Rijks Geologische Dienst RGD

Explanation to map sheet II Ameland-Leeuwarden

Geological Atlas of the Subsurface of The Netherlands

Rijks Geologische Dienst RGD

Geological Atlas of the Subsurface of The Netherlands

Explanation to map II Ameland-Leeuwarden

Contents

Preface

1 Introduction *9*
1.1 Extent of area studied *9*
1.2 History of exploration and data base *9*
1.3 Research set up *10*
1.4 Maps and Sections *12*
1.5 Explanation *14*
1.6 Summary *15*

2 Limburg Group *19*
2.1 Stratigraphy *19*
2.1.1 Coal Measures *20*
2.2 Sedimentary development and palaeogeography *21*

3 Upper Rotliegend Group *22*
3.1 Stratigraphy *22*
3.1.1 Slochteren Sandstone Formation *22*
3.1.2 Silverpit Claystone Formation *25*
3.2 Sedimentary development and palaeogeography *25*
3.3 Petrophysical evaluation *27*

4 Zechstein Group *30*
4.1 Stratigraphy *30*
4.1.1 Zechstein 1 Formation *30*
4.1.2 Zechstein 2 Formation *30*
4.1.3 Zechstein 3 Formation *32*
4.1.4 Zechstein 4 Formation *33*
4.1.5 Upper Zechstein *33*
4.2 Sedimentary development and palaeogeography *33*

5 Lower and Upper Germanic Trias Groups *36*
5.1 Lower Germanic Trias Group *36*
5.1.1 Stratigraphy *36*
5.1.2 Lower Buntsandstein Formation *37*
5.1.3 Main Buntsandstein Formation *38*
5.2 Upper Germanic Trias Group *39*
5.2.1 Stratigraphy *39*
5.2.2 Röt Formation *39*
5.2.3 Muschelkalk Formation *40*
5.3 Sedimentary development and palaeogeography *40*

6 Central Graben Group *42*
6.1 Stratigraphy *42*
6.1.1 Delfland Formation *42*
6.2 Sedimentary development and palaeogeography *42*

7 Rijnland Group *43*
7.1 Stratigraphy *43*
7.1.1 Vlieland Formation *43*
7.1.2 Holland Formation *45*

7.2 Sedimentary development and palaeogeography *46*
7.3 Petrophysical evaluation *46*

8 **Chalk Group** ***49***
8.1 Stratigraphy *49*
8.1.1 Texel Chalk Formation *49*
8.1.2 Ommelanden Chalk Formation *49*
8.2 Sedimentary development and palaeogeography *51*
8.3 Petrophysical evaluation *51*

9 **North Sea Super Group** ***52***
9.1 Stratigraphy *52*
9.1.1 Lower North Sea Group *52*
9.1.2 Middle North Sea Group *54*
9.1.3 Upper North Sea Group *54*
9.2 Sedimentary development and palaeogeography *55*

10 **Geological History** ***56***
10.1 Introduction *56*
10.2 Late Carboniferous *56*
10.3 Permian *57*
10.4 Triassic *59*
10.5 Jurassic *62*
10.6 Cretaceous *64*
10.7 Cenozoic *66*
10.8 Salt movements *67*

Appendices ***73***
Appendix A: List of seismic data used *73*
Appendix B: List of wells used *74*
Appendix C: Reservoir calculations Upper Rotliegend Group *76*
Appendix D: Show, status and test data Upper Rotliegend Group *78*
Appendix E: Reservoir calculations Vlieland Sandstone *79*
Appendix F: Show, status and test data Vlieland Sandstone *80*

References ***81***

Maps and Sections:
Map 1: Depth map of the base of the Upper Rotliegend Group
Map 2: Depth map of the base of the Zechstein Group
Map 3: Depth map of the top of the Zechstein Group
Map 4: Thickness map of the Zechstein Group
Map 5: Depth map of the base of the Lower Germanic Trias Group
Map 6: Thickness map of the Upper and Lower Germanic Trias Group
Map 7: Depth map of the base of the Central Graben Group
Map 8: Thickness map of the Central Graben Group
Map 9: Depth map of the base of the Rijnland Group
Map 10: Thickness map of the Rijnland Group
Map 11: Depth map of the base of the Chalk Group

Map 12: Thickness map of the Chalk Group
Map 13: Depth map of the base of the North Sea Super Group
Map 14: Subcrop map below the base of the Rijnland Group
Map 15: Structural sections

Preface

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 of The Netherlands has only published maps and explanations on the shallow subsurface geology of The Netherlands and the North Sea. Reports on the deeper subsurface geology (deeper than about 500 m) were limited because of the status of the data required. These data are acquired from seismic investigations and deep boreholes, which are nearly exclusively carried out by oil companies. Because of their commercial interest to the exploration industry, such data remain confidential.

The data are made available to the Geological Survey of The Netherlands within the framework of the mining legislation. Data collected on the Dutch Continental Shelf are released after a period of ten years, when everyone is free to interpret the data to gain knowledge of the subsurface geology of the North Sea. However, the existing mining legislation that applies to the mainland does not cover the general release of information. The Geological Survey has made special arrangements with the companies about using the mainland data that allow the Geological Survey to process the data and publish the results, once the data are more than ten years old. Data from concession areas form an exception, with a limit of five years. This agreement enables the Geological Survey of The Netherlands to bring the geological framework of the subsurface of The Netherlands to wider attention.

The Ameland-Leeuwarden map sheet of the Geological Atlas of the Subsurface of The Netherlands is the second sheet to be published in the framework of the systematic mapping of The Netherlands based on these data. The complete atlas will comprise 15 map sheets, on a scale of 1:250,000. The distribution of the map sheets is shown in figure 1.1. The Annual Report of the Geological Survey of The Netherlands gives an overview of the progress of this mapping.

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 and 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.

As well as those people 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 including, especially, C.M. Elmers-Kathmann and N. Parker-Witmans. I greatly appreciate all their efforts. Pertinent and constructive criticism from Dr. W.J.M. van der Linden and the reviewing committee added much to the quality of the explanation. Special thanks are due to Chevron, Elf Petroland, NAM, Mobil, Placid, Billiton and Western Geophysical, who all provided data used in this map sheet.

Chr. Staudt, *Director*

1 Introduction

1.1 Extent of area studied

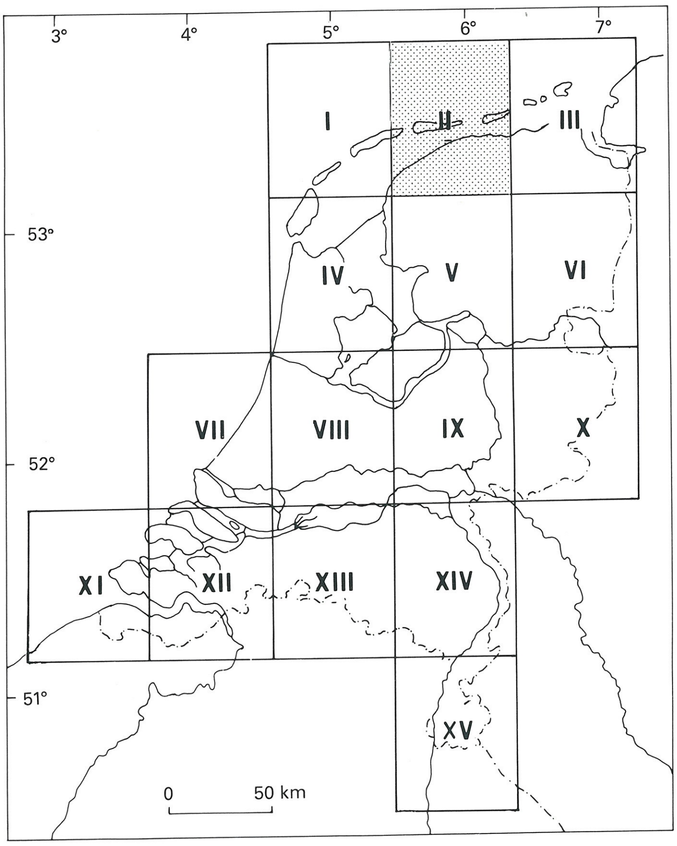
The map sheet area lies in the north of the province of Friesland and extends to the territorial water boundary (fig. 1.1).

1.2 History of exploration and data base

The discovery of the Groningen gasfield in 1959 provoked a lot of exploration activity in the map sheet area. Different companies have since tried to localise occurrences of hydrocarbons in Friesland and the Friesian part of the Wadden Sea, using seismic surveys and deep boreholes.

The exploration target in the first instance was the Slochteren Sandstone, the gas reservoir unit of the Groningen field. The exploration efforts broadened after Elf Petroland discovered gas in the Vlieland Sandstone (Harlingen-1) in 1964 and in the Ommelanden Chalk (Harlingen-2) in 1965, in the direct vicinity of the area covered by the map sheet.

Figure 1.1. Map sheet areas for the regional mapping of the subsurface of The Netherlands.



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

After the Act on Mineral Resources Exploration became law in 1967, drilling licences and concessions, which lay partly or wholly inside the area mapped, were granted to Elf Petroland, the Nederlandse Aardolie Maatschappij (NAM) and to the partnership NAM/Mobil Producing Netherlands Inc. (MPNI). 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. Figure 1.2 gives an overview of the concession areas and shows the known gas occurrences within the map sheet area as per 1-1-1991. The formations in which the gasfields occur are also given.

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. Much use has also been made of the available literature. The regional geological framework has been taken from Ziegler (1982), Glennie (1986a) and Heybroek (1974), among others.

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 the Wadden Sea, especially in the eastern part around Schiermonnikoog, because of limitations related to nature conservation, technical difficulties caused by the type of terrain or because of the slight prospectivity of the area concerned.

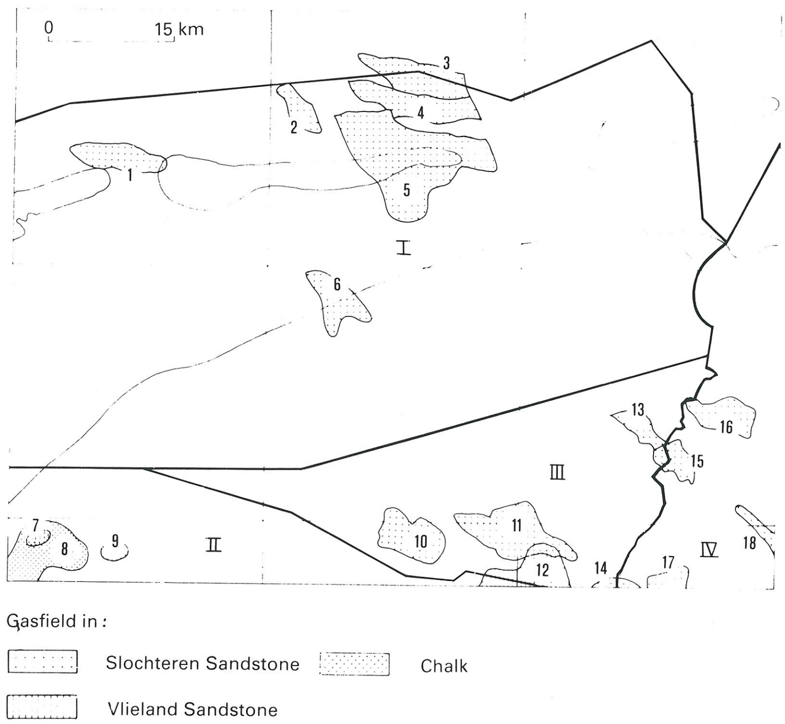


Figure 1.2. Overview of the concessions granted in the map sheet area, with the concession holder in brackets and the gasfields shown.

I North Friesland (NAM)
1 Hollum Ameland
2 Nes Noord
3 Ameland Noord
4 Ameland Westgat
5 Ameland Oost
6 Blija Ferwerderadeel
II Leeuwarden (Petroland)
7 Franeker
8 Harlingen 2
9 Ried
III Tietjerksteradeel (NAM)
10 Suawoude
11 Tietjerksteradeel
12 Friesland
13 Kollumerland
14 Marum
IV Groningen (NAM)
15 Grootegast
16 Grijpskerk
17 Opende Oost
18 Boerakker

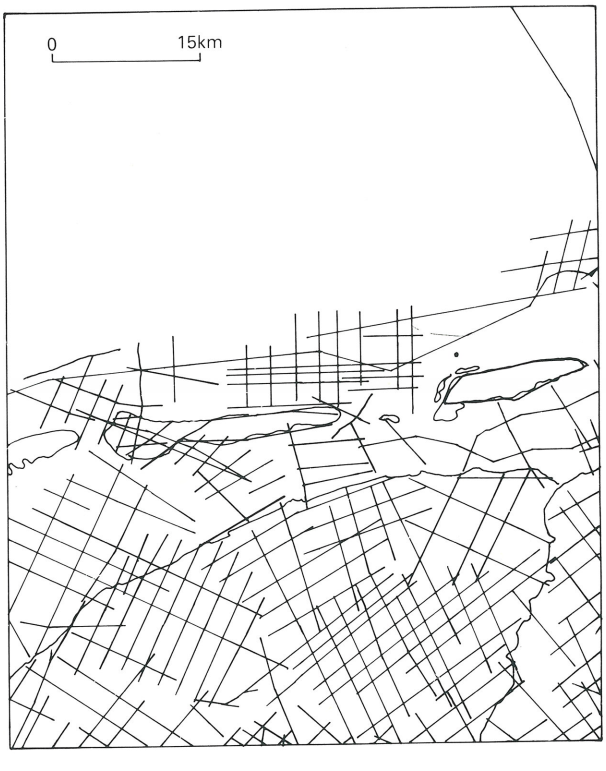
The seismic lines used date from the period 1961-1985, but most were recorded after 1978 (see appendix A). The location of the lines is shown in figure 1.3.

The picked reflectors form the boundaries between the large lithostratigraphic units (groups and formations). 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). The layers, which correspond with litho-stratigraphic divisions, each have a specific velocity distribution. For this purpose a linear relation between the interval velocity and the depth of the layer was assumed ($Vz = Vo + kz$; see table 1). This conversion was not used for the Zechstein Group; because of its specific stratigraphical composition, a hyperbolic relation between the interval velocity and time interval was chosen:

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

The same velocity relations were used for all the map sheets in order to obtain a consistent fit for comparable maps of adjoining 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% in the seismically determined depth of any particular phenomenon was considered acceptable. Table 1 presents an overview of the parameters that were used for the linear velocity distribution.

Figure 1.3. Location of the seismic line grids used for mapping. Appendix A gives details of the owners and vintage of the various lines.



Geological research:

The geological research was directed towards the lithostratigraphic composition of the rocks present in the map sheet area (fig. 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 and their locations are shown in figure 1.5.

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.

1.4 Maps and Sections

The results of the seismic mapping are shown in a series of depth and thickness maps and two sections. Depth maps have been made to the base of the following groups: Upper Rotliegend Group, the Zechstein Group, the Lower Germanic Trias Group, the Central Graben Group, the Rijnland Group, the Chalk Group and the North Sea Super Group, as well as a depth map to the top of the Zechstein Group. These groups are given in figure 1.4 in chronological order.

table 1 Applied velocity distribution:

a. based on $Vz = Vo + kz$

Vz = formation/group velocity at depth z; k = constant;
Vo = formation/group velocity at depth o; z = depth (m).

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

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

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

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

Thickness maps were made of the Zechstein Group, the Upper and Lower Germanic Trias Groups together, the Central Graben Group, the Rijnland Group and the Chalk Group. The depth map of the North Sea Super Group also serves as a thickness map for this unit and a subcrop map of the important unconformity at the base of the Rijnland Group was made.

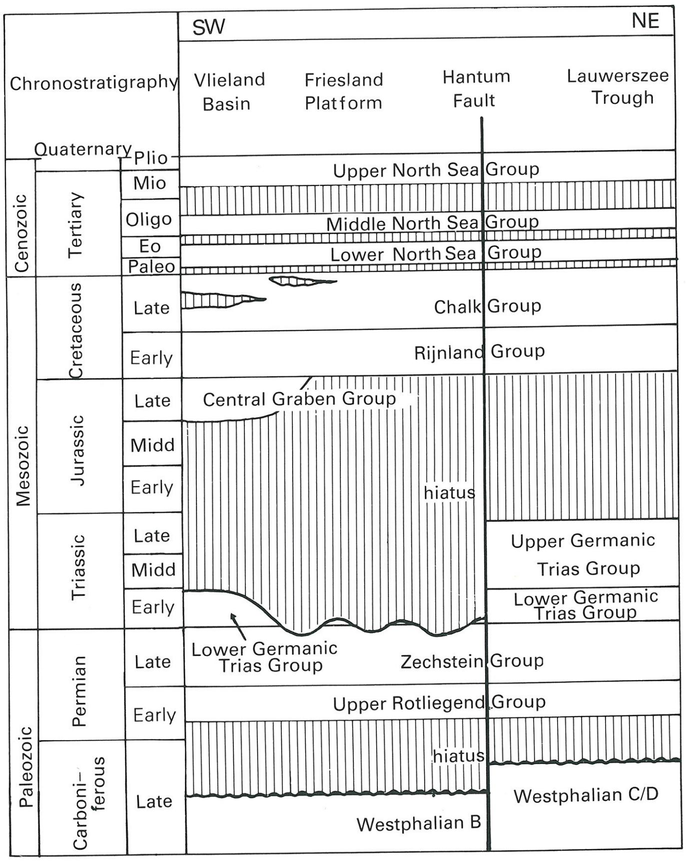
Although, in general, the seismic lines used for mapping the map sheet area were of reasonable to good quality, the base of the Upper Rotliegend Group could not be determined everywhere from the seismic data. The depth map of this group is therefore based on the depth map of the base of the Zechstein to which a regional thickness of the Upper Rotliegend Group based on well data (see fig. 3.2) has been added.

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

The quality of the maps depends on the quality and density of the data available. In the Wadden Sea both factors have had a negative influence on the results of the mapping.

The subcrop map of the base of the Rijnland shows the stratigraphic units which occur under this unconformity and thus gives an impression of the degree of erosion. Subcrop maps of the base of the Central Graben Group and the base of the North Sea Super Group are not

Figure 1.4. Diagram of the lithostratigraphic units present in the map sheet area. Vertical shading marks the hiatuses.



presented since both these groups only cover one other group in the map sheet area, these are the Lower Germanic Trias Group and the Chalk Group, respectively.

The depth map to the top of the Zechstein Group (map 3) shows a marked change in the contours. This is because the Zechstein Group is only partly conformably overlain by the Lower Germanic Trias and partly unconformably by the Rijnland Group. The boundary between these areas is shown on the map.

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 is intended to underscore the information from the different maps and thereby to provide as complete a picture as possible of the geology of the map sheet area. The text comprises a first part, in which a description of the lithostratigraphy is given, and a second part, which gives more detail on the geological history of the study area.

In the descriptions of the lithostratigraphy, the emphasis lies on the variation and extent of the different groups, formations and members. The extent of a unit is mainly related to the important structural features of the map sheet area which are described in §1.6. In chapters 2

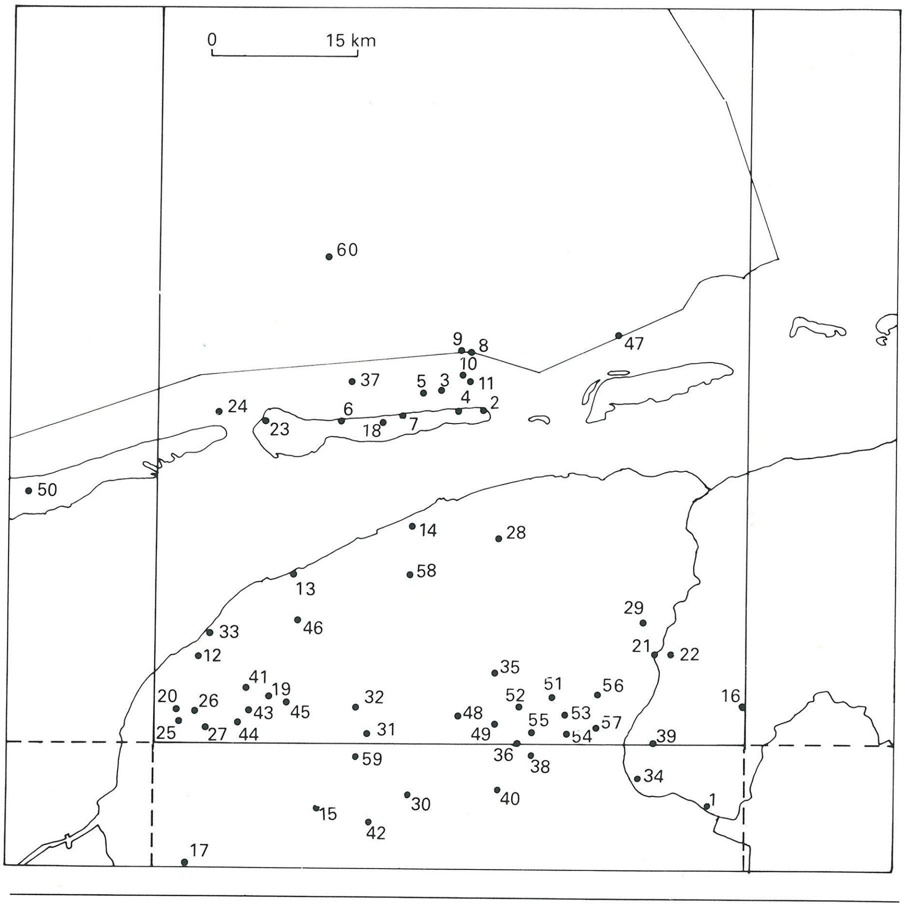


Figure 1.5. Location map of the wells used for mapping. The numbers refer to Appendix B, which gives the names, owners, final depths and dates of the wells.

to 9, the lithostratigraphic composition and development is considered per group, from old to younger, in the light of these structural features. Unless stated otherwise, the descriptions follow the Stratigraphic Nomenclature of The Netherlands (NAM & RGD, 1980). Thereafter, there is a paragraph on the sedimentary development and palaeogeography. Finally, we consider the economic importance of the Upper Rotliegend, the Rijnland and Chalk Groups as reservoir rocks.

In a number of cases units have been mapped at group or formation level and these are included as figures in the text. The Cenozoic sediments are not treated as separate groups but considered as a whole as the North Sea Super Group. This description is limited to Tertiary sediments. A description of the Quaternary deposits will be published in 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.

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

1.6 Summary

Figure 1.4 shows the stratigraphic column of the map sheet area against the background of the structural units. The (current) distribution of the sediments is determined to a large extent by the structural development of the area. Carboniferous sediments are of clastic composition and predominantly of fluvial or lacustrine origin. The Upper Rotliegend Group from the Early Permian is also built up of clastic material but it was deposited in a desert on the edge of a desert lake. The sediments display fluvial and lacustrine as well as aeolian features. The Zechstein Group, Late Permian, contains a number of evaporite cycles. These sequences of clay, limestone, anhydrite and rock salt were formed under marine conditions. The Lower Germanic Trias Group is also composed of clastics and had a continental origin (fluvial and lacustrine). The composition of the Upper Germanic Trias Group, with carbonates and evaporites, reflects an increasing marine influence. Early and Middle Jurassic sediments are not found in the map sheet area because of subsequent erosion. The Central Graben Group (Late Jurassic) represents mainly clastic, continental deposits. Marine sediments were laid down during the entire Cretaceous and these can be divided into the clastic Lower Cretaceous sediments of the Rijnland Group and the marine carbonates of the Chalk Group in the Late Cretaceous. The Cenozoic sequence is built up of clastic sediments deposited under varying marine and continental conditions.

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

The geological history is described using the structural units distinguished in the map sheet area. To a greater or lesser degree, these units contain original Variscan elements, which have been reactivated or modified during later tectonic phases. The depth maps to the base of the Upper Rotliegend Group and the Zechstein Group (maps 1 and 2) indicate the structural trend in the area. The dominant fault direction is WNW-ESE and a secondary trend is nearly E-W. A NNW-SSE direction is dominant in the northeast, in the Lauwerszee Trough, and a secondary trend lies E-W to WSW-ENE.

The map sheet area belongs to the *North Netherlands High* (fig. 1.6.) which extends over the

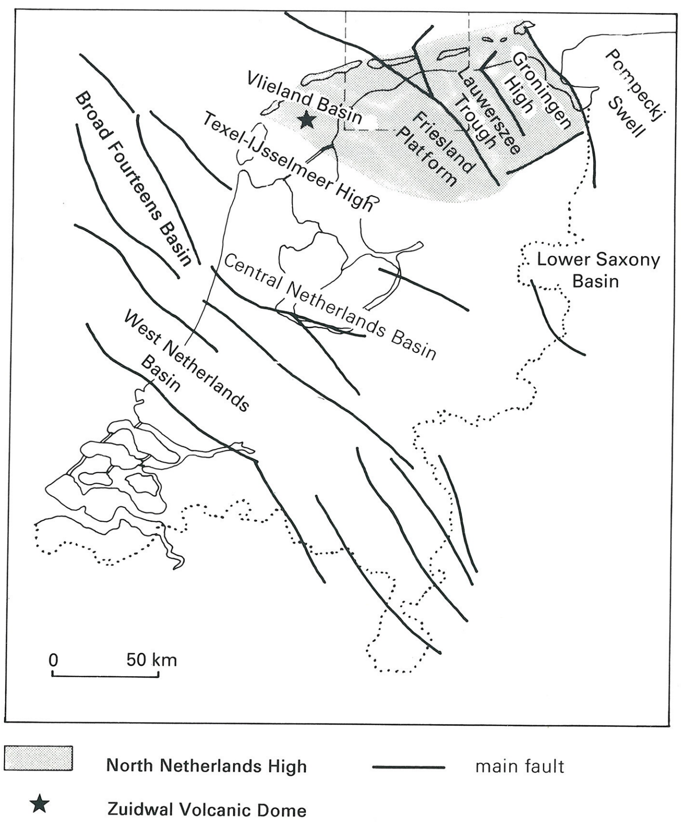
provinces of Friesland and Groningen and which forms the link between the Texel-IJsselmeer High and the Pompeckj Schwelle ('t Hart, 1969; Heybroek, 1974). The North Netherlands High was formed during the Late Jurassic - Late Kimmerian phase of deformation (Stäuble & Milius, 1970) and is composed of a number of sub-units. As far as the map sheet area is concerned these are the Vlieland Basin in the extreme southwest, the Friesland Platform in the central part, and the Lauwerszee Trough in the northeast. The latter two features are separated by the Hantum Fault (fig. 1.6). To the east of the map sheet area (Rottumeroog-Groningen map sheet, RGD, in preparation), the Groningen High borders the Lauwerszee Trough, and the Friesland Platform grades into the Texel-IJsselmeer High to the south of the map sheet area.

Only a small part of the *Vlieland Basin* lies within the map sheet area, the larger part extends over the Vlieland-Terschelling map sheet (RGD 1991). This Late Jurassic basin is the only place within the map sheet area where Jurassic sediments occur (Delfland Formation, Central Graben Group). The boundary with the Friesland Platform is difficult to determine structurally and the shape of the basin was therefore defined by the extent of the Late Jurassic deposits.

A characteristic of the *Friesland Platform* is that the Lower Cretaceous deposits lie directly on sediments of Early Triassic and even Late Permian (Zechstein Group) age.

To the south the *Lauwerszee Trough* is connected to the most westerly part of the Lower Saxony Basin via a structurally complex zone. In contrast to the Friesland Platform, sediments

Figure 1.6. Overview of the structural elements pertinent to the map sheet area.

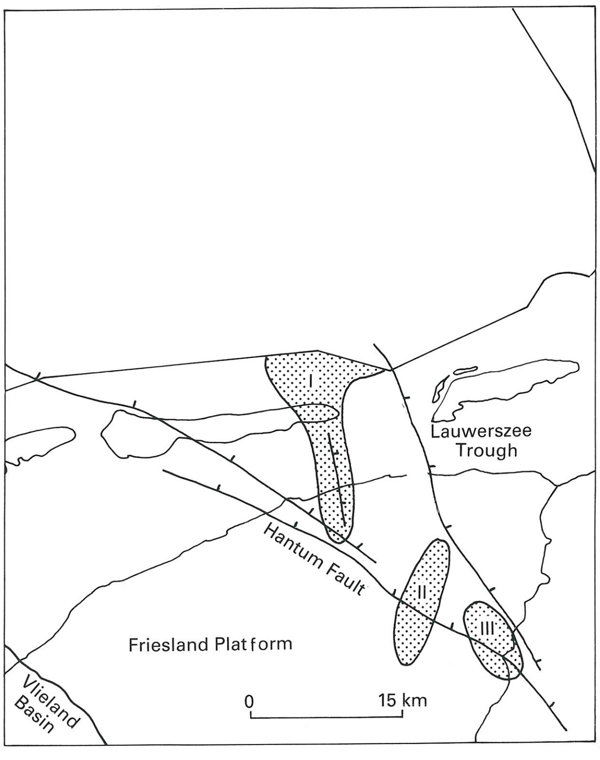


of both the Lower and Upper Germanic Trias Groups occur in the Lauwerszee Trough. The great thickness of Tertiary deposits should also be noted.

The *Hantum Fault* is the name of the most evident fault zone in the map sheet area. It has been active several times during the geological history of the area, which has led to obvious differences in development on both sides of the fault (section 2, map 15 and fig. 1.7). The fault zone runs from the southeast corner of the map sheet area in a northwesterly direction to the coast of Friesland, where it splits into a primary NW-SE branch to the west of Ameland, and a secondary N-S branch towards East Ameland. The fault zone is assumed to embody a lateral displacement with a component of extension. It links the Central North Sea Graben in the northwest and the fault system of the Lower Saxony Basin and the southern Ems Trough to the southeast of the map sheet area (Van Wijhe, 1987). The displacement along the Hantum Fault is greatest in the centre of the map sheet and in the Wadden Sea; it reaches a net maximum of approximately 1100 m (map 2) vertically. The faults within the zone are arranged en echelon and variations along one and the same fault show that the most important movement was taken over laterally by sequential faults.

The structural picture of the map sheet under discussion was determined to a large extent by the Hantum Fault and salt in the Zechstein Group. The plastic behaviour of the salts caused detachment between the over- and underlying rocks, so that the shaping which took place was

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



I Salt dome Ternaard

II Salt dome Engwierum

III Salt dome Gerkesklooster

disharmonic. This can be clearly seen when the depth maps to the top and the base of the Zechstein Group (maps 2 and 3) are laid side by side. Only the large-scale structures such as the Friesland Platform and the Lauwerszee Trough, which are separated by the Hantum Fault, are evident above the salt member. The normal faults which occur many times on the depth map of the base of the Zechstein Group were accommodated by the salt. The structures in the sedimentary unit overlying the Zechstein Group are mainly related to the salt domes which formed by plastic flow. There are three very pronounced salt domes in the map sheet area (from north to south: Ternaard, Engwierum and Gerkesklooster; fig. 1.7 and map 4). The salt domes are elongated parallel to the dominant fault trends, the NW-SE direction of the primary Hantum Fault and N-S direction of the secondary Hantum Fault. The salt domes lie more or less in echelon along the edge of the Lauwerszee Trough, where there was an excellent combination of factors to promote the formation of salt structures: a sufficiently thick original layer of salt, a thick sediment cover, extension faults and lateral displacements which caused variations in the thickness of sedimentary fill and cover, and fault movements and the accompanying differential force field to initiate salt flow.

2 Limburg Group

2.1 Stratigraphy

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

Since the Carboniferous rocks in the map sheet area and the direct surroundings were seldom an exploration target, most drilling was halted shortly after reaching the Carboniferous. Thus the data on the Carboniferous is restricted to the upper tens of metres. The thickness of the group is unknown because none of the wells penetrated the Limburg Group completely, nor can the base be determined from seismic information.

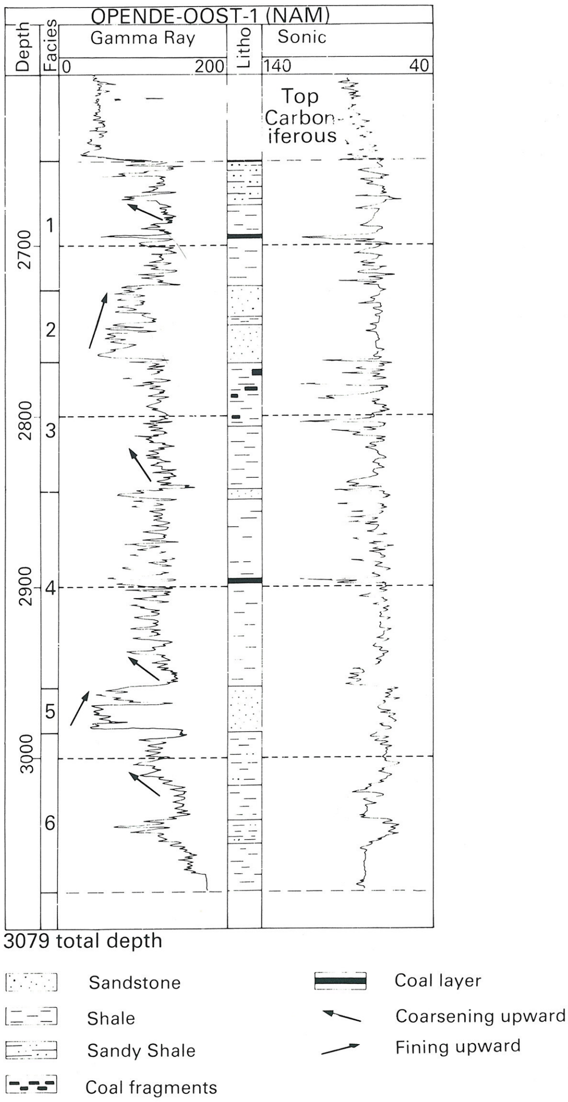


Figure 2.1. Lithological well section of the Limburg Group in the Opende-Oost-1 well (depth in metres). Interpretation of the lithological phenomena is based on the gamma ray log (in API units) and the sonic log (μs/ft).
Facies interpretation:
1 = small channel systems, with several crevasse breakthroughs lower in the sequence;
2 = fluvial, stacked flow channels of a meandering system with varying curvature;
3 = lacustrine/marsh with crevasse breakthroughs;
4 = several crevasse channels and breakthroughs in marshes;
5 = fluvial channel system with low curvature;
6 = possibly marine pro-deltas and mouthbar.

Since the limited data does not permit further subdivision, the Limburg Group is included in the Coal Measures (for this map sheet). This term, which is adopted from the English Carboniferous stratigraphy, was introduced by NAM & RGD (1980) as the formation name for the coal-bearing Late Carboniferous (Westphalian) deposits.

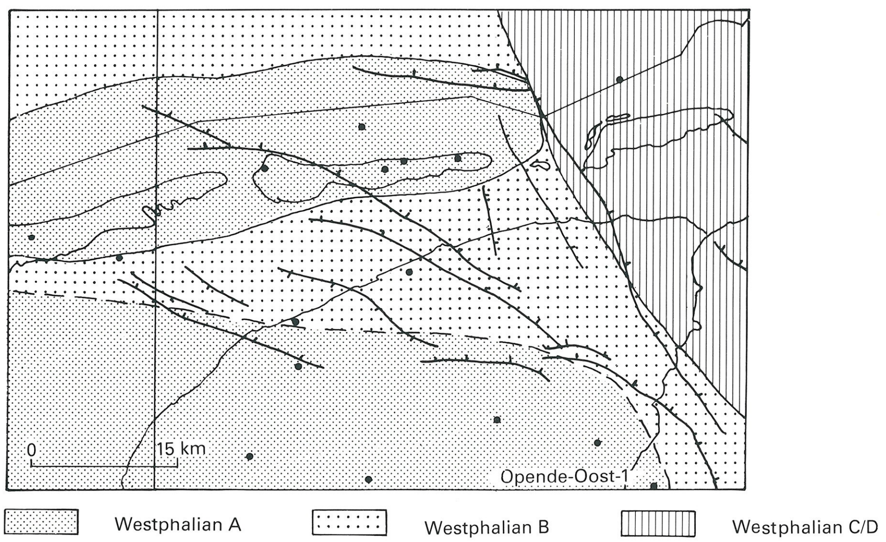
The lithological description of the Limburg Group is illustrated using the Opende-Oost-1 well (fig. 2.1). The Limburg Group sequence drilled in this well is relatively thick, approximately 430 m. Log correlation dating of this sequence suggests a Westphalian A age.

2.1.1 Coal Measures

The Coal Measures comprise mainly dark grey to violet coloured silty claystones, in which sandstones and coal seams occur. 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. The thicknesses of the individual sandstone sequences vary widely (fig. 2.1). Coal seams or coal-containing layers are often only a few millimetres to several centimetres thick, but they can also reach a thickness of several metres. They occur in both coarsening-upwards and fining-upwards sequences. Coal also occurs in non-sorted silty claystones. Based on the character of the different logs, it is thought that there are different thin marine levels in the deposits.

Biostratigraphic research (RGD, 1989; 1990; etc.) and data from the literature (Van Wijhe, 1987) point to a Westphalian A age in the south of the map sheet area and around Terschelling and Ameland. In North Friesland and the extreme southwest the uppermost Carboniferous has a Westphalian B age, whereas in the northeast it belongs to Westphalian C (fig. 2.2).

Figure 2.2. Subcrop map below the Lower Rotliegend Group (Saalic unconformity). Variation in age of the top of the Limburg Group is an indication of the structure as it was at that time. (after Van Staalduinen et al., 1979; Van Wijhe, 1987).



2.2 Sedimentary development and palaeogeography

The Coal Measures in the map sheet area were deposited in a sequence of varying fluvial, deltaic and lacustrine environments, with thin marine intercalations (fig. 2.1; RGD, 1989b).

The continental deposits of the Limburg Group were formed over an extensive and very flat landscape lying just above normal sea level. The low height of the land above sea level is evident from the large extent of the thin, intercalated marine sediments (characterised by high gamma ray measurements on the basis of units 4 and 5 in fig. 2.1). A slight rise in sea level was sufficient to inundate large areas. The clayey character of the sediments and the occurrence of coal seams are characteristic of a very flat landscape. These deposits were formed in lakes and marshes with abundant plant growth and often stagnant surface water. Finally, the fining-upwards sequences, which are generally interpreted as being deposits from meandering rivers, are also indicative of only slight relief (Moody Stuart, 1966). Coarsening-upwards sequences formed where these rivers flowed into lakes. Breakthroughs in the river banks led to crevasse deposits and peat was formed in both the marshes and the cutoff channels. Coal was eventually formed by coalification of the peat, under high temperature and pressure, consequent to its deep burial.

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 in the south and the Silverpit Claystone Formation in the north, which grade laterally into each other (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 an unconformity related to the Saalian tectonic phase. The Late Permian Zechstein Group deposits lie directly on the Upper Rotliegend Group and the contact between these two groups is conformable.

The thickness of the Upper Rotliegend (fig. 3.2) increases towards the north, from more than 200 m in the south to more than 400 m to the north of the map sheet.

The stratigraphic sequence of the Upper Rotliegend Group within the map sheet area is illustrated by a stratigraphic correlation section (fig. 3.3), which shows the gradual change, from south to north, of the Slochteren Sandstone Formation into the Silverpit Claystone Formation.

3.1.1 Slochteren Sandstone Formation

To the south of the map sheet area the Upper Rotliegend Group is composed almost entirely of the Slochteren Sandstone Formation (fig. 3.3, Heegermeer-1). The formation consists of reddish-brown sandstone with local conglomerates. Over the whole map sheet area the Slochteren Sandstone Formation is divided into two parts by a claystone tongue of the Silverpit Claystone Formation (the Ameland Claystone, figs 3.1 and 3.3, Dronrijp-1). This division into the Upper and Lower Slochteren Sandstone can be recognised over a large area of the northern Netherlands.

The *Lower Slochteren Sandstone* can be found throughout the map sheet area and is mainly composed of coarse to fine, red to reddish-brown sandstones. They form beds with small

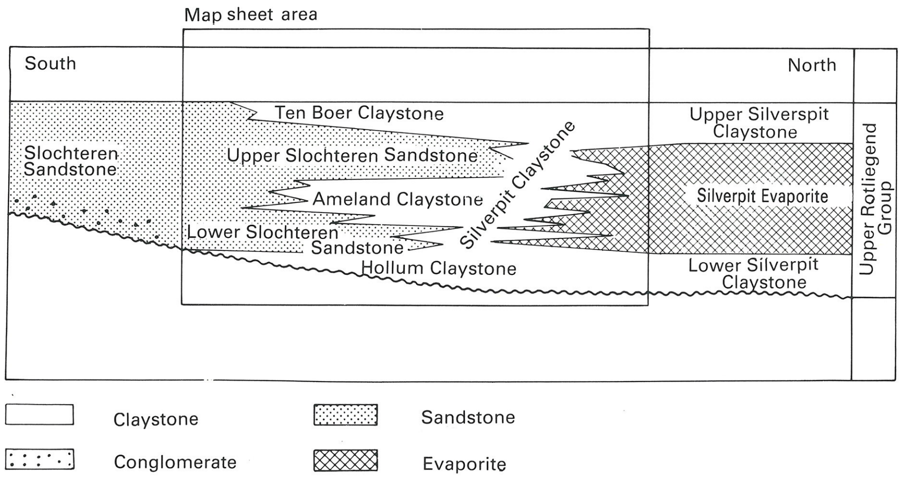


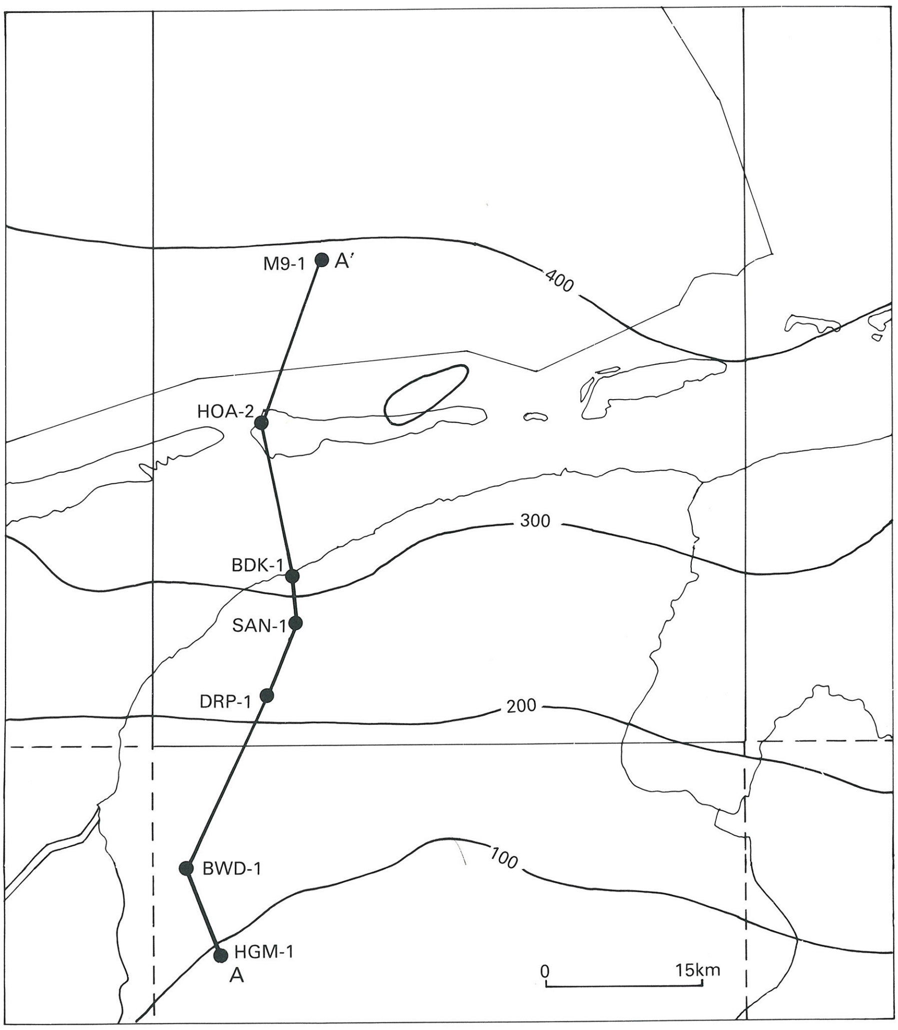
Figure 3.1. Stratigraphic diagram of the Upper Rotliegend Group, showing the lateral transition from the Slochteren Sandstone Formation to the Silverpit Claystone Formation. The position of the map sheet area is shown in the inset (from NAM & RGD, 1980).

intercalated conglomerates and claystone layers. A conglomerate was deposited at the base of the sandstone beds, which often have an erosive contact. There are small-scale cross-stratifications and fining-upwards sequences in the sandstone beds. The conglomerates have a fine sandy to clayey matrix. The grains are fairly well sorted and generally well rounded. These characteristics are typical of fluvial deposits.

The *Upper Slochteren Sandstone* can be recognised throughout the map sheet area. Towards the north of the area mapped (fig. 3.3, M9-1) the units grades laterally into the Silverpit Claystone Formation. The Upper Slochteren Sandstone comprises mainly reddish-brown, well sorted, fine sandstones. In the south very coarse-grained, poorly sorted sandstones occur locally. The sandstones are fairly well cemented and comprise mainly quartz. Small quantities of feldspar, volcanic material and shale fragments are also found. The red colouring mostly grades into beige in the top ten metres.

The well-sorted sandstones of the Upper Slochteren Sandstone are described as aeolian deposits, formed in a desert-type environment (e.g. 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.

Figure 3.2. Thickness map of the Upper Rotliegend Group. The map is based on well data. AA′ shows the location of the stratigraphic section in fig. 3.3.



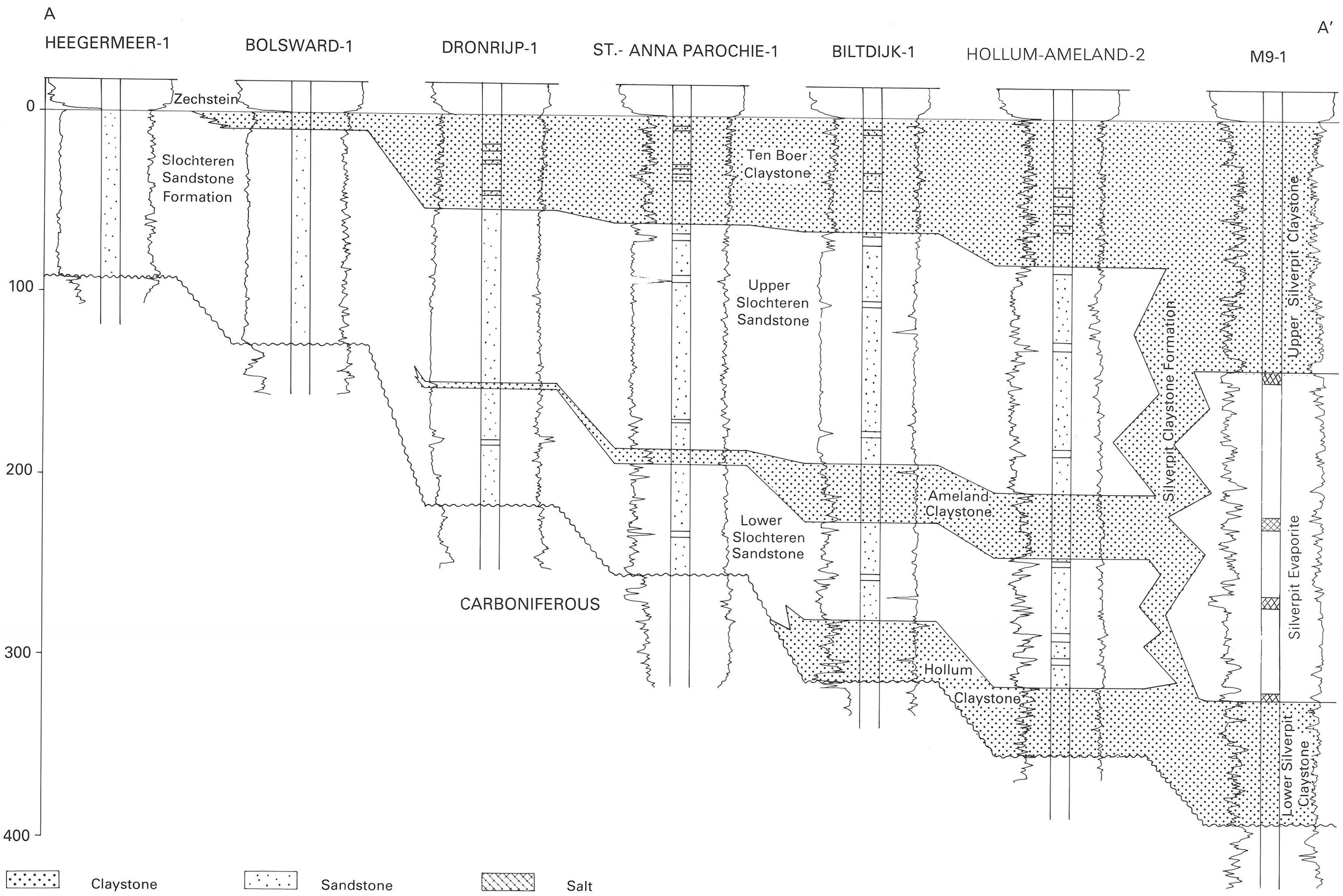


Figure 3.3. Stratigraphic section of the Upper Rotliegend Group, showing the transition of the Slochteren Sandstone into the Silverpit Claystone, from south to north (see fig. 3.2 for location). The correlation is based on the gamma ray log (in API units) and the sonic log (μs/ft). See text for further information

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 (fig. 3.3, well M9-1), and fine sandstones in the transitional area with the Slochteren Sandstone Formation. Within the map sheet area this formation reaches a thickness of 400 m.

In the transitional area with the Slochteren Sandstone Formation, the Silverpit Formation can be subdivided (from old to young) as follows: the Hollum Claystone, the Ameland Claystone and the Ten Boer Claystone (fig. 3.1). The boundary between the above units is somewhat arbitrary because the sandstones of the Slochteren Formation grade gradually into the claystones of the Silverpit Formation. These latter are interpreted as playa lake deposits (Glennie, 1986a).

The *Hollum Claystone Member* is a locally developed claystone tongue which occurs below the Lower Slochteren Sandstone, at the base of the Rotliegend. This tongue is found in the area around Ameland, one of the Wadden Islands, and is 20-30 m thick. The reference section (NAM & RGD, 1980) of this member is present in the Hollum-Ameland-2 well (fig. 3.3).

The *Ameland Claystone Member* is found in the northern part of the map sheet area. Dronrijp-1 is the most southern well which penetrates this member and the claystone is only some ten metres thick (fig. 3.3). The thickness increases northwards to a maximum of 50 m.

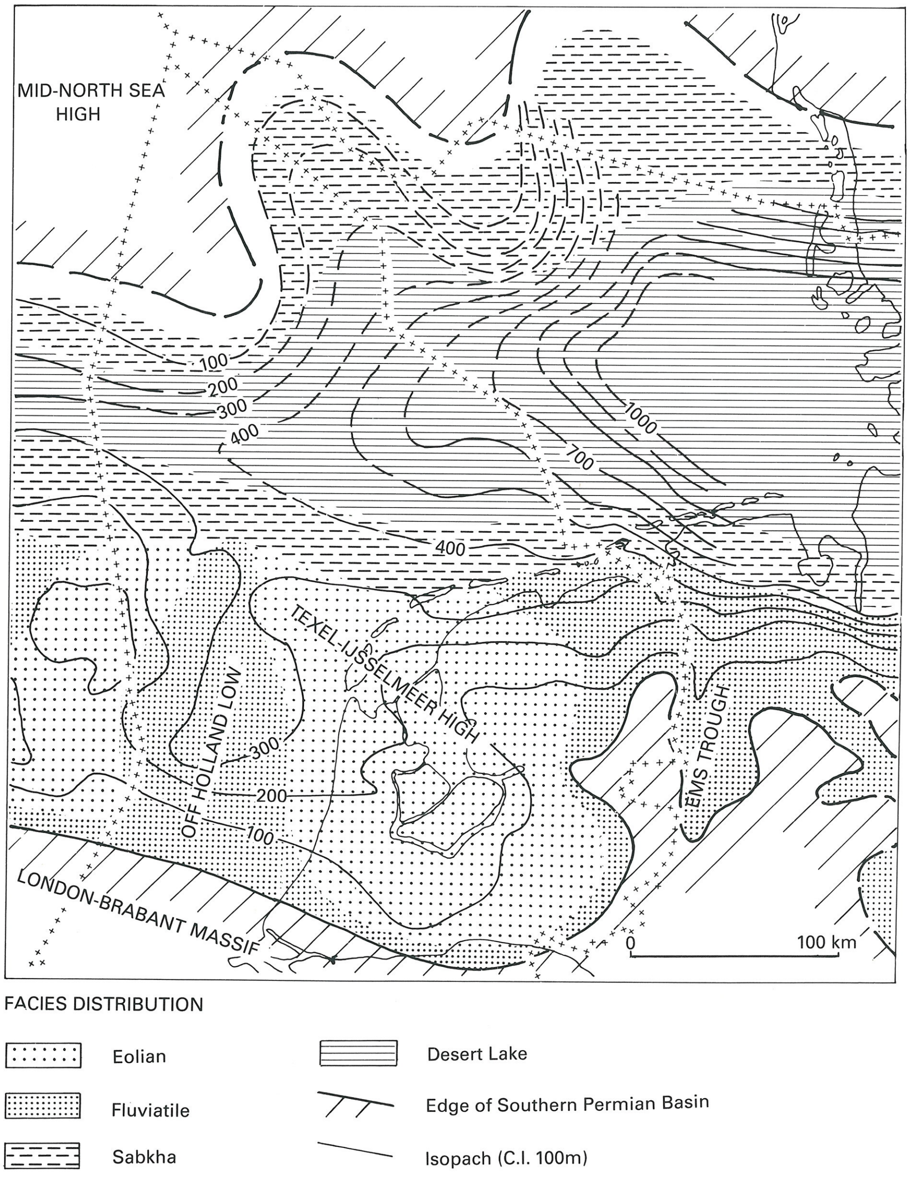
The *Ten Boer Claystone Member* is the youngest tongue of the Silverpit Claystone Formation and is overlain by the Coppershale of the Zechstein Group. The thickness of the Ten Boer Claystone also increases northwards, from at least 40 m in the south to more than 100 m to the north of Ameland.

3.2 Sedimentary development and palaeogeography

The Upper Rotliegend Group was deposited under continental conditions in the intra-cratonic Southern Permian Basin (fig. 3.4). Under the influence of the arid climate, a desert area formed along the southern edge of the basin, while a lake formed in the centre of the basin (to the north of the map sheet area). The deposits within the map sheet area reflect the fluctuations in the lake's water level. The Hollum, Ameland and Ten Boer Claystones represent the most southern lacustrine deposits that were formed during periods with a high water level. The Lower and Upper Slochteren Sandstones comprise aeolian and fluvial deposits laid down in the desert area, which extended northwards during periods of low water level.

The source areas for the Slochteren Sandstones probably lay to the south and east of the map sheet area (Stäuble & Milius, 1970). 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 were carried by trade winds and probably originated from a much larger area, which stretched far to the east of the map sheet area. Deflation of the sediments deposited by the degraded rivers and in the wadis may also have played a 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, the basin lay below sea level (Glennie, 1986a).

Figure 3.4. Palaeogeographic map of the Permo-Triassic Basin in the Early Permian. The map sheet area, situated in the southern part of the basin, lays in a transition area from fluvial/aeolian to sabkha facies. Clastic sediments were transported from the south via two depressions (after Van Wijhe et al., 1980).

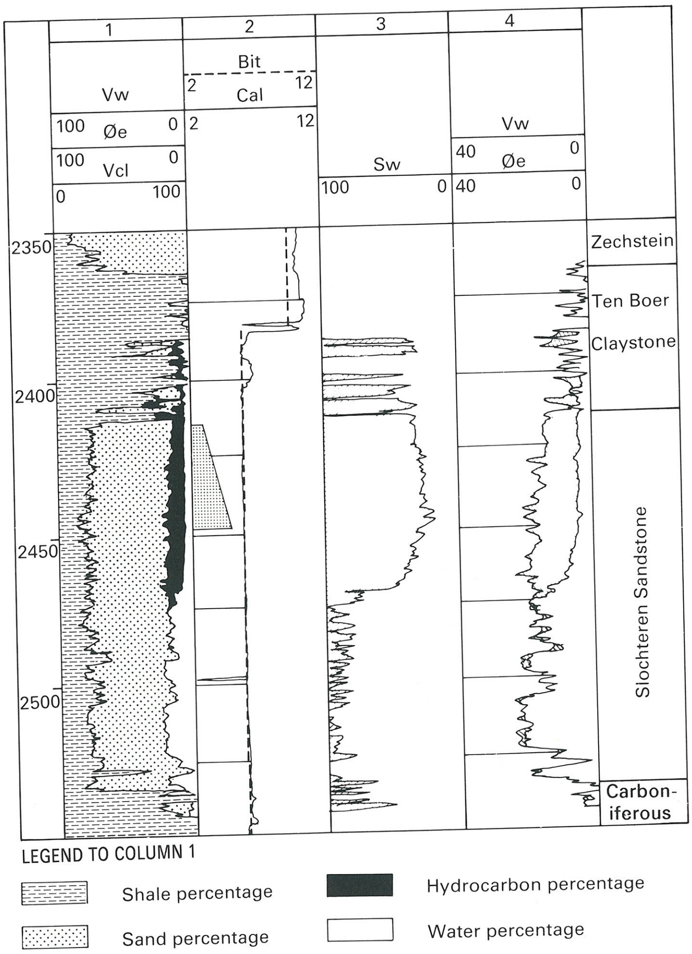


3.3 Petrophysical evaluation

The sandstones of the Upper Rotliegend Group form one of the principal targets for exploration in The Netherlands' territory and on the continental shelf. Deposits of this group, from eleven wells drilled in the map sheet area and the direct surroundings, were evaluated petrophysically (appendix C). In some five wells, the sandstones of the Upper Rotliegend Group are gas-bearing (appendix D; RGD, 1990b). The result of a log evaluation of the Upper Rotliegend reservoir sequence is exemplified by the Marum-2 well in figure 3.5. Figure 3.6 shows schematically the distribution of the average effective porosity (Øem) of the Upper Rotliegend Group in the map sheet area and surroundings.

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 B in figure 3.6 was used for calculating the reduction of porosity as a consequence of pressure increase due to burial. The value of the surface porosity (38.0%) falls within the limits of 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, fig. 21). The porosity-reduction was caused by diagenesis as well as by physical compaction due to sediment cover. Core studies show that quartz, anhydrite, calcite and dolomite are present as cements and

Figure 3.5. Petrophysical evaluation of the Upper Rotliegend sequence in Marum-2. Column 1: clay content Vcl, effective porosity Øe and pore water volume Vw, all in per cent. The clay content was determined from the gamma ray log. The effective porosity was taken from acoustic logs (Raymer-Hunt comparison in single porosity model; Raymer et al., 1980) after correction for clay content. Column 2: wellhole diameter (cal) and drillbit diameter (bit), both in inches; the tested interval is marked by a trapezium (appendix D). Column 3: water saturation Sw (in per cent). The Indonesian formula, which is suitable for clayey formations, was used to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe and the volume of water in the pores Vw. The formation boundaries are given in the right-hand column. Depths are actual depths.



4 Zechstein Group

4.1 Stratigraphy

The Zechstein Group comprises four evaporite cycles, which were formed by the periodic flooding and subsequent evaporation of sea water. The Group lies conformably on the Upper Rotliegend Group and is overlain conformably by the Lower Germanic Trias Group (map 5). Where the Trias sediments have been eroded, the Zechstein Group is overlain unconformably by the Rijnland Group (map 14). The age of the Zechstein Group is Late Permian.

The deposits of the Zechstein Group occur over all the map sheet area. The average thickness is approximately 700 m on the Friesland Platform, to the southwest of the Hantum Fault (fig. 1.7). In the other part, especially the Lauwerszee Trough, the thickness varies widely as a result of salt flow. The greatest thickness, of nearly 3000 m, is reached in the Ternaard salt structure (maps 4 and 5).

The four evaporite cycles each have the status of a formation and are named Zechstein 1 to Zechstein 4, from old to younger. The youngest Zechstein deposits, an anhydrite claystone between the Zechstein 4 Formation and the Lower Germanic Trias Group, are informally described as the Upper Zechstein. This member is the equivalent of higher evaporite cycles that were deposited further to the north, in the centre of the Southern Permian Basin. This name deviates from that used by NAM & RGD (1980).

The composition of the Zechstein Group is illustrated by Boerakker-1, which penetrated a complete section (fig. 4.1).

4.1.1 Zechstein 1 Formation

The Zechstein 1 Formation is composed of the Coppershale, the Zechstein 1 Carbonate and the Zechstein 1 Anhydrite members. In the map sheet area the thickness of this formation is fairly constant at about 35 m.

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 (fig. 3.4). It is characterised by a peak on the gamma ray log, caused by a high content of radioactive minerals (fig. 4.1).

The *Zechstein 1 Carbonate* is a grey-brown dolomitic limestone. The lowest part of this unit contains some clay, but the clay content decreases upwards. This unit is approximately 10 m thick.

The *Zechstein 1 Anhydrite* comprises anhydrite with some interbedded dolomite and it is about 20-25 m thick

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. The Zechstein 2 Formation contains a complete evaporation cycle.
This formation is approximately 400 to 700 m thick to the southwest of the Hantum Fault. In the northeast it can be 1000 m thick because of salt flow and it reaches at least 1500 m in Ameland-Oost-1. The original sedimentary thickness is difficult to determine because of the

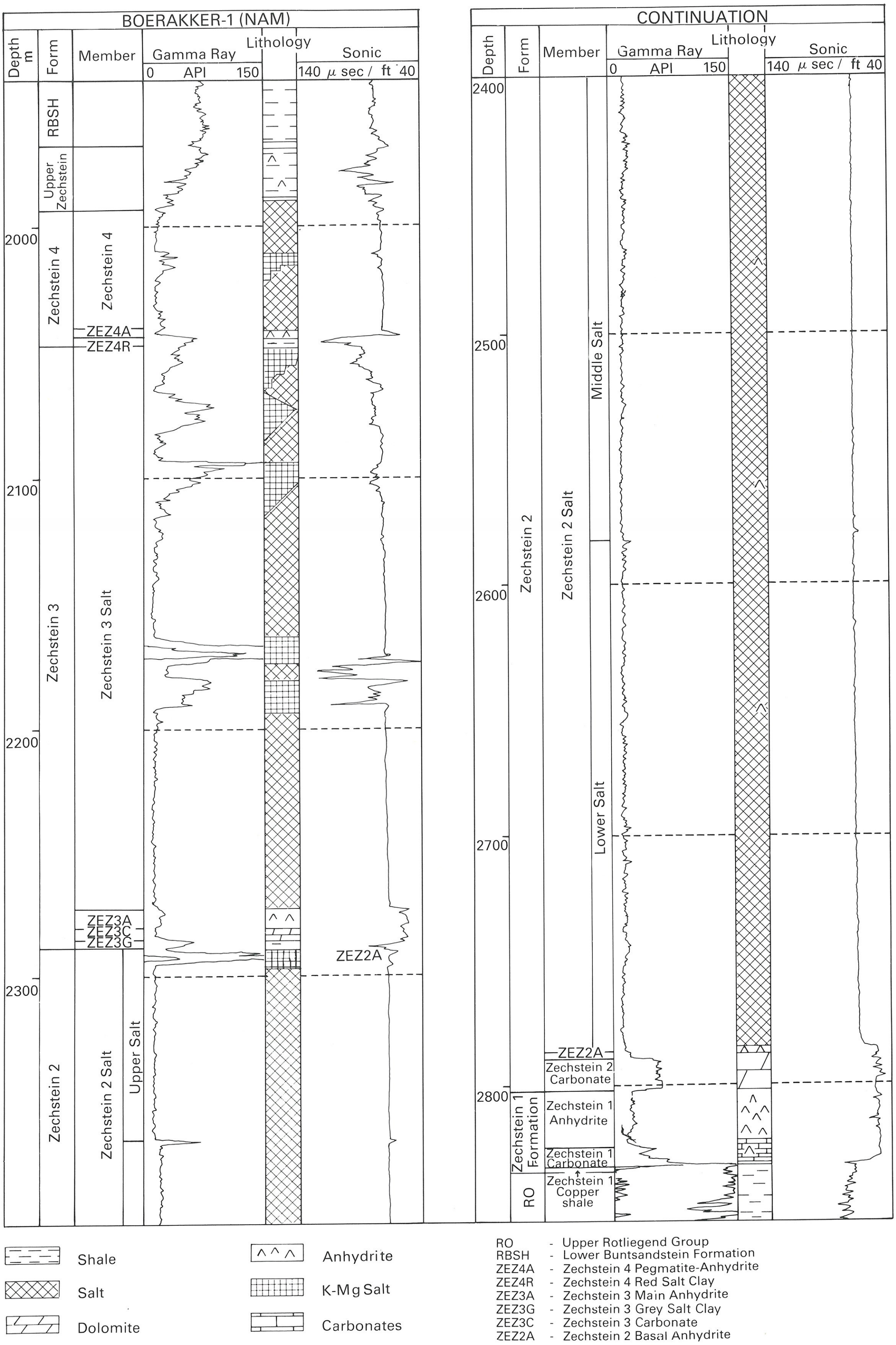


Figure 4.1. Composition of the Zechstein Group in the well Boerakker-1. For further information see text.

salt flow, but on the Friesland Platform it appears to be reasonably undisturbed and reaches 600 to 700 m. There are indications in a few places that the original thickness was greater because of synsedimentary fault movements (e.g. in the Lauwerszee Trough).

The *Zechstein 2 Carbonate* (Main Dolomite) is composed of a brown compact dolomite, with increasing clay content towards the top. The average thickness of the Zechstein 2 Carbonate is approximately 10 m.

The *Zechstein 2 Basal Anhydrite* is a white to beige coloured anhydrite, 3 to 5 m thick.

The *Zechstein 2 Salt* is a white to translucent, mostly coarse but sometimes finely crystalline member of mainly halitic composition. The thickness of this unit varies strongly as a consequence of salt flow; the greatest thickness in the map sheet area is reached in the Ternaard salt structure.

Three salt members can be distinguished in the Zechstein 2 Salt (fig. 4.1). The members are separated by polyhalite layers: a calcium-, magnesium- and potassium-bearing anhydrite. This triple sequence can be correlated regionally in The Netherlands and on the adjacent continental shelf.

The lowest member is characterised in the lower part by interbedded anhydrite layers and above by layers of potassium-magnesium salts interbedded 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 uppermost salt member, which is characterised by very pure rock salt, potassium-magnesium rich salt layers are present at the top. 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 8 m in the Boerakker-1 well. At Barradeel these salts are abnormally thick (40 m) which makes them economically attractive. At the beginning of the 1970s solution mining was used to exploit these salts but technical difficulties, caused by the plastic character of the minerals present (such as carnallite, kieserite, sylvite and halite) and the great depth, rendered the project unviable.

The Zechstein 2 cycle ended with the deposition of the *Zechstein 2 Roof Anhydrite.* This is a pure anhydrite with a maximal thickness of a few metres. It is scarcely developed in Boerakker-1; only a small peak on the sonic log in combination with a low gamma ray recording indicates its presence directly below the Zechstein 3 Formation (fig. 4.1).

4.1.3 Zechstein 3 Formation

The Zechstein 3 Formation is divided into: the Grey Salt Clay, the Zechstein 3 Carbonate, the Zechstein 3 Main Anhydrite and the Zechstein 3 Salt Member. The Zechstein 3 Main Anhydrite is covered unconformably by Lower Cretaceous deposits at several places in the southwestern part of the map sheet area.

The *Grey Salt Clay* is a 2-3 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. This unit is generally less than 5 m thick within the map sheet area.

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, from 2 m to more than 200 m. This may be due to a difference in primary sedimentation, or to erosion at the end of the Jurassic, or to distortions caused by salt flow which make the drilled thickness greater than the true thickness.

The *Zechstein 3 Salt* comprises orange to red coloured rock salt. Potassium-magnesium salt layers are found at different places in the sequence, and especially at the top of this member. The thickness varies between 35 m and 350 m. The variation is caused by differences in primary sedimentation, as well as both erosion and salt flow. Erosion took place especially on the Friesland Platform, while salt flow occurred mainly along the western edge of the Lauwerszee Trough.

4.1.4 Zechstein 4 Formation

The Zechstein 4 Formation comprises the *Red Salt Clay* with a maximal thickness of 7 m, the 1-4 m thick *Zechstein 4 Pegmatite-Anhydrite,* and the *Zechstein 4 Salt.* The current distribution of these units is less extensive than that of the older cycles because of erosion that took place at the end of the Jurassic (Kimmerian phase).

4.1.5 Upper Zechstein (informal)

The Upper Zechstein is an anhydritic claystone succession between the Zechstein 4 Salt and the base of an easy-to-correlate 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 sequence between the Zechstein Group and the Lower Germanic Trias Group, they put this succession in the Basal Buntsandstein of the Lower Germanic Trias Group (fig. 4.2). The equivalents of the higher Zechstein cycles, especially as described in Germany (Best, 1989), can also be distinguished in The Netherlands. Here they are informally called the Upper Zechstein (RGD, 1989c; 1991).

The Upper Zechstein consists of claystones with thin anhydrite layers. The claystones of this succession are characterised by low acoustic velocities. A fifth evaporite cycle seems to be distinguishable in this succession, e.g. in the Boerakker-1 well (fig. 4.2). The anhydrite bank is recognisable on the logs (1982 m) from the high velocity visible on the sonic log and the high recording on the gamma ray log. The formation is approximately 20 m thick.

4.2 Sedimentary development and palaeogeography

As in the deposition of the Upper Rotliegend Group, during the deposition of the Zechstein Group the study area was still part of the Southern Permian Basin (fig. 3.4). This continental basin lays below sea level during the Early Permian (Glennie, 1972, 1986a) and at the beginning of the Late Permian it was flooded by a rapid transgression, possibly under catastrophic circumstances (Glennie & Buller, 1983). Several large transgressions occurred during the Late Permian, each of which heralded the deposition of a new evaporite cycle.

The four evaporite cycles of the Zechstein Group each reflect a new influx of fresh seawater followed by a period of stagnation and evaporation. These fluctuations in sea level were probably related to alternating glacial and interglacial periods during the Late Permian (Ziegler, 1988).

The Coppershale was deposited, directly after the first Zechstein transgression, in a stagnating basin (Taylor, 1986). The carbonates were formed in an open marine environment. Sea level fell and salinity increased because of a reduction in the amount of inflowing sea water and a high rate of evaporation. Sulphates were the first deposits from the brine thus formed, initially in the form of gypsum, and then as anhydrite after dehydration. These sulphates were deposited over a more restricted area than the carbonates because of the low water level. The carbonates intercalated in the anhydrite indicate a changing amount of sea water flowing into the basin. Only a partial evaporation of the sea water took place during the deposition of the Zechstein 1 Formation; apart from a few sites along the edge of the Southern Permian Basin, the salinity was not high enough to cause rocksalt to be deposited during the first Zechstein cycle.

The initial transgression of the second cycle extended less far southwards than those of the first and third cycles (Plomp & Geluk, 1988). For this map sheet area the Zechstein 2 Formation reflects a complete evaporation cycle, with halite deposited after the carbonates and gypsum/anhydrite. Halite is only precipitated when the sea water reaches one tenth of its original volume. If the inflow of fresh sea water is matched by the rate of evaporation, the concentration will stay constant and the formation of halite will persist. Polyhalite ($Ca_2K_2Mg(SO_4)_4.2H_2O$) is a salt which forms when $CaSO_4$ saturated sea water flows into a basin filled with $MgSO_4$ and K_2SO_4 saturated brine (Braitsch, 1971). The polyhalite banks that separate the various rocksalt successions in the Zechstein 2 Salt must be of primary origin given their extensive distribution over the northern Netherlands. After each phase of deposition of polyhalite, the salinity was once again reduced. This cyclicity was caused by fluctuations in the inflow of fresh sea water and/or the influx of meteoric water. The very pure rocksalt in the topmost salt succession of the Zechstein 2 Salt probably indicates reworking of this salt. The potassium-magnesium salts were formed when the brine in the basin reached its highest salt

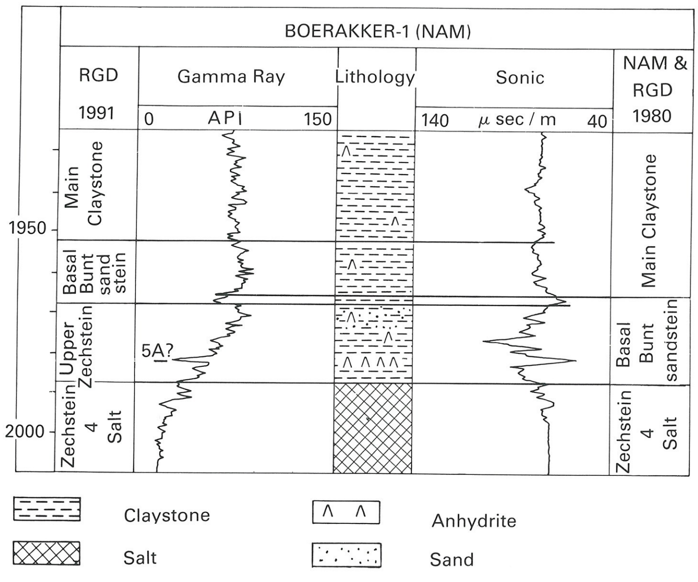


Figure 4.2. Stratigraphic division of the sedimentary succession around the transition from the Zechstein Group to the Lower Germanic Trias Group. On one side the vision as defined by NAM & RGD (1980), on the other the division used in this description. The Boerakker-1 well is used as an example.

concentration. The minerals present and the large regional extent of these salts show that the basin cannot have dried out completely.

The third, large transgression again caused the salinity of the brine in the basin to diverge from that of normal sea water and started 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 locally.

The Zechstein 4 Salt was probably only deposited to the east of the Hantum Fault, which suggests that the Lauwerszee Trough had a tectonic boundary. The absence of carbonates in the fourth cycle indicates that the water in the basin had a persistently hypersaline character. It is thought that the Zechstein 4 Formation and the Upper Zechstein deposition took place on the edge of the basin, under playa-type conditions.

5 Lower and Upper Germanic Trias Groups

This chapter deals with both the Lower and Upper Germanic Trias Groups. Figure 5.1 shows the sedimentary sequence. The thickness of the Triassic sequence varies greatly over the map sheet area (map 6) and in the central part there are no Triassic deposits. In the Vlieland Basin a unit of more than 200 m has been preserved after erosion, while to the northeast of the Hantum Fault the thickness increases to more than 950 m. Directly to the southwest of the Hantum Fault the Triassic is represented only by the Lower Buntsandstein Formation, with a maximum thickness of a few tens of metres. These isolated occurrences have not been mapped because their thickness is less than the resolution of the seismic surveys, so only the fact that they occur can be stated.

5.1 Lower Germanic Trias Group

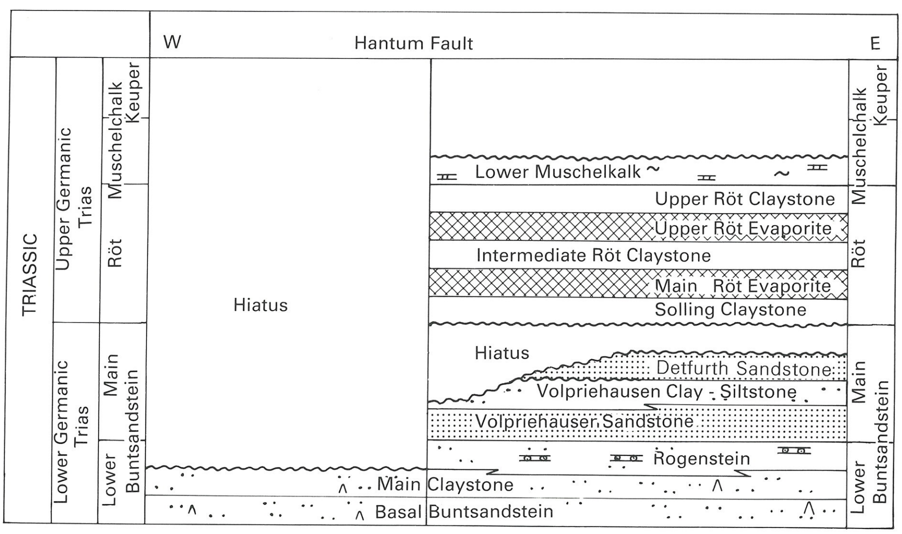
5.1.1 Stratigraphy

The group is composed of two formations in the map sheet area: the Lower Buntsandstein Formation, which consists mainly of claystone, and the Upper Buntsandstein Formation, with alternating sandstone and claystone. The sediments were deposited under continental conditions and are characteristically red in colour.

The Lower Germanic Trias Group, although incomplete, is found over a large part of the map sheet area. The whole group is missing only in a zone lying northwest-southeast, more or less coinciding with the culmination of the Friesland Platform, the Ternaard and Gerkesklooster salt domes, where strong salt movement has occurred (map 6).

The Lower Germanic Trias Group lies conformably on the Zechstein Group, while the top is unconformably overlain by different lithological units, including the Upper Germanic Trias Group in the northeast of the map sheet area, the Central Graben Group in the extreme southwest (the Vlieland Basin), and by the Rijnland Group in the remaining part (fig. 5.2).

Figure 5.1. Schematic stratigraphic division of the Triassic sequence in the map sheet area. Kimmerian movements along the Hantum Fault and erosion have caused the differences between the sedimentary sequences on the Friesland Platform and in the Lauwerszee Trough.



In this work we chose a lower boundary for the group that is slightly different to the one adopted by NAM & RGD (1980). The Lower Germanic Trias Group is of Scythian age.

5.1.2 Lower Buntsandstein Formation

The Lower Buntsandstein Formation is composed of the Basal Buntsandstein, the Main Claystone and the Rogenstein Member. The formation is incomplete to the southwest of the Hantum Fault and is either overlain conformably by the Upper Buntsandstein Formation, or unconformably by the Central Graben Group or the Rijnland Group.

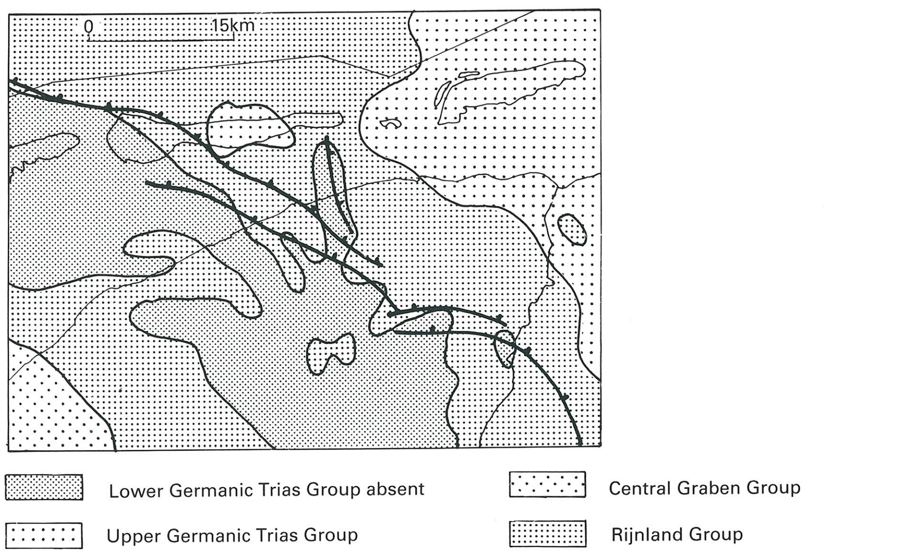
The *Basal Buntsandstein* consists of a basal fine-grained sandstone and an overlying claystone unit. These comprise a fining-upwards sedimentary cycle.

As already stated in chapter 4 (fig. 4.2) a different boundary for the member has been used than that adopted in NAM & RGD (1980). Work in northwest Germany has shown that their upper boundary appears to lie in the middle of a sedimentary cycle (Brüning, 1986). Here we have followed Brüning and taken the boundary to be at the top of the cycle. The lower boundary of the Basal Buntsandstein, as set by NAM & RGD (1980), includes the equivalents of the higher Zechstein cycles. In the present description, the equivalents of the higher Zechstein cycles are included in what is informally called the Upper Zechstein (see 4.1.5). The boundary of the Basal Buntsandstein is set so that the unit correlates with the lowest clastic cycle of the Triassic. According to this description the Basal Buntsandstein correlates well with the "Obere Bröckelschiefer" in Germany (Best, 1989).

The unit has a thickness of 5 to 25 m in the map sheet area. Locally the basal sandstone has an anhydrite cement. The claystone of the Basal Buntsandstein can be distinguished from the claystone of the overlying unit by its higher gamma ray values and lower acoustic velocities.

The *Main Claystone* is composed of a cyclic sequence of fining-upwards successions with thin fine-grained sandstone beds at the base. The cyclic composition can be correlated well on a regional scale and the development in the map sheet area is exceptionally easy to compare

Figure 5.2. Map of the lithological units which overlie the Lower Germanic Trias Group. Remains of the Lower Buntsandstein were drilled on the Friesland Platform in local depressions. The largest part of the formation was eroded. These occurrences are not shown in the figure because of their limited extent and thickness.



with those in North Holland and northwest Germany, as described by Brüning (1986). The composition of the Main Claystone is very uniform throughout the northern Netherlands (RGD, 1989a). The thickness of the unit varies between 190 and 240 m within the map sheet area.

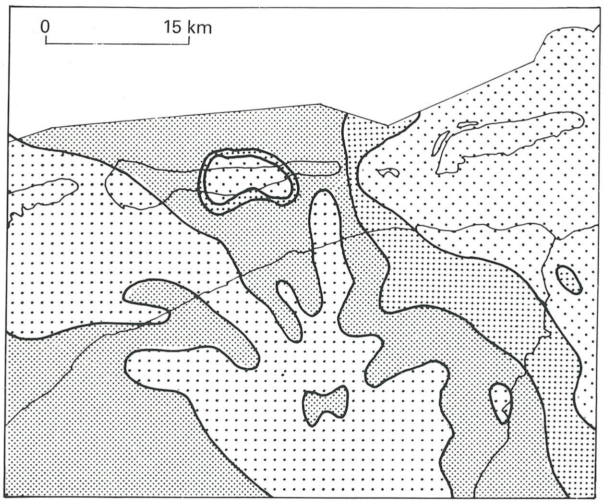
The *Rogenstein* consists of red and green coloured, finely laminated claystone, as in the Main Claystone. However, in the Rogenstein the claystones alternate with oolite banks. The oolites are cemented grainstones, with ooids up to a few millimetres in size. The member is characterised by the low gamma ray radiation, high density and high acoustic velocity measured in the oolite banks.

In contrast to the Main Claystone, the Rogenstein shows no uniform regional development in The Netherlands (RGD, 1989a).

5.1.3 Main Buntsandstein Formation

This formation lies conformably on the Lower Buntsandstein Formation, and is overlain unconformably by the Upper Germanic Trias Group or the Rijnland Group. Occurrences of the formation are limited to the area to the northeast of the Hantum Fault (fig. 5.3), where the sequence drilled reaches a maximum of 102 m (Schiermonnikoog-Zee-1). In the map sheet area the formation can be subdivided, from bottom to top, into the Volpriehausen Sandstone, the Volpriehausen Clay-Siltstone and the Detfurth Sandstone. The Detfurth Claystone and the Hardegsen Member are absent in this area. The limits of distribution of these units have largely been determined by erosion. The formation has only been penetrated by three wells in the map sheet area: Schiermonnikoog-Zee-1, Buren-1 and Boerakker-1.

Figure 5.3. Distribution map of the Lower Buntsandstein, the Main Buntsandstein and the Upper Germanic Trias Group. As in figure 5.2 the local remaining occurrences of the Lower Buntsandstein on the Friesland Platform are not shown.



Lower Buntsandstein (incomplete)

Lower Buntsandstein and Main Buntsandstein (incomplete)

Lower Buntsandstein, Main Buntsandstein (incomplete) and Upper Germanic Trias Group (incomplete)

Trias absent

The *Volpriehausen Sandstone* forms the basal sand unit of the formation. It comprises a succession of fine-grained sandstone beds, with sandstones that are cemented, to some extent, with calcite and locally with anhydrite. The thickness of the unit has only been determined in the three wells mentioned above and was 10, 9 and 5 m, respectively. The top and bottom of the unit have sharp boundaries.

The *Volpriehausen Clay-Siltstone* consists of reddish-brown to green clay- and siltstone with sandy levels and anhydrite reefs. The sand content increases upwards and the unit gradually grades into the Detfurth Sandstone. Lamelli branchia occur in the uppermost, sandy part of the member, for which this part is called 'Avicula Schichten'. Locally the sand content in this top part can be high, making the transition to the Detfurth Sandstone less evident. The member is approximately 70 m thick in Schiermonnikoog-Zee-1.

The *Detfurth Sandstone* is composed of white to grey, fine-grained sandstone. It is subdivided in two by a characteristic claystone bed; the lower part has no structure, while the upper part has small-scale cross-bedding. The maximum thickness is 33 m and the member is unconformably overlain by the Röt Formation.

5.2 Upper Germanic Trias Group

5.2.1 Stratigraphy

The Upper Germanic Trias Group is composed of clastic sediments, limestones, marls and evaporites. The group lies unconformably on the Lower Germanic Trias Group and is unconformably overlain by the Rijnland Group. The Röt, Muschelkalk and Keuper Formations can be distinguished.

There are deposits of the Upper Germanic Trias Group to the northeast of the Hantum Fault. There is also an isolated occurrence near Ameland, where a tectonically disturbed unit has remained in a border syncline of a salt structure (fig. 5.2). The deposits have been eroded from the rest of the map sheet area. The group's maximum thickness, more than 250 m, is reached to the south of Schiermonnikoog. This great thickness means that, as well as the Röt and Muschelkalk Formations, the Keuper Formation is also likely to be present. In the overview below, the thicknesses for the members refer to those in the Schiermonnikoog-Zee-1 well.

The Upper Germanic Trias Group is Late Scythian to Norian in age (NAM & RGD, 1980).

5.2.2 Röt Formation

The Röt Formation occurs over the whole area covered by the Upper Germanic Trias Group. It can be subdivided into the Solling Claystone, the Main Röt Evaporite, the Intermediate Röt Claystone, the Upper Röt Evaporite and the Upper Röt Claystone. The formation lies unconformably over the Upper Buntsandstein Formation and its thickness in Schiermonnikoog-Zee-1 is 218 m.

The *Solling Claystone* consists of greyish-green and red claystone and is approximately 50 m thick. Anhydrite reefs and a few layers strongly enriched with radioactive minerals are found in this member.

The *Main Röt Evaporite* comprises a thin basal anhydrite and rock salt. There is a sharp transition from the Solling Claystone and it is 70 m thick.

The *Intermediate Röt Claystone* is a reddish-brown, silty, anhydritic claystone, which is distinguished from both the evaporites because by its high clay content. The member is only 13 m thick.

The *Upper Röt Evaporite* in this area comprises a thin, clayey anhydrite bed. The clay content and the slight thickness of 5 m indicates sedimentation on the very edge of the basin.

The *Upper Röt Claystone* consists of a reddish-brown claystone, 80 m thick. The lower part of the unit is anhydritic while the upper part has an increasing calcium content. There is a gradual transition to the Muschelkalk Formation.

5.2.3 Muschelkalk Formation

The Muschelkalk Formation lies conformably on the Röt Formation and, as far as is known, it is unconformably overlain by the Rijnland Group. Only the lowest member of the Muschelkalk Formation (the Lower Muschelkalk) has been drilled in the map sheet area. Several members of the Muschelkalk Formation and even of the Keuper Formation are likely to be present considering the great thickness of the Triassic deposits in the Lauwerszee Trough (map 6).

The lowest part of the *Lower Muschelkalk* consists mainly of grey marls and shows an upwards increase of limestone and dolomite. At the same time a few claystone beds also occur here. The drilled thickness of the member is 28 m.

The other Muschelkalk members are composed of marls, clay-rich dolomites and carbonates, anhydritic claystones and interbedded rocksalt. The Keuper Formation comprises silty, anhydrite-rich claystones with interbedded anhydrite and rock salt layers.

5.3 Sedimentary development and palaeogeography

During the deposition of the Lower Buntsandstein Formation, the map sheet area was part of a very extensive, flat region. Given the continental environment of deposition, the good correlations that are possible in the region, and the fine-grained composition, it seems likely that sedimentation took place in a lacustrine environment. The oolites would have formed during periods of low clastic influx and stronger current flow, in brackish, calcium-rich water (Peryt, 1975; Brüning, 1986). The alternating green and red colouring and the dessication cracks that are present point to a fluctuating water level and regular drying up of the lake. 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 no longer played a role as a tectonic element during the Early Triassic.

The differences in composition of the Rogenstein Formation in Noord-Holland and in the northeastern Netherlands indicates separate developments for these two occurrences. This was due to the concurrent development of a northeast-southwest high in the northern Netherlands (fig. 10.3), the so-called Netherlands Swell.

The sediments of the Main Buntsandstein in the map sheet area are characterised by a succession of braided river systems building out to the north, abruptly alternating with transgressive lacustrine deposits (Fisher, 1984; RGD, 1989a). Changes in the lake's water level and tectonic activity in the hinterland probably influenced the alternations and extent of the sandstones and claystones. The deposits in the map sheet area were formed within the sphere of influence of the Netherlands Swell and the Ems Trough to the southeast of the area. The thickness of deposits, especially the fluvial ones, clearly increases towards the trough. Uplift and erosion of the Hardegsen tectonic phase disrupted the sedimentation.

The deposits of the Upper Germanic Trias Group can be distinguished from the Lower Germanic Trias Group because of the influence of several transgressions. The Röt Formation is characterised by deposits of rock salt formed by evaporation following a transgression. The claystone of the Röt Formation formed in a probably hypersaline, playa environment. The influence of a new transgression is evident in the uppermost part of the Röt Formation. Normal marine conditions returned and because the source area of the clastic sediments was then largely below sea level, the proportion of carbonates in the sediments increased greatly. Thereafter the limestones and dolomites of the Muschelkalk Formation were laid down over the map sheet area and to the east.

6 Central Graben Group

6.1 Stratigraphy

The occurrences of the Central Graben Group within the map sheet area are limited to that part of the Vlieland Basin which lies within the area of study (map 8); they consist only of the continental deposits of the Delfland Formation.

6.1.1 Delfland Formation

The Delfland Formation (Herngreen et al., 1991) consists of irregular alternations of grey, green or brown, mica-bearing siltstones and claystones, sometimes with red spots, and light to dark brown coloured sandstones. The upper part of the formation contains many plant remains, coal layers and a few limestone or dolomite banks. A brackish water to marine ostracode fauna is present in the limestone banks. Palynological data also indicate that the Delfland Formation was subjected to marine influence, although only to a very slight extent.

The Delfland Formation lies unconformably on the Lower Germanic Trias Group and is separated by a small hiatus from the overlying, conformable Rijnland Group. The deposits reach a thickness of 200 m within the map sheet area (map 8), but they thin rapidly towards the edges of the basin.

Palynological research has shown that the Delfland Formation is of Late Kimmeridge to Ryazanian age (Herngreen et al., 1991).

6.2 Sedimentary development and palaeogeography

The southern part of the Vlieland Basin was largely protected from marine influence by a barrier in the basin (Zuidwal Volcanic Dome: fig. 1.6) so that fluvial and lacustrine conditions were dominant in this area (Herngreen et al., 1991). However, the marine features and limestone banks in the Delfland Formation indicate that from time to time marine conditions were prevalent. Poor drainage in the Vlieland Basin led to the formation of peat, which was later subjected to coalification.

7 Rijnland Group

7.1 Stratigraphy

The Rijnland Group consists of a sequence of sandstones, siltstones, claystones and marls. These sediments were deposited in an originally shallow but gradually deepening, open marine environment. The Rijnland Group dates from Late Ryazanian up to and including the Albian (RGD, 1990a).

In most of the map sheet area the Rijnland Group lies unconformably on the Zechstein Group and the Lower Germanic Trias Group except in the extreme northeast where it overlies the Upper Germanic Trias Group, also unconformably. In the Vlieland Basin the group lies, with a slight hiatus, conformably on deposits of the Central Graben Group and it is overlain conformably by deposits of the Chalk Group.

Rijnland Group deposits occur throughout the map sheet area, with the greatest thickness, more than 550 m, reached in the Vlieland Basin. There are also thicker deposits, up to 450 m, in the northeast, in the border synclines along the salt structures. A sequence of about 150 m is present on the Friesland Platform.

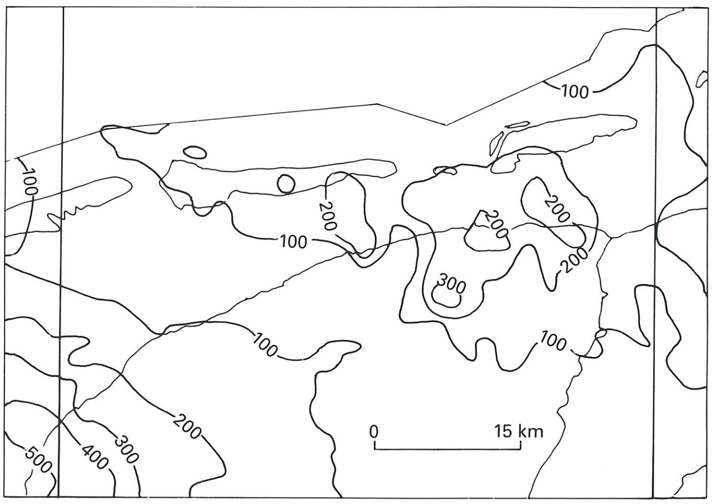
The Rijnland Group can be subdivided into the Vlieland Formation and the Holland Formation.

7.1.1 Vlieland Formation

The Vlieland Formation consists of two members, the basal Vlieland Sandstone and the overlying Vlieland Shale Member. The Vlieland Formation was deposited during a transgression, in which the sedimentation which was originally limited to the Vlieland Basin spread over much of the map sheet area. The formation is Late Ryazanian to Barremian in age.

The Vlieland Formation is conformably overlain by deposits of the Holland Formation; they are separated by a small hiatus. Because of strong erosion prior to the deposition of the Vlieland Formation, the underlying rocks belong to various formations. For details, you are referred to the subcrop map of the base of the Rijnland Group (map 14).

Figure 7.1. Thickness map of the Vlieland Formation, based on seismic data.

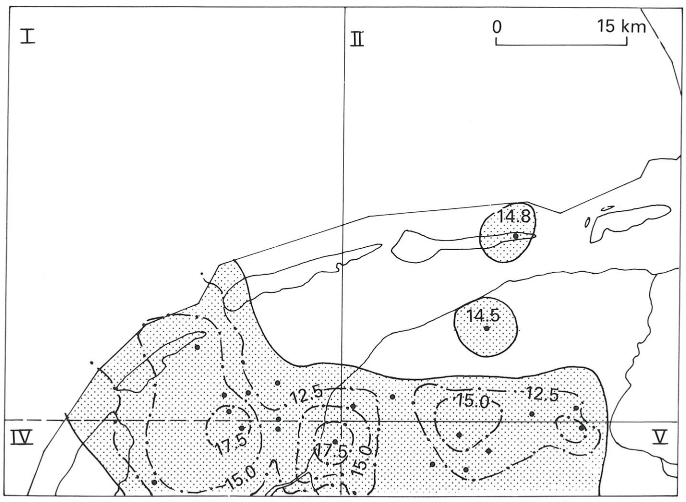


The Vlieland Formation occurs throughout the map sheet area. Its thickness shows more or less the same distribution as the thickness map of the whole Rijnland Group (map 10): a relatively thin unit in the central part of the map sheet area (50 to 100 m) and thicker deposits in the extreme southwest (Vlieland Basin - 350 m) and northeast (Lauwerszee Trough - 250 m).

The *Vlieland Sandstone* mainly occurs in the southern part of the map sheet area (fig. 7.2.) and dating has shown that the oldest deposits of the member are found in the Vlieland Basin. The dates also show that the Early Cretaceous transgression flooded parts of the North Netherlands High (fig. 1.6) so that the Vlieland Sandstone was deposited increasingly higher up. The thickest deposits are found in the Vlieland Basin and measure more than 150 m in the centre of the basin. In the part of the basin lying within the map sheet area a maximum of 75 m is observed. The thickness decreases rapidly towards the edges of the basin. The member is also found on the east side of Ameland, in North Friesland and in the south of the map sheet area, where the thickness is between 10-30 m. It is not known whether the sandstone was also deposited in the other depocentre, to the south of Schiermonnikoog, because no wells have been drilled there. The Vlieland Sandstone is an important reservoir rock in Friesland.

The Vlieland Sandstone comprises alternations of mainly well-layered, little lithified, greyish 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. Locally they contain glauconite. The sandstones may grade gradually upwards into siltstones and claystones and the claystones may grade into sandstones (fining and coarsening-upward trends). The more silty and clayey intervals are often laminated and rich in organic material. In the sandy intervals there are intercalations of brown coloured sandstones, cemented with calcite and siderite. The Vlieland Sandstone was deposited in a shallow sea, with strongly bioturbated sands laid down close to the coast, while the coarse, poorly sorted sands reflect deposition in a bank front facies. The transition of the Vlieland Sandstone into the Vlieland Shale is rather abrupt and can be easily identified on gamma ray and sonic logs. The Vlieland Sandstone is of Late Ryazanian age in the Vlieland Basin and Early Valanginian on the North Netherlands High. The top is Early to Middle Valanginian (Herngreen et al., 1991; RGD, 1990a).

Figure 7.2. Configuration of the Vlieland Basin during deposition of the Vlieland Sandstone and reservoir-average effective porosity Øem of the sandstone (appendix E). Roman numbers correspond to the map sheet numbers (fig. 1.1).



The *Vlieland Shale* consists of dark brown to dark grey, silty claystones. At the top of the unit the claystone is slightly marly. Deposition took place 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 a maximum of 350 m in the Vlieland Basin to approximately 70-90 m on the Friesland Platform.

7.1.2 Holland Formation

The Holland Formation is the topmost unit of the Rijnland Group. It consists of successive light to dark grey, sometimes coloured, marly claystone, dark grey claystone 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 they are of Aptian to Albian age.

The Holland Formation is conformably overlain by deposits of the Chalk Group. There is often a hiatus, which may represent all of the Aptian, between the base and the Vlieland Formation.

The Holland Formation occurs throughout the map sheet area, although it is not always complete. Its thickness varies from approximately 70 m in the northern half (the Waddenzee) and the extreme southwest of the map sheet area, to 40 m in the remaining area.

The Holland Formation is divided into the Lower Holland Marl, the Middle Holland Shale and the Upper Holland Marl Members. This characteristic three-fold division is not complete throughout the map sheet area but it is easy to recognise in well logs.

The *Lower Holland Marl* comprises a light to dark grey, sometimes red, brown or yellowish marly claystone and it is Aptian to oldest Early Albian in age (RGD, 1990a). The Lower Holland Marl overlies the Vlieland Shale, separated by a hiatus. This hiatus encompasses nearly all the Early Aptian. There is another hiatus between the Lower Holland Marl and the Middle Holland Shale. The member has a maximum thickness of 15 m (in the south and southwest of the map sheet area).

The *Middle Holland Shale* consists of dark grey claystone with a sandy character at its base. It dates from the Early Albian (RGD, 1990a). The Middle Holland Shale may overlie either the Lower Holland Marl or the Vlieland Formation, and is separated by a hiatus. The hiatus is greatest in the centre of the map sheet area, where it contains at most the entire Aptian and a part of the early Middle Albian. It appears to be smaller to the north and west (RGD, 1990a). The contact with the Upper Holland Marl is conformable and the member is 10-20 m thick.

The *Upper Holland Marl* consists of light grey and coloured marly claystone. It is of Middle to Late Albian age. Biostratigraphic dating suggests that several small hiatuses probably occur in the Upper Holland Marl (RGD, 1990a). The contacts with both the Middle Holland Shale and the overlying Chalk Group are conformable. The unit varies in thickness from approximately 15 m in the south of the map sheet area up to 40-50 m near Ameland.

7.2 Sedimentary development and palaeogeography

A transgression advanced from the north during the Late Ryazanian and brought to an end the continental conditions under which the Central Graben Group had been deposited. The Vlieland Sandstone was deposited in a shallow marine environment at the beginning of this Cretaceous transgression. The depocentre was originally determined mainly by the configuration of the Vlieland Basin. The regional distribution and age of the Vlieland Sandstone indicate that the borders of the basin were already transgressed during the deposition of the sandstone.

A more open, marine environment developed as a consequence of the continuing net rise in sea level and the fine clastic deposits of the Vlieland Shale were laid down. Palynofacies analyses point to a number of fluctuations in water depth during this period, which led to condensed successions and hiatuses (RGD, 1990a). Dates from the base of the formation indicate a younger age towards the North Netherlands High, which confirms its transgressive nature. A small hiatus or condensed succession is found at the base of the Vlieland Shale within the Vlieland Basin for the period from the Late Valanginian to Early Hauterivian. On the North Netherlands High this hiatus is larger and lasts into the Late Hauterivian (RGD, 1990a). The input of clastic sediment gradually decreased as the sea flooded nearly all of the North Netherlands High during the Barremian, and the sediments thus acquired a more marly nature. The limey components mainly originated from planktonic organisms.

A marine environment was also prevalent during the deposition of the Holland Formation. Palaeontological datings (RGD, 1990a) indicate different short periodes of stillstand in the sedimentation, small tectonic movements and sea level fluctuations. The sandy character at the base of the Middle Holland Shale reflects the beginning of the Albian phase in the Cretaceous transgression (NAM & RGD, 1980; Crittenden, 1987). As the transgression extended the source area for clastic sediments retreated, thus causing a further increase in the marly character of the Lower Holland Marl deposits compared to those of the Vlieland Shale. The Vlieland Basin no longer had much effect on the distribution of sediment thickness during the deposition of the Holland Formation.

7.3 Petrophysical evaluation

The Vlieland Sandstone contains locally exploitable amounts of natural gas and is therefore of economic importance. The Vlieland Sandstone from eleven wells was evaluated petrophysically in the map sheet area and direct surroundings to gain some insight into its reservoir properties (RGD, 1990c). The sandstone is gasbearing in six of these wells (appendix E). An example of a log evaluation of the Vlieland Sandstone is given in figure 7.2 from the Tietjerksteradeel-305 well. The gamma ray log cannot be used as a clay indicator because the Vlieland Sandstone contains 5-10% glauconite. The effective porosity was determined from the sonic (density) porosity (Wyllie comparison in single porosity model; Wyllie et al., 1956; 1958) after corrections for clay content and any hydrocarbonate content. The Indonesian formula, which is suitable for clayey formations, was used to determine water saturation (Fertl, 1987). Figure 7.3 shows a schematic distribution of the reservoir-average effective porosity for the Vlieland Sandstone in the study area. The map of this distribution shows that the reservoir-average effective porosity decreases towards the edges of the subbasins.

The reduction in porosity in the Vlieland Sandstone is not only due to compaction but also to cementation (fig. 7.4), with core material revealing the presence of calcite and siderite as cement. In the area around Leeuwarden illite comprises 15-40% of the clay minerals (Berge, 1983) and it is possible that the formation of illite fibres is responsible for a reduction in permeability (Seemann, 1979; Pallatt et al., 1984).

The claystone deposits of the Vlieland Shale form an effective caprock for the Vlieland Sandstone reservoirs.

Elf Petroland has been producing natural gas from the Leeuwarden gasfield since 1971. There was an initial gas reserve of 11.7 billion cubic metres (Cottençon et al., 1975).

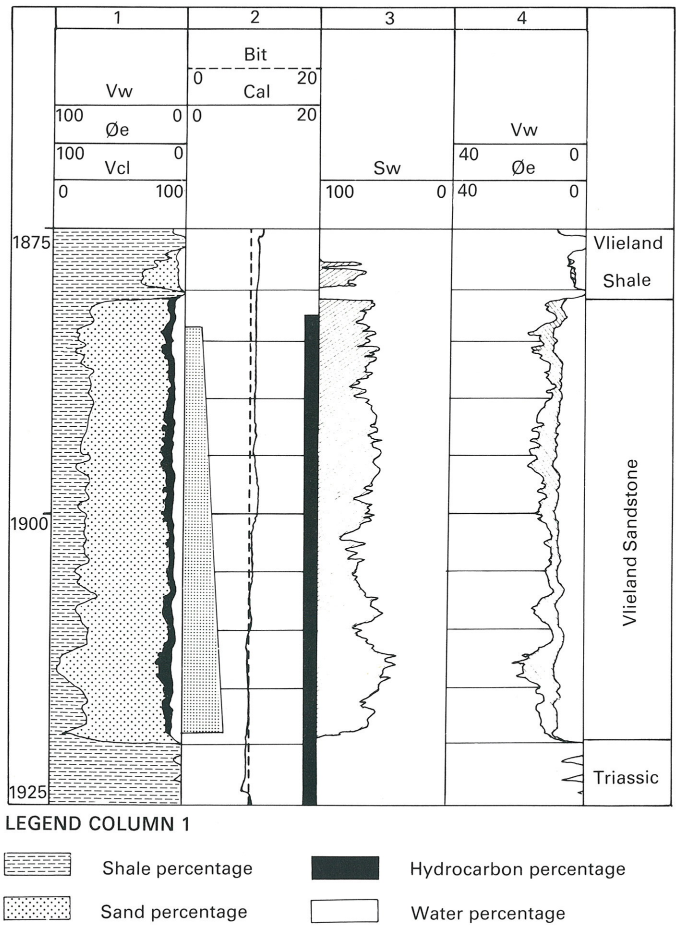
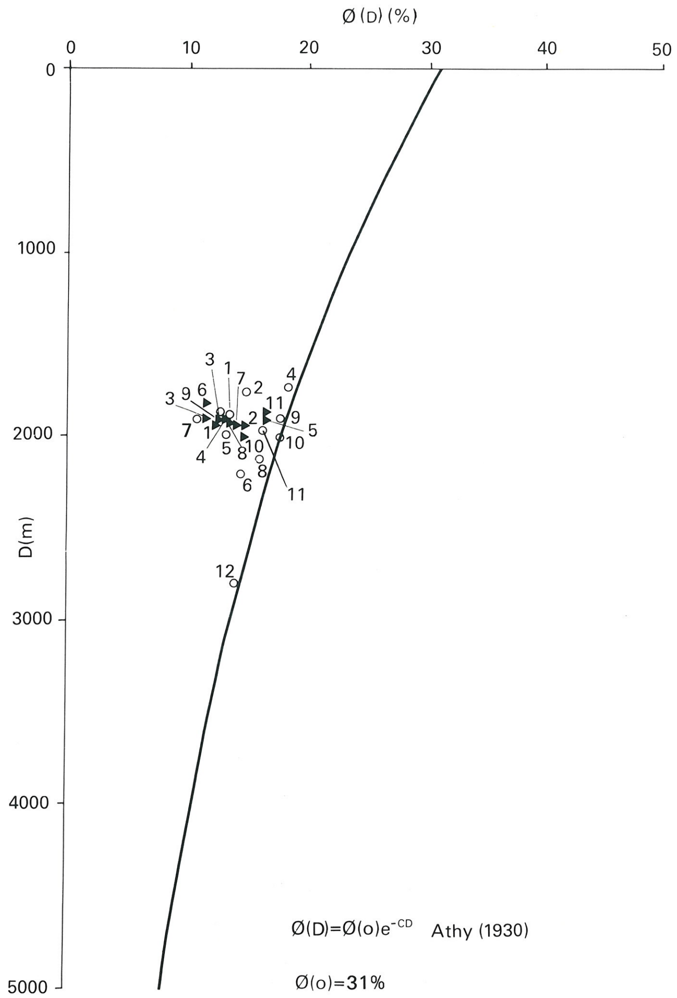


Figure 7.3. Petrophysical evaluation of the Vlieland Sandstone sequence in the Tietjerksteradeel-305 well. Column 1: clay content Vcl, effective porosity Øe and pore water volume Vw (in per cent). Column 2: wellhole diameter (cal) and drillbit diameter (bit), both in inches; the tested interval (appendix E) and the cored interval are marked by a trapezium and black bar, respectively. Column 3: water saturation Sw (in per cent). Column 4: effective porosity Øe (left-hand curve) and the water volume in the pores Vw (right-hand curve) both in per cent. The right-hand column shows the formation boundaries. Depths are actual depths.

Figure 7.4. 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 0.0002734 per metre was used for the constant c (Sclater & Christie, 1980). The data points represent the reservoir-average effective porosity of the Vlieland Sandstone.



○ Wells map sheet I

1 Bolsward -1
2 Franeker -1
3 Harlingen West -1
4 Harlingen -1
5 Oude Inschot -1
6 Riepel -1
7 Slenk -1
8 Vlieland Oost -1
9 Zuidwal -1
10 Zuidwal -2
11 Zuidwal -3
12 L12 -2

▲ Wells map sheet II

1 Oudega-Akkrum -8
2 Ameland Oost -101
3 Bozum -1
4 Leeuwarden -3
5 Opeinde -2
6 Peins -1
7 Rauwerd -2
8 Suawoude -2
9 Tietjerksteradeel -305
10 Wanswerd -1
11 Wirdum -1

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.

The Chalk Group is divided into the Texel Chalk Formation and the Ommelanden Chalk Formation (fig. 8.1). The boundary between these formations is set at the top of the Actinomax plenus Marl. This so-called marl is, in fact, composed of a prominent, dark, shale layer in the map sheet area. It belongs to the Texel Chalk. 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 North Sea Super Group.

The age of the Chalk Group within the map sheet area has been dated as Cenomanian-Maastrichtian using foraminifera and ostracods (RGD, 1988b, 1989c-f). In various wells the youngest Maastrichtian deposits are missing and possibly also part of the Upper or Middle Santonian deposits (fig. 8.1).

The Chalk Group deposits occur throughout the map sheet area and their thickness is a minimum of 300 m in the Vlieland Basin in the southwest and over the salt structures (to less than 200 m). The maximum thickness in the map sheet area of more than 1000 m is found in the north and east (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, with the Actinomax plenus Marl at the top. This dark shale layer is a few metres thick and can generally be traced over large distances. It can be identified by a marked peak on the gamma ray log (Schiermonnikoog-Zee-1; fig. 8.1) and occurs throughout the map sheet area except in a few wells near Ameland and Tietjerksteradeel.

The composition and structure of the Texel Chalk is uniform over the map sheet area. The thickness decreases towards the northeast from 65 m to 25 m. The Texel Chalk is predominantly Cenomanian in age although the youngest part of the formation may possibly belong to the Early Turonian.

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, mainly in the Campanian. These alternations cause a strongly peaked pattern on the sonic log, especially in the wells Wanswerd-1 and Schiermonnikoog-Zee-1 (fig. 8.1). Cutting samples and sonic logs show that the Turonian, Coniacian and Santoniand deposits are more competent rocks than the younger sediments of the Campanian and Maastrichtian.

Although the monotonous lithological character of the sequence makes it very difficult to subdivide the Ommelanden Chalk into mappable units, it is possible to locally mark the base of the Campanian using the above log features. The other chronostratigraphic boundaries given in

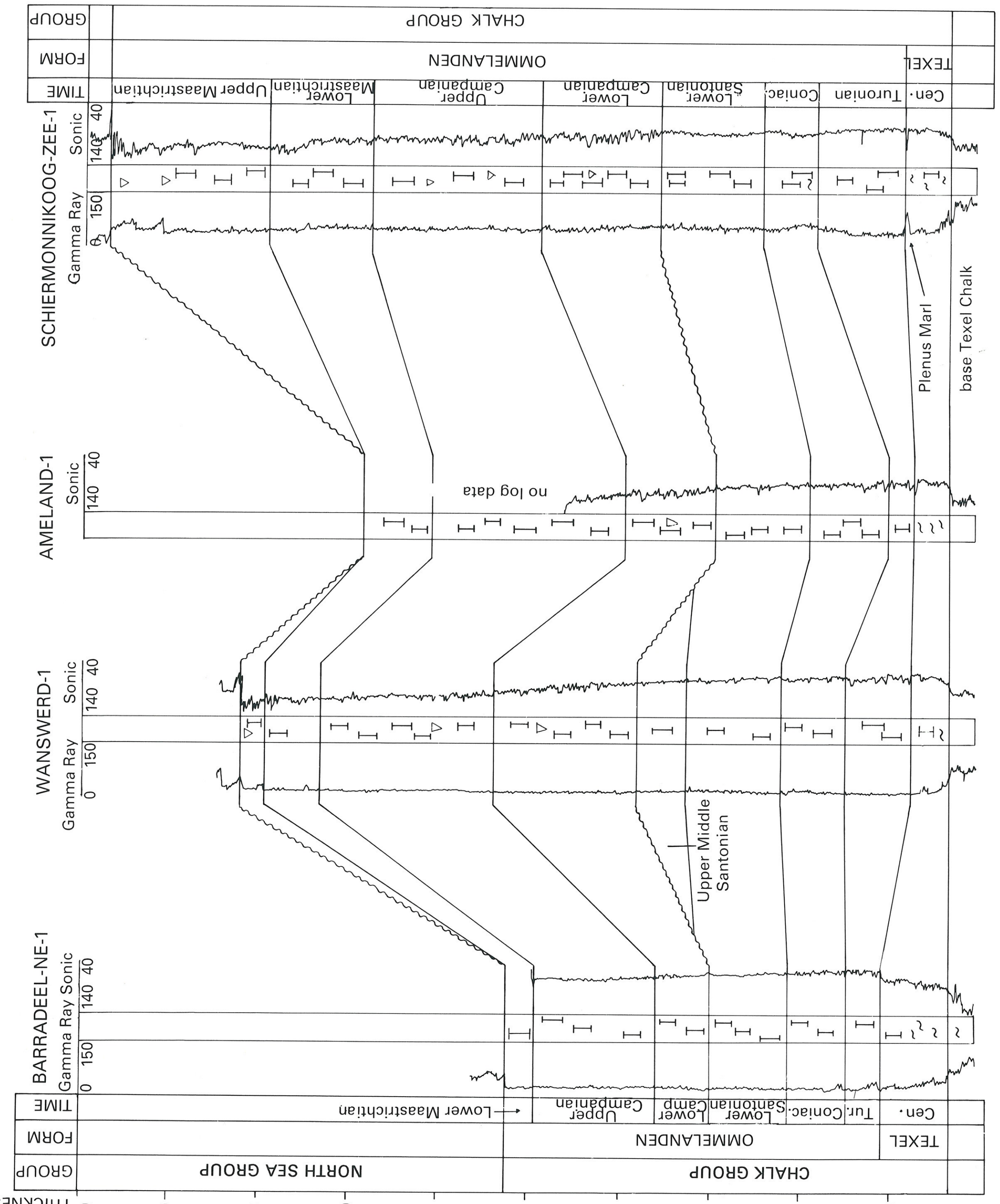


Figure 8.1. Stratigraphic section of the Chalk Group, with the Plenus Marl as reference level. Correlations are based on the gamma ray log (in API units), sonic log (in μs/ft) and paleontological dates. In the Ameland-1 well only a sonic log was available for the lower half of the Chalk sequence, so that correlation with this well is based mainly on paleontological data.

figure 8.1 do not always agree with the subdivision of the Ommelanden Chalk made on the basis of log correlations.

The formation is underlain by the Texel Chalk Formation and the top is covered unconformably by clastic deposits of the North Sea Super Group. The formation is Turonian to Maastrichtian in age. It is also apparent that several intraformational hiatuses occur (RGD, 1988b, 1989c-f), with the missing Late Santonian and Late Maastrichtian being the most obvious.

The thickness of the formation varies greatly within the map sheet area. Erosion and only slight sedimentation resulted from the tectonic upheaval (inversion) of the Vlieland Basin. The thickness of the Ommelanden Chalk in the southwest only reaches 250 m and over salt structures the thickness may be less than 200 m. But in the north and northeast of the map sheet area it is more than 1000 m.

8.2 Sedimentary development and palaeogeography

The Cretaceous transgression developed into a worldwide phenomenon (Pitman, 1978; Donovan & Jones, 1979) and flooded the last land masses in the map sheet area. It thus became an area of 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 shales and marls. The transition between the two formations was gradual and the sedimentation was more or less continuous. This is clearly shown in the well recordings of gamma ray logs in which the gradual increase in the proportion of carbonate in the sediments causes a decrease in the values measured (fig.8.1).

The variations in thickness of the Texel Chalk suggest strong subsidence in the southeast of the map sheet area while the deposits of the Ommelanden Chalk reflect two tectonic phases, in the form of a hiatus between the Santonian and the Late Maastrichtian and associated salt movements.

Biostratigraphic (including the wells Oude Inschot-1 and Zuidwal-2; RGD, 1985, 1989g) and seismostratigraphic research has revealed that the sedimentation of the Ommelanden Chalk Formation was slowed or interrupted several times by the inversion of the Vlieland Basin, leading to possible erosion. This led to a condensed sequence with intraformational hiatuses so that the Campanian sediments are clearly less well represented above the axis of inversion, implying that the Sub-Hercynian tectonic activity was strongest during this period. The erosion products from the uplifted areas were re-deposited in the subsiding areas. The uplift and erosion linked with the Laramide tectonic phase had relatively little influence within the map sheet area. The Upper Maastrichtian was locally eroded.

8.3 Petrophysical evaluation

To date gas is produced from the Chalk at only one location in The Netherlands: the Harlingen Field, discovered in 1964. The gas is produced from the highest part of the Chalk unit (Lower Maastrichtian and Campanian). Van den Bosch (1983) gave the following reservoir parameters: porosity is composed of a matrix porosity (up to a maximum of 38% rock volume), on the one hand, and of pores formed by solution and cracks (up to 5% rock volume) on the other. The average porosity is approximately 29%. Permeability varies from 8 mD at the top to 0.7 mD lower in the reservoir with an average of 1.5 mD. The permeability is low compared to the porosity, which can be explained by the very small connections between the pores.

9 North Sea Super Group

9.1 Stratigraphy

The North Sea Super Group comprises clays, with some sandy intercalations. In the map sheet area the sediments were largely deposited in a marine environment. 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-b). Quaternary sediments will be described fully in the information to the Geological Survey's 1:50,000 map of the shallow subsurface.

The North Sea Super Group is found throughout the area, with the thickness increasing gradually towards the north from 1000 to 1450 m. Erosion and salt movements have caused the thickness in the northeastern part to vary considerably: over the salt structures the thickness decreases to less than 400 m, while a maximum of nearly 1800 m is found at Schiermonnikoog, in an area where the salt has flowed away (map 13). Two sections in figure 9.1 illustrate the following description of the North Sea Super Group.

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 0 to 13 m in thickness. The *Landen Clay* is a green-grey clay or claystone containing glauconite, mica and pyrite. There are a few levels bound by calcite cement. The Landen Clay reaches a thickness of 15 to 25 m.

The *Dongen Formation* comprises the Basal Dongen Tuffite, Ieper Clay, Brussels Marl and the Asse Clay. The thickness of the Dongen Formation was affected by erosion (fig. 9.1) and increases gradually from the southwest (Harlingen-1; 360 m) towards the north (Hollum-Ameland-3; 635 m) and east (Tietjerksteradeel-101; 510 m). Only thin sequences are found over the salt structures. The formation is of Eocene age. The *Basal Dongen Tuffite* comprises glauconitic clays with intercalations of tuff. The unit is 15 to 20 m thick and this is fairly constant in the area. The *Ieper Clay* is composed of a brown-grey clayey base and a grey-green sandy upper part. The clayey part may contain pyrite, shell remains and carbon fragments. The uppermost part contains silty to sandy intercalations with pyrite and glauconite. The thickness of the unit varies very gradually from approximately 250 m to 330 m and it, too, is thinner over the salt structures. The *Brussels Marl* comprises glauconitic, green-grey to light grey, fine-sandy clays, marls, calcareous sandstones and clayey sandstones. The thickness of this unit varies between 80 and 100 m without any clear trend. In the area around Harlingen the member has been partly eroded and above salt structures it is locally completely absent. 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 member is absent over salt structures and in the southwest of the map sheet area. The greatest thickness, of more than 200 m, was observed in the Schiermonnikoog-Zee-1 well.

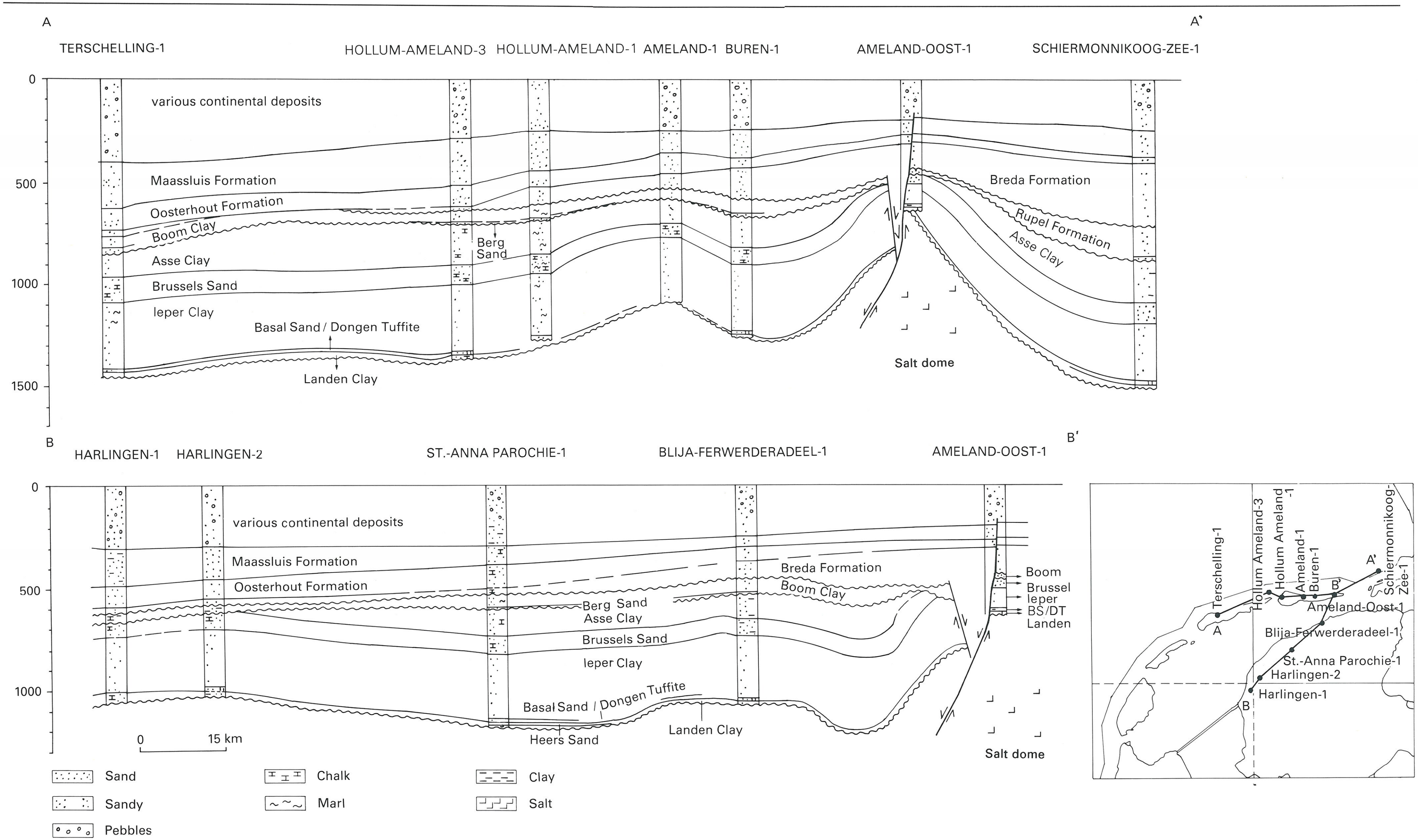


Figure 9.1. Schematic sections through the Cenozoic deposits (after RGD, 1984a). Note the hiatuses related to tectonic phases and the development of the Ternaard salt dome.

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, in principle, the Rupel Formation and, at the top, the Veldhoven Formation. The latter does not occur in the map sheet area, probably because of erosion since it is found to the south (RGD, 1984a).

The *Rupel Formation* is divided into the Berg Sand at the base and the Boom Clay. The thickness of the formation is determined by erosion to a large extent. It disappears in the extreme southwest, west and above the salt structures. The thickness increases towards the north and east, from a few tens of metres in the southwest (Harlingen-1 and Harlingen-2) to 170 m in the depocentre (Schiermonnikooog-Zee-1). The formation is of Oligocene age.
The *Berg Sand* is a fine sandy unit, with a green-grey to dark grey colour, locally containing pyrite and glauconite. The unit is approximately 10 m thick. 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.

9.1.3 Upper North Sea Group

The Upper North Sea Group contains the youngest rocks. It is divided into the Tertiary Breda and Oosterhout Formations, the Quaternary Maassluis Formation and a group of most recent Quaternary formations. The Upper North Sea Group lies unconformably on the Middle North Sea Group. It is generally 500-550 m thick. In the southeast it is less thick, 400-450 m, while in the depocentres at Hollum-Ameland and Schiermonnikoog it reaches 650 m and 700 m, respectively.

The *Breda Formation* shows a clear two-fold subdivision: a lower part of very glauconite-rich, green-black clays and an upper part of grey-green clays with a few sandy and/or silty intercalations. The subdivision is clearly shown on gamma ray logs. The large amount of glauconite and the clayey character of the basal part ensure a higher gamma radiation than that from the upper part. The Breda Formation is unconformably overlain by the Oosterhout Formation. The thickness varies greatly within the map sheet area. In the west of the study area it wedges out completely or almost completely; in the northeast and east it increases markedly to a maximum in Schiermonnikoog-Zee-1 (300 m). This variation in thickness is the result of salt flow and 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 clear trend in thickness in the Oosterhout Formation. The thickness increases from approximately 50 m in the eastern part to approximately 90 m in the western part of the map sheet. 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 is thinnest above the salt structures and in the southeast (20-70 m). The thickness increases strongly especially towards the west, to 250 m in the Hollum-Ameland-3 well (fig. 9.1). The formation is of Quaternary age (Early Pleistocene).

The other Quaternary formations comprise clays, sands and gravels, deposited in continental and shallow marine conditions. They increase in thickness from approximately 250 m over most of the area to 400 m in the west.

9.2 Geological developments and palaeogeography

Changes in sea level had a significant 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. A number of Alpine tectonic phases during the Tertiary, including the Early Oligocene Pyrenean phase and the Oligocene-Miocene Savian phase, led to uplift of the area and erosion, thereby affecting the thickness and distribution of the sediments present. The variation in thickness was also determined by salt movements. The present, mainly continental, conditions were already evident in the Pilocene.

10 Geological History

10.1 Introduction

This chapter describes the geological history from the Late Carboniferous (the Variscan orogeny) up to the Quaternary. There is little data concerning the period prior to the Late Carboniferous while the geological history of the Quaternary will be described in future publications on the geological map of The Netherlands on a scale of 1:50,000 by the Geological Survey of The Netherlands (see also Zagwijn, 1989). The most important structural elements are described in paragraph 1.6.

Since the Variscan orogeny there have been a number of important phases of uplift and related erosion. These have occurred in the Early Permian (Saalic phase; fig. 2.2), the Jurassic (Kimmerian phase; map 14) and the Late Cretaceous (Sub-Hercynian and Laramide phases). During this last phase the Vlieland Basin was uplifted (inverted). This is evident from the profiles (map 15) and from a comparison of the thicknesses of the Rijnland Group and the Chalk Group (maps 10 and 12).

10.2 Late Carboniferous

Although the Variscan orogeny took place far to the south of this map sheet area, it still had a significant effect on the geological history. 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 Saalian.

The Sudetic phase, at the beginning of the Late Carboniferous, is evidence of the collision between the Gondwana landmass from the south and Laurasia to the north. The north-south compression resulted in the formation of a mountain chain running east-west across Europe. 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 filled relatively rapidly by erosion products originating from the Variscan mountains. Sedimentation took place 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 map sheet area lay in this very flat basin, where meandering rivers and marshes determined the physiography to a large extent.

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, around the map sheet area, 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 to an arid one and a desert climate became dominant in the Permian.

The Saalian 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 and earliest Permian. The north-south compression was replaced by an east-west oriented extension during the Permian and Triassic. This gave rise to an approximately northwest-southeast oriented fault system to the north of the Variscan orogenic front and including the map sheet area, 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).

In the map sheet area, the erosion related to this phase cut deeply into the Carboniferous sediments. The hiatus, caused partly by non-deposition at the end of the Late Carboniferous, covers a maximum period from Westphalian A 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 deposited in the map sheet area during the Permian and Triassic.

The structures that were formed at the end of the Carboniferous around the map sheet area are shown by the subcrop map of the pre-Permian (fig. 2.2). It shows that there were a few structural elements that were the forerunners of later highs and basins. Thus, the presence of a Late Carboniferous high over the northwest Netherlands is deduced from the deeply incised erosian. This original Asturian/Saalian high was a precursor to the Netherlands Swell during the Triassic, and the Texel-IJsselmeer High, which was evident during the Late Jurassic. The high, with the presence of Westphalian C and D, indicates a depression near Schiermonnikoog, which has been called the Lauwerszee Trough in this publication. The high has been of varying significance to the geological development. The limits of distribution of the Westphalian C/D, which were mainly determined by erosion, coincide with the zone in which the southern part of the Hantum Fault and its north-south branch towards East Ameland were active. This observation suggests that this part of the Hantum Fault is a Mesozoic reactivation of an earlier Variscan fault zone. The northwestern part of the Hantum Fault, running more northwest-southeast, had no obvious affect on the distribution pattern of the Upper Carboniferous sediments, as can be seen from the subcrop map of the pre-Permian. Since this map is compiled primarily from well data and not from a geophysical survey, the conclusions based on it should be drawn with due care.

10.3 Permian

In the Early Permian, faulting, volcanic activity and the regional uplift, which accompanied the Saalian phase of the Variscan orogeny, resulted in an exceptionally extensive landmass. Subsequent cooling of the lithosphere induced subsidence, especially in areas of Early Permian volcanic activity. This resulted in an extensive, intra-cratonic continental basin known as the Southern Permian Basin (fig. 10.1) or as the Permo-Triassic Basin after the period in which it existed (Ziegler, 1982).

Superimposed on the large-scale thermal subsidence, the east-west Saalian extension 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 most influence on the development of the map sheet area (fig. 3.4). The drainage of the Variscan hinterland to the south was concentrated into these depressions. They contain thick successions of mainly fluvial deposits laid down by braided rivers and in wadis. The extent of the sedimentary facies, as described by Van Wijhe et al. (1980) seems to follow the route of the Hantum Fault in North Friesland. This appears to indicate synsedimentary fault movement. Between the fluvial deposits, there was a desert in which aeolian deposits were dominant. The desert lay along the edge of the basin and there was a salt lake in the centre. The transition between the lake and desert was a sabkha (fig. 3.4).

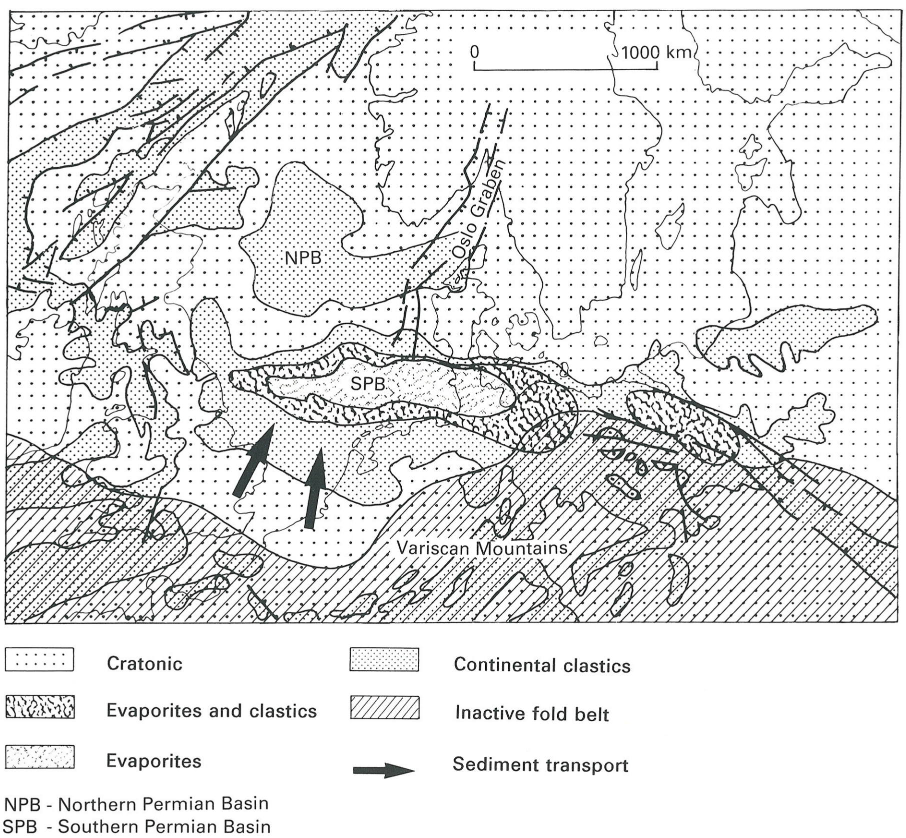
In the map sheet area, the sedimentary development during the Early Permian reflects not only the tectonically determined topography but also fluctuations in the level of the salt lake. Three rises in the water level resulted in three southwards extensions of the lacustrine sediments (Hollum, Ameland and Ten Boer Claystones).

There was an important change at the beginning of the Late Permian. 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 continental Northern and Southern Permian Basins. The basins had probably subsided below the sea level at that time, thus allowing a very rapid transgression to take place. This is apparent from the reworked sediments at the top of the Rotliegend (Glennie & Buller, 1983).

The Late Permian was essentially a relatively quiet tectonic period. Along with the cooling of the lithosphere, the sedimentary loading from the large amounts of salt deposited over a short period would probably also have played a role in the subsidence of the Southern Permian Basin. Locally there were synsedimentary fault movements, indicated by the rapid increase in thickness of the Zechstein Group northwards from the Texel-IJsselmeer high, abrupt facies changes, and the stepped increases in thickness in North Holland.

A carbonate-anhydrite platform formed around the Texel-IJsselmeer High, while mainly salt was deposited in the map sheet area. Especially the thick salt successions in the second evaporite cycle began to play an important role in the further structural development of this area. The

Figure 10.1. Palaeogeography of Northwest Europe during the Early Permian (after Ziegler, 1982).



influence of the depositional highs was primarily limited to the Zechstein 1, 2 and 3 Formations. The composition of the higher Zechstein cycles reflects the Permo-Triassic Basin becoming progressively terrestrial and an infilling of the relief.

The extent of the fourth cycle was probably more limited than that of the earlier cycles; within the map sheet area it was only penetrated by a few wells. The fourth cycle is absent particularly on the Friesland Platform, where the Lower Cretaceous sediments were deposited directly on top of the Zechstein sequence. In the Vlieland Basin the clastic members of the fourth cycle are found at the top of the non-eroded Zechstein sequence but the salt is missing. The salt deposits of the fourth cycle have only been penetrated by wells sited to the northeast of the Hantum Fault. Although it is not possible to be certain of the original extent of the fourth cycle because it is absent on the Friesland Platform, the above evidence suggests that the Hantum Fault acted as a barrier in the basin during the Late Permian, with salt being deposited on the deep side and clastic sediments representing the fourth cycle on the higher side. This is once again an indication of synsedimentary movement on the Hantum Fault.

With the equalisation of the relief, the influence of the structural units came to a temporary end, including the Texel-IJsselmeer High, the Off-Holland Low and the Ems Trough. A fall in sea level at the end of the Zechstein finally resulted in a definite transition from a marine to a continental environment (Vail et al., 1977; Fisher, 1984).

10.4 Triassic

After the thorough equalisation of the topography at the end of the Permian, an extensive, flat flood plain developed during the Early Triassic, of which the map sheet area also formed a part (fig. 10.2). The clastic sediments were transported from the south mainly by fluvial systems and sedimentation took place under fluvial and lacustrine conditions.

After an initially uniform development during the beginning of the Early Triassic, the Permian structural units, such as the Off-Holland Low, the Ems Trough and the interlying Netherlands Swell were again evident. Lateral differences in the composition of the younger Lower Buntsandstein deposits (the Rogenstein Member) on the high and to both sides of it indicate renewed tectonic activity. The Netherlands Swell corresponds to a certain extent with the Texel-IJsselmeer High and with the high during the Carboniferous (fig. 2.2). The map sheet area lay on the northern edge of the more or less NNE-SSW oriented Netherlands Swell. During the rest of the Triassic the sedimentation was concentrated increasingly in the areas of subsidence, while only a relatively thin succession was deposited on the Netherlands Swell.

This structural development was probably linked to a change in intra-plate stresses in Northwest Europe. During the Triassic, intensification of the extension in the mega-rifts in the Arctic/ North Atlantic and the Tethys/ Central Atlantic domains led to an increasing amount of regional extension. A complex rift system developed, of which the southernmost part extended into the region studied. This tectonic activity resulted in progressive changes in the Permo-Triassic Basin (Ziegler, 1982).

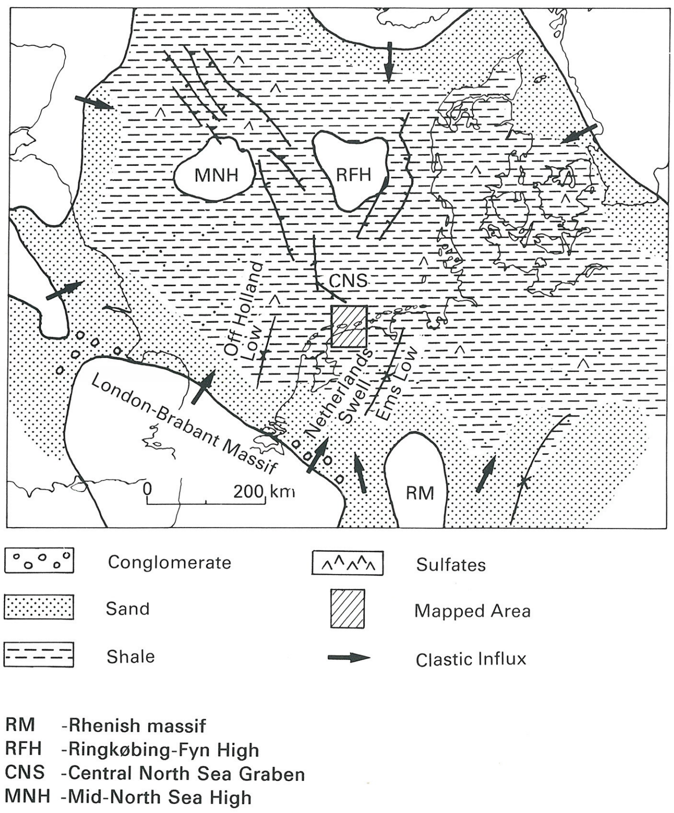
The tectonic activity that occurred in The Netherlands and northwest Germany during the Triassic was fairly weak. It comprised a number of epeirogenic movements, which caused various inclined depressions and archings within the basin, with only a few local faults (Van Hoorn, 1987; Trümphy, 1971; and 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 tectonic activity and variations in water level in the Permo-Triassic Basin which occurred during its deposition. Periods of tectonic activity in the hinterland and low water levels are reflected by fluvial systems prograding into the basin, while periods of relative quiet and high water levels are represented by the southwards extension of lacustrine sediments.

Little or no sediment was deposited on the re-uplifted areas. At the end of the Early Triassic, the uplift was sufficient for the Netherlands Swell to have even been subject to erosion. This so-called Hardegsen phase of erosion (which is in fact the base of the Röt) can onle be observed to the east of the Hantum Fault. Incision reached the Volpriehausen Sandstone (base Main Buntsandstein) at maximum (fig. 10.3). The Hardegsen unconformity was in turn removed by erosion from the rest of the map sheet area.

During the Middle Triassic the combination of progressive basin subsidence and a net sea-level rise after various swings (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).

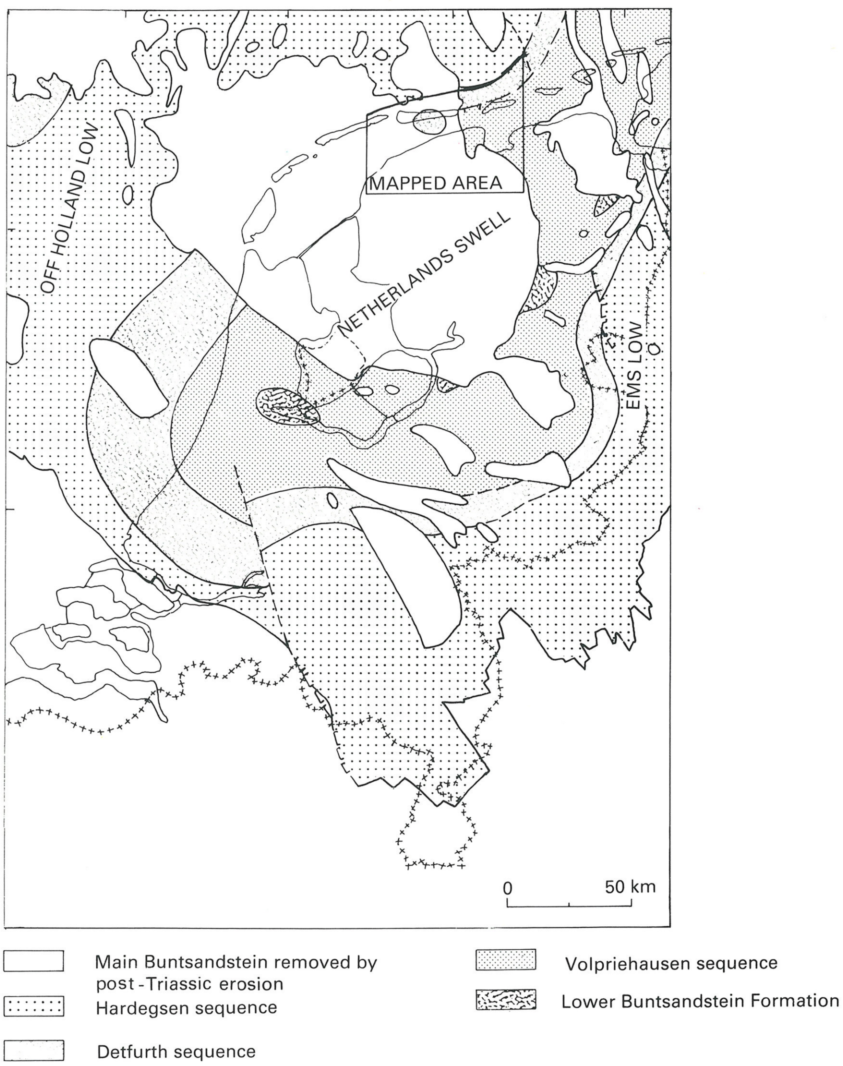
Figure 10.2. Palaeogeography of Northwest Europe during the Triassic (after Ziegler, 1982).



The younger Triassic units (the Röt, Muschelkalk and Keuper Formations) were probably deposited over the whole of the map sheet area but removed by later erosion, although a thin sequence may possibly have been preserved in the Lauwerszee Trough because of strong local subsidence. During the Middle and Late Triassic, there were lateral facies changes from the Ems Trough towards the Netherlands Swell (Schroder, 1982). These suggest that the map sheet area, as part of the Netherlands Swell, may have been slowly subsiding, with a condensed succession laid down as a rim facies.

Although there are few indications within the map sheet area, it seems, based partly on data from Germany (Jaritz, 1987), that the first phase of flow in the Zechstein salt took place during the Late Triassic. An erosive, angular unconformity has been observed at the contact between the Main Buntsandstein and the Röt Formation (the Hardegsen unconformity), near Buren on Ameland. The increase in thicknesses of the Late Triassic sequences, as seen in the rim synclines in Groningen, also points towards these early salt movements (Map Sheet Rottumeroog-Groningen, RGD, in preparation). The salt flow seems to have been initiated by fault movements and the differential forces related to the Hardegsen phase. The salt

Figure 10.3. Subcrop map of the Hardegsen unconformity, with the most important structural elements. The framed map sheet area lay on the northern edge of the Netherlands Swell (after NAM & RGD, 1980).



movements near Buren are possibly an indication of movement along the northern branch of the Hantum Fault.

10.5 Jurassic

A number of phases of strong erosion during the Jurassic and at the beginning of the Cretaceous removed all the Lower and Middle Jurassic and a large part of the Triassic sediments from the map sheet area. Upper Jurassic sediments were preserved only in the Vlieland Basin in the southwest of the map sheet (map 8). The description of the geological history of this area during this period is therefore taken from the literature and from data from the direct surroundings.

At the beginning of the Rhaetian (Triassic), there was the active Early Kimmerian phase (Haanstra, 1963; 't Hart, 1969), which 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. For practical reasons, these so-called 'Kimmerian' phases are related to the most important discontinuities in the stratigraphic sequence. In reality, the boundaries between the different phases are not so explicitly evident (Stille, 1924; Ziegler, 1978, 1982).

The Early Kimmerian phase was of little tectonic significance in the northern Netherlands and was characterised by a slight uplift and accompanying erosion (Haanstra, 1963). The most significant feature was the change in the sedimentary environment. From the Rhaetian onwards, marine conditions were again prevalent; these were due to tectonic subsidence and a large rise in sea level. Although there are no sediments of Early Jurassic age in the map sheet area or over large areas of The Netherlands, it is fairly certain that they were widely distributed originally. The present occurrences of Early Jurassic sediments are now separated (West and Central Netherlands Basin, Broad Fourteens Basin, Central North Sea Graben, Lower Saxony Basin), but in fact they all show a uniform composition of fine-grained marine sediments, which points to contemporary deposition in a continuous and extensive basin. It is still questionable whether areas like the Netherlands Swell, as it existed in the Triassic, had a different rate of subsidence during the Jurassic.

The regressive nature of the Middle Jurassic sediments found elsewhere indicates that their distribution became increasingly restricted and was finally limited to the deeper parts of the basins (Van Wijhe, 1987). A similar pattern of sedimentation is also found along the western edge of the Lower Saxony Basin (Betz et al., 1987). This regression, at the beginning of the Middle Jurassic, was linked with an intensification of tectonic activity (Vail et al., 1977; Ziegler, 1982) in a so-called Mid-Kimmerian phase (Ziegler, 1975, 1977). The possible beginning of the uplift of the North Netherlands High at this time would have meant that there was therefore no, or only a little, sedimentation in the map sheet area.

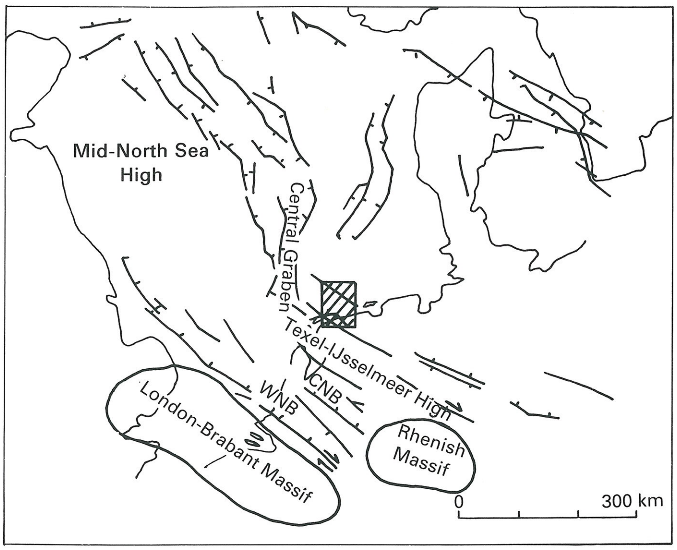
The tectonic activity of Northwest Europe was increasingly influenced during the course of the Jurassic period by the opening of the Arctic/North Atlantic rift system. In The Netherlands this culminated in the Late Kimmerian tectonic phase ('t Hart, 1969). From the Late Jurassic onwards, the Central North Sea Graben extended further southwards under the influence of east-west extensional forces. The extensions in the crust under the graben were accommodated at its southern end by transverse dextral strike-slip movements, along a system of reactivated faults running NW-SE. 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 were formed, parallel to the London-Brabant Massif (Ziegler, 1982). The formation of the Texel-IJsselmeer High and the North Netherlands High (with the Vlieland Basin) had a direct effect on the development of the geology in the map sheet area (fig. 10.4).

Two main impulses can be distinguished in the Late Kimmerian phase: the first, the Late Kimmerian I, took place in the Oxfordian and is related to the unconformity at the base of the Delfland Formation ('t Hart, 1969; Bodenhausen & Ott, 1981). The Late Kimmerian II occurred at the end of the Late Jurassic and the beginning of the Cretaceous and is related to the unconformity at the base of the Vlieland Formation. It was accompanied by a eustatic fall in sea level which had repercussions throughout Northwest Europe (Ziegler, 1982). This second pulse was reflected by a sharper definition of the basin configuration. It is noteworthy that no Upper Jurassic sediments have been found in the Lauwerszee Trough or the rim synclines of the salt structures. This indicates that subsidence only occurred there at the end of the Jurassic and was probably related to the Late Kimmerian II.

Based on the extent of the Upper Jurassic sediments (Delfland Formation) as well as the age of the volcanicity (Perrot & Van der Poel, 1987), it is likely that the main structure of the northern Netherlands was already determined by the first impulse. The North Netherlands High was uplifted, tilted, eroded and broken into different pieces during both the first and second Late Kimmerian (Stäuble & Milius, 1970). The Vlieland Basin was formed as a small extensional structure by transverse movements along reactivated, more or less NW-SE oriented faults (Herngreen et al., 1991). This movement was accompanied with intra-cratonic volcanicity in the form of the Zuidwal Volcanic Dome (Dixon et al., 1981; Perrot & Van der Poel, 1987; fig. 6.1).

Since the hiatuses in the sedimentary successions amalgamate on the highs, it is seldom possible to distinguish to which Kimmerian phase of deformation the movements in the map

Figure 10.4. Structural units during the Jurassic. Just to the north of The Netherlands, the N-S oriented rifting changed to the NW-SE oriented strike-slip thrusts along rejuvenated Variscan structures (Ziegler, 1982).



CNB -Central Netherlands Basin
WNB -West Netherlands Basin

sheet area may belong. However, for the whole Kimmerian deformation phase, it can be stated that enormous movements took place along the Hantum Fault. Section 2 (map 15) confirms this by showing the great difference in thickness between the Triassic units on either side of the fault. The relatively slight uplift to the northeast of the fault saved the Triassic sediments from deep-cutting erosion. Earlier Kimmerian erosion can no longer be distinguished because of the deeper erosion of the Late Kimmerian II. These movements, with those likely to have occurred in the Permian and Triassic, resulted in a maximum net vertical displacement of 1100 m (map 2). The transverse dextral component assumed to have taken place along the fault cannot be quantified (Ziegler, 1982; Van Wijhe, 1987).

Tectonically controlled sedimentation took place during the Late Jurassic to Early Cretaceous. Differential movements created fault-bounded sedimentary basins, with the uplifted border areas serving as a source for the clastic deposits of the Delfland and Vlieland Formations. Within the map sheet area deposits of Late Jurassic age are only found in the Vlieland Basin (map 8). There was probably little or no sedimentation in the rest of the area, although no definite statement can be made because the Late Kimmerian II interrupted sedimentation and was followed by erosion.

10.6 Cretaceous

At the beginning of the period there was a change in the tectonic regime; because the sea-floor spreading in the Early Cretaceous was increasingly concentrated in the North Atlantic Ocean and the Bay of Biscay, there was less rifting activity in the North Sea (Hancock, 1984; Ziegler, 1989). This brought to an end the extensional tectonic activity characteristic of the Kimmerian phases. The differential basin subsidence in the North Sea gave way to a regional subsidence that was a consequence of the thermal disruption in the crust being redressed. After a period of relative quiet during the Middle Cretaceous, the region came under the influence of a new compressive tectonic regime in the Late Cretaceous, following the collision between Africa and Europe (Sub-Hercynian and Laramide deformation phases).

The Cretaceous is also characterised by a number of successive transgressions that culminated in an open marine environment, which extended over a large part of Europe to the north of the Alps and Carpathians (Hancock & Scholle, 1975). This Cretaceous transgression was part of a global rise in sea level, probably in response to an increased rate of sea-floor spreading and the accompanying volume increase of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979). The sea level reached its maximum height in the Late Campanian (Hancock & Scholle, 1975).

These worldwide events led to a gradual change in the structural geometry of the map sheet area. The Vlieland Basin and the Lauwerszee Trough were filled in after the end of the differential subsidence. This infilling began in the Late Ryazanian with the deposition of the Vlieland Sandstone in a marginal marine environment (RGD, 1990a). A very slight but clear unconformity separates the Vlieland Formation from the Delfland Formation (Van den Bosch, 1983). The borders of the Vlieland Basin were transgressed following a continuous rise in sea level during the Valangian and the Hauterivian, and sedimentation spread over the whole of the map sheet area, thereby ending the role of the Vlieland Basin as a depocentre. This is confirmed partly by the base of the Vlieland Sandstone becoming younger towards the North Netherlands High. The later start of sedimentation on the high is confirmed in the area around Leeuwarden by a small hiatus at the base of the Vlieland Shale (RGD, 1990a). This hiatus and the presence of condensed sequences in the Vlieland Formation are indicative of its transgressive character and both features are observed over large parts of the North Sea.

Movements in the Late Kimmerian II phase led to a deepening of the Lauwerszee Trough, which was accompanied by salt flow as shown by the thickness developed in the Vlieland Formation (fig. 7.1). Great thicknesses were achieved in the basin and the rim synclines on both sides of the Ternaard salt structure near Ameland. It is difficult to be specific about the possible purely tectonic movements along the Hantum Fault since the effects of the salt flow are superimposed on them.

The period from the Late Aptian to Middle (or Late) Albian was characterised by a new transgressive phase, the so-called Albian transgression, which the different unconformities and hiatuses show was made up of several pulses. These combine together on the highs and thus appear to be a single phenomenon. This phase was influential throughout Northwest Europe and, finally, the Texel-IJsselmeer High and the North Netherlands High were also flooded (Crittenden, 1987). A fairly flat topography existed at the beginning of the Aptian, as shown by the uniform thickness of the Holland Formation.

The distance from the source areas of clastic material increased as the Cretaceous transgression continued to extend, while the source area was reduced in size. The proportion of terrigenous clastic material therefore gradually diminished, so that finally the Late Cretaceous sediments were composed of mainly marine bioclastic material.

The relative tectonic quiet and regional subsidence came to an end in the Santonian. The compressive regime generated by the collision between Europe and Africa must have intensified and gradually extended over the Northwest European Platform (Ziegler, 1982). This caused the reactivation of old faults, probably with sinistral, strike slip movements (Van Wijhe, 1987), which resulted in the uplift (inversion) of a number of basins in Northwest Europe, 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).

Within the map sheet area, the inversion activity was limited to the Vlieland Basin. From the isopach maps of the Chalk Group and the Rijnland Group (maps 10 and 12) and the structural sections (map 16), it is clear that the area of the 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). The reversed relief is evident from the onlap of sediments against the flanks of the inverted basins and from the angular unconformities in the inverted areas.

Despite the inversion, sedimentation in the most of the map sheet area continued. Although the Chalk succession that was deposited near the inversion axis is very thin (100-150 m; RGD, 1991), it appears to be a condensed sequence which contains sediments from nearly all the stages of the Late Cretaceous (fig. 8.1). Small intraformational hiatuses occur as well as thinning, cutoffs and prograding successions, especially during the Santonian and Campanian (RGD, 1988a, 1989d-g). They point to an intermittent uplift in which, either a thinned sequence was laid down or erosion occurred, depending on the rate of uplift. In tectonically quiet periods, sedimentation again took place over the whole area.

During the Late Cretaceous, sedimentation continued fairly quietly over most of the map sheet area outside the Vlieland Basin. Only the Upper Santonian is missing in places (Ameland-1 and Barradeel-1 wells; RGD, 1989d,e).

The Laramide phase at the end of the Cretaceous was of only slight significance in the map sheet area. Only a little or nothing of the Maastrichtian was eroded (fig. 8.1; Van den Bosch, 1983; Perrot & Van den Poel, 1987).

Assuming that the Friesland Platform and Groningen High were relatively stable during the Sub-Hercynian and Laramide phases, the approximately 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 (without correcting for compaction). Most of this uplift was completed during the Sub-Hercynian phase.

There are clear indications of slight salt movements during the Late Cretaceous. Seismic sections show the same composition for the Chalk succession on both sides of the salt ridges, with a slight thinning of sedimentation on top of the ridges. Moreover, the thickness increases along the salt ridges and in the Lauwerszee Trough. Figure 8.1 shows this with a thicker sequence of Santonian and Upper Maastrichtian in Wanswerd-1, a well located in a salt depletion area. The Schiermonnikoog-Zee-1 well shows that, certainly during the Campanian and Maastrichtian, subsidence in the Lauwerszee Trough was greater than in the rest of the map sheet area. The thinning over the salt ridges, especially to the south of Ameland, is partly a consequence of salt-tectonic thinning. The overlying sedimentary units collapsed locally, mainly in the Tertiary, because of subrosion, extensional forces over the crests of the salt structures, and lateral migration of the salt.

10.7 Cenozoic

After the compressive Laramide tectonic phase, a new basin, the North Sea Basin, formed in Northwest Europe and 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 and in approximately 65 million years, more than 3000 m of sediment have been deposited. These sediments are mainly composed of erosion products from the uplifted Alpine areas. The Netherlands is located on the southern edge of the North Sea Basin.

The change in sedimentary facies in the Tertiary reflects the transition into a new phase in the collision between the European and African plates. Large areas were strongly uplifted and subject to erosion, so that great amounts of terrigenous clastic degradation products invaded the bioclastic sedimentation. The regional subsidence was disrupted by local differential subsidence related to a large extent to salt flow, especially in the Lauwerszee Trough. The thickness of Tertiary and Quaternary sediments increases here to more than 1700 m, while it is only 400-600 m over the salt ridges and along the edge of the basin (map 13). Mainly marine clays and sands accumulated in the rapidly subsiding North Sea Basin but fluvial influences from the east became more important from the Miocene onwards.

The depositional processes during the Tertiary were widely influenced 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, erosion and salt movements, 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 (related to the Savian phase). Occurrences of tuffs in the Eocene deposits were related to volcanic activity in for instance the present Skagerrak area (Ziegler, 1982).

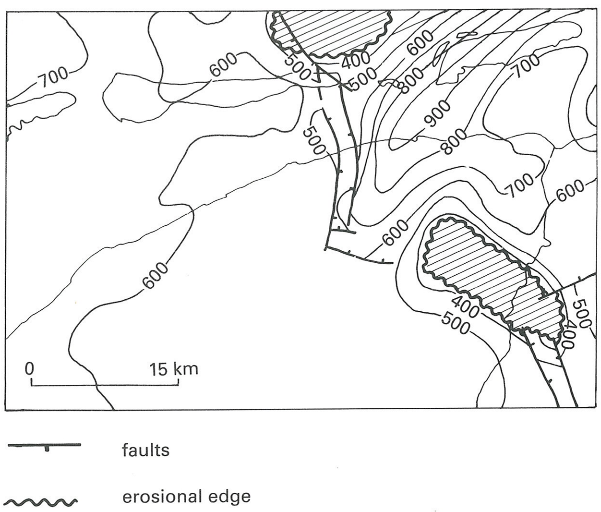
The depth map to the Pyrenean unconformity (map 10.5) and the seismic sections (figs 10.7 and 10.8) show that the Tertiary deposits were disturbed in various places by salt movements that took place during the Eocene and Oligocene. The existing salt structures continued to develop under the influence of tectonic forces and differential cover, thereby stretching the units overlying the tops of the salt ridges which led to faulting. There were both growth faults along the flanks of salt structures and grabens over the tops of these structures (map 13). The salt movements were weaker during the Miocene and the relief was filled in. The depth map to the base of the Pleistocene deposits shows that, from this time onwards, the salt structures had no significant effect on subsidence or the topography (fig. 10.6).

10.8 Salt movements

As is evident from the preceding sections, the salt's plastic behaviour had a significant effect on deformation within the map sheet area. This section gives more details about the salt movements and these are illustrated by two seismic sections over the Ternaard and Gerkesklooster salt domes (figs 10.7 and 10.8, respectively).

Salt movements are mostly expressed as upwards salt flow under the influence of gravity (halokinesis) or tectonically generated forces (halotectonics). Because the relative density of salt (2.2 g/cc) is less than that of the overlying sedimentary units (2.6 g/cc), the burial of salt entails a reversal in the density distribution and the salt becomes buoyant. This, combined with its plastic characteristics, enables the salt to move towards the surface. It is also probable that tectonic forces play an important role in causing or initiating salt structures (Koyi, 1988; Stephenson et al., in prep.). Intra-plate stresses in the North Sea can reach 1 kbar (Kooi et al., 1989) and are therefore much greater than the gravity instability arising from the difference in densities of salt and sedimentary cover. Displacements along the faults in the Lauwerszee

Figure 10.5. Depth map to the Pyrenean unconformity, at the base of the Middle North Sea Group, revealing clearly the influence of later salt movements (after RGD, 1984a).



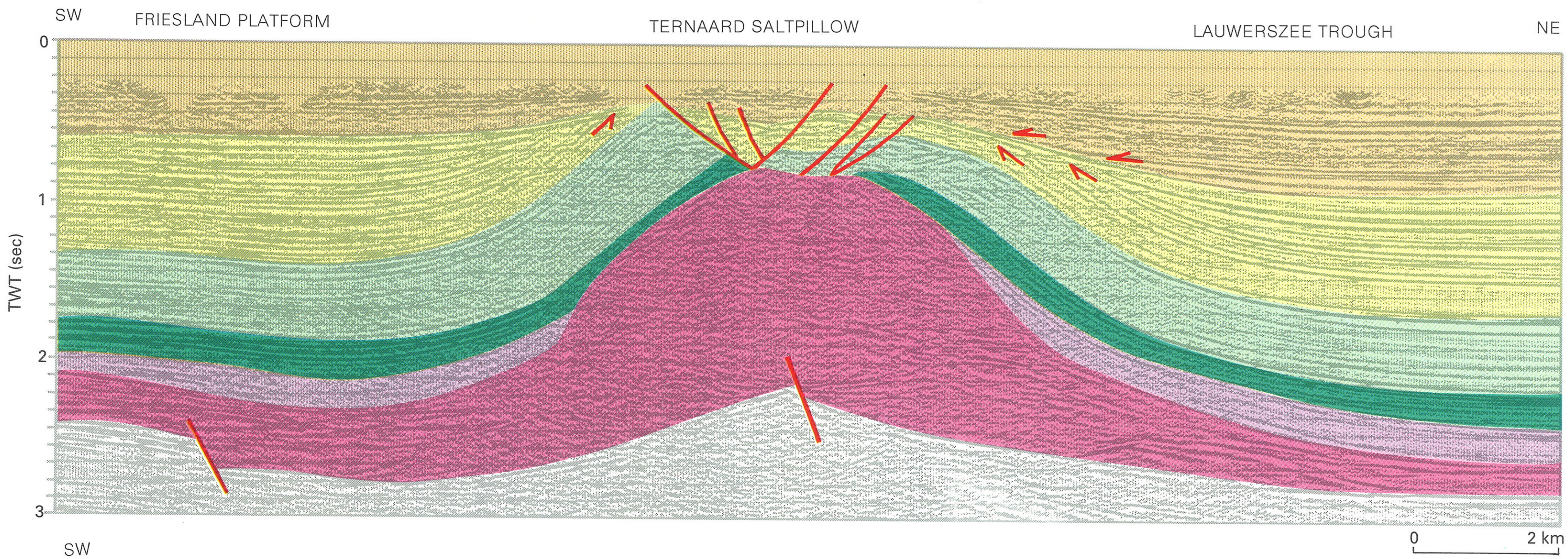


Figure 10.7 Seismic section across the Ternaard salt dome. The Hantum Fault, lying under the salt structure, is not clearly shown because of the 'velocity pull up'. The Friesland Platform is in the southwest and the Lauwerszee Trough in the northeast. Disturbance of the Tertiary sediments indicates the latest salt movements.

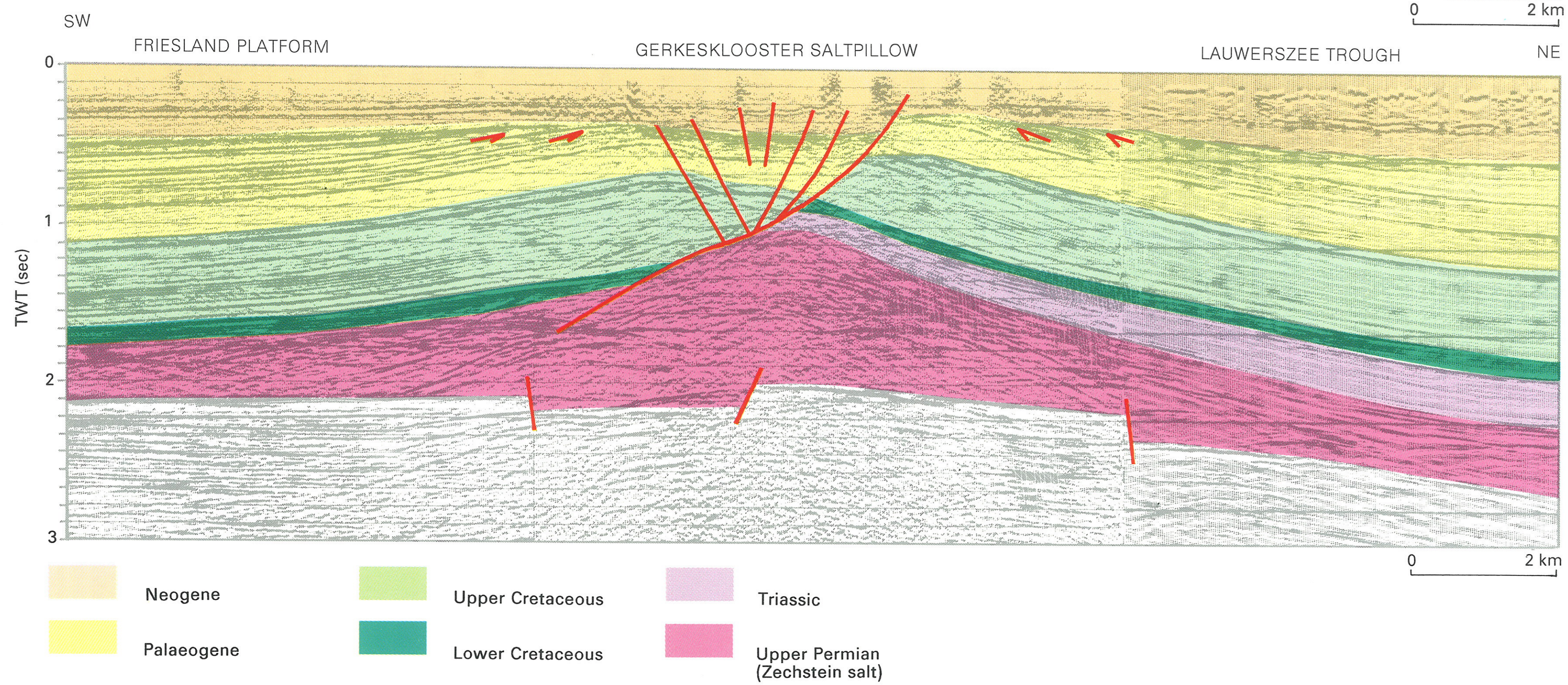


Figure 10.8 Seismic section across the Gerkesklooster salt dome. The structural setting is comparable to the one at Ternaard.

Trough, which were caused by the relaxation of large differential tectonic stresses, show that such forces were operative in the map sheet area. It seems that the most important salt movement phases were synchronous with the strong deformation phases.

The map sheet can be divided broadly into two areas based on the behaviour of the Zechstein salts: the Lauwerszee Trough and the Friesland Platform. The original structure of the Zechstein deposits has remained reasonably intact on the Friesland Platform. The deposits lie almost undisturbed, subhorizontal, and they are conformable with the rest of the sedimentary cover. In general, the Zechstein unit is 500-700 m thick. Where Cretaceous deposits lie directly on Zechstein deposits (map 14), the Zechstein 3 Salt and younger members are missing because of erosion. The substrate rocks of pre-Zechstein age also lie subhorizontally and the vertical movements along the faults were less than 300 m. These movements were probably partly synsedimentary, which resulted in primary differences in the thickness of the Zechstein. The movements could also have been accommodated by the plastic behaviour of the rock salt without giving rise to swellings. There could be various explanations for the absence of these swellings: a slight and uniform thickness of sedimentary cover; absence of large irregularities in the substrate with respect to the thickness of the salt unit; only a slight differential in the stresses built up; the relaxation of forces in fault movements.

In contrast, important salt flow did occur in the Lauwerszee Trough. Initial salt flow was from the centre of the basin towards the edges, the so-called 'basin-edge' diapirism (Jenyon, 1982). This theory assumes that the sedimentary cover was greatest in the centre of the basin, thus pushing the salt to the edges. A comparison of the depth map and the thickness map of the base of the Zechstein Group (maps 2 and 4) shows that the thickest accumulation (3000 m, Ternaard) lay in the deepest part of the basin. The other two structures have a thickness of 1800 m and lay in shallower parts of the basin. The border faults of the basin blocked the lateral flow of salt and thus determined the locations where the salt structures developed. The differences in thickness in the cover of the unstable salt succession on both sides of the fault would have been great enough to cause the rocksalt to flow. The salt tended to flow towards the higher block. A number of large salt domes developed along the border faults on both the east and west sides of the basin. On the west side, against the Hantum Fault and from north to south, the Ternaard, Engwierum and Gerkesklooster salt domes are clearly expressed on the depth map to the top of the Zechstein Group (map 3). The salt structures of Pieterburen, Groningen and Hoogezand lie along the border fault on the east side of the Lauwerszee Trough (Map Sheet III, Rottumeroog-Groningen. RGD, in preparation).

The hiatus in the sedimentary succession at the base of the Rijnland Group makes it difficult to gain understanding of the events during the period from the Middle Triassic to the Late Jurassic. It is generally assumed that the first salt movements took place in the relatively rapidly subsiding area of the North Sea during the Late Triassic and that these were related to the extensional forces which also formed the Central North Sea Graben and other structures (Jaritz, 1987).

The local angular unconformity of the Lower Cretaceous with the Triassic rocks is an indication that the first salt movements took place before the Late Kimmerian phase. This angular unconformity can be seen as a kink in the contours on the depth map to the top of the Zechstein Group. Pre-Cretaceous salt movements are also indicated by the isolated occurences of Lower Buntsandstein on the Friesland Platform and the small rim syncline, filled with Triassic sediments, on the west side of the Ternaard salt dome.

The Ternaard and Gerkesklooster salt domes must have reached the surface since the Lower Cretaceous lies directly on the Zechstein sequence. This exposure to the atmosphere led to erosion and the formation of a caprock.

The rim synclines in the north of the Lauwerszee Trough (map 10) indicate some salt flow during the Early Cretaceous, while only a general slight thickening of the Lower Cretaceous deposits occurred in the south, near the Gerkesklooster dome (fig. 1.7). In the south this thickening can be purely accounted for by tectonic subsidence of the basin, while the salt flow that took place in the north was probably due to the more rapid subsidence.

The Gerkesklooster salt dome is hardly evident on the thickness map of the Rijnland Group (map 10), although the maps of the Chalk Group and the North Sea Super Group (maps 12 and 13) reveal a depletion area in the Lauwerszee Trough along the salt dome. This implies that movements in the southern part of the Lauwerszee Trough ran a different course to those in the north.

During the Late Cretaceous the differential movements within the map sheet area came to an end and were followed by a more regional subsidence. This is evident from a comparison of the thickness maps of the Rijnland Group (map 10) and of the Chalk Group (map 12). There are two, more rapidly subsiding areas in the Rijnland Group, which prominently reveal the presence of the Hantum Fault line. During the Late Cretaceous there was an average thickness of 800 m over the whole of the northern part of the map sheet area (with the exception of the unit worn down by erosion in the inverted Vlieland Basin). The Hantum Fault had no significant influence in this period. The Chalk Group above the salt domes was thinned by erosion following uplift caused by salt flow, or by the overlying units collapsing or sliding downwards. The rim synclines on map 12 are more likely to be a phenomenon due to erosion than to deposition. In contrast to the uplifted flanks, the subsided synclines were protected from erosion by a combination of salt flow and tectonic uplift during the Laramide inversion phase at the end of the Cretaceous (fig. 10.8). The salt flow that occurred during the Late Cretaceous only took place at the end of this period and was related to the Laramide inversion phase.

It is noteworthy that the Lauwerszee Trough was again manifest during the Cenozoic. This was due to the differential movements occurring along the north-south Dokkum to Ameland branch rather than the western branch of the Hantum Fault. The accompanying salt flow reinforced their effect. Salt was removed mainly from the trough and hardly at all from the Friesland Platform, along the high side of the Hantum Fault. This was a consequence of the pressure gradient in the salt unit caused by the differential cover. The Cenozoic sediments in the Lauwerszee Trough even increase in thickness, to more than 1750 m.

The subdivisions of the Paleogene and Neogene in the Tertiary are clearly visible on the seismic sections, based on the tectonic and salt movements which took place (figs 10.7 and 10.8). At the base of the Paleogene there is a unit of uniform thickness that was laid down over the whole area, including over the flanks of the salt structures. Salt flow was at a maximum at the end of the Eocene and during the Oligocene. The pinching out and intersection of Eocene and Oligocene deposits can also be seen extremely clearly (figs 9.1, 10.7 and 10.8). The hiatus thus formed encompasses mostly the Late Oligocene but sometimes the Middle Oligocene too (Van Wijhe, 1987). The rapid pinching out of Late Paleogene sediments against the salt structures (i.e. over a short distance) is an indication of synsedimentary salt flow. This salt flow had nearly stopped by the end of the Oligocene. The light curving evident in the Neogene deposits is largely due to compaction of the rapidly deposited Paleogene sediments. The deeper position of the base of the Miocene deposits in the Lauwerszee Trough implies that it was still subsiding during the Neogene. The Neogene deposits were otherwise laid down with a fairly uniform thickness in a deepening North Sea Basin, as shown by the foresets that have often been observed (Van Wijhe, 1987). If the Ternaard and Gerkesklooster salt domes are compared, Ternaard is seen to be steeper and higher, so that this dome would seem to be further developed than Gerkesklooster. This difference arose especially in the Late Paleogene.

It is apparent from the thickness maps of the Chalk Group and the North Sea Super Group (maps 12 and 13) that the salt depletion area moved northwards in the Cenozoic. The salt flowed mainly towards the northern extension of Ternaard during this period. This is also evident from the seismic sections across Ternaard and Gerkesklooster (figs 10.7 and 10.8).

Faults in the sedimentary succession above the Zechstein Group are mostly associated with the development of salt structures. The rising salt pushes the cover upwards, causing extension over the structure. These forces can be released by the formation of a more or less symmetrical graben over the top of the structure or by movements along listric faults flanking the salt structure (and fading out in the Zechstein). The seismic data seems to indicate that a graben appears in a phase of little or no salt flow, while the listric faults appear when there is active salt flow during faulting. Listric faults are therefore caused, on the one hand, by a rising ridge, and on the other, by a flank subsiding owing to salt depletion directly below it. This resulted in an asymmetric build up of the salt dome, as for example in Gerkesklooster. Extra space was created by the subsidence of the western flank, leading to antithetic faults and the collapse of part of the covering units.

In some cases faults in the cover cannot be related to the development of salt domes and the accompanying extensional forces over the crown of the structure. A number of graben-like slumps in the unit above the Zechstein occur in the map sheet area, especially to the southwest of Dokkum. These are slightly offset and lie parallel to the Hantum Fault in the uplifted block (map 13). Laboratory experiments have shown that this type of graben is related to the thickness of the plastic layer (salt) and down-faulting in the substrate (Richard, 1991; Richard & Krantz, 1991). Thus, a graben structure can develop in the cover directly above a normal fault in the basement when the cover behaves in a brittle manner; the graben is determined by an antithetic fault and one or more synthetic faults (fig. 10.9b). When there is a sufficiently thick layer of plastic rocks (salt) between the brittle-acting cover and the basement (as in the area described here), the same normal fault in the substrate leads to the development of a graben structure in the cover that is laterally offset with respect to the fault (fig. 10.9b).

When a fault in the substrate is reactivated by lateral slipping, in echelon faults can appear in the grabens in the cover. In the map sheet area, the jumps in the largest displacements along the border faults, from one side of the graben to the other, could be caused by this in echelon faulting. This could be an explanation for the lateral displacements related to the Tertiary deformation along the Hantum Fault. Assuming such a relation between the faulting in the substrate and the location of the salt domes, the fact that the salt structures lie NNW-SSE en echelon along the Hantum Fault also seems to indicate lateral dextral movements.

Appendix B

Overview of wells used

Well	Code	Owner	*Final depth (log depth in metres)*	*Year (completed)*
1 Allardsoog-1	ALO-1	NAM	3180	1984
2 Ameland Oost-1	AME-1	Mobil	3673	1964
3 Ameland Oost-2	AME-2	NAM	4006	1974
4 Ameland Oost-101	AME-101	NAM	3715	1983
5 Ameland Oost-201	AME-201	NAM	3630	1978
6 Ameland-1	AML-1	Chevron	3839	1964
7 Ameland-2	AML-2	Chevron	3623	1964
8 Ameland Noord-1	AMN-1	Mobil	3592	1965
9 Ameland Noord-3	AMN-3	NAM	4030	1981
10 Ameland-Westgat-1	AWG-1	NAM	3512	1975
11 Ameland-Westgat-101	AWG-101	NAM	645	1984
12 Barradeel-1	BAR-NE-1	Billiton	2554	1970
13 Biltdijk-1	BDK-1	Chevron	3147	1964
14 Blija-Ferwerderadeel-102	BLF-102	NAM	3446	1977
15 Bozum-1	BOZ-1	Petroland	1963	1982
16 Boerakker-1	BRA-1	NAM	3262	1984
17 Bolsward-1	BWD-1	NAM	2679	1971
18 Buren-1	BUR-1	B.P.	3771	1964
19 Dronrijp-1	DRP-1	Petroland	3019	1984
20 Franeker-1	FRA-1	Petroland	1837	1978
21 Grootegast-1	GGT-1	NAM	3022	1961
22 Grootegast-102	GGT-102	NAM	3244	1976
23 Hollum-Ameland-1,2	HOA-1,2	NAM	3366	1964
24 Hollum-Ameland-3	HOA-3	NAM	3212	1973
25 Harlingen-2	HRL-2	Petroland	1871	1965
26 Harlingen-4	HRL-4	Petroland	1101	1984
27 Harlingen-5	HRL-5	Petroland	1112	1985
28 Hantum-1	HTM-1	NAM	3608	1975
29 Kollumerland-1	KOL-1	NAM	3467	1981
30 Leeuwarden-3	LEW-3	Petroland	1973	1968
31 Leeuwarden-5	LEW-5	Petroland	2754	1969
32 Leeuwarden Stad-1	LWS-1	Petroland	1946	1986
33 Minnertsga-1	MNG-1	NAM	3845	1986
34 Marum-2	MAR-2	NAM	2737	1978
35 Noord-Bergum-1	NBG-1	NAM	2640	1965
36 Nijega-3	NGA-3	Petroland	1965	1977
37 Nes Noord-1	NSN-1	NAM	3615	1970
38 Opeinde-2	OPE-2	Petroland	1955	1979
39 Opende Oost-1	OPO-1	NAM	3100	1979
40 Oudega-Akkrum-8	AKM-8	Chevron	2003	1977
41 Peins-1	PEI-1	Petroland	1884	1982
42 Rauwerd-2	RWD-2	Petroland	1981	1982
43 Ried-1	RID-1	NAM	3039	1952
44 Ried-2	RID-2	Petroland	1806	1980
45 Ried-3	RID-3	Petroland	1110	1980
46 Sint-Annaparochie-1	SAN-1	NAM	3062	1973
47 Schiermonnikoog-Zee-1	SCZ-1	Chevron	4139	1964

Well	*Code*	*Owner*	*Final depth (log depth in metres)*	*Year (completed)*
48 Suawoude-1	SUW-1	NAM	2654	1965
49 Suawoude-2	SUW-2	NAM	3161	1978
50 Terschelling-1	TER-1	NAM	3036	1964
51 Tietjerksteradeel-101	TID-101	NAM	2620	1965
52 Tietjerksteradeel-201	TID-201	NAM	2663	1971
53 Tietjerksteradeel-305	TID-305	NAM	2196	1976
54 Tietjerksteradeel-401	TID-401	NAM	2300	1978
55 Tietjerksteradeel-501	TID-501	NAM	2724	1979
56 Tietjerksteradeel-701	TID-701	NAM	2215	1980
57 Tietjerksteradeel-801	TID-801	NAM	2070	1980
58 Wanswerd-1	WAW-1	NAM	2150	1981
59 Wirdum-1	WRM-1	Petroland	1916	1972
60 M9-1	M9-1	NAM	3587	1968

Reservoir calculations Upper Rotliegend Group

The calculations in the four tables below were carried out for the whole of the Upper Rotliegend Group, the Slochteren Sandstone Formation, and the Upper- and Lower Slochteren Sandstones, respectively.
Cut-off values applied: clay content Vcl (co) = 50%; effective porosity Øe(co) = 6%; water saturation Sw (co) = 90%. The cut-off values for the effective porosity are based on core analyses. 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*
ALO-1	161.7	125.9	19.8	19.9	66.8	18.9	23.6	82.6
AMN-3	316.0	64.7	7.9	35.0	64.7	7.9	35.0	52.1
*BLF-102	198.1	104.2	16.6	27.3	104.2	16.6	27.3	51.6
GGT-102	220.1	190.7	19.4	32.1	168.7	19.6	33.2	52.3
HTM-1	218.5	109.8	11.6	31.0	104.6	11.8	31.0	68.1
LEW-5	191.0	135.2	18.4	28.2	135.2	18.4	28.2	62.6
MAR-2	168.2	121.2	17.6	24.3	82.0	16.7	24.9	45.5
NBG-1	209.0	134.9	15.0	28.4	125.3	15.3	27.9	76.9
NSN-1	344.5	91.4	11.9	35.8	85.0	11.6	36.1	73.8
OPO-1	201.2	149.2	18.2	22.7	119.0	18.2	23.3	57.6
SAN-1	253.5	167.8	17.9	26.4	153.6	18.2	27.3	76.8

Slochteren Sandstone

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
ALO-1	121.3	120.9	20.1	19.0	62.3	19.3	22.3	83.5
GGT-102	199.9	185.4	19.2	31.9	163.4	19.5	33.0	54.0
MAR-2	121.1	119.4	17.6	24.1	80.2	16.8	24.6	45.8
NBG-1	155.0	134.6	15.1	28.4	125.0	15.3	27.8	76.9
OPO-1	155.5	148.4	18.2	22.5	118.4	18.3	23.2	57.8

Upper Slochteren Sandstone

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
AMN-3	83.9	33.2	8.0	31.1	33.2	8.0	31.1	45.3
BLF-102	112.1	103.3	16.6	27.2	103.3	16.6	27.2	51.5
HTM-1	100.9	94.8	11.6	30.7	91.9	11.7	30.7	66.8
LEW-5	129.0	127.2	18.6	27.8	127.2	18.6	27.8	62.7
NSN-1	98.0	66.8	11.9	33.3	65.5	11.8	33.4	72.0
SAN-1	105.0	98.1	19.8	25.3	96.2	19.9	25.3	75.7

Lower Slochteren Sandstone

Well	*Gross*	*Reservoir*			*Pay*			
		Net	*Øem*	*Vclm*	*Net*	*Øem*	*Vclm*	*Swm*
AMN-3	68.4	27.9	8.0	38.9	27.9	8.0	38.9	58.6
HTM-1	12.4	11.4	11.9	32.2	10.4	12.2	31.9	76.4
NSN-1	104.0	23.6	11.9	42.5	18.4	11.2	45.2	80.2
SAN-1	61.5	55.2	14.8	28.3	43.2	14.8	31.8	79.5

Show, status and test data Upper Rotliegend Group

D&A dry and abandoned; RFT repeat formation tester (test interval in metres log depth; amount in litres); PRP production test (gas flow, Q50, in 1000m^3/d; water and condensate flow in m^3/d; FIT formation interval test (amount in litres); DST drill stem test (amount in litres); SW saltwater; MF mud filtrate; G gas; FW formation water; W water; C condensate; M mud; WCM water cut mud; u upper chamber; 1 lower chamber; Rw electrical resistivity of the formation water in ohm m^2/m (temperature, °C); Unit formation or member; ROSL Slochteren Sandstone; ROSLU Upper Slochteren Sandstone; ROSLL Lower Slochteren Sandstone; ROCLT Ten Boer Claystone; ROCLH Hollum Claystone; ROCLA Ameland Claystone; DC Limburg Group.

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Rw*	*Unit*
ALO-1	–	D&A	RFT 1	2769.5	SW+MF(u)	10.3		ROCLT
					SW+MF(l)	3.8		
			RFT 2	2782.1	G (u)	0.5		ROCLT
					FW (u)	3.6	0.0527(23)	
					FW (l)	9	0.0509(25)	
			PRP 1	2762-2790	SW			ROCLT
					G	0		
AMN-3	gas	GAS	RFT 1	3439-3591	-			ROCLT, ROSLU
			RFT 2	3660-3770	-			ROSLL, ROCLH, DC
			PRP	3549-3575	G	56 (acid, frac)		ROSLU
BLF-102	gas	GAS	PRP 1	3310-3321	G	26.5		ROSLU
			PRP 2	3269-3287	G	21		ROSLU
					W	51		
GGT-102	gas	GAS	PRP	3021-3077	G	860		ROSL
					W	2.4		
					C	11.6		
HTM-1	–	D&A	FIT 1	3615.2	M	1.1		ROSLL
			FIT 2	3614.5	M	2.2		ROSLL
			FIT 3	3541.8	WCM	2.6		ROCLA
			FIT 4	3499.7	WCM	0.3		ROSLU
LEW-5	–	D&A	DST 2	2518-2533	SW	11500		ROCLT, ROSLU
MAR-2	gas	GAS	PRP	2580-2616	G	680		ROSL
					W	2.7		
					C	7.3		
NBG-1	–	D&A	FIT 1	2481	M	3.6		ROSL
					MF			
			FIT 2	2491	M	6		ROSL
			DST	2381-2437	M	325		ROCLT
NSN-1	gas	D&A	–					
OPO-1	gas	GAS	RFT	2544.5	G (u)	19.8		ROSL
					G (l)	622		
					MF+W+C(l)	2.3		
			PRP	2513-2549	G	840		ROSL
					W	0.7		
					C	12.5		
SAN-1	–	D&A	FIT 1	2839				ROSLU
			FIT 2	2829	SW+M	3.5		ROSLU

Appendix E

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*
AKM-8	17.7	8.8	12.6	30.6	8.8	12.6	30.6	52.6
AME-101	20.0	18.7	14.8	25.9	1.6	20.0	18.3	84.0
BOZ-1	42.2	25.2	11.4	35.0	11.0	13.1	35.7	76.9
LEW-3	21.0	14.4	13.2	36.2	14.4	13.2	36.2	50.3
OPE-2	18.5	17.1	16.6	14.3	17.1	16.6	14.3	60.9
PEI-1	20.0	16.6	11.7	31.2	2.4	10.0	40.9	87.5
RWD-2	17.8	17.1	14.4	25.8	17.1	14.4	25.8	49.8
SUW-2	17.6	17.1	13.6	23.0	17.1	13.6	23.0	69.6
TID-305	38.5	38.1	12.8	23.6	37.8	12.8	23.7	60.9
WAW-1	25.7	0.9	14.5	36.5	0.9	14.5	36.5	61.2
WRM-1	29.0	23.6	16.7	21.9	22.5	17.0	21.4	66.4

Show, status and test data Vlieland Sandstone

For explanation of the symbols see appendix D.

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*
AKM-8	–	GAS	PRP 1	1964-1980	G	190 before acid
			PRP 2	1964-1980	G	310 after acid
AME-101	–	D&A	–			
BOZ-1	gas	GAS	PRP	1880-1889	G	0
LEW-3	gas	GAS	PRP	1894-1913	G	0
OPE-2	gas	GAS	PRP	1889-1906	G	250
PEI-1	–	D&A	–			
RWD-2	gas	GAS	PRP	1927-1944	G	75
					W	0.2
SUW-2	gas	D&A	DST	2229-2238	W	
TID-305	gas	GAS	PRP	2028-2072	G	110 after acid
WAW-1	–	D&A	–			
WRM-1	–	D&A	DST 1	1869-1886	W	17820
			DST 2	1887-1915		

References

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

Berge, J. (1983) *Sédimentologie des dépôts de base transgression dans les séries récentes et leurs homologues anciens. Application a l'interpretation des prospects pétroliers au niveau du Rhetien du Bassin de Paris et du Crétace Inférieur de Hollande.* Thèse, Université de Bordeaux I, 165 pp.

Best, G. (1989) *Die Grenze Zechstein/Buntsandstein in Nordwestdeutschland und in der südlichen deutschen Nordsee nach Bohrlochmessungen.* Z. dt. Geol. Ges., bd.140, p.73-85.

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

Blanche, J.B. (1973) *The Rotliegendes Sandstone Formation of the United Kingdom sector of the Southern North Sea Basin.* Trans. Inst. Min. Metal., Sect.B, Appl. Earth Sc., vol.82, p.B85-B89.

Blatt, H., Middleton, G. & Murray, R. (1972) *Origin of Sedimentary Rocks.* Prentice-Hall, Englewood Cliffs, New Jersey. p.518-522.

Bodenhausen, J.W.A. & Ott, W.F. (1981) *Habitat of the Rijswijk oil province, onshore the Netherlands.* In: Petroleum Geology of the Continental Shelf of NW Europe (Illing, L.V. & Hobson G.D. eds., Heyden & Son, London. p.301-309.

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

Brüning, U. (1986) *Stratigraphie und Lithofazies des Unteren Buntsandsteins in Südniedersachsen und Nordhessen.* Geologisches Jahrbuch, A 90, p.3-125.

Chadwick, R.A. (1986) *Permian, Mesozoic and Cenozoic structural evolution of England and Wales in relation to the principles of extension - and inversion tectonics.* In: Atlas of onshore sedimentary basins of England (Whittaker, A. ed.), Blackie & Son Ltd, Glasgow, p.9-26.

Cottençon, A., Parant, B. & Flacelière, G. (1975) *Lower Cretaceous gas fields in Holland.* In: Petroleum and the Continental Shelf of North-West-Europe (Woodland A.W. ed.), Applied Science Publ. Barking, p.403-412.

Crittenden, S. (1987) *The 'Albian transgression' in the Southern North Sea Basin.* Journal of Petroleum Geology, vol.10, p.395-414.

Dixon, J.E., Fitton, J.G. & Frost, R.T.C. (1981) *The tectonic significance of Post-Carboniferous igneous activity in the North Sea Basin.* In: Petroleum Geology of the Continental Shelf of NW Europe (Illing, L.V. & Hobson G.D. eds.), Heyden & Son, London. p.121-137.

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

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

Fisher, M.J. (1984) *Triassic.* In: Introduction to the Petroleum Geology of the North Sea (Glennie, K.W. ed.), Blackwell Scientific Publications, Oxford, p.113-132.

Glennie, K.W. (1972) *Permian Rotliegend of North-Western Europe, interpreted in the light of modern desert sedimentation studies.* AAPG Bulletin, vol.56, p.1048-1071.

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

Glennie, K.W. (1986a) *Early Permian - Rotliegend* Introduction to the Petroleum Geology of the North Sea (Glennie K.W. ed.), Blackwell Scientific Publications, Oxford, Second edition, p.25-62.

Glennie, K.W. (1986b) *Development of N.W. Europe's Southern Permian Gas Basin.* In: Habitat of Palaeozoic gas in N.W.Europe (Brooks, J., Goff, J.C. & Van Hoorn, B. eds.), Geol. Soc. Spec. Publications, No.23, Scot. Ac. Press Ltd., Edinburgh, p.3-22.

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

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

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

Hancock, J.M. & Scholle, P.A. (1975) *Chalk of the North Sea.* In: Petroleum and the Continental Shelf of North-West Europe (Woodland A.W. ed.), Applied Science Publ., Barking, p.413-427.

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

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

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

Jenyon, M.K. (1982) *Basin edge diapirism and updip saltflow in Zechstein of the Southern North Sea.* AAPG Bull. vol.69, p.53-64.

Kooi, H., Cloetingh, S.A.P.L. & Remmelts, G. (1989) *Intraplate stresses and the tectono-stratigraphic evolution of the North Sea Central Graben.* Geologie en Mijnbouw, vol. 68, p.49-72.

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

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

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

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

Marie, J.P.P. (1975) *Rotliegendes stratigraphy and diagenesis.* In: Petroleum and the Continental Shelf of North-West Europe (Woodland, A.W. ed.), Applied Science Publ. Barking, p.205-211.

Moody-Stuart, N. (1966) *High- and low-sinuosity stream deposits, with examples from the Devonian of Spitsbergen.* Journ. of Sediment Petrology, vol.36, p.1102-1117.

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

NAM & RGD (1980). (Nederlandse Aardoliemaatschappij BV and Rijks Geologische Dienst) *Stratigraphic nomenclature of The Netherlands.* Kon. Ned. Geol. Mijnb. Genootschap, Verhandelingen, deel 32, 77pp.

Pallatt, N., Wilson, J. & McHardy, B. (1984) *The relationship between permeability and the morphology of diagenetic illite in reservoir rocks.* Journ. Petr. Techn., p.2225-2227.

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

Peryt, T.M. (1975) *Significance of stromatolites for the environmental interpretation of the Buntsandstein (Lower Triassic) rocks.* Geologische Rundschau, bd.64, p.143-158.

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

Plomp, A.N. & Geluk, M.C. (1988) *Marginal deposits of the Zechstein evaporite basin (Upper Permian), The Netherlands.* Abstracts 9th European Regional Meeting IAS, Leuven, p.172-174.

Raymer, L.L., Hunt, E.R. & Gardner, J.S. (1980) *An improved sonic transit time-to-porosity transform.* SPWLA 21st Ann.Log.Symp.Trans., Paper P. p.1-13.

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

Richard, P. (1991) *Experiments on faulting in a two-layer cover sequence overlying a reactivated basement fault with oblique slip.* Journ. of Structural Geology, Vol.13, p.459-469.

Richard, P. & Krantz R.W. (1991) *Experiments on fault reactivation in strike-slip mode.* Tectonophysics, 188, p.117-131.

Rijks Geologische Dienst (1984a) *Geologische en Hydrogeologische inventarisatie van Tertiaire en Onder-Kwartaire afzettingen in Noord-Nederland t.b.v. ondergrondse opslag en winning van warm water.* Rapport no.84KAR08ex, project BP10371.

Rijks Geologische Dienst (1984b) *Inventarisatie van slechtdoorlatende laagpakketten in de ondergrond van het Nederlandse vasteland.* Rapport no.OP6009.

RGD (1991) *Geologische Atlas van de Diepe Ondergrond van Nederland, Toelichting bij blad I: Vlieland-Terschelling,* Rijks Geologische Dienst, Haarlem. 79 pp.

RGD (in prep) *Geologische Atlas van de Diepe Ondergrond van Nederland, Toelichting bij blad III: Rottumeroog-Groningen,* Rijks Geologische Dienst, Haarlem.

Schröder, B. (1982) *Entwicklung des Sedimentbeckens und Stratigraphie der klassischen Germanischen Trias.* Geologische Rundschau, Bd.71, p.783-794.

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

Seemann, U. (1979) *Diagenetically formed interstitial clay minerals as a factor in Rotliegend sandstone reservoir quality in the Dutch sector of the North Sea.* Journ. of Petroleum Geology, vol.1, p.55-62.

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

Stephenson, R.A., Van Berkel, J.T. & Cloetingh, S.A.P.L. (in prep.). *Relation between salt diapirism and in-plane stresses in the Sverdrup Basin, Arctic Canada.*

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

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

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

Trümphy, R. (1971) *Stratigraphy in mountain belts.* Quart. Journ. Geol. Soc. London, 126, p.293-318.

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

Van Adrichem Boogaert, H.A. (1976) *Outline of the Rotliegend (Lower Permian) in the Netherlands.* In: The continental Permian in Central, West, and Southern Europe (H. Falke, ed.), Reidel Publ.Comp., Dordrecht, Series C, vol.22, p.23-27

Van den Bosch, W. J. (1983) *The Harlingen Field, the only gasfield in the Upper Cretaceous Chalk of The Netherlands.* Geologie en Mijnbouw, vol.62, p.145-156.

Van Hoorn, B. (1987) *Structural evolution, timing and tectonic style of the Sole Pit inversion.* Tectonophysics, 137, p.239-284.

Van Staalduinen, C.J., Van Adrichem Bogeart, H.A., Bless, M.J.M., Doppert, J.W.Chr., Harsveldt, H.M., Van Montfrans, H.M., Oele, E., Wermuth, R.A. & Zagwijn, W.H. (1979) *The Geology of The Netherlands.* Meded. Rijks Geologische Dienst. Vol.31-2, p.9-49.

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

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

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

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

Wyllie, M.R.J., Gregory, A.R. & Gardner, L.W. (1956) *Elastic wave velocities in heterogeneous and porous media.* Geophysics, vol.21, p.41-70.

Wyllie, M.R.J., Gregory, A.R. & Gardner, L.W. (1958) *An experimental investigation of factors affecting elastic wave velocities in porous media.* Geophysics, vol.23, p.459-493.

Zagwijn, W.H. (1989) *The Netherlands during the Tertiary and the Quaternary: A case history of coastal lowland evolution.* Geologie en Mijnbouw, vol. 57, p.589-626.

Ziegler, P.A. (1975) *The North Sea in the Tectonic Framework of North-Western Europe.* In: Petroleum and the Continental Shelf of North-West Europe (Woodland A.W. ed.), Applied Science Publ. Barking, p.131-148.

Ziegler, P.A. (1977) *Geology and hydrocarbon provinces of the North Sea.* Geojournal 1. p.7-31.

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

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

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

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

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

Internal reports of the Geological Survey of the Netherlands[1]

RGD 1985 Schuurman, H.A. & Lissenberg, T. *Stratigrafische interpretatie van het Mesozoïsche gedeelte van boring HH 34 (Oude-Inschot-1).* Rapport Micropal Mesozoïcum no.433.

RGD 1988a Geel, C.R. *Logcorrelaties binnen de Chalk Groep in NW Nederland.* Rapport no.88KAR18.

RGD 1988b Witte L. & Schuurman H.A. *Biostratigrafische interpretatie van het Mesozoische traject van boring X.Y.-35, met uitzondering van de Trias.* Rapport Paleontologie Mesozoïcum no.473.

RGD 1989a Geluk, M.C. & Parker, N. *Geologie van de Trias afzettingen in het kaartblad Texel - Purmerend (kaartblad IV).* Rapport no.89KAR17.

RGD 1989b Pagnier, H.J.M. *Correlatie en interpretatie van een aantal boringen die het Carboon bereikt hebben, in het kader van de diepe kartering van kaartblad I.* Rapport no.GB-2252.

RGD 1989c Witte, L. & Schuurman, H.A. *Biostratigrafische interpretatie van het Mesozoische gedeelte van boring H.I.-36.*. Rapport Paleontologie Mesozoïcum no.480.

RGD 1989d Witte, L. & Schuurman, H.A. *Stratigrafische (her)interpretatie van het Mesozoicum in de boring Barradeel NE-01.* Rapport Paleontologie Mesozoïcum no.103a.

RGD 1989e Witte, L. & Schuurman, H.A. *Biostratigrafische interpretatie van het Mesozoische gedeelte (voor wat betreft Jura en Krijt) van boring HU-64 (Ameland-01).* Rapport Paleontologie Mesozoïcum no.485.

RGD 1989f Witte, L. & Schuurman, H.A. *Biostratigrafische interpretatie van het Mesozoische gedeelte van boring RE-23 (Hollum-Ameland).* Rapport Paleontologie Mesozoïcum no.498.

RGD 1989g Witte, L. & Schuurman, H.A. *Stratigrafische (her)interpretatie van het Boven Krijt in boring UW31 (Zuidwal-02)* Rapport Paleontologie Mesozoïcum no.107b.

RGD 1990a Herngreen, G.F.W. *Boven-Jura - Onder-Krijt stratigrafie van het Vlieland Bekken.* Rapport Paleontologie Mesozoïcum no.2213.

RGD 1990b Ramaekers, J.J.F. *Petrofysica Boven-Rotliegend Groep Kaartblad II.* Rapport no.90KAR14.

RGD 1990c Ramaekers, J.J.F. *Petrofysica Vlieland Zandsteen Kaartblad II.* Rapport no.90KAR15.

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

Geological Maps

The maps were compiled by
E.J.Th. Duin
G. Remmelts

Design
A. Walkeuter

Cartography
European Institute of Cartography, Zoetermeer

Printing
Haagse Drukkerij, The Hague

Explanation

Contributions to the explanation accompanying the maps were made by
G. Remmelts
M.C. Geluk
J.J.F. Ramaekers

Translation
J.L. Senior, Zeist

Figures
D. Moeliker

Design
BRS Premsela Vonk, Amsterdam

Printing
SDU, The Hague

Project management
Th.E. Wong

ISBN 90-72869-13-3

This publication should be referred to as
RGD 1991 - Geological Atlas of the Subsurface of The Netherlands, Explanation to map sheet II: Ameland-Leeuwarden, Geological Survey of The Netherlands, Haarlem.

This publication is a translation of the Dutch version,
ISBN 90-72869-12-5.