlands Swell (Heybroek, 1974; RGD, 1989a). This arching was located in more or less the same place as the Texel-IJsselmeer High, but it extended further. The map sheet area was on the northwestern edge of the high zone. The structure was flanked in the west by the Off-Holland Low and in the east by the Ems Trough (fig. 10.3). The existence of the high is shown by the composition of the Rogenstein, which, in contrast to the uniform development of the Main Claystone, is clearly different on both sides of the Netherlands Swell. During the rest of the Triassic, sedimentation was concentrated to an increasing extent in the areas of subsidence, such as the Off-Holland Low and the Ems Trough, while only a relatively thin sequence of sediments was laid down on the Netherlands Swell.

Figure 10.2 Palaeogeography during the Early Triassic. The map sheet area is located in the southern part of the basin. Clastic influx sediments originated from a southern source area; the London-Brabant Massif and the Central Massif. There was a lacustrine environment in the centre of the basin. After Ziegler (1982).



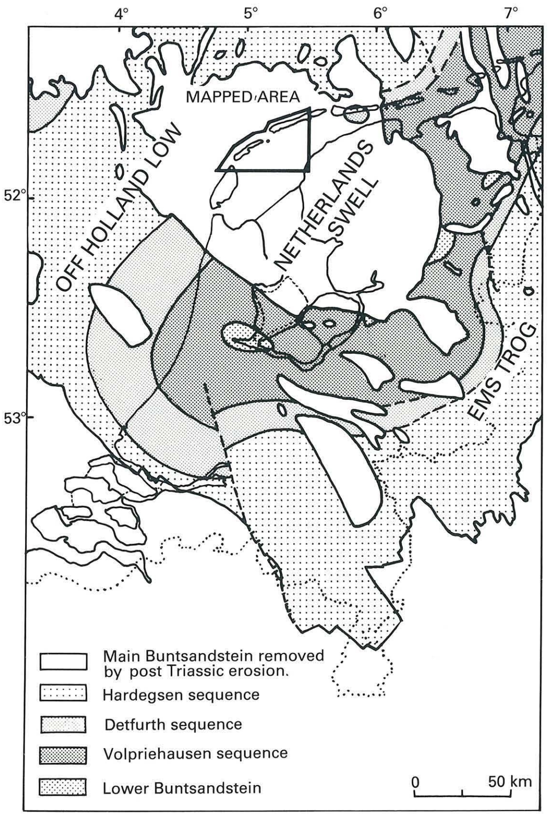
The tectonic activity that occurred in The Netherlands and northwest Germany during the Triassic was fairly weak. It comprised a number of epeirogenic movements, which caused various inclined depressions and archings within the basin, with only a few local faults (Van Hoorn, 1987; Trümphy, 1971; and others). These movements are expressed as intraformational hiatuses in the sedimentary sequence (Wolburg, 1967, 1969). Isopachs and facies distribution of Triassic sediments show that the position of the structural elements during the Triassic was constant (Schröder, 1982).

The composition of the sedimentary sequence of the Main Buntsandstein reflects the pulses of tectonic activity which occurred during its deposition. Periods of tectonic activity are seen as river systems prograding into the basin (Brennand, 1975).

Condensed sedimentary sequences were laid down on the areas that had been uplifted once again. At the end of the Early Triassic, the uplift was sufficient for the Netherlands Swell to have been subject even to erosion. This so-called Hardegsen phase of erosion cut into the Netherlands Swell locally as far as the Lower Buntsandstein and thereby removed approximately 150 m of sediment.

From the end of the Early Triassic (Anisian and Ladinian), the combination of progressive basin subsidence and a net sea-level rise (Vail et al., 1977) resulted in an increasingly extensive transgression. Sedimentation in distal flood plain, sabkha and shallow marine environments alternated with periods of evaporite formation. The drastic reduction of clastic influx also influenced the environment of deposition. Continental conditions became dominant once again after a regression during the Late Triassic (Keuper).

Figure 10.3 Subcrop map of the Hardegsen unconformity, with the most important structural elements. The map sheet area lay on the northwest edge of the Netherlands Swell. This was flanked by the Ems Trough and the Off-Holland Low. After NAM & RGD (1980).



The younger Triassic units (the Röt, Muschelkalk and Keuper Formations) were probably deposited in the map sheet area but removed by later erosion. This is deduced from the complete Triassic sequence present in the Central Netherlands Basin and in the southern Central North Sea Graben, as well as from the absence of lateral facies changes towards the Netherlands Swell.

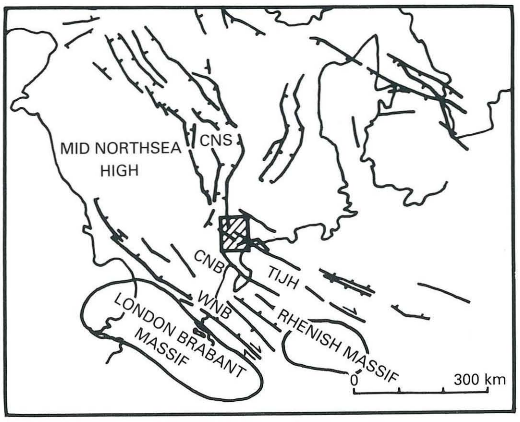
Jurassic

Although the Rhaetian formally belongs to the Triassic, it is more logical in the framework of this description of the geological history to consider it with the Jurassic. At the beginning of the Rhaetian, there was the so-called Early Kimmerian phase. This was the first in a number of large-scale extensional tectonic phases that would determine the structural development of northwest Europe during the Jurassic. This was the period when the disintegration of Pangaea began, in a more or less continuous process in which it is possible to distinguish a number of phases. Although the tectonic activity of these different Kimmerian phases was related to the most important discontinuities in the stratigraphic sequence, this does not imply that the tectonic events were strictly separate (Stille, 1924; Ziegler, 1978, 1982).

Under the influence of the stretching during the Kimmerian phase, the Central North Sea Graben expanded further southwards. In fact, before the rift reached the territory of The Netherlands, the tension was accommodated by strike-slip NW-SE faulting. This happened under the influence of, on the one hand, the rigid London-Brabant Massif which hindered southwards progradation, and on the other, a relatively weak zone to the north of the massif. The zone was formed by a fault system which was originally Variscan (or possibly even Caledonian). Thus, a number of NW-SE lying basins and highs (fig. 10.4) were formed, parallel to the London-Brabant Massif. These were mainly rejuvenations of Late Carboniferous structures, of which the Central Netherlands Basin, the Texel-IJsselmeer High and the Vlieland Basin had a direct effect on the development of the geology in the map sheet area.

The Early Kimmerian phase was of little tectonic significance in the northwest Netherlands, as far as can be seen in the stratigraphic sequence. It was limited to a slight uplift and accompanying erosion (Haanstra, 1963). In the east of the country and in Germany, it was of much greater significance (locally some 600 m was eroded; Schröder, 1982). The most striking feature of this

Figure 10.4 Tectonic units during the Jurassic. Just to the north of The Netherlands, the north-south oriented rifting of the Central North Sea Graben changed into the northwest-southeast oriented strike-slip thrusts along rejuvenated Variscan structures. After Ziegler (1982).



CNB Central Netherlands Basin
CNS Central North Sea Graben
TYH Texel IJsselmeer High
WNB West Netherlands Basin

tectonic phase in the map sheet area was the change of sedimentary environment. From the Rhaetian onwards, marine conditions were again prevalent. These were caused by tectonic subsidence and a large rise in sea level lasted until the Middle Jurassic. Although there are no sediments of Early Jurassic age in the map sheet area, it is fairly certain that they were deposited here. The present occurrences of Early Jurassic sediments (Central Netherlands Basin, Central North Sea Graben, Lower Saxony Basin) in fact all show a uniform composition of fine-grained sediments, which points to deposition in a continuous and extensive basin. After the early Kimmerian tectonic phase, it is likely that the Netherlands Swell, as it existed in the Triassic, formed a relatively slowly subsiding part of a larger basin during the deposition of the Lower Jurassic sediments.

The nature of the Middle Jurassic sediments found in the West Netherlands Basin points to the fact that the sedimentation was increasingly restricted to the basins (Van Wijhe, 1987). A similar regressive pattern of sedimentation is also found along the western edge of the Lower Saxony Basin (Betz et al., 1987). This is all related to an eustatic drop in sea level which, together with an intensification of tectonic activity, occurred at the beginning of the Middle Jurassic (Vail et al., 1977; Ziegler, 1982). In Northwest Europe, this so-called Mid Kimmerian phase was evident as a great heat-induced doming in the central North Sea. The uplift was accompanied by deep cutting erosion and it is therefore likely that there was no, or only a little, sedimentation in the map sheet area. The sediments that were deposited in the area during the Early Jurassic were probably eroded during the Mid Kimmerian phase.

The Late Kimmerian phase was the last of the Kimmerian deformation phases and occurred mainly during the Late Jurassic. Two main impulses can be distinguished in this phase: the first at the end of the Middle Jurassic or at the start of the late Jurassic; the second at the end of the Late Jurassic and the beginning of the Cretaceous. In the northern Netherlands, this Late Kimmerian phase of deformation gave rise to the North Netherlands High and caused rejuvenation of the Texel-IJsselmeer High. Stäuble and Milius (1970) proposed that the North Netherlands High was Late Jurassic/Early Cretaceous in age. Based on the distribution of the Late Jurassic sediments (Delfland Formation), as well as the age of the volcanicity, it is likely that the main structure of the northern Netherlands was already determined by the first phase. The North Netherlands High was broken into different elements during the first and second phases of the uplifting, tilting and erosion process (Stäuble & Milius, 1970). Particularly the Texel-IJsselmeer High and the Vlieland Basin were of importance in the map sheet area.

The Vlieland Basin was formed, as a small extension structure by transverse movements along reactivated Late Carboniferous faults, oriented more or less northwest-southeast (Herngreen et al., in press; map 1). This movement was associated with volcanic activity in the Zuidwal area. The composition of the volcanic rocks indicates they were related to a basaltic magma, which is associated with intra-cratonic volcanicity (Dixon et al., 1981; Perrot & Van der Poel, 1987). It is possible that the Jurassic volcanic activity was related to the earlier activity assumed to have occurred in the Zuidwal area in the Late Carboniferous or Early Permian.

It is probable that the Zuidwal Volcano was located on a domed structure, which was formed prior to the volcanic activity by an intrusion that reached to a high level in the crust. The presence of a broad magnetic anomaly in the Zuidwal area (Perrot & Van der Poel, 1987, fig. 12) indicates rocks of magmatic origin at great depth beneath the Carboniferous sediments. The Carboniferous and Permian rocks lie in a higher structural position on this complex (known as the Zuidwal Volcanic Dome) than in the surrounding area (map 1).

The Vlieland Basin was divided into a northern and a southern sub-basin by the Zuidwal Volcanic Dome. A regressive marine sequence was deposited during the Late Jurassic and oldest Early Cretaceous period in the northern sub-basin. The Zuidwal Volcanic Dome almost completely protected the southern sub-basin against marine incursions, so that it contained mainly continental deposits (Herngreen et al., in press).

Tectonically controlled sedimentation took place during the Late Jurassic and Early Cretaceous. Differential movements, belonging to the Late Kimmerian phase, created both fault-bounded basins and adjacent uplifted areas. The latter acted as source areas for the clastic deposits of the Delfland and Vlieland Formations.

Cretaceous

From the beginning of the Early Cretaceous, the differential basin movements gave way to a regional subsidence. Hancock (1984) and Ziegler (1989) use the concentration of sea-floor spreading in the North Atlantic Ocean and the Bay of Biscay to explain the reduction in rifting in the North Sea. Those faults controlling the rift system that had not already stopped moving in the Early Cretaceous, became inactive in the Late Cretaceous.

A number of subsequent transgressions (Ryazanian, Albian and Cenomanian) brought a period of continental sedimentation to an end. This finally culminated, in the Late Cretaceous, as an open marine environment, which extended over a large part of Europe to the north of the Alps and Carpathians (Hancock & Scholle, 1975). The transgression was the result of a global rise in sea level, which was probably a response to increased sea-floor spreading in the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979). The transgression reached its maximum extent in the Late Campanian (Hancock & Scholle, 1975). The increasing extent of the transgression led to the source areas for clastic sediments becoming proportionally further distant. This, and the reduced surface area of the source regions, resulted in an almost negligible proportion of terrigenous clastic material, so that the Late Cretaceous deposits comprise mainly bioclastic components.

The sands at the base of the Vlieland Formation were deposited at the beginning of the Early Cretaceous transgression. These are of economic importance because they are gas-bearing in the Zuidwal structure and in various gasfields in Friesland. The relief of the Zuidwal Volcano was subsequently levelled during the Early Cretaceous both by infilling of the Vlieland Basin and by erosion of the volcano. This is evident from the thickness maps of the Upper Jurassic, the Rijnland Group and the Chalk Group (maps 8, 10 and 12). The borders of the Vlieland Basin were transgressed as a result of the continuing rise in sea level during the Hauterivian and Barremian. The sea extended over an increasingly larger part of the Texel-IJsselmeer High and the North Netherlands High and thereby ended the Vlieland Basin's role as a depocentre. During this period, a local reactivation of faults occurred forming horsts and grabens, particularly along the Texel-IJsselmeer High. The sea level swings which took place during the second half of the Early Cretaceous always show a larger hiatus on the highs than in the centre of the Vlieland Basin. The Texel-IJsselmeer High and the North Netherlands High were finally flooded by the Albian transgression (Crittenden, 1987).

The relative lack of tectonic activity and the regional subsidence probably came to an end at the beginning of the Late Cretaceous. A compressive field of force developed, thought to have been due to the collision between the European and African plates. These forces would have been partly transferred to the Northwest European platform (Ziegler, 1982) and caused the reactivation of old faults by means of shearing, probably in a sinistral sense (Van Wijhe, 1987). This resulted in the inversion of a number of former basins, including the Vlieland Basin. The inversion was completed in a series of pulses, grouped into two main phases; the Sub-Hercynian phase (Santonian and Campanian) and the Laramide phase (end Cretaceous).

From the isopach maps of the Chalk Group and the Rijnland Group (maps 10, 12 and 16), it is clear that the area of the Vlieland Basin which subsided (Late Jurassic/Early Cretaceous) is the same as the inverted area (Late Cretaceous). This supports the idea that inversion occurs due to the reactivation of already existing faults (Betz et al., 1987; Van Hoorn, 1987; Ziegler, 1987; and others). No depositional troughs developed along the inverted zone of the Vlieland Basin in contrast to, for example, the Sole Pit High (Van Hoorn, 1987), the Lower Saxony Basin (Betz et al., 1987) and the Central Netherlands Basin (Van Wijhe, 1987). This is possibly because it was a reasonably small structure, which was uniformly inverted.

At the same time as the Sub-Hercynian inversion of the former basins, the Texel-IJsselmeer High and the platform in Friesland underwent a relative subsidence. The reversed relief is shown by the onlap of sediments against the flanks of the inverted basins and by the angular unconformities in the inverted areas. Despite the inversion, sedimentation continued in most of the map sheet area. The Chalk sequence, which was deposited near the inversion axis, is very thin (100-150 m) but biostratigraphic research revealed that it is a condensed sequence, which contains sediments from nearly all the stages of the Late Cretaceous. Small intraformational hiatuses, interruptions and progradational as well as thin sequences occur, especially during the Santonian and Campanian (RGD 1989c; RGD 1988a). They point to an intermittent uplift in which either a thinned sequence was laid down or erosion took place, depending on the rate of uplift. In tectonically quiet periods, sedimentation again took place over the whole area.

The Laramide phase at the end of the Chalk was accompanied by slight erosion in the study area. It is evident that little or nothing of the Maastrichtian was removed (Perrot & Van der Poel, 1987; Van den Bosch, 1983) and it is striking that a similar variation in the intensity and age of inversion structures has been observed in Germany (Betz et al., 1987; Baldschuhn et al., in press).

Assuming that the North Netherlands High was relatively stable during the Sub-Hercynian and Laramide phases, the 700-800 m thick Chalk Group that is deposited there can be chosen as a reference for determining the relative tectonic movements. A sequence of only 100 m remains in the Vlieland Basin, which implies a total relative uplift of 600-700 m. An important part of this uplift occurred during the Sub-Hercynian phase. The subsidence in the Central Netherlands Basin continued during the inversion of the Vlieland Basin. The northeastern edge of the basin subsided by approximately 800 m with respect to the North Netherlands High.

Draping of the sandstones at the base of the Vlieland Formation occurred because of differential compaction over the Zuidwal Volcanic Dome. This, combined with the raised structural relief of the top of the Vlieland Sandstone Member due to basin inversion, were important conditions for the origin of the later Zuidwal gasfield.

Tertiary

After the compressive Laramide tectonic phase, a new basin, the North Sea Basin, formed in Northwest Europe. This has influenced sedimentary processes till the present day. During the

Tertiary and the Quaternary, the rate of subsidence of the North Sea Basin increased spectacularly. In approximately 65 million years, more than 3000 m of sediment were deposited in its centre. These sediments were mainly composed of erosion products from the recently uplifted Alpine areas. The Netherlands is located on the southern edge of the North Sea Basin.

The relief, which originated from inversion of the various basins, was mostly levelled by erosion at the beginning of the Tertiary. The change in sedimentary facies reflects the transition into a new phase in the collision between the European and African plates. The strongly uplifted areas were subject to erosion and large amounts of clastic degradation products invaded the open marine environment. The Tertiary subsidence was 1100 m in the southeast of the map sheet area, although it increased to 1600 m in the direction of the North Sea Basin's axis of subsidence (map 13). Mainly marine clay and sand sequences were deposited initially in this rapidly subsiding basin but, from the Miocene onwards, fluvial influences (from the east) became more important.

The depositional processes during the Tertiary were influenced to a large extent by changes in sea level, so that clays were mainly deposited during periods of high sea level and sands mainly during regressions. A number of the tectonic phases related to the Alpine orogeny led to uplift and erosion, which affected the thickness and the extent of the sediments present (Letsch & Sissingh, 1983). There were important phases of erosion in the Early Oligocene (related to the Pyrenean phase) and close to the Oligocene-Miocene transition (in connection with the Savic phase). These tectonic phases were caused by the advances of the European and African-Arabic plates. The occurrences of tuffs in the Eocene deposits were related to volcanic activity in the present Skagerrak area and elsewhere (Ziegler, 1982).

The Tertiary deposits are disturbed in various places by salt movements, which took place during the Eocene and Oligocene. The rocksalt swelled under the influence of tectonic forces, thereby stretching the Tertiary cover above the tops of these salt ridges and leading to faulting. There were both growth faults along the flanks of salt structures and grabens over the tops of these structures. The most conspicuous graben runs from west of Terschelling in a southeasterly direction (map 13).

Appendix A

Overview of seismic data used

Survey/line	*Year*	*Owner*
2273	1961	NAM
2277	1961	NAM
845	1964	NAM
69W-	1969	Petroland
S69-	1969	Petroland
7090	1970	NAM
717142	1971	NAM
7180	1971	NAM
71W	1971	Petroland
7281	1972	NAM
799	1979	NAM
80-W-	1980	Petroland
FR75-	1975	Petroland
FR77-29	1977	Petroland
FR78-38	1978	Petroland
NSW-1	1984	Western Geophysics
PL-	1970	Placid

Overview of wells used

Well	*Code*	*Owner*	*Final depth*	*Year*
Barradeel NE-1	BAR-NE-1	Shell	2553	1970
Bolsward-1	BWD-1	NAM	2679	1971
Den Burg-1	BRG-1	Petroland	2865	1964
De Cocksdorp-1	COC-1	Petroland	2798	1964
Franeker-1	FRA-1	Petroland	1837	1978
Harlingen West-1	HAW-1	Placid	3348	1965
Harlingen-1	HRL-1	Petroland	3103	1965
Harlingen-2	HRL-2	Petroland	1870	1965
Harlingen-3	HRL-3	Petroland	2003	1965
Heegermeer-1	HGM-1	Chevron	2144	1973
Hollum-Ameland-1	HOA-1	NAM	2934	1964
Hollum-Ameland-3	HOA-3	NAM	3212	1972
Meep-1	MEE-1	NAM	3240	1969
Oude Inschot-1	OIS-1	Petroland	2350	1972
Peins-1	PEI-1	Petroland	1884	1982
Ried-1	RID-1	NAM	3039	1952
Ried-2	RID-2	Petroland	1806	1980
Riepel-1	RPL-1	Petroland	2509	1972
Slenk-1	SLK-1	Petroland	2482	1971
Terschelling-1	TER-1	NAM	3036	1964
Terschelling-2	TER-2	NAM	2862	1964
Terschelling South-1	TES-1	MOBIL	2981	1965
Vlieland Oost-1	VLO-1	NAM	2572	1965
Zuidwal-1	ZDW-1	Petroland	3002	1970
Zuidwal-2	ZDW-2	Petroland	2632	1971
Zuidwal-3	ZDW-3	Petroland	2060	1971
Zurich-1	ZUR-1	Placid	2164	1965
L9-1	L09-1	Phillips	3824	1973
L12-1A	L12-1-A	Signal	3451	1969
L12-2	L12-2	NAM	3276	1976
L12-3	L12-3	NAM	3150	1979
M7-1	M07-1	Phillips	3590	1969
M9-1	M09-1	NAM	3587	1968

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%. The cut-off values are to some extent arbitrary because there are no core analyses available of the Upper Rotliegend sandstone sequences that were studied. øem average effective porosity; Vclm average clay content; Swm average water saturation. Gross, Net in metres; øem, Vclm and Swm in per cent. 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*
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
*HOA-3	176.0	40.2	8.7	18.3	40.2	8.7	18.3	65.2
*HRL-1	79.5	17.5	8.0	33.4	5.6	9.7	32.7	83.9
MEE-1	305.0	130.4	12.9	26.9	67.1	15.0	24.8	83.4
OIS-1	161.0	129.0	14.6	34.4	89.2	15.9	32.5	83.2
RPL-1	162.5	160.5	14.8	24.9	159.1	14.8	24.9	75.5
TES-1	329.0	77.3	10.5	23.1	37.9	11.9	20.1	77.8
*ZDW-2	163.1	112.5	13.3	27.4	31.8	12.9	28.0	81.0
L12-1-A	250.5	23.2	10.7	29.3	23.2	10.7	29.3	45.6
*M07-1	294.3	16.3	9.1	27.2	1.4	7.6	35.8	81.7

Slochteren Sandstone

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*øem*	*Vclm*	*Net*	*øem*	*Vclm*	*Swm*
BWD-1	119.0	116.0	14.3	21.0	1.7	14.8	17.5	88.1
RPL-1	162.5	160.5	14.8	24.9	159.1	14.8	24.9	75.5

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
*HOA-3	87.5	40.0	8.7	18.2	40.0	8.7	18.2	65.4
*HRL-1	57.0	17.5	8.0	33.4	5.6	9.7	32.7	83.9
MEE-1	133.4	123.7	13.1	26.8	64.1	15.2	24.8	83.4
OIS-1	120.5	113.8	14.7	34.3	81.1	15.8	32.8	83.2
TES-1	123.0	72.9	10.6	22.9	35.4	12.2	19.4	78.6
ZDW-2	110.0	102.2	13.7	27.6	24.4	13.8	29.2	81.4
L12-1-A	25.0	19.7	10.7	29.7	19.7	10.7	29.7	46.4
M07-1	57.3	14.6	9.3	26.3	0.0	–	–	–

Lower Slochteren II

Well	Gross	Reservoir			Pay			
		Net	øem	Vclm	Net	øem	Vclm	Swm
COC-1	46.5	35.9	11.8	31.9	17.4	14.2	28.9	78.6
OIS-1	10.0	9.2	15.4	31.7	5.6	18.9	25.9	82.1
ZDW-2	9.0	4.2	7.3	19.7	3.2	7.5	19.5	80.8
L12-1-A	9.5	0.6	6.7	36.4	0.6	6.7	36.4	57.1

Lower Slochteren I

Well	Gross	Reservoir			Pay			
		Net	øem	Vclm	Net	øem	Vclm	Swm
COC-1	12.5	6.6	13.2	29.6	5.2	13.6	29.8	55.7
MEE-1	24.7	0.8	6.3	22.8	0.8	6.3	22.8	78.6
L12-1-A	9.5	0.0	–	–	0.0	–	–	–

Show, status and test data Upper Rotliegend Group

D&A dry and abandoned; FIT formation interval test (test interval in metres log depth); DST drill stem test; PRP production test; W water; GCW gas cut water; G gas; flow water in litres per hour; n.c. not commercial amount; Rw electrical resistivity of the formation water in Ohm m^2/m (measuring temperature, °C).

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*	*Unit*
BWD-1	–	D&A	FIT 1	2500	W	20		ROSL
COC-1	–	D&A	DST 3	2413-2431	W	3500		ROCLT
HOA-3	–	D&A	PRP 1	3075-3125	W	7850		ROSLU
HRL-1	gas	D&A	DST 5	3013-3031	GCW	107		ROCLT
			DST 6	3081-3103	GCW	1600		ROSLU
MEE-1	–	D&A	–					
OIS-1	–	D&A	DST 1	2161-2197	W	3200		ROSLU
RPL-1	–	D&A	DST 2	2304-2324	W	22300		ROSL
TES-1	–	D&A	DST	2645-2654	W	1270		ROSLU
ZDW-2	–	D&A	DST 2	2372-2393	W		0.0424(24)	ROSLU
L12-1-A	gas	D&A	PRP	2950-2975	G	n.c.		ROSLU
			DST	3042-3451	GCW			ROCLH, ROSLLII, ROSLLI, DC
M07-1	–	D&A	DST 1	3198-3258	GCW	680		ROCLT
			DST 2	3139-3590	W	10200	ROCLT,	ROSLU, ROCLA,DC
			DST 3	3198-3400	W		0.0532(33.3)	ROCLT

Reservoir calculations uppermost Delfland Formation

Uppermost sandstone unit 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.

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
OIS-1	18.0	9.4	14.5	19.5	0.1	17.2	47.5	89.0
SLK-1	6.4	4.8	19.7	13.3	0.0	–	–	–
VLO-1	7.0	6.0	17.8	13.9	0.0	–	–	–
ZDW-2	26.0	16.2	16.3	19.0	1.5	16.8	23.0	79.6
ZDW-3	6.0	4.1	16.3	6.2	0.0	–	–	–

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
OIS-1	124.5	107.0	13.2	25.9	3.4	16.6	33.2	85.4
RPL-1	24.0	15.8	14.9	21.2	8.2	15.9	32.7	75.0
SLK-1	99.0	70.7	11.2	38.6	0.0	–	–	–
VLO-1	190.5	158.3	16.0	22.4	5.3	14.4	38.4	85.8
ZDW-1	81.0	78.8	17.9	17.8	78.6	17.9	17.8	49.5
L12-2	35.0	15.0	14.0	6.2	0.0	–	–	–

Show, status and test data Vlieland Sandstone

Gas flow (Q50) in 1000 m³/day; flow water in litres/hour. For an explanation of the other symbols see appendix D.

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*
BWD-1	–	D&A	–				
FRA-1	gas	GAS	DST 2	1776 -1779	W	53	0.0590 (20)
			PRP 1	1741 -1747	G	52	
					W	15	
			PRP 2	1750 -1765	W		
HAW-1	–	D&A	–				
HRL-1	gas	GAS	DST 2	1690.5-1702.3	G & W		
			DST 3	1679.5-1702.3	G & W		
			FIT	1694.5-1699.5	W		
			PRP	1679.5-1702.3	G	200	
OIS-1	–	D&A	–				
RPL-1	–	D&A	DST 1	2220.4-2238.0	–		
SLK-1	–	D&A	FIT	2141 & 2142	–		
VLO-1	–	D&A	–				
ZDW-1	gas	GAS	PRP 1	1938 -1944	G		
			PRP 2	1871.5-1944	G	530	
L12-2	–	D&A	DST 2	2372.5-2393	W		0.0424 (24)

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

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