Rijks Geologische Dienst RGD

Explanation to map sheet V
Sneek-Zwolle

Geological Atlas of the Subsurface of The Netherlands

Explanation to map sheet V
Sneek–Zwolle

Geological Atlas of the Subsurface of The Netherlands

Contents

One of the main tasks of the Geological Survey of The Netherlands (Rijks Geologische Dienst, 'RGD') is to collate knowledge about the geology of The Netherlands. This information is being made widely available to the general public by the Geological Survey of The Netherlands, mostly in the form of maps and explanations to map sheets which, until a few years ago, only dealt with the subsoil geology of The Netherlands and the North Sea.

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

The Sneek-Zwolle map sheet of the Geological Atlas of the Subsurface of The Netherlands is the fourth sheet to be published in the framework of the systematic mapping of The Netherlands based on these data, which will comprise 15 map sheets on a scale of 1:250.000 (see figure 1.1 for an overview of the area of the map sheets). The Annual Report of the Geological Survey of The Netherlands gives an overview of the progress of this mapping.

Each map sheet has its own features. The map sheet in question outlines the geology of an important part of the provinces of Friesland and Overijssel. The pronounced Texel-IJsselmeer High, whose influence can be observed on many of the maps, forms the structural basis not only of this map sheet but also of The Netherlands. For many millions of years it was a feature separating the relatively stable northeast of The Netherlands from the southwest which was influenced by major subsidence and uplift. The large variety of gas-bearing stratigraphic units (north)east of the high is striking. In that area, reservoirs are found in Permian dune sands and limestones as well as in fluvial and shallow-marine sandstones of the Triassic, Cretaceous and Tertiary. The only gas field found up to now in the Upper Cretaceous limestone is situated in the extreme northwest of the map sheet area. In the east of the map sheet area, the first salt pillows appear as the marginal occurrences of the vast salt province of the northeastern part of The Netherlands.

The Geological Survey anticipates that this map sheet, together with those already published or in progress, will contribute to a greater understanding of the structure and composition of the subsurface of The Netherlands. This is important not only to companies who are active in the fields of exploration and exploitation for minerals and natural resources, but also to the government, provincial and local authorities, state and semi-governmental institutions and various other non-governmental organisations. They are all increasingly confronted with questions relating to the possible consequences of exploitation of natural resources and the other opportunities for sustainable development of the subsurface of The Netherlands. For example, these may concern issues of storage or disposal of waste, energy storage, and geothermal energy as an alternative energy source.
The explanation accompanying the map sheet is not only aimed at professional earth scientists in industry and government, but should also be of interest to teachers, scientists and non-professional geologists.

As well as those people acknowledged in the credit column who are directly responsible for compiling this map sheet, many other employees of the Geological Survey have been involved, with especial mention of the substantial contributions made by N. Witmans. I greatly appreciate her efforts. Pertinent and constructive criticism from Dr. W.J.M. van der Linden and the reviewing committee added much to the quality of the explanation. Special thanks are due to Amoco, Chevron, Conoco, Elf Petroland, NAM, Placid and Superior, who all provided data used in this map sheet.

Chr. Staudt,
Director

1 Introduction

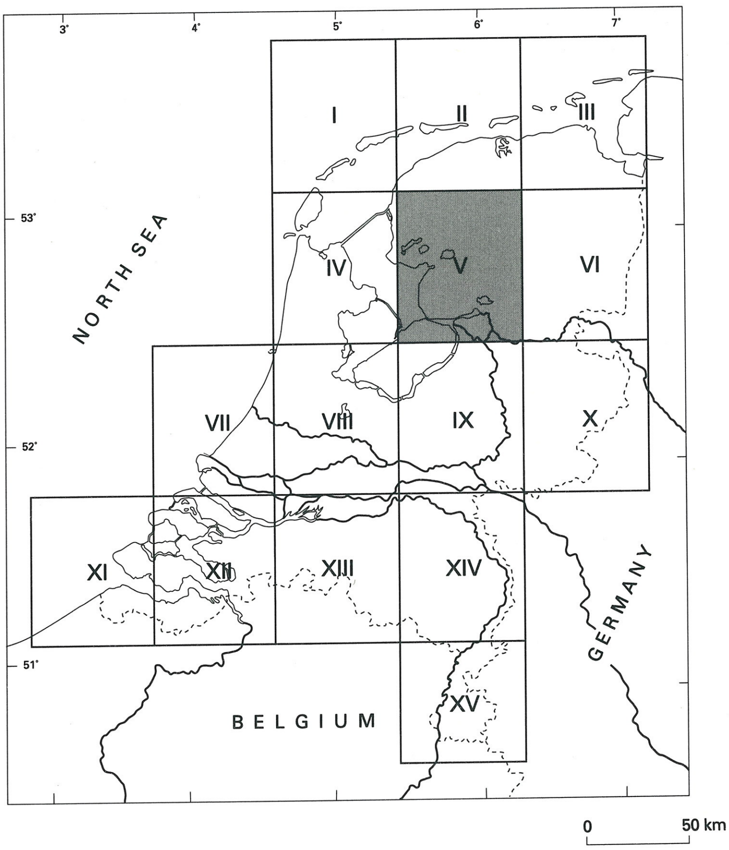
1.1 Extent of area studied.

Map sheet V (Sneek - Zwolle) covers the southern part of the province of Friesland, the eastern part of the IJsselmeer, the northern part of de province of Flevoland, the western part of the province of Drenthe and the northwest of the province of Overijssel (fig. 1.1).

1.2 History of exploration and data base.

Since 1959 there has been considerable interest in exploration in the areas immediately to the south of Leeuwarden. The initial target for exploration after the discovery of the gigantic Groningen gasfield was the Slochteren Sandstone, the gas reservoir unit of the Upper Rotliegend, from which the oil companies expected the best results. Prospective sands of the Lower Cretaceous and the carbonates of the Zechstein were discovered during exploration activities in the '60s and '70s. In the De Wijk field, gas-productive sediments are of Carboniferous, Triassic and Tertiary age. Figure 1.2 gives an overview of the hydrocarbon accumulations within the map sheet

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

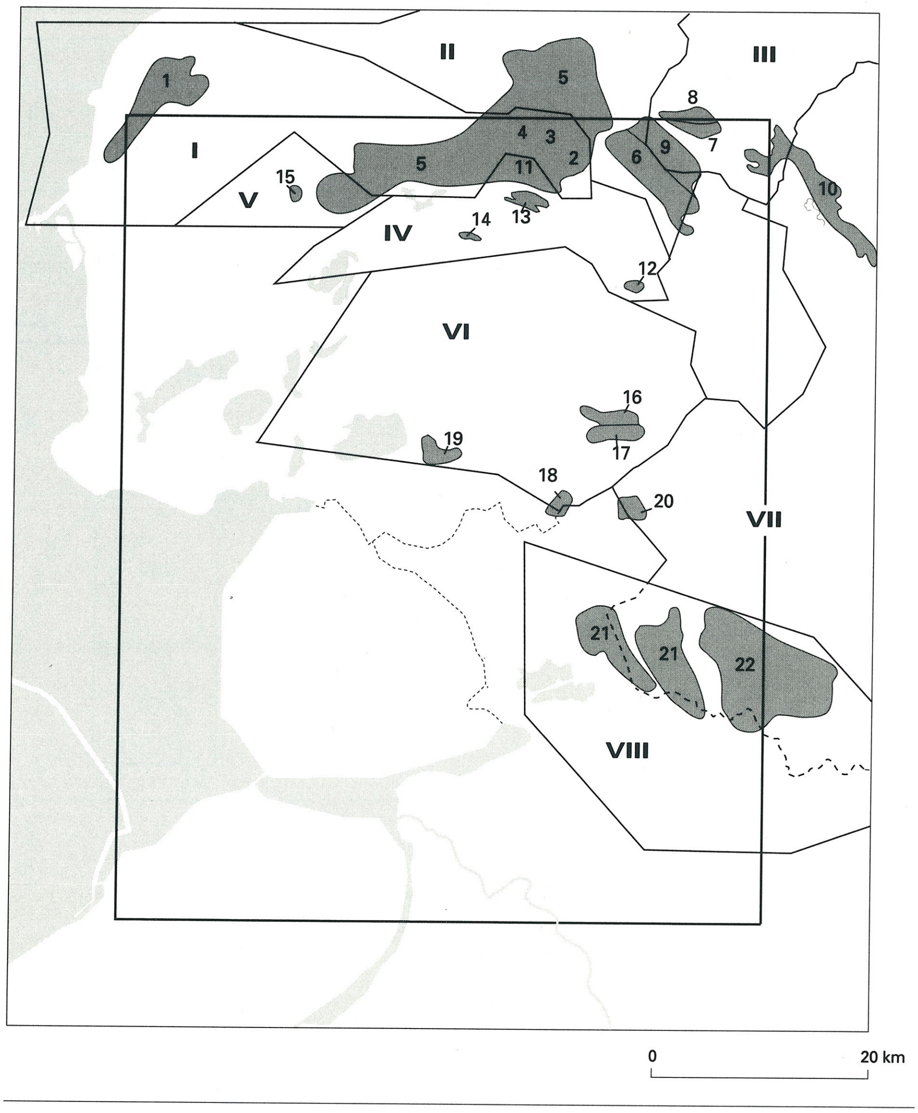


I	Vlieland-Terschelling	IX	Harderwijk-Nijmegen
II	Ameland-Leeuwarden	X	Almelo-Winterswijk
III	Rottumeroog-Groningen	XI	Middelburg-Breskens
IV	Texel-Purmerend	XII	Roozendaal-Terneuzen
V	Sneek-Zwolle	XIII	Breda-Valkenswaard
VI	Veendam-Hoogeveen	XIV	Oss-Roermond
VII	Noordwijk-Rotterdam	XV	Sittard-Maastricht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

Figure 1.2 Overview map of the concession licence areas within the map sheet area, with the name of the operator in brackets. The identified gas fields (as at 1-1-1993) have been numbered. Each field is followed by the stratigraphic units comprising the reservoir.

Concessions

I	**Leeuwarden (Elf Petroland)**	
	1 Harlingen 2	Chalk
	2 Nijega	Zechstein
	3 Middelburen	Upper Rotliegend
	4 Leeuwarden	Upper Rotliegend
II	**Tietjerksteradeel (NAM)**	
	5 Ureterp	Upper Rotliegend
	6 Friesland	Vlieland
III	**Groningen (NAM)**	
	7 Marumerlage	Upper Rotliegend
	8 Opende Oost	Upper Rotliegend
	9 Marum	Upper Rotliegend
	10 Zevenhuizen	Upper Rotliegend
IV	**Akkrum (Chevron)**	
	11 Akkrum 1	Upper Rotliegend
	12 Akkrum 11	Upper Rotliegend Zechstein 2 Carbonate
	13 Akkrum 3	Upper Rotliegend,
	14 Akkrum 13	Upper Rotliegend, Zechstein 2 Carbonate
V	**Oosterend (Elf Petroland)**	
	15 Bozum	Vlieland
VI	**Gorredijk (Elf Petroland)**	
	16 Weststellingwerf	Zechstein 2 Carbonate
	17 Noordwolde	Vlieland
	18 De Blesse	Zechstein 3-4 Carbonate
	19 Oldelamer	Zechstein 2 Carbonate
VII	**Drenthe (NAM)**	
	20 Nijensleek	Zechstein 2 Carbonate (oil), Vlieland
VIII	**Schoonebeek (NAM)**	
	21 Wanneperveen	Zechstein 2 Carbonate, Rogenstein, Vlieland, Basal Dongen Tuffite
	22 De Wijk	Limburg, Rogenstein, Vlieland, Basal Dongen Tuffite



area (as at 1-1-1993), most of which are in the north of the map sheet area. The best results have been obtained by drilling the sandstones of the Upper Rotliegend Group and the Vlieland Group.

Most of the data used to compile this map sheet have been provided by the oil companies. These data are mainly reflection seismics and well-log data collected in the past years for hydrocarbon exploration.

In the northern part of the map sheet area many seismics lines were shot. In the concession areas of Leeuwarden and Schoonebeek, a considerable amount of well-log data are available from the many production wells lying in clusters. The borehole distribution and the seismic coverage is not homogeneous over the map sheet area, the south and west of the map sheet area having been less intensely covered than the northern and the eastern part of the map sheet area (fig. 1.3 & 1.4).

Figure 1.3 Location of the seismic lines used. Appendix A gives additional information on the owner and the age of the various lines.

1.3 Research set up.

1.3.1 Seismic mapping

The mapping was carried out using a seismic line-grid of approximately 4 by 4 km, although this coverage could not be achieved in the southwestern quarter of the map sheet and in the southern part of the province of Friesland owing to the quality and the availability of the data. For the compilation of the various maps, approximately 250 non-migrated seismic lines were used (appendix A & fig. 1.3), varying in length from 3 to 30 km.

The mapped reflectors form the boundaries between the lithostratigraphic units. Calibration of the seismic data with the interpreted well loggings was carried out by means of acoustic logs and well-shooting survey data. The time-to-depth conversion of the seismic data was carried out per layer (the so-called 'layer-cake method'). For this purpose a linear equation between the velocity and the depth of the layer was taken:

$V_z = V_0 + k.z$ (see table 1a under a)

An exception to this is made in the case of the Zechstein Group. Because of the specific lithological composition of this group, a hyperbolic equation between the interval velocity and the time interval was chosen:

$V_{int} = a + [d/(\delta t - b)]^c$ (see table 1a under b)

To obtain a good fit for depth maps of adjacent map sheets, a regional velocity distribution was made, which is applied to all the map sheets, with a distinction being made between inverted and non-inverted structural units. The velocity distribution of table 1a was applied in the case of the non-inverted areas, such as the Friesland Platform and the Texel IJsselmeer High. Table 1b shows the velocity modifications used for the inverted areas such as the Central Netherlands Basin. The parameters of the regional velocity distribution were determined from acoustic data from 65 wells located throughout The Netherlands.

1.3.2 Geological research

The geological research was focused on the lithostratigraphic composition of the rocks present in the map sheet area (fig. 1.5) and their geological history with respect to the regional developments. Figure 1.6 represents the geological timetable used in this explanation (Harland et al., 1990). The tectonic phases which are referred to and discussed in this explanation are also indicated in figure 1.6. Appendix B provides an overview of the wells used shown in figure 1.4. Data from a total of 108 wells have been used for this explanation.

Table 1a: Applied velocity distribution for non-inverted areas.

a. based on $V_z = V_0 + k.z$

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

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

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

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

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

Table 1b: Modified velocity distribution applied to inverted areas.

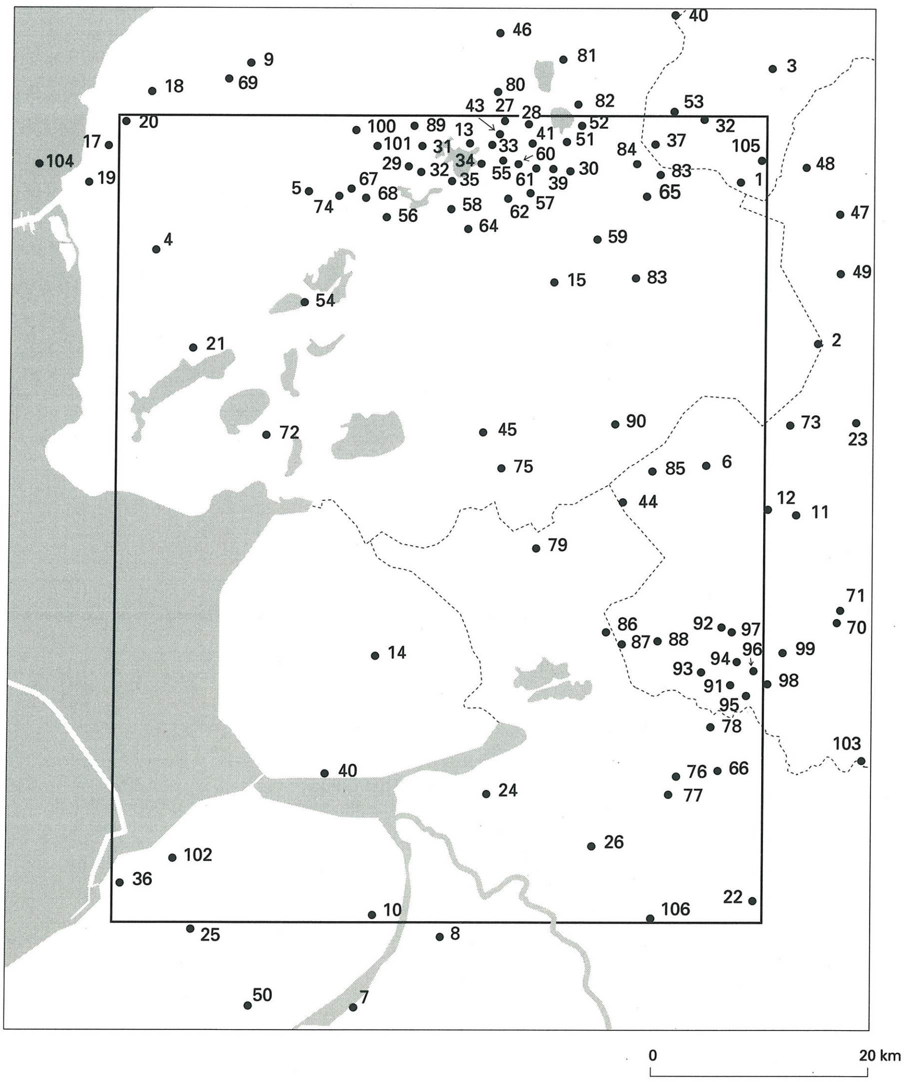
Unit	V_0	*k*
Jurassic deposits	2297	0.62
Lower and Upper Germanic Trias Groups	3254	0.56

In the extreme south of the map sheet area considerable attention has been paid to structural geological problems. The geological structures in this area are more complex than the map sheet would lead one to suppose. Although the quantity of seismic data in the southwestern quarter of the map sheet area is insufficient, a geological map sheet is presented which, though not complete in detail, nevertheless enables a geological concept to be derived. The mapped structures in this zone have produced the structural geological interpretation which is discussed in section 11.2.

1.3.3 Petrophysical research

As well as the geological research, attention has also been paid to the reservoir characteristics of a number of lithological units. The map sheet area contains a great variety of units which are (or have been) productive. Gas/oil-bearing reservoir rocks in the map sheet area are: the Tubbergen Sandstone, the Slochteren Sandstone, the Zechstein Carbonates, the Rogenstein, the

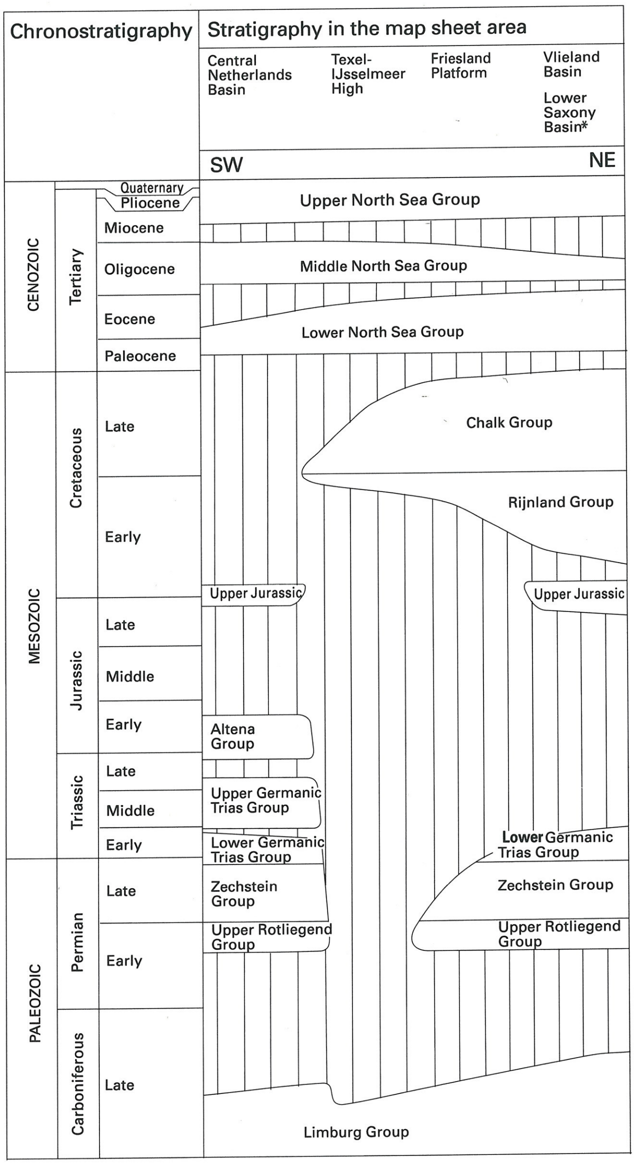
Figure 1.4 Location of the wells used for the geophysical and geological mapping. Appendix B gives additional information on the owner, final depth and the date of the wells.



Volpriehausen Sandstone, the Vlieland Sandstone, the Ommelanden Chalk and the Basal Dongen Tuffite (fig. 1.2).

The chapters on the Slochteren Sandstone, the Zechstein 2 Carbonate and the Vlieland Sandstone include a petrophysical evaluation. Appendices C, E and G contain the effective porosities for these rocks. Results of various production tests are given in appendices D, F and H. The reservoir-geological aspects of the Carboniferous, the Triassic, the Chalk and the Basal Dongen Tuffite are only referred to briefly.

Figure 1.5 Diagram of the lithostratigraphic units within the map sheet area.
(* In the Lower Saxony Basin is also the Upper Germanic Trias Group and the Altena Group present).



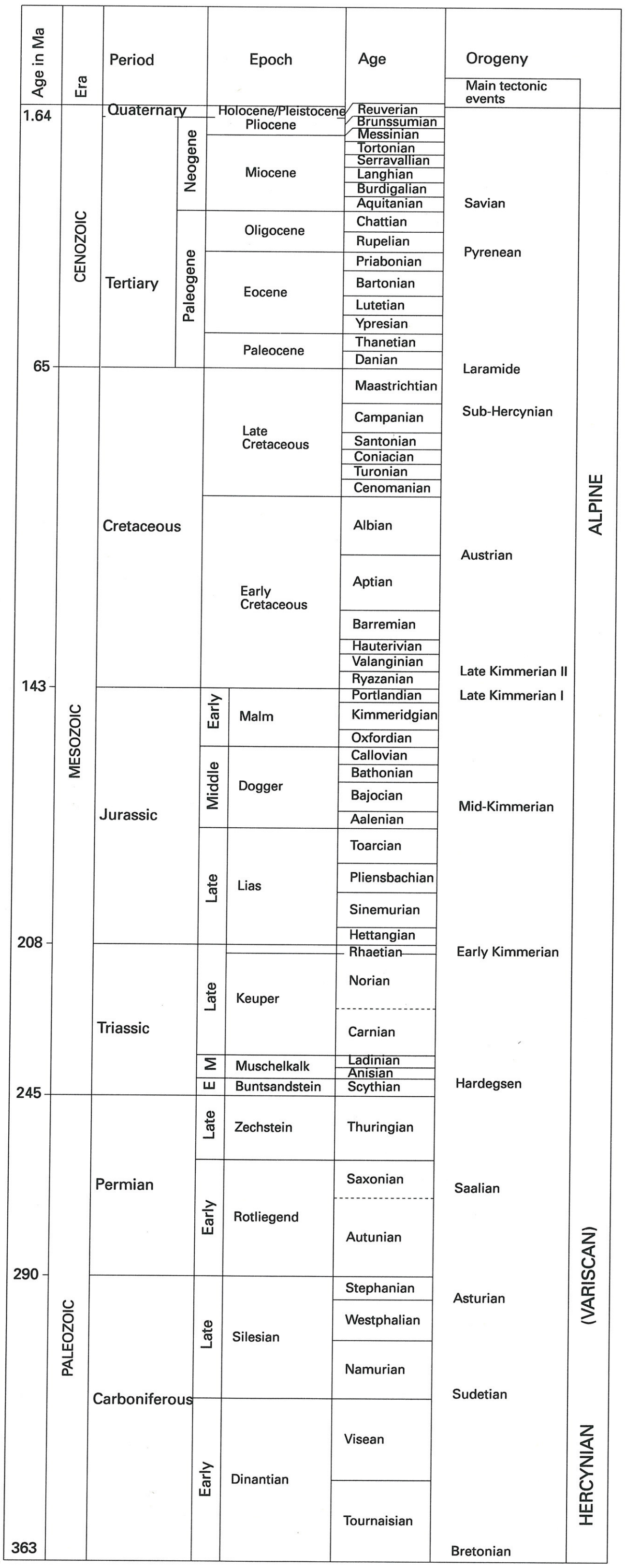


Figure 1.6 Geological timetable, as used in the explanation (after Harland et al., 1990). The tectonic phases which are referred to have also been indicated.

1.3.4 Geochemical research

Vitrinite analyses have been made on coal-bearing layers of the Limburg Group and the Upper Jurassic deposits as well as on the Coppershale of the Zechstein Group in order to reconstruct the burial history of the map sheet area. The procedures, the results of the analyses and the reconstructions are discussed in section 11.3.

1.4 Maps and sections

The results of the seismic mapping are shown in a series of depth maps, thickness maps and subcrop maps at a scale of 1:250.000. Depth maps have been plotted to the bases of the Upper Rotliegend Group, the Zechstein Group, the Lower Germanic Trias Group, the Altena Group, the 'Upper Jurassic' Group, the Rijnland Group, the Chalk Group and the North Sea Supergroup. As the base of the Lower Germanic Trias Group is not present everywhere in the map sheet area, also a depth map has been plotted of the top of the Zechstein Group.
The depth maps may show discrepancies between the seismically determined depth of a reflector and the comparable depth found in the borehole, owing to the conversion of time to depth with a regionally determined average velocity distribution. The depth maps have not been corrected for these discrepancies.

The thickness of each stratigraphic unit was obtained by subtracting the depth of the overlying unit from the depth of the base of each unit. An exception is the Upper Rotliegend map. Owing to the poor reflective quality of the base of the Rotliegend, this map was drawn by adding the thickness map of the Upper Rotliegend Group to the depth map of the base of the Zechstein Group. The thickness map of the Upper Rotliegend Group is based on well-log data and included in the explanation as a text figure (fig. 3.4). The depth and thickness maps of the Triassic (Maps 5 & 6) may, within the hatched area, include some thin erosion remains which although not seismically identifiable, nonetheless are occasionally found during drilling. The depth map of the base of the North Sea Supergroup can also be used as a thickness map of this unit.
Subcrop maps were plotted to illustrate the geology below the base of the Rijnland Group and below the base of the North Sea Supergroup. In particular these maps show the stratigraphic units below large unconformities and give an impression of the amount of erosion during the corresponding tectonic phases.

Finally, the structure and the location of the highs and the basins are shown in three NW-SE or NE-SW trending geological sections, selected in such a way as to link up with the sections of the adjacent map sheets.

1.5 Explanation

The explanation is intended to support the information in the various maps and to outline as completely as possible the geology of the map sheet area. The text consists of two parts.

The first part gives a lithostratigraphic description of the rocks within the map sheet area. The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members. Figure 1.5 is a lithostratigraphic diagram of all the deposits present in the map sheet area. Unless stated otherwise, the names and ages of the lithostratigraphic units correspond to the Stratigraphic Nomenclature of The Netherlands (NAM & RGD, 1980). The lithostratigraphic succession and development from old to young is explained in chapters 2 to 10 for each group in turn. Each chapter ends with an overview of the sedimentary development and the palaeogeography. The chapters are illustrated with facies maps, thickness sections and well logs. The basin modelling is supported by log correlations. Where relevant, structural-geological aspects are discussed together with the sedimentary developments. The Cenozoic sediments are treated in their entirety as the North Sea Supergroup which, moreover, is limited to the Tertiary. For the description of the Quaternary deposits, reference should therefore be made to the 'Explanation of the Geological map of The Netherlands, 1:50.000' ('Toelichting bij de Geologische kaart van Nederland, 1:50.000') of the Geological Survey of The Netherlands.

In the second part (chapter 11) the structural-geological framework and development of the main structural units in the map sheet area is discussed with the use of burial history curves. This is then followed by a description of the geological history of the map sheet area, thus placing a large number of events in a regional context.

1.6 Summary

The Texel-IJsselmeer High has had a strong influence on the sedimentary processes and the structural development of the study area, as appears both from the palaeogeography and from the structural-geological aspects.

1.6.1 Stratigraphic succession

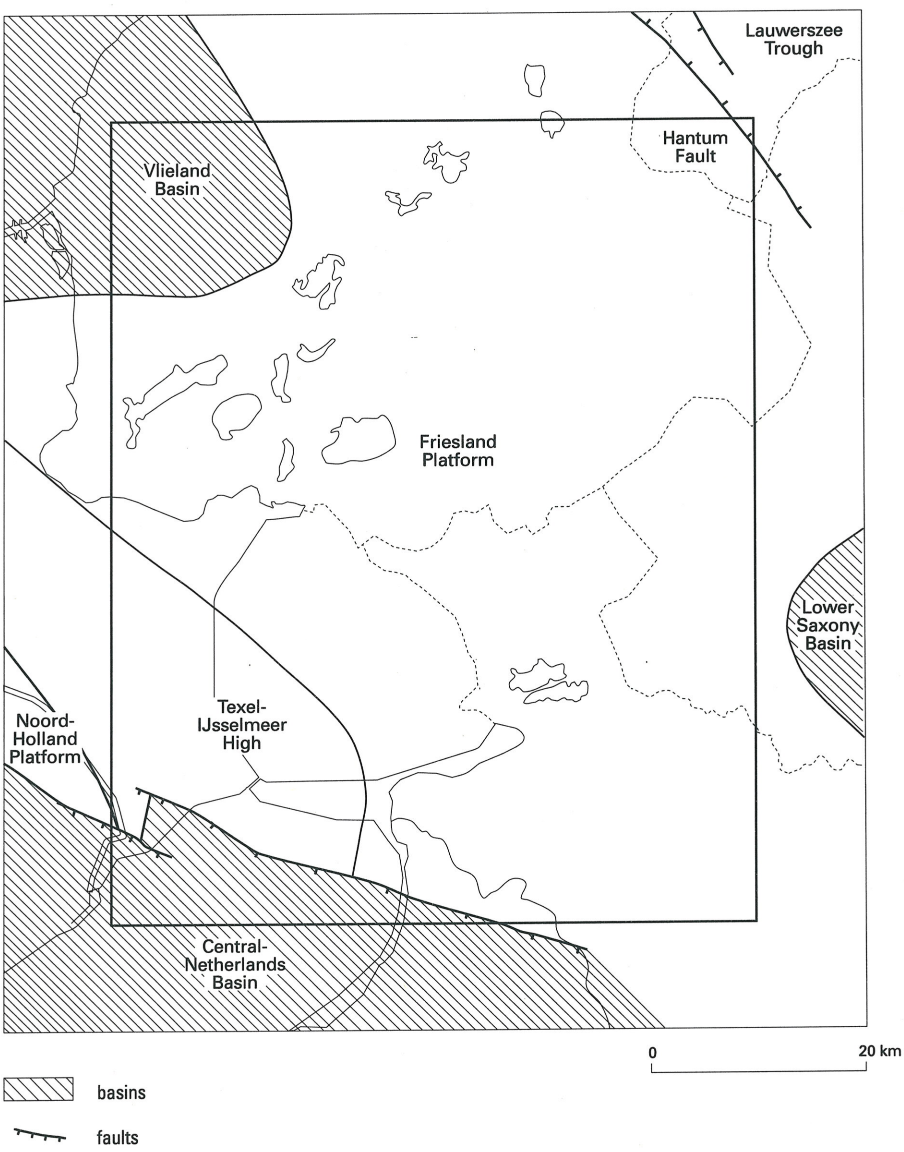
Sediments from the Carboniferous are clastics and were deposited by rivers and in freshwater lakes. The Upper Rotliegend Group was deposited during the Early Permian along the margin of a continental basin in fluvial, aeolian and lacustrine facies. During the Late Permian, the marine Zechstein Group was deposited in a number of evaporitic cycles. In the map sheet area, mainly thick successions containing limestone and anhydrite developed. Rock salt was deposited in the south and the north of the map sheet area, only in the basins. The Lower Germanic Trias Group is composed of clastics and is of a continental (lacustrine and fluvial) depositional environmental origin. The lithological composition of the Upper Germanic Trias Group (claystones, marls, evaporites and limestones) increasingly reflects a marine depositional environment which, in the map sheet area, persisted into the Early Jurassic. The Keuper reflects a depositional environment with a high clastic influx. Owing to later erosion, hardly any deposits of the Upper Germanic Trias Group and the Altena (Lower Jurassic) Group have been maintained. No Middle Jurassic deposits at all are found in the map sheet area. Upper Jurassic deposits are found in the Vlieland, the Central Netherlands and the Lower Saxony Basins (fig. 7.1). These continental sediments are mainly composed of sandy claystones and marls, but also comprise coal seams and limestone beds. Marine sediments were deposited throughout the Cretaceous. They are divided into the clastic sediments of the Rijnland Group (Lower Cretaceous) and the open marine limestones of the Chalk Group (Upper Cretaceous). The sediments of the North Sea Supergroup were deposited in the Cenozoic and are composed of clastic material deposited partly in marine and partly in continental environmental conditions.

1.6.2 Structural elements

The main structural elements determining the geological history of the map sheet area are the Central Netherlands Basin, the Vlieland Basin and the Lower Saxony Basin, the Texel-IJsselmeer High, the Friesland Platform and the Hantum Fault (fig. 1.7). The elements were repeatedly active, although in a diversity of manifestations.

The *Central Netherlands Basin* is defined by the presence of Jurassic sediments and characterised by the absence of Upper Cretaceous deposits. The contact of this basin with the more northerly Texel-IJsselmeer High is defined by normal faults with an offset of up to 1600 m. In response to inversion movements, the Central Netherlands Basin was strongly uplifted and consequently strongly eroded. The *Vlieland Basin* and the *Lower Saxony Basin* are defined by the presence of Upper Jurassic sediments. The rate of subsidence of both these basins with respect to the Texel-

Figure 1.7 Basin structures and structural elements prominent in the geological development within the map sheet area.



IJsselmeer High and the Friesland Platform was great during the Late Jurassic and the Early Cretaceous.

The aforementioned basins are separated from each other by the *Texel-IJsselmeer High* and the *Friesland Platform*. The Texel-IJsselmeer High is characterised by the absence of sediments of Late Permian up to and including Early Cretaceous (Aptian) age. The southern margin of the Texel-IJsselmeer High, in contrast to the northern margin, is defined by faults. The Friesland Platform lies immediately to the north of the Texel-IJsselmeer High and is characterised by the presence of Permian and Lower Cretaceous sediments and the (partial) absence of Triassic and Jurassic sediments. Zechstein salt was not deposited on the Texel-IJsselmeer High, in contrast to the Vlieland Basin, the Lower Saxony Basin and the Central Netherlands Basin.

In the northeast of the map sheet area, the Friesland Platform is delimited by the southern prolongation of the *Hantum Fault*. This old fracture zone, probably of Variscan age, reflects itself in this mapped area in graben structures in the superimposed Tertiary. During the Miocene, the *Zuiderzee Low* developed in the southwest of the map sheet area (fig. 11.1).

1.6.3 Structural geology

Erosion periods associated with tectonic phases gave rise to a number of hiatuses in the stratigraphic successions. The names of these tectonic phases and the related orogeny are classified in figure 1.6. The size of the hiatuses and their place in the lithostratigraphic column reflect the course of structural development within the map sheet area (fig. 1.5).

The description of the geological history is based on the differentiated structural units within the map sheet area (fig. 1.7). The Texel-IJsselmeer High occupies a prominent position in a structural-geological sense. Sedimentation in the map sheet area is strongly affected by the tectonic development of the Texel-IJsselmeer High. The directions of faults generated during the different tectonic phases, as well as the location of the basin structures are strongly influenced by the Texel-IJsselmeer High.

The figures in chapter 11 give a clear overview of the structural geology in the map sheet area. Fault tendencies vary from N-S, NW-SE to E-W. The Variscan faults in the map sheet area are WNW-ESE trending. The Kimmerian tendency varies in strike from E-W to NNW-SSE. The axes of the basin structures surrounding the map sheet area are analogous with the previously mentioned directions (approx. NW-SE). The compressive, Sub-Hercynian and Laramide fault directions in the south of the map sheet area have a NW-SE trend and a comparatively large offset by reverse faulting. In the northeast and the east of the map sheet area, Tertiary NW-SE to NNE-SSW trending normal faults occur along old basement faults and on the flanks of salt pillows.

During the Permian, the Texel-IJsselmeer High was a major factor in the sedimentological processes and the thickness development of the deposits. A large part of the Triassic sediments deposited in the map sheet area was subsequently removed by the Hardegsen erosive phase. This area, the present Texel-IJsselmeer High, was elevated above the erosion base during most of the Kimmerian phase, causing erosion of the sediments of the Altena Group down to, and including, the Limburg Group. The Permian, Triassic and Lower Jurassic sediments are assumed to have been deposited on the Texel-IJsselmeer High as a condensed sequence. During the Late Jurassic the Friesland Platform also developed, after which Lower Cretaceous sediments were deposited.

Along the northern, eastern and southern flanks of the Texel-IJsselmeer High, the Vlieland Basin, the Lower Saxony Basin and the Central Netherlands Basins, respectively, developed during the Late Jurassic. This phase of basin development was generated by a large-scale extensional (Kimmerian) stress regime, which prevailed throughout Northwestern Europe. As a result of this tectonic phase the sediments of the 'Upper Jurassic' Group and the basal part of the Rijnland Group were restricted to the aforementioned basins.

During Sub-Hercynian and Laramide inversion tectonics the basins became uplifted at the end of the Cretaceous, thus causing the erosion of all Cretaceous and a part of the Jurassic deposits in the Central Netherlands Basin (Map 17). These regional compressive tectonics reactivated old faults and weakness zones causing reverse faulting. In the Vlieland Basin the inversion tectonics were much less pronounced than in the Central Netherlands Basin.

2 Limburg Group

2.1 Stratigraphy

The sediments of the Limburg Group form the oldest deposits drilled within the map sheet area and are, in this map sheet area, subdivided into the Coal Measures or Productive Measures and the Tubbergen Sandstone Formation. The Limburg Group is present throughout the map sheet area. The lithology consists mainly of irregularly alternating layers of claystones, sandstones, siltstones and coal.

The sediments of the Limburg Group described here were deposited during the Late Carboniferous (Westphalian A, B and C). The stratigraphic division of the Carboniferous is for the most part based on palynological datings, correlation of which can be performed from a number of intraformational marine bands which can be distinguished by means of well logging. The Sarnsbank band separates the Namurian C from the Westphalian A, the Wasserfall band the Early Westphalian A from the Late Westphalian A, the Catharina band the Westphalian A from the Westphalian B while the Aegir band indicates the boundary between the Westphalian B and C (Thiadens, 1963; fig. 2.1).

The Limburg Group is unconformably overlain in the majority of the extent of the map sheet area by the Upper Rotliegend Group of Early Permian age. On the Texel-IJsselmeer High the Limburg Group is overlain unconformably by the Rijnland Group (Map 16). In the southeast of the map sheet area, where the Upper Rotliegend Group is absent, Carboniferous sediments are overlain unconformably by the Zechstein Group. A map of the base of the Limburg Group has not been drawn because this level is not, or scarcely, seismically recordable owing to the great depth and because of insufficient well data.

In the map sheet area only a small number of the available wells reaches the Carboniferous. With the exception of Nagele-1, Steenwijkerwold-1 and Dwingelo-1, wells penetrate the Limburg Group only by some tens of metres. The sediments of the Westphalian A in the map sheet area lie on the continental shale series of the Namurian (Ziegler, 1990). In the south of The Netherlands the base of the Limburg Group has been drawn at the top of the Visé limestones which were deposited during the Dinantian (Bless et al., 1983).

The top of the Carboniferous in the map sheet area in previously published data (Van Wijhe & Bless, 1974; Van Wijhe et al., 1980; Van Wijhe, 1987a) is dated Westphalian A, B or C. From a number of wells, these ages have been confirmed by our own research. Figure 2.2 indicates the age of the top of the Carboniferous in the map sheet area and the figure also shows a structural concept that will be discussed in section 2.3.

Locally, igneous rocks occur in the Carboniferous sediments. These will be discussed in section 2.2. The stratigraphy of the oldest part of the Westphalian is in this explanation illustrated by the wells Nagele-1 and Steenwijkerwold-1 (fig. 2.1; RGD, 1992a).

2.1.1 Coal Measures

The Coal Measures in the map sheet area consist of predominantly dark grey to black silty shales, irregularly alternating with reddish-brown to grey siltstone and sandstone beds, and lustrous black coal seams. The claystones contain mica and pyrite. Throughout the Coal Measures sequence, sandy systems exhibit coarsening-up as well as fining-up, while the highly bituminous, argillaceous lithology predominates (fig. 2.1). The dark shales contain bands of fine sand, silt, mica and pyrite. The thicknesses of the siltstones and silty shales vary from a few metres to some tens of metres. The coal streaks achieve a thickness of one metre at the most. The coal is black, hard and pyritic.

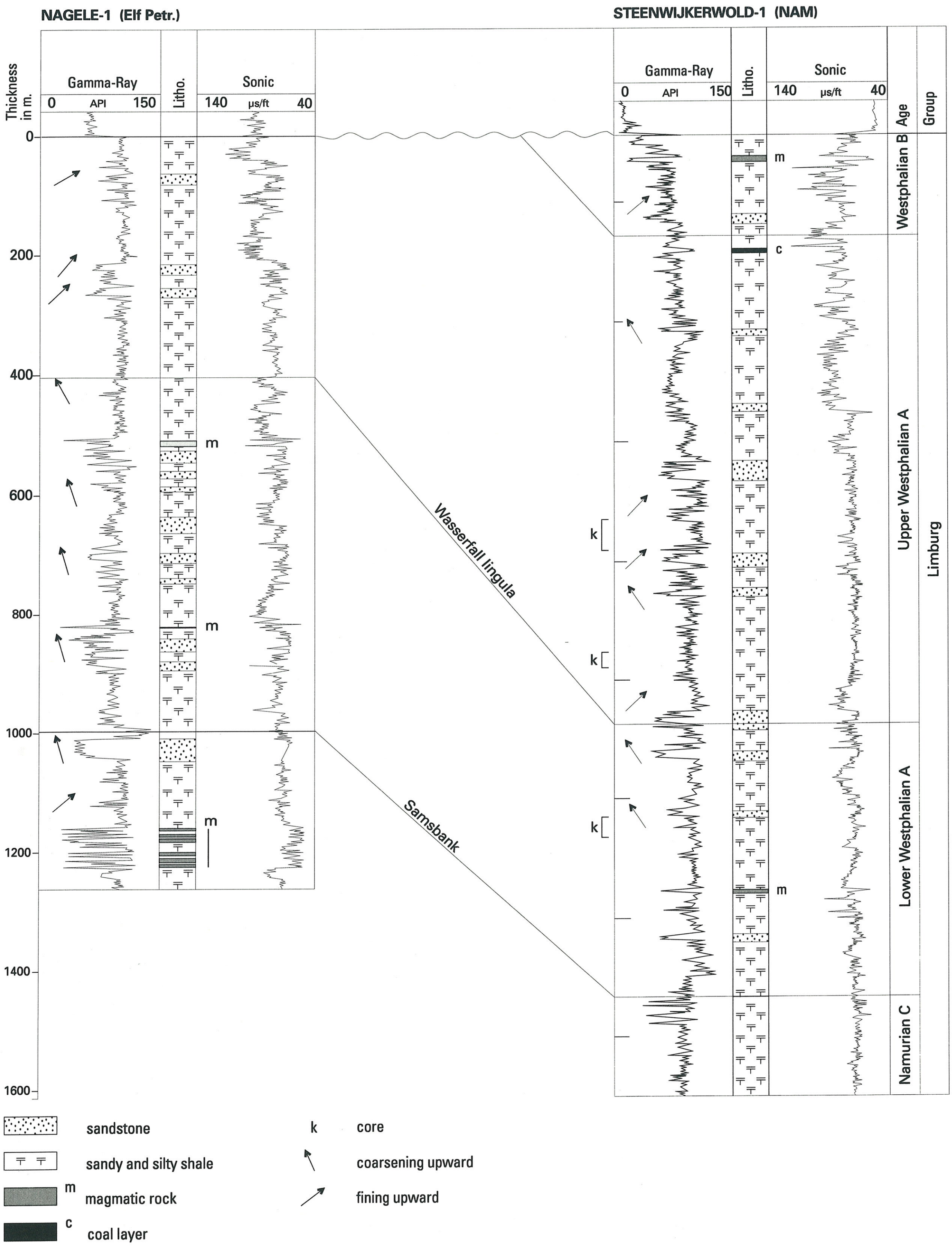
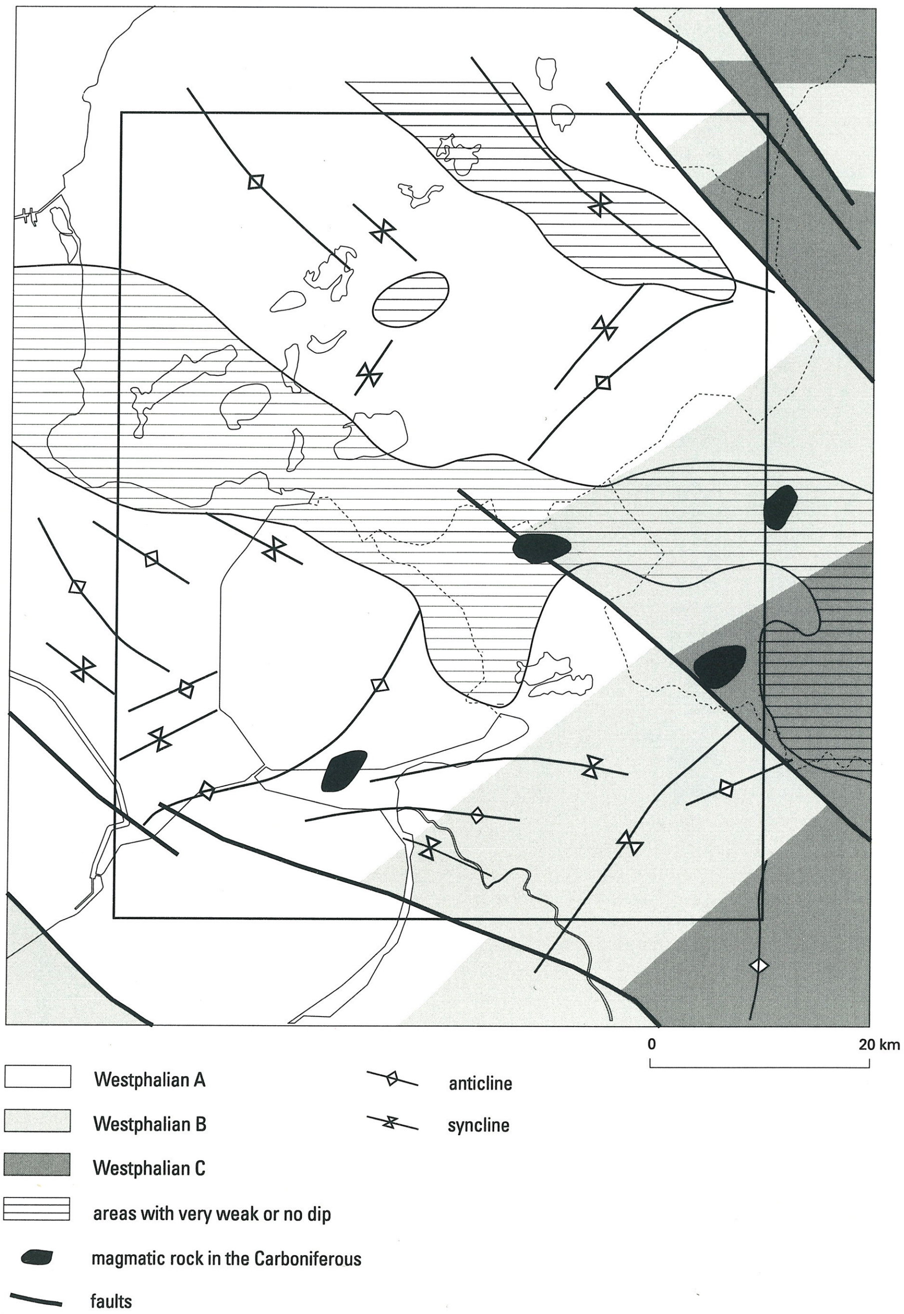


Figure 2.1 Composition of the Limburg Group and correlation of the Nagele-1 and Steenwijkerwold-1 wells. In these wells, the low gamma-ray reading and a high sonic velocity reflect the presence of magmatic rocks. The Carboniferous in the Nagele-1 well is overlain by claystones of the Holland Formation and by the Slochteren Formation in the Steenwijkerwold-1 well.

The Coal Measures in most of the map sheet area are overlain unconformably either by the Upper Rotliegend Group or, in the south east of the map sheet where the Upper Rotliegend Group has not been deposited, by Zechstein deposits. Where these coal-bearing shales of Carboniferous age are overlain by the Tubbergen Sandstone Formation, as is the case on the eastern edge of the map sheet area, these are referred to as the Productive Measures (NAM & RGD, 1980).

Figure 2.2 Subcrop geological map of the deposits below the Saalian unconformity and Variscan fold axes. The map shows antiformal and synformal structures and a non-folded platform area. This area in the north of the map sheet area is very gently folded. The occurrence of magmatic rocks on the map is based on information derived from wells.



The sediments of the Coal Measures are of Westphalian A/B age and are present throughout the map sheet area (fig. 2.2). In the Nagele-1 well the base of the Westphalian A has been reached. The thickness of the Westphalian A in this well is 850 m. In the Steenwijkerwold-1 well the Westphalian A has a minimum thickness of 1000 m (fig. 2.1). The Nagele-1 and Steenwijkerwold-1 wells have been correlated by biostratigraphical dating and by the abovementioned marine bands, with the Westphalian A being subdivided into Lower and Upper Westphalian A. Both the wells Nagele-1 and Steenwijkerwold-1 have reached the base of Westphalian A.

2.1.2 Tubbergen Sandstone Formation

The Tubbergen Sandstone Formation consists of alternating sandstones, shales and coal streaks. Isolated sandstone beds reach a thickness of up to 25 m and are separated from each other by shale layers a few metres thick. Both the separate sandstone beds and the stacked sandstone beds themselves are fining-upwards (fig. 2.1). In comparison with the Productive Measures, Tubbergen Sandstone Formation displays a sandier lithology. The Tubbergen Sandstone Formation was deposited during the Westphalian C.

The sediments of the Tubbergen Sandstone Formation rest upon those of the Productive Measures. In the opinion of Van Wijhe & Bless (1974), the contact is probably unconformable but this has not as yet been demonstrated. The formation is found only in the extreme northeast and in the south-eastern part of the map sheet area (fig. 2.2) where it is overlain by a thick sand layer of the Slochteren Formation.

The maximum thickness of this formation found in boreholes in the map sheet area amounts to ca. 100 m. The Tubbergen Sandstone Formation in the De Wijk gas field (fig. 1.2) proved to be gas-bearing (Gdula, 1983).

2.2 Igneous rocks in the Carboniferous.

In the map sheet area a relatively large number of igneous rocks has been drilled in the Carboniferous. As well as typical coarse-grained olivine gabbros (Wanneperveen-1) and quartz-bearing gabbros (Dwingelo-2 and De Wijk-7) basalt has been found (Steenwijkerwold-1). All the magmatic rocks in map sheet V are situated in sedimentary series of Westphalian age. From well logging, magmatic rocks can be recognised by the low value on the gamma-ray log and by the characteristic, high acoustic velocity.

The De Wijk-7 well has penetrated two gabbroic bodies. The age of the gabbro at a depth of 2684 to 2691 m is 289 ± 7 Ma (NAM 1991, pers comm.) and is of the same age as the Saalian phase of the Variscan orogeny (Stephanian-Autunian; geological time scale: Harland et al., 1990). Another body, at a depth of 2443 to 2486 m, is an olivine gabbro with a determined age of 155 ± 4 Ma (NAM 1991, pers. comm.). This coincides with the Late Kimmerian phase. During this phase, with the occurrence of local extensional tectonics, the Vlieland Basin and the Lower Saxony Basin were formed. Plutonism regularly occurs during extensional tectonic processes and therefore reflects this phase.

The Steenwijkerwold-1 well has penetrated a basalt, at a depth of 1937.50 - 1944 m, with identified erosion structures in cores. The country rocks are of Upper Westphalian A age (fig. 2.1). The basalt has a dated age of 291 ± 8 Ma (NAM 1991, pers. comm.) and corresponds with the age of the gabbro in De Wijk-7. The Dwingelo-2 well has encountered an olivine gabbro (Eigenfeld, 1986) at a depth of 3753 - 3792.20 m age dated at 322 ± 15 Ma (NAM 1991, pers. comm.).

The intrusive rocks of the Wanneperveen-1 well, including basalts, dolerites and olivine gabbros, have been studied by Kimpe (1953). All the intrusives in this well have been hydrothermally carbonitised, albitised and serpentinitised. The sediments, intruded by the aforementioned rocks, represent the Westphalian A and are contact- metamorphically affected. The gabbroic body (appendix I; photo 1) encountered in the deepest part of this well (2064 - 2069.5 m) has not been dated. The gabbros are probably part of a laccolith whose base in the well has not been reached (Kimpe, 1953).

In the Nagele-1 well a number of intrusives are present which have not been dated either. The minor thickness of these doleritic rocks (basalt with green and brown constituents) and their numerous occurrences (fig. 2.1) suggest the configuration of a dolerite cluster.

The gabbro of De Wijk-7 and the basalt of Steenwijkerwold-1 both have been dated to approx. 290 Ma. These datings suggest a magmatically active period in this area during the Saalian phase of the Variscan orogeny (Stephanian-Autunian) in the map sheet area. The basaltic body in De Wijk-7 enclosed in sediments of the Late Westphalian A points to extrusive activity at 310 Ma (boundary Westphalian A / Westphalian B).

According to Kimpe (1953) and Eigenfeld (1986) the gabbros, dolerites and basalts in the northeast of The Netherlands have a clear genetic relation because the mineralogical variation of the magmatic bodies is not extensive. In the literature, extrusive and intrusive activity in Northwest Europe is assumed by Lorenz & Nicholls (1976, 1984) and Francis (1988) also to have occurred during the Stephanian-Autunian (Saalian tectonic phase). Eckhardt (1979) found that the sub-alkaline and mafic rocks predominate near the Variscan deformation front. Magmatic activity is then related to Variscan strike-slip tectonics.

2.3 Sedimentary development and palaeogeography

The Westphalian A sequence of the Nagele-1 well was investigated for different log facies types and a subdivision into two sequences was decided on. The Westphalian A exhibits shales and sandstones from the base up to 2130 m, in which the often coarsening-upward sandstone beds reach a thickness of 20 m (fig. 2.1). These sandstone beds represent prograding deltaic systems which probably flowed into a lake. This depositional condition was present in this particular area during the Early Westphalian A. The interval from 2130 to 1614 m of the Nagele-1 well consists of fining-upward, 20 m thick sandstone beds (fig. 2.1). The interval mostly consists of shales which represent overbank deposits. These sediments were deposited during the late Westphalian A.

The Coal Measures in the map sheet area were deposited in a sequence of varying fluvial, deltaic and lacustrine environments, with thin marine intercalations. These sediments were deposited in a very flat landscape lying just above sea level. The great extent of thin, marine intercalated bands explains the flat palaeo-landscape. A small rise in sea level was sufficient for large areas to be inundated. The argillaceous character of the sediments and the presence of fining-upward sands, interpreted as meandering river deposits, are indicative of a very flat landscape. Peat was formed in lakes and marshes with abundant plant growth and a frequently stagnating discharge of surface water. Coal was eventually produced by coalification of the peat at high temperatures and pressure consequent to its considerable burial depth.

The sands of the Tubbergen Sandstone were deposited by meandering rivers, while the argillaceous sediments were deposited behind the natural levee. Breaches in the embankment of the rivers resulted in the formation of sandy crevasse splay deposits. Peat formation occurred both in the marshes and in the cut-off channels.

Mapping of the age of the top of the Limburg Group, and of the angle of dip of the Limburg Group compared to the angle of dip of the base of the Rotliegend Group (= Variscan inclination), has shown that folding during a Late Variscan tectonic phase had a great influence on the map sheet area. Faults on the available seismic records can rarely be mapped. Correlation of these faults is not possible because of the lateral discontinuous tracking of the reflectors. Two clearly different Variscan directions of the fold axis in the map sheet area can be distinguished. (fig. 2.2). Fold axes with a NW-SE tendency (and in the south of the map sheet area E-W) are related to the Asturian phase of the Variscan orogeny. The principle stress direction $\sigma 1$ then lies N-S, normal to the direction of the fold axis). The mapped fold axes, SW to NE trending, are probably younger, but still Variscan (Saalian) in age, and overprint the NW - SE (E-W) trend (fig. 2.2).

3 Upper Rotliegend Group

3.1 Stratigraphy

In the map sheet area the Upper Rotliegend Group, Early Permian, comprises reddish-brown sandstones, claystones and conglomerates. The sediments deposited under continental conditions, often have a characteristic red colouring which is caused by a thin haematite coating on quartz grains. The Upper Rotliegend Group in the map sheet area consists predominantly of sediments of the Slochteren Sandstone Formation.

In the north of the map sheet area the uppermost part of the Slochteren Sandstone Formation grades laterally into the Silverpit Claystone Formation (fig. 3.1). The Ameland Claystone Member of the Silverpit Formation is insufficiently present in the map sheet area to subdivide the Slochteren Sandstone Formation in this area into a Lower and Upper Slochteren Sandstone Member.

The Upper Rotliegend Group, for the major part composed of the Slochteren Sandstone Formation, is found virtually throughout the map sheet area, except on the Texel-IJsselmeer High and in the extreme southeast of the map sheet area (Map 1 & fig. 3.2). The sediments of the Upper Rotliegend Group lie unconformably on the Limburg Group. The groups are separated by the Saalian unconformity. The sediments of the Upper Rotliegend Group are overlain conformably by the evaporitic series of the Zechstein member. On the northeastern flank of the Texel-IJsselmeer High, the Upper Rotliegend Group is unconformably overlain by deposits of the Rijnland Group (Map 16).

The thickness of the Upper Rotliegend Group decreases rapidly towards the southeast (fig. 3.3 & 3.4). The number of intercalated conglomerate beds increases at the same rate in the aforementioned direction, which is indicative of the existence of a basin margin in the southeast (fig. 3.2). The southeastern part of the map sheet area illustrates the absence of the Upper Rotliegend, indicative of an area situated above basin level.

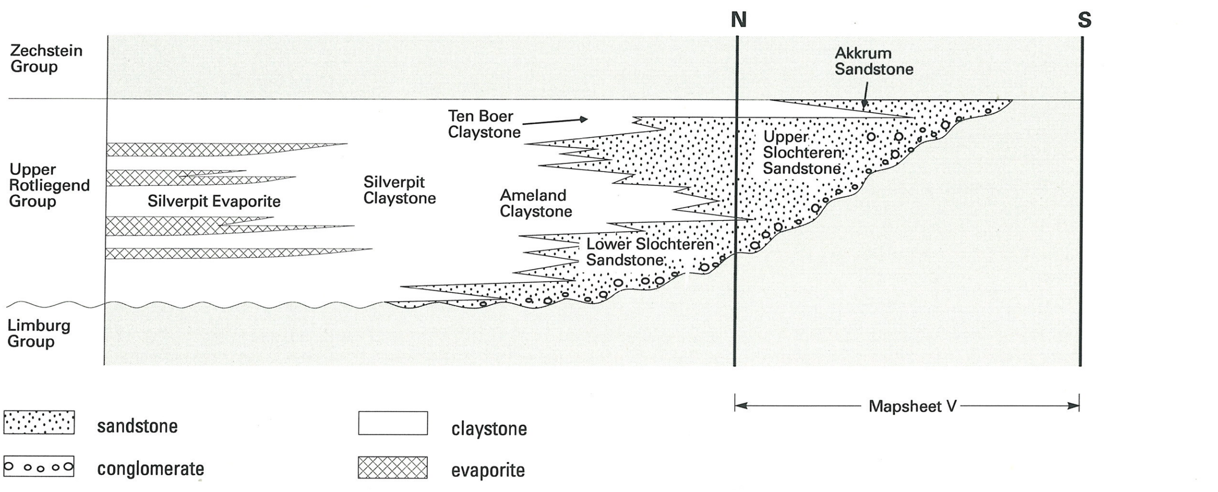


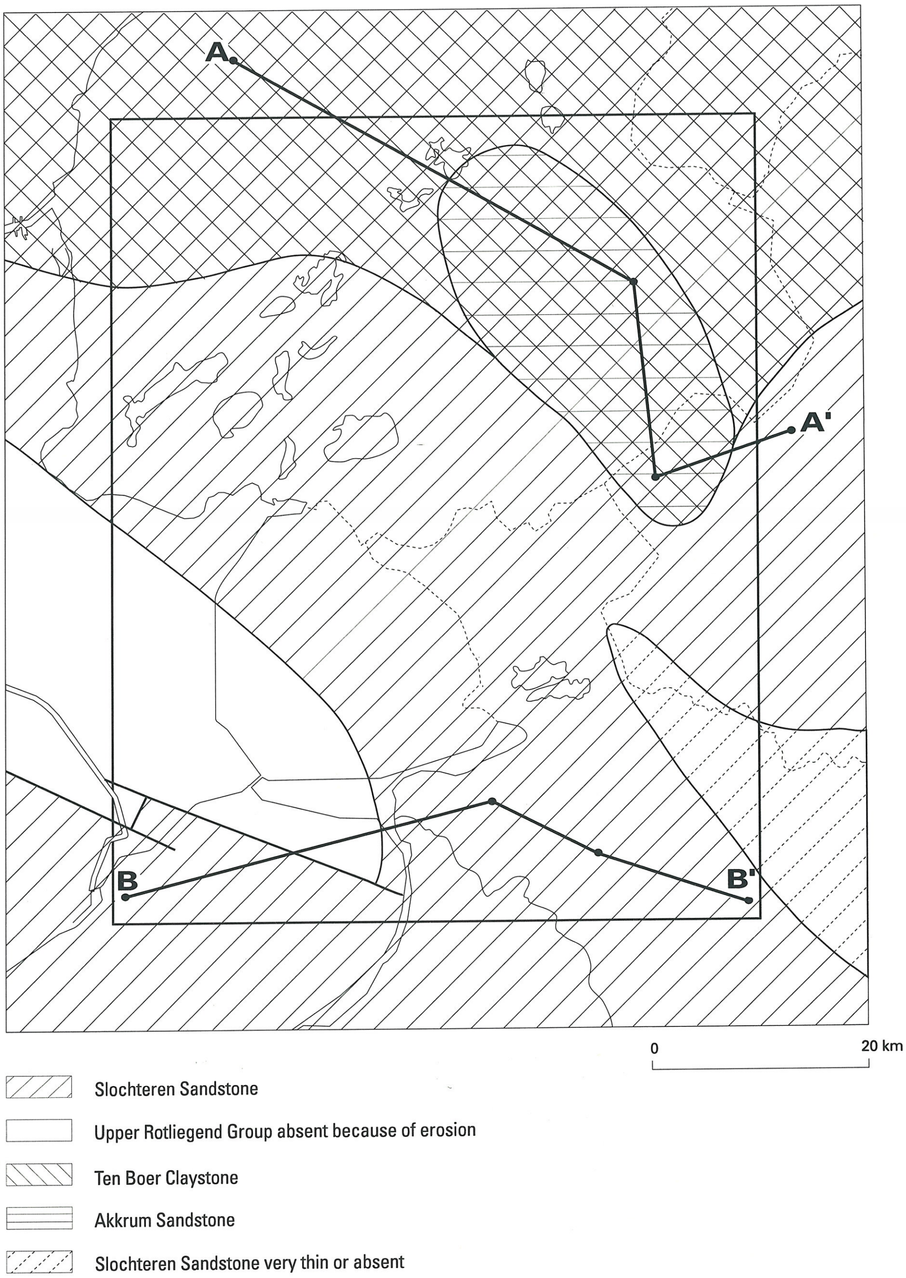
Figure 3.1 Schematised stratigraphic diagram of the Upper Rotliegend Group within and north of the map sheet area.

The central western part of the map sheet area was relatively shallow, resulting in less sediment being accumulated than in the area to the north and south. This shallow area was located at the place where the Texel-IJsselmeer High would later arise. Most of the sedimentation occurred in the Central Netherlands Basin and the area to the north of the Texel-IJsselmeer High.

3.1.1 Slochteren Sandstone Formation

The Slochteren Sandstone Formation in the map sheet area is composed of the Slochteren Sandstone Member and the Akkrum Sandstone Member, separated by the Ten Boer Claystone

Figure 3.2 The extent of the various lithological successions of the Upper Rotliegend Group in the map sheet area and the location of the stratigraphic correlation sections A-A' and B-B'. The Upper Rotliegend does not occur on the Texel-IJsselmeer High. In the bottom right hand corner, in the southeast of the map sheet area, the Upper Rotliegend is absent. The Akkrum Sandstone only occurs in the northeast of the map sheet area.



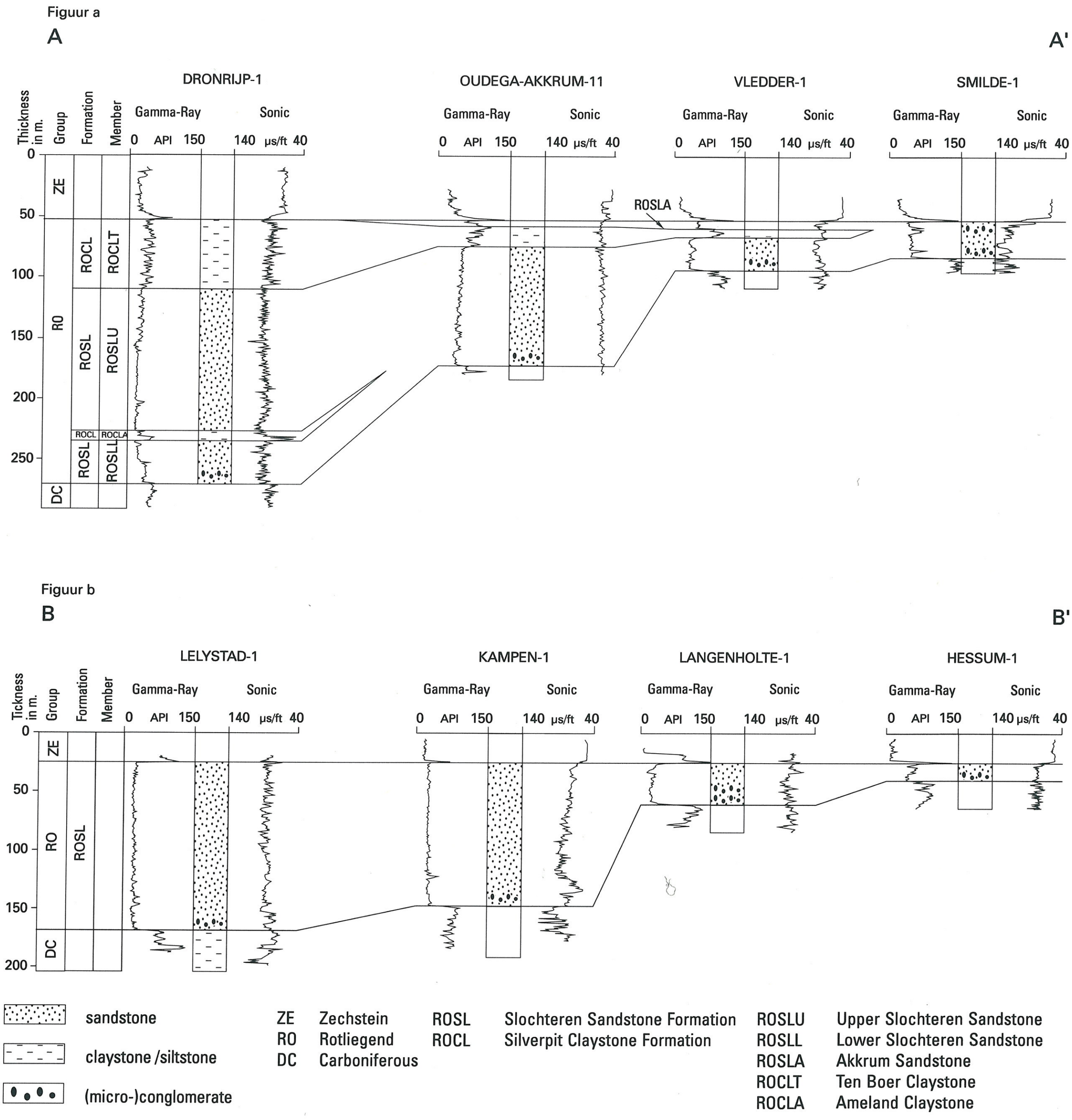


Figure 3.3 Stratigraphic correlation sections of the Upper Rotliegend Group with the base of the Zechstein Group as the level of reference. The location of the sections is indicated in figure 3.2. All the Rotliegend sediments in the wells in this figure rest upon sediments of the Limburg Group and are, in their turn, overlain by the sediments of the Zechstein Group.

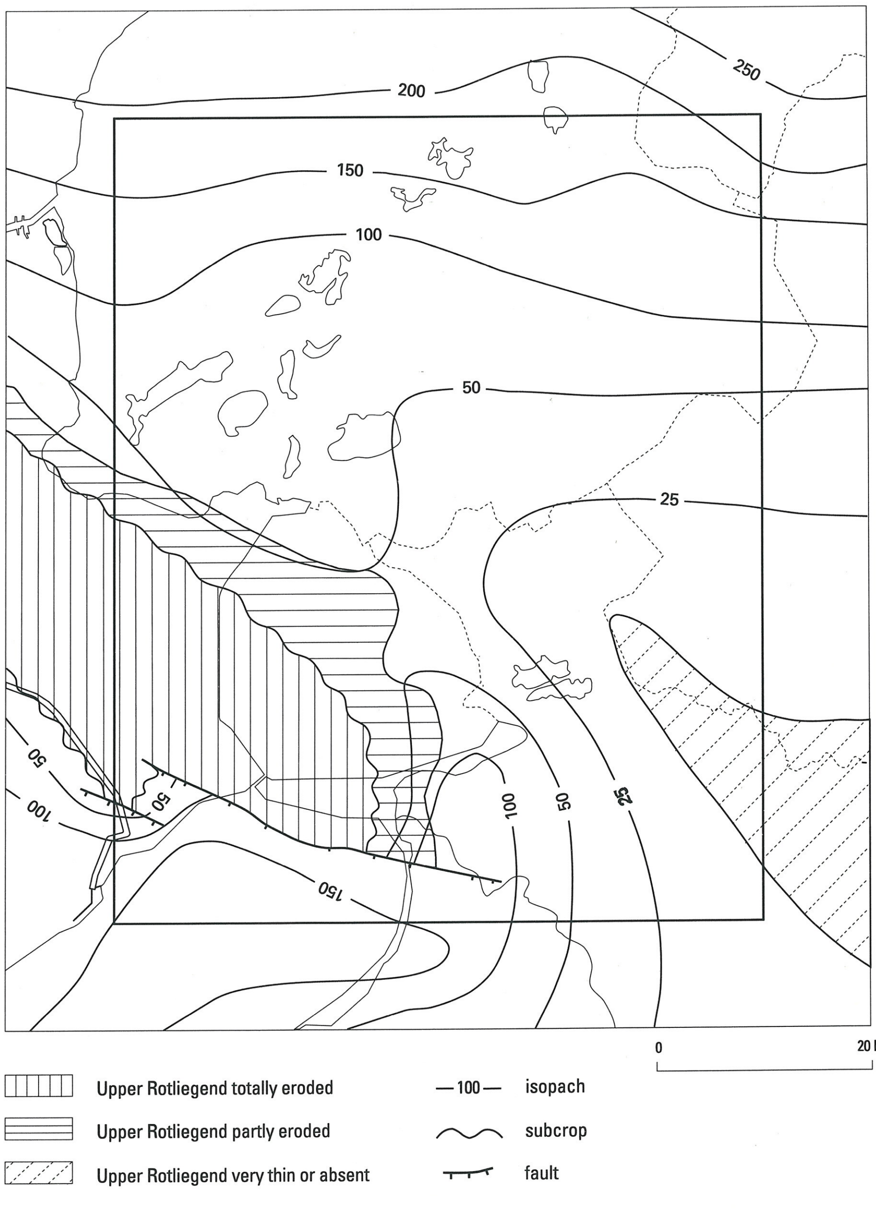
a Section A-A' shows the deepening of the Southern Permian Basin north of the Texel-IJsselmeer High and the stratigraphic position of the Akkrum Sandstone Member.

b Section B-B' shows the depression in the subbasin south of the Texel-IJsselmeer High (Central Netherlands Basin) and the absence of argillaceous successions occurring north of the Texel-IJsselmeer High (Ten Boer and Ameland Claystone members). The section crosses the Texel-IJsselmeer High, where the sediments of the Upper Rotliegend Group are not present, owing to Late Kimmerian erosion.

Member, a southern pinch out of the Silverpit Formation (fig. 3.1). The Akkrum Sandstone Member has not been described by NAM & RGD (1980) and will therefore now be treated as an informal member.

The Slochteren Sandstone Formation consists mainly of sandstones in which conglomerates may occur. The formation thickness reaches a maximum of 150 m in the north and the southwest of the map sheet area (fig. 3.3 & 3.4). The sandstones are composed of reddish-brown coloured, moderately to well sorted, coarse to fine quartz grains, subrounded to well rounded. Small quantities of shale fragments and mica also occur, which decrease towards the centre of the Central Netherlands Basin as well as to the north. Thin reddish-brown silty claystones are regularly interbedded. The red staining in the uppermost ten metres mostly grades gradually over into beige

Figure 3.4 Thickness map of the Upper Rotliegend Group. This figure indicates where the Upper Rotliegend Group was deposited and where the sediments were entirely eroded.



and white. Locally, the sandstones are strongly cemented with anhydrite (appendix I; photo 2). Whole pores have been filled with the authigenic anhydrite during a late-diagenetic phase.

The conglomerates of the Slochteren Sandstone Formation are found both at the base of the formation and interbedded in the sandy lithology. The basal conglomerate is no thicker than 10 metres and consists of components of Carboniferous deposits, including fragments of black and red shales and fine-grained grey sandstones. The interbedded conglomerates consist of well rounded to poorly rounded quartz in a sandy matrix. The size of the pebbles is a few centimetres at the most. Traces of coal and mica have also been found. Sandstone with less well rounded components occurs in alluvial fans in the southeast along the basin margin.

In the area between the wells Diever-1 and Oudega-Akkrum-1 there is a further deposit of a light grey, relatively coarsely grained sandstone on top of the southerly extending tongue of the Ten Boer Claystone which is also classed as part of the Slochteren Sandstone Formation and is here referred to informally as the *Akkrum Sandstone Member.* This member is 7 m thick in the well Vledder-1. The moderately rounded grains of the sandstones vary from coarse to fine (Wentworth scale; Scholle, 1979). The contact with the underlying Ten Boer Claystone is very sharp. The sandstone member only occurs locally in the northeast of the map sheet area (fig. 3.2 & 3.3a). Towards the north, the east and the west this sandstone member pinches out completely.

3.1.2 Silverpit Claystone Formation

The Silverpit Claystone Formation is the distal equivalent of the Slochteren Sandstone Formation. In the transitional area with the Slochteren Sandstone Formation, the Silverpit Formation can be divided into three members, namely, from base to top, the Hollum Claystone, the Ameland Claystone and the Ten Boer Claystone (NAM & RGD, 1980). In the map sheet area there are no deposits of the Hollum and the Ameland Claystone Members recorded.

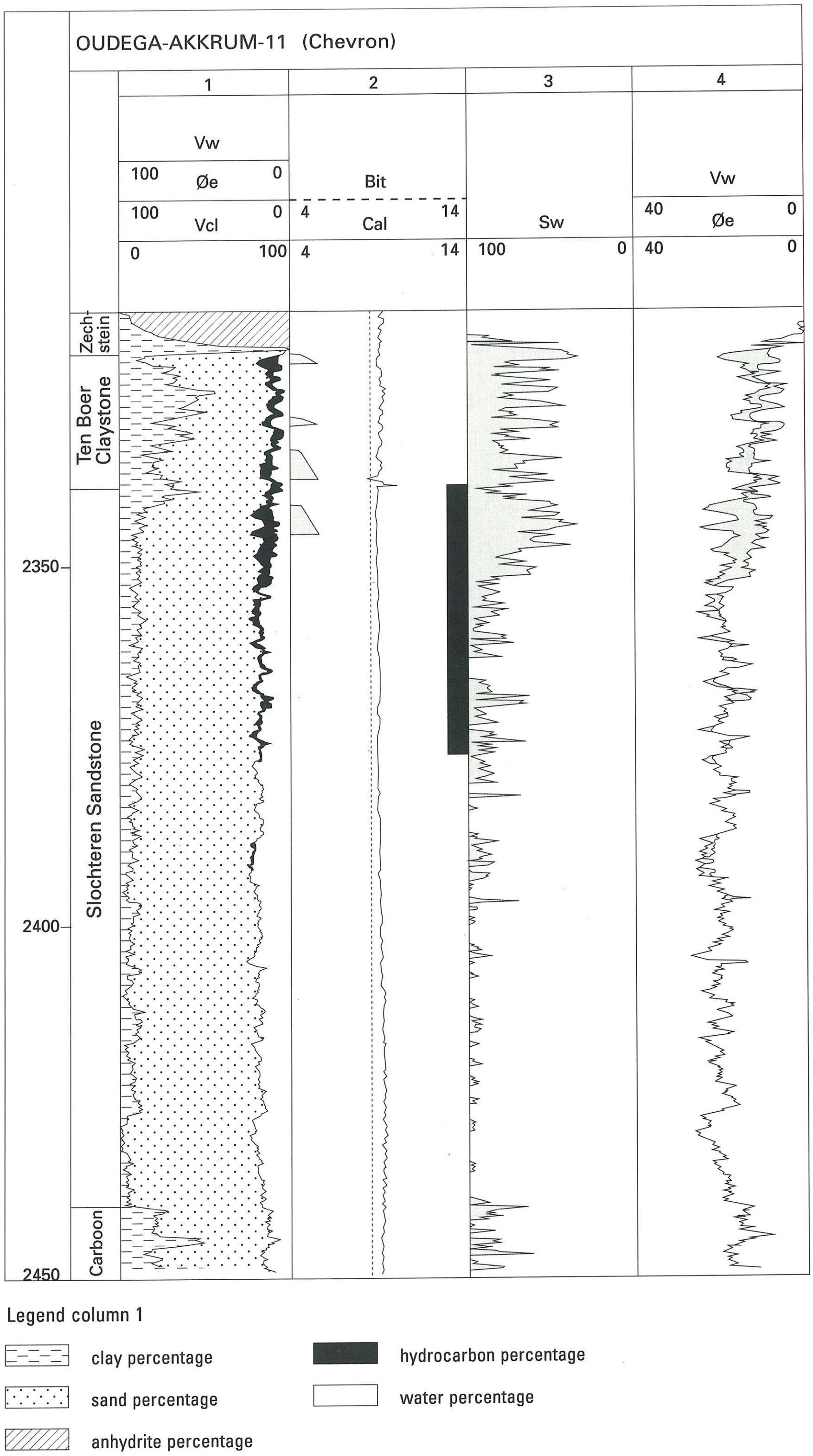
The *Ten Boer Claystone Member* is the uppermost clay tongue of the Silverpit Formation (fig. 3.1) and consists mainly of silty, reddish-brown claystone and siltstone. There are regular occurrences of intercalated fine-grained and light coloured sandstone beds several metres thick. The siltstones are frequently cemented with anhydrite and calcite. In the map sheet area, the member achieves a maximum thickness of 50 m and is only present in the northern part. The southern areal extent has been indicated in figure 3.2.
In a southerly direction, the Ten Boer Claystone grades laterally into the sandstones of the Slochteren Formation (fig. 3.1 & 3.3a) and is overlain conformably by the Akkrum Sandstone or by the Coppershale of the Zechstein Group.

3.2 Sedimentary development and palaeogeography

The Early Permian sandstones and conglomerates of the Upper Rotliegend Group are continental sediments, deposited under (semi-) arid conditions in the intra-cratonic Southern Permian Basin. The claystone is the distal equivalent of the sandstones and was deposited in a lake located to a large extent to the north of the map sheet area (fig. 11.9).

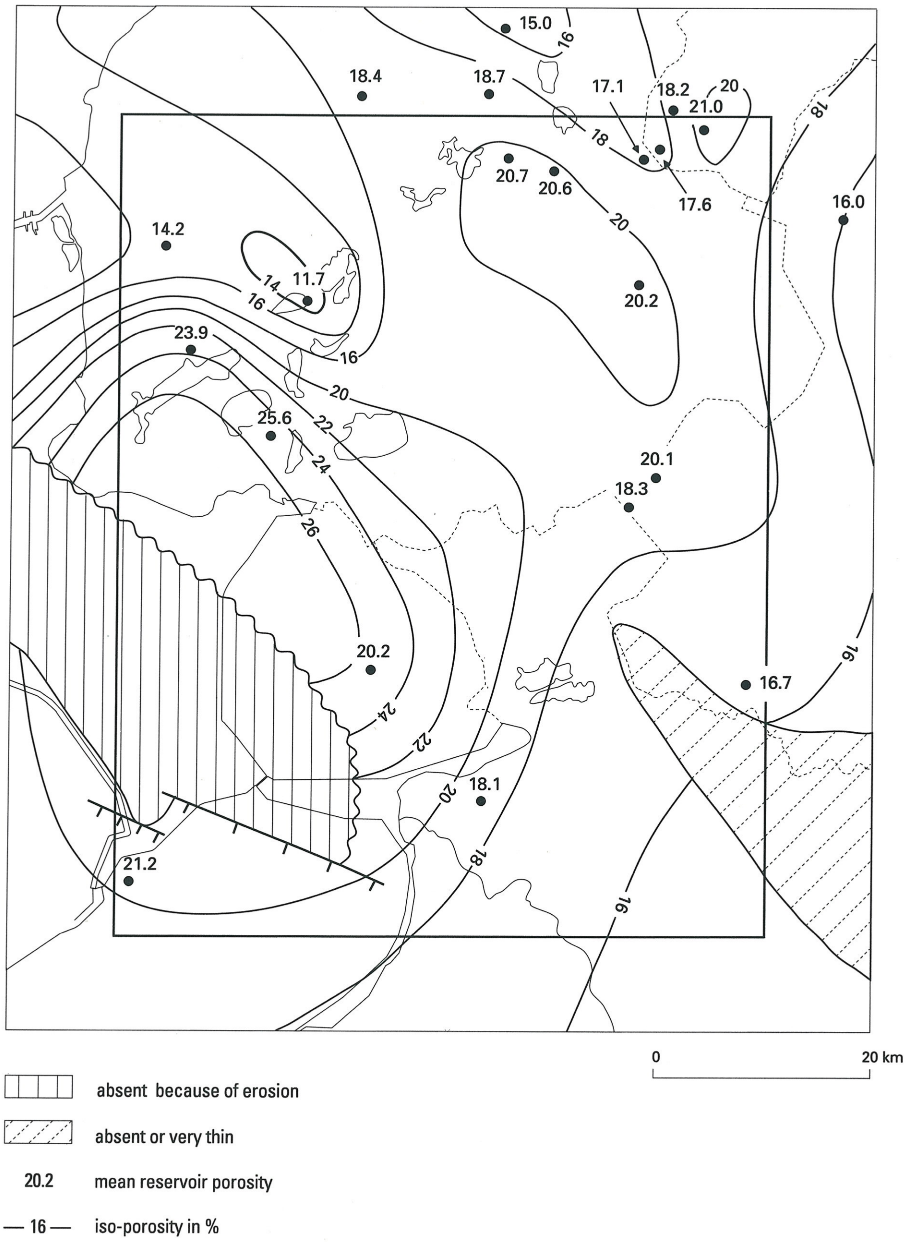
The coarse conglomeratic sediments of the Slochteren Sandstone Formation in the southeast of the map sheet area are interpreted as fan systems and as proximal river deposits. Slightly further from the source area, the braided river systems and wadis mainly predominate. Parts of the Upper Slochteren Sandstone, exhibiting well-sorted and rounded grains and a monomict composition, are interpreted as dune deposits (Glennie, 1972, 1983; Marie, 1975, and Blanche, 1973).

Figure 3.5 Petrophysical evaluation of the Upper Rotliegend interval in the Oudega-Akkrum-11 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained using the single porosity model (density log), for which the calculated log porosity was corrected for the clay and hydrocarbons present. Column 2: drill hole diameter (Cal) and bit diameter, both in inches; furthermore the tested intervals (appendix D) are indicated by trapezia signs, and the cored interval by a black bar. Column 3: water saturation Sw %. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe (left curve) and the volume of water in the pores Vw (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the actual depths.



The sediment succession becomes thinner towards the Texel-IJsselmeer High and it is probable that the sedimentation rate of the oldest part of the Slochteren Sandstone was very low here. The Upper Rotliegend Group was, however, deposited on the high (Rijks Geologische Dienst, 1991a), but as a consequence of the Late Kimmerian erosion it is absent on its crown (Map 18; section 2). In this connection, it should also be noted that the isopachs of the Upper Rotliegend Group run far more northwardly than one would expect on a basis of the current position of the Texel-IJsselmeer High. This means that the Texel-IJsselmeer High was situated slightly further to the north. This palaeohigh functioned as a barrier which separated the depression to the south of the Texel-IJsselmeer High (the precursor of the Central Netherlands Basin) from the Southern Permian Basin

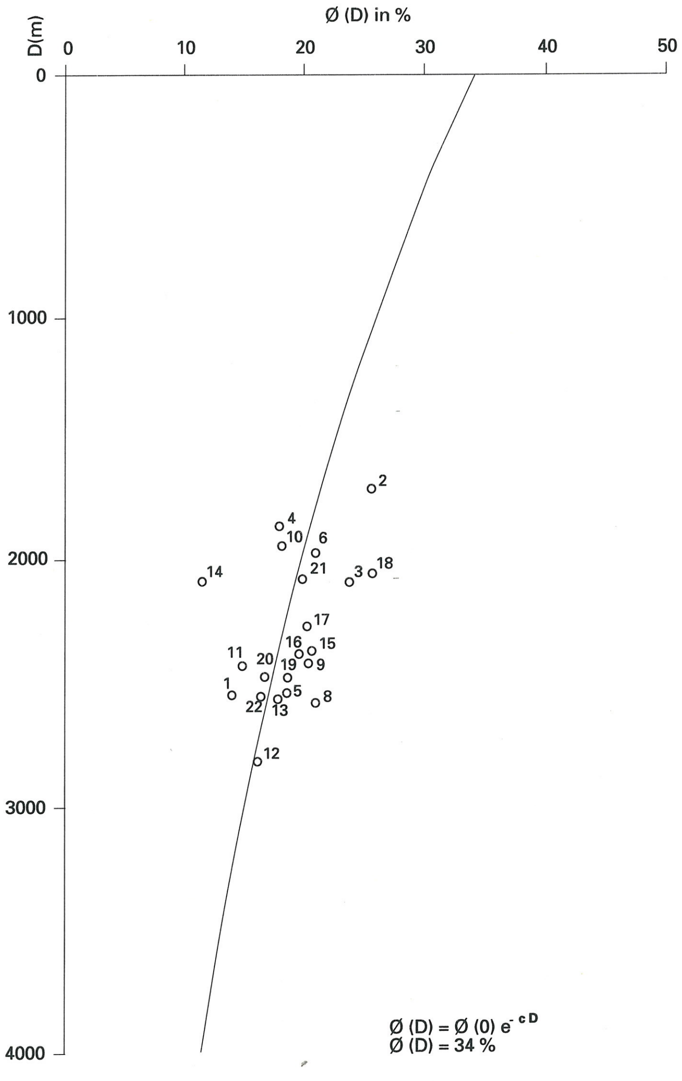
Figure 3.6 Schematic contour map of the reservoir-average effective porosity Øem of the Upper Rotliegend Group (in percentages). The values of the marked data points are also given in appendix C.



located further to the north. The southern margin of the lacustrine deposits of the Ten Boer Claystone would appear also to have been defined by the Texel-IJsselmeer High.

The dune sands of the Slochteren Sandstone Formation were stained red in a high acidity oxidising environment. The red colouring is of a very early diagenetic origin (Walker, 1967; Turner, 1980) and have occurred while the groundwater table was gradually rising already before the

Figure 3.7 Porosity versus depth plot for the Upper Rotliegend Group for the evaluated wells on map sheet. The drawn line is the compaction curve according to Athy's (1930) relation, with a surface porosity Ø(0) = 34%. For the constant c a value of 0.00027 per metre was taken (Sclater & Christie, 1980). The data points represent the reservoir-average effective porosity of the Upper Rotliegend Group (see appendix C; for the porosities of the Bolsward-1, Leeuwarden-5 and Noord-Bergum-1 wells reference should be made to Rijks Geologische Dienst 1991a and 1991b.



1	Bolsward-1	9	Middelburen-1	16	Oudega-Akkrum-11
2	Emmeloord-1	10	Nijensleek-1	17	Oudega-Akkrum-13
3	Heegermeer-1	11	Noord - Bergum-1	18	Sloten-1
4	Kampen-1	12	Norg-1	19	Suawoude-2
5	Leeuwarden-5	13	Opende Oost-1	20	Ureterp-101
6	Lelystad-1	14	Oppenhuizen-1	21	Vledder-1
7	Marum-2	15	Oudega-Akkrum-1	22	De Wijk-15
8	Marumerlage-1				

Zechstein transgression. Glennie & Buller (1983) found that the grey and white coloured members in the top of the Upper Rotliegend Group (Akkrum Sandstone) were never situated below the Early Permian water level.

The material, from which the Slochteren Sandstone is composed, was transported from the south and east, according to Stäuble & Milius (1970) and Glennie (1972). The relatively angular components of the breccia along the basin margin to the south, and the coarse conglomerates and sands of the Slochteren Sandstone Formation derived predominantly from a source area to the south and were transported to the north by braided rivers, and by wadis further downstream. In the opinion of Glennie (1972) the aeolian deposits probably originate from a much larger area and were carried westwards largely by easterly trade winds. At the end of the Early Permian a large depression appeared below sea level during the deposition of the Upper Rotliegend Group, caused by the basin subsidence. This basin was surrounded by Variscan mountain chains, which prevented the sea water flowing into the Southern Permian Basin during the Early Permian (Glennie, 1986; Ziegler, 1982).

3.3 Petrophysical evaluation

The sandstones of the Upper Rotliegend Group form an important target for exploration in the north of the map sheet area. Some ten gasfields in the Upper Rotliegend Group have been drilled during the past 30 years (fig. 1.2) in the map sheet area.

A petrophysical evaluation of nineteen boreholes has been carried out on the deposits of this group in the map sheet area and the immediate vicinity (appendix C). The sandstones of the Upper Rotliegend Group from nine of these boreholes proved to be gas-bearing (appendix D). Figure 3.5 shows the result of the Oudega-Akkrum-11 well, as an example of a log evaluation of the Upper Rotliegend reservoir.

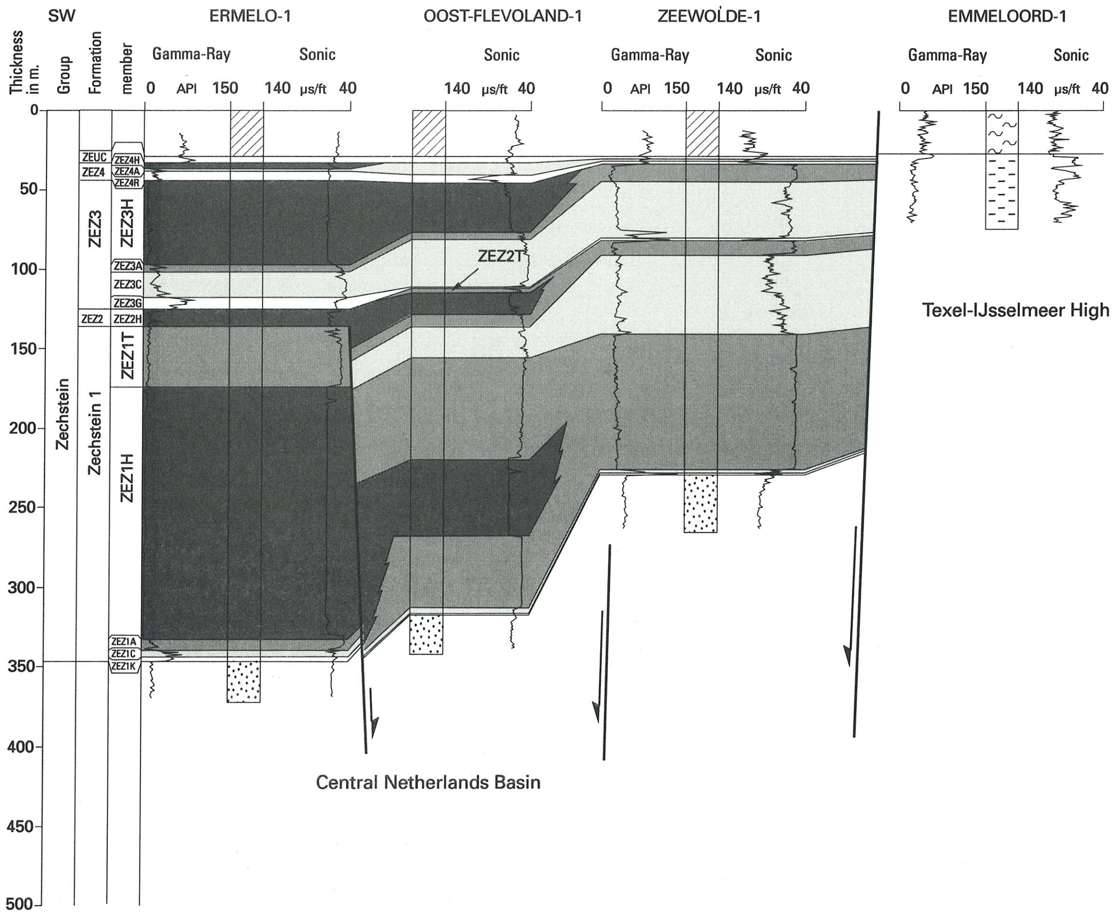
Figure 3.6 gives the distribution of the average reservoir porosity (Øem) of the Upper Rotliegend Group of this area. In this figure, the analogy of the porosity contours with the geological structures is particularly notable. Immediately to the north of the Texel-IJsselmeer High and on the northeastern part of the Friesland Platform, the Upper Rotliegend Group is characterised by a high porosity percentage. The relation between the reservoir porosity and the present burial depth of the Upper Rotliegend Group is shown in figure 3.7. The porosity decreases with the depth, as a consequence of compaction, quartz cementation and illite growth (Van Wijhe et al., 1980). The differences in porosity (from 12 to 26 %, see fig. 3.7) within the map sheet area are the result of variation in primary depositional conditions and burial evolution. The high porosity percentages immediately to the north of the Texel-IJsselmeer High (25.8%, 25.6% and 23.9%, in Emmeloord-1, Sloten-1 and Heegermeer-1 resp.; see fig. 3.7) are attributed to leaching of the Slochteren Formation during the Middle and Late Jurassic, when the crest of the Texel-IJsselmeer High and the Friesland Platform lay immediately above or below the surface, as a result of Kimmerian uplift.

4 Zechstein Group

4.1 Stratigraphy

In the map sheet area the Zechstein Group is composed of four more or less complete evaporation cycles. The most complete cycle in the map sheet area comprises, from bottom upwards, claystone – limestone/dolomite – anhydrite – halite – potassium/magnesium salts – halite – anhydrite. In the southwest of the map sheet area there are also conspicuous, clayey intercalations present (RGD,

Figure 4.1 Distribution map of the Zechstein Group and the position of the stratigraphic correlation section C-C′. A distinction has been made between entirely eroded, partially eroded and non-eroded areas.



salt

anhydrite

carbonate

claystone

Rijnland Group

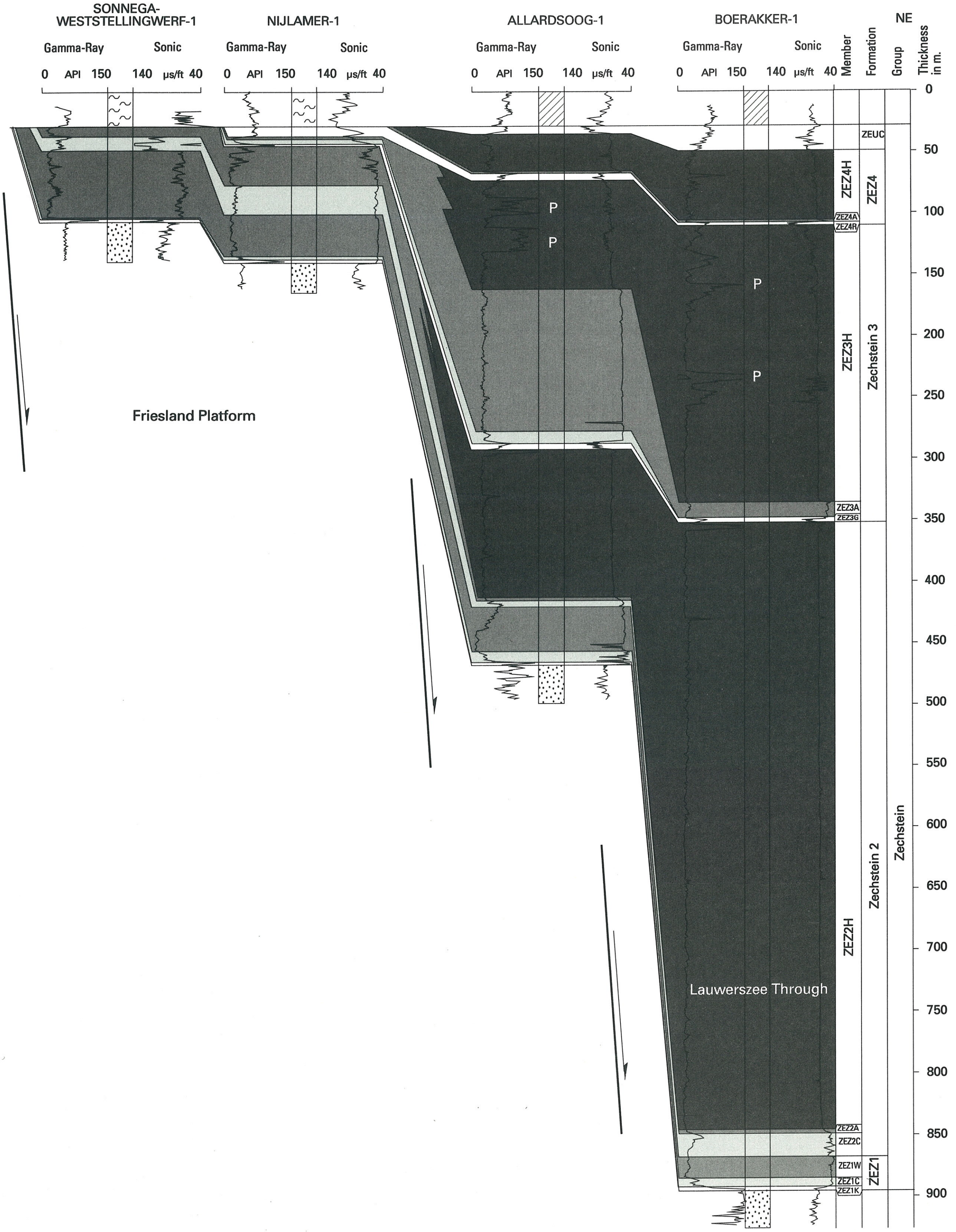
Lower Germanic Trias Group

Upper Rotliegend Group

Limburg Group

ZEZ1K Coppershale
ZEZ1C Zechstein 1 Carbonate
ZEZ1W Zechstein 1 Anhydrite
ZEZ1A Zechstein 1 Onder-Anhydriet
ZEZ1H Zechstein 1 Salt
ZEZ1T Zechstein 1 Upper Anhydrite
ZEZ2C Zechstein 2 Carbonate
ZEZ2A Zechstein 2 Basale Anhydrite
ZEZ2H Zechstein 2 Salt
ZEZ2T Zechstein 2 Roof Anhydrite
ZEZ3G Gray salt Clay
ZEZ3C Zechstein 3 Carbonate
ZEZ3A Zechstein 3 Main Anhydrite
ZEZ3H Zechstein 3 salt
ZEZ4R Red Salt Clay
ZEZ4A Zechstein 4 Pegmatite-Anhydrite
ZEZ4H Zechstein 4 salt
ZEUC Upper-Zechstein
P potassium-magnesium salt

Figure 4.2 Stratigraphic correlation section C-C' of the Zechstein Group with as reference level the base of the Lower Buntsandstein Formation. The wells are located in a SW-NE section from the Central Netherlands Basin over the Texel-IJsselmeer High and the Friesland Platform up to the Lauwerszee Trough. The (synsedimentary) faults on the northern and southern flanks of the high are pronounced features. The locations of the wells are indicated in figure 4.1.



SONNEGA-WESTSTELLINGWERF-1
NIJLAMER-1
ALLARDSOOG-1
BOERAKKER-1
NE
Gamma-Ray
Sonic
0 API 150
140 μs/ft 40
Member
Formation
Group
Thickness in m.
ZEUC
ZEZ4H
ZEZ4
ZEZ4A
ZEZ4R
ZEZ3H
Zechstein 3
ZEZ3A
ZEZ3G
ZEZ2H
Zechstein 2
Zechstein
ZEZ2A
ZEZ2C
ZEZ1W
ZEZ1C
ZEZ1K
ZEZ1
P
Friesland Platform
Lauwerszee Through
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900

1986). They represent the clastic facies margin of the Southern Permian Basin in The Netherlands. The Zechstein Group was deposited during the Late Permian.

The Zechstein sediments lie conformably on the Upper Rotliegend Group with the exception of the extreme southeast of the map sheet area, where the Rotliegend Group is not present, and the Zechstein Group lies unconformably on the Carboniferous. The Zechstein in the map sheet area is overlain conformably by the Lower Buntsandstein Formation and, in particular to the north of the Texel-IJsselmeer High, unconformably by the sediments of the Rijnland Group (Map 16 & fig. 4.2).

On the crest of the Texel-IJsselmeer High the Zechstein Group has been eroded (Map 4, fig. 4.1 & 4.2). Locally, in the northwest of the map sheet area the group achieves a thickness of over 900 m. On the Friesland Platform and in the Central Netherlands Basin the thickness attains several hundred metres. Near the eastern side of the map sheet area, a number of salt pillows are located, some of which are over 1000 m in thickness (Map 4). These structures will be discussed in section 4.3.

The four evaporation cycles each have the status of formation and are, in stratigraphic order, termed the Zechstein 1 to Zechstein 4 Formation. Above these are deposits of the Upper Zechstein Claystone Formation (Rijks Geologische Dienst, 1991a; RGD & NOGEPA, 1993) which also occur in the map sheet area.

The succession of the Zechstein Group is illustrated in the wells Ermelo-1, Oost-Flevoland-1, Zeewolde-1, Emmeloord-1, Sonnega-Weststellingwerf-1, Nijlamer-1, Allardsoog-1 and Boerakker-1. The various Zechstein intervals of these wells have been correlated (fig. 4.2) over the Texel-IJsselmeer High.

4.1.1 Zechstein 1 Formation

The Zechstein 1 Formation is composed of Coppershale, the Zechstein 1 Carbonate and the Zechstein 1 Anhydrite Member. The Zechstein 1 Salt in the Central Netherlands Basin, if present, divides the Zechstein 1 Anhydrite into the Zechstein 1 Lower Anhydrite and the Zechstein 1 Upper Anhydrite. In the north of the map sheet area, the thickness of the Zechstein 1 Formation is only 25 m. In the Central Netherlands Basin the formation reaches a thickness of 150 m (fig. 4.2).

The *Coppershale* is a highly bituminous black shale, 1 to 2 m thick. This member has a characteristically high gamma-ray log reading.

The *Zechstein 1 Carbonate* is a 2 to 15 m thick grey-brown, dolomitic limestone. At the top, the limestone has developed anhydritically, which means that the boundary with the overlying Zechstein 1 Anhydrite tends to be indistinct. In the area to the north of the Texel-IJsselmeer High, the limestone is thin and with a low clay content. To the south, the Zechstein 1 Carbonate grades into the *Zechstein 1 Boundary Carbonate* and the *Zechstein 1 Lower Claystone.* The Zechstein 1 Lower Claystone lies under the Zechstein 1 Boundary Carbonate. In the Lelystad-1 well the Zechstein 1 Claystone is an approximately 10 m thick succession of reddish-brown silty claystone. Furthermore, the Zechstein 1 Carbonate manifests an argillaceous lithology in the Doornspijk-2 and Langenholte-1 wells. More than 50 % of the total Zechstein succession in the Doornspijk-2 well consists of clastic components (Van Adrichem Boogaert & Burgers, 1983). This argillaceous sequence grades laterally into the Zechstein 1 Carbonate.

The *Zechstein 1 Anhydrite* on the northern flank of the Texel-IJsselmeer High consists of a

maximally 200 m thick member of anhydrite with intercalated calcareous beds. In the zone directly to the south of the Texel-IJsselmeer High, the absence of Zechstein 1 Salt deposits makes subdivision into Zechstein 1 Lower and Upper Anhydrite not appropriate. Here, the Zechstein 1 Anhydrite exceeds a thickness of 80 m (fig. 4.3a).
The *Zechstein 1 Salt* is a succession built up of translucent, crystalline halite, approximately 50 m thick. The Zechstein 1 Salt occurs only in the Central Netherlands Basin and does not occur north of the Texel-IJsselmeer High (fig. 4.3a).

The *Zechstein 1 Upper Anhydrite* is appropriate in those places in the Central Netherlands Basin where the Zechstein 1 Salt has been deposited. The maximum thickness of this anhydrite succession may be as much as 60 m in the Central Netherlands Basin (fig. 4.3a).

4.1.2 Zechstein 2 Formation

Immediately beyond the southern extent of the map sheet area, the Zechstein 2 Formation in its most complete development comprises the Zechstein 2 Carbonate, the Zechstein 2 Basal Anhydrite, the Zechstein 2 Salt and the Zechstein 2 Roof Anhydrite (Oost-Flevoland-1; fig. 4.2). On the northern flank of the Texel-IJsselmeer High, the Zechstein 2 Formation has been partially eroded.

The thickness of this formation varies considerably, from 50 m on the northern flank of the Texel-IJsselmeer High to more than 600 m in the extreme north of the map sheet area, as a consequence of differences in basin subsidence (synsedimentary fault movements, fig. 4.2) and of post sedimentary salt flow.

The *Zechstein 2 Carbonate* (Main Dolomite) consists of brown-black and beige, compact limestone and dolomite. The thickness of the Zechstein 2 Carbonate may reach 42 m directly to the north of the Texel-IJsselmeer High and approximately 50 m in the Central Netherlands Basin. In the northeast of the map sheet area, the Main Dolomite is composed of laminated recrystallised limestone. Between the crystals of the calcite pore filling there are zones consisting of argillaceous and organic material (appendix I; photo 4a). Fluorescence analysis reveals the presence of oil or organic material in situ (appendix I: photo 4b). Bivalves and ostracods are found in the sediments. The very argillaceous lithology of the Zechstein 2 Carbonate in the Doornspijk-2 well changes laterally into the Zechstein 2 Carbonate.

The *Zechstein 2 Basal Anhydrite* consists of white to beige coloured anhydrite. The anhydrite exhibits extremely constant thickness, of approx. 8 metres in the north to approx. 10 metres in the south of the map sheet area (fig. 4.3b).

The *Zechstein 2 Salt* was deposited in the extreme north of the map sheet area. In the Allardsoog-1 well 120 m of salt was penetrated (fig. 4.1). Further to the north, the Zechstein 2 Salt thickens rapidly. The Zechstein 2 Salt is white coloured to translucent. In the Central Netherlands Basin, the thickness is less than 11 m. To the north of the Texel-IJsselmeer High, layers of potassium-magnesium salts were deposited in varying thicknesses up to 20 m (fig. 4.3b).

With the deposition of the *Zechstein 2 Roof Anhydrite* the Zechstein 2 cycle in the Central Netherlands Basin ended. The anhydrite reaches a thickness of 10 m. In a zone directly to the north of the Texel-IJsselmeer High, the Zechstein 2 Salt was deposited and also overlain by the Zechstein 2 Roof Anhydrite (fig. 4.2 & 4.3b). In this zone, the anhydrite reaches a maximum thickness of 8 m. Further to the north, no Zechstein 2 Roof Anhydrite was deposited.

4.1.3 Zechstein 3 Formation

The Zechstein 3 Formation is divided into four members: the Grey Salt Clay, the Zechstein 3 Carbonate, the Zechstein 3 Main Anhydrite and the Zechstein 3 Salt. The thickness of the formation on top of the Texel-IJsselmeer High is only 12 m, but increases up to 220 m towards the north. In the Central Netherlands Basin the thickness of the Zechstein 3 Formation is 45 metres.

The *Grey Salt Clay* is a 2 to 8 m thick, grey claystone. It is thickest on the flanks of the Texel-IJsselmeer High. This succession has a characteristically high gamma-ray log reading and is very appropriate for regional correlations.

The *Zechstein 3 Carbonate* (Platy Dolomite) comprises finely crystalline, beige to light brown laminated dolomite. In the Zeewolde-1 well the considerable thickness (45 m) of the Platy Dolomite is remarkable. The thickness on the north flank of the Texel-IJsselmeer High is around 14 metres, whereas more to the north, it diminishes to 10 m. The cored Zechstein 3 Carbonate of Zeewolde-1 is highly dolomitic over the entire interval. The dolomite displays a vuggy porosity caused by leaching of calcareous fossils. The carbonate largely comprises strongly laminated beige micritic limestone or dolomite. Locally, to the southeast of the Texel-IJsselmeer High, the claystone percentage is extremely high.

The *Zechstein 3 Main Anhydrite* comprises white anhydrite, with carbonate interbedding and small claystone layers in the lowest part. The thickness in the map sheet area varies from a few metres in the south to over 100 m in the northeast (fig. 4.3c).

The *Zechstein 3 Salt*, in contrast to the Zechstein 1 Salt, was deposited to the north of the Texel-IJsselmeer High as well as in the Central Netherlands Basin (fig. 4.2). In the Allardsoog-1 well the thickness reaches up to 90 metres and three bands of potassium-magnesium salt have also been identified, each with a thickness of 20 m (fig. 4.2). Bands of potassium-magnesium salts several metres thick were also deposited in the Central Netherlands Basin, usually in the top of the halite sequence (fig. 4.3c).

4.1.4 Zechstein 4 Formation

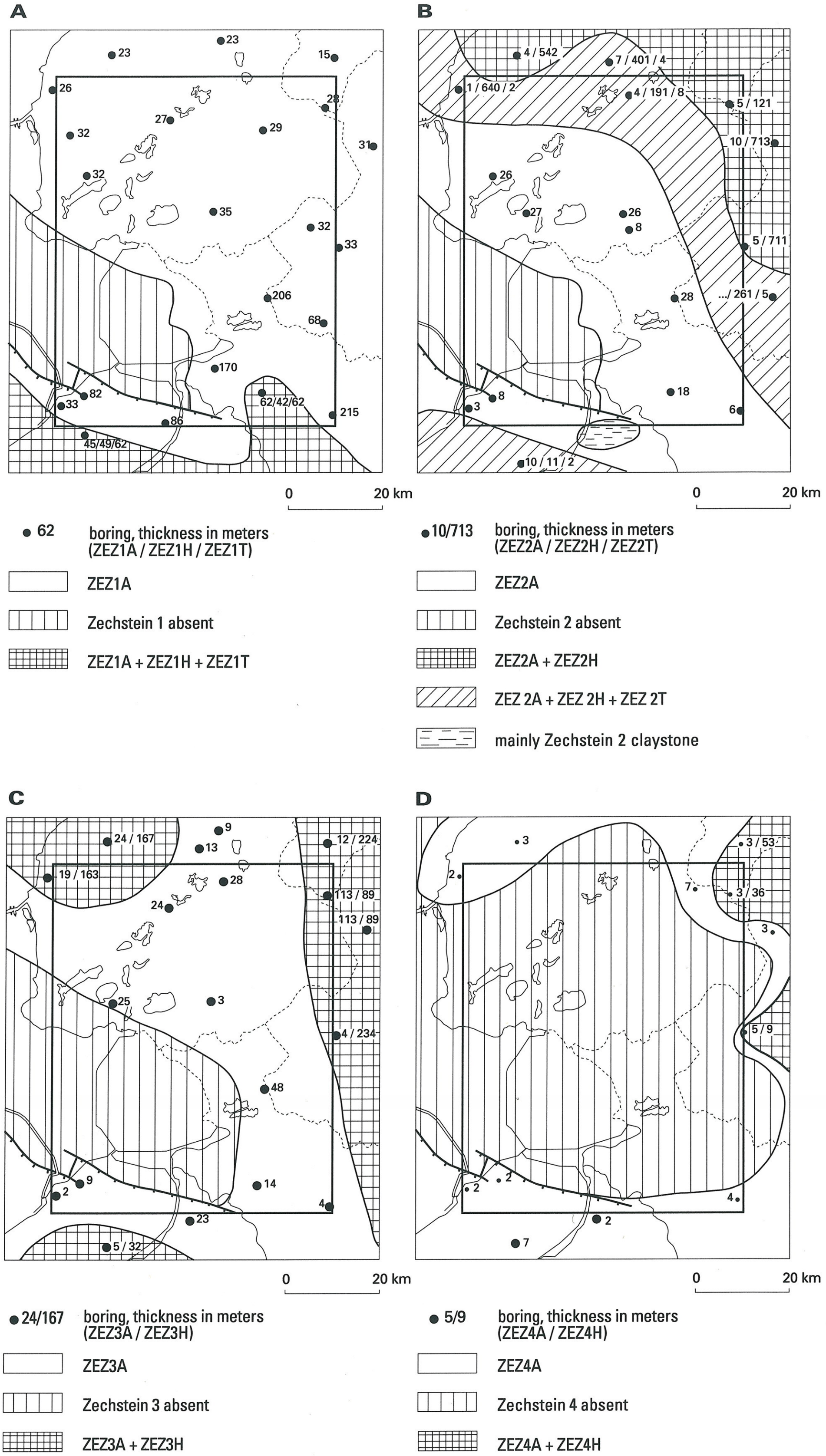
The Zechstein 4 Formation in the map sheet area comprises the Red Salt Clay, the Zechstein 4 Pegmatite-Anhydrite and the Zechstein 4 Salt Members.

The *Red Salt Clay* is an average of 2 to 10 m thick and consists of red anhydrite-bearing clay. The Red Salt Clay is found both to the north and to the south of the Texel-IJsselmeer High. In the southeast of the map sheet area the Red Salt Clay has become sandier.

The *Zechstein 4 Pegmatite-Anhydrite* only occurs in the map sheet area in the Central Netherlands Basin, approximately 2 m thick, and locally in the north, 3 m at the most (fig. 4.3d). This member is clearly identifiable on logs, owing to a low gamma-ray amplitude peak and high acoustic velocity.

The *Zechstein 4 Salt* is hardly present at all in the area, with the exception of the extreme northeast. There, the evaporitic series ends with rock salt and a thin anhydrite layer (Allardsoog-1). The Zechstein 4 Salt achieves a thickness of 53 m (Boerakker-1) immediately to the northeast of the map sheet area. A band of a few metres of potassium-magnesium salt is generally present in the top of the halite sequence. In the Central Netherlands Basin little Zechstein 4 Salt is present with a thickness up to a maximum of 7 m (fig. 4.3d).

Figure 4.3 Distribution and thickness of various members of the Zechstein Group within the map sheet area.
a Zechstein 1 Lower Anhydrite, Zechstein 1 Salt and Zechstein 1 Upper Anhydrite.
b Zechstein 2 Basal Anhydrite, Zechstein 2 Salt and Zechstein 2 Roof Anhydrite.
c Zechstein 3 Main Anhydrite and Zechstein 3 Salt.
d Zechstein 4 Pegmatite-Anhydrite and Zechstein 4 Salt.



ZEZ1A = Zechstein 1 Onder-Anhydriet
ZEZ1H = Zechstein 1 Haliet
ZEZ1T = Zechstein 1 Boven-Anhydriet
ZEZ2A = Zechstein 2 Basale Anhydriet
ZEZ2H = Zechstein 2 Zout
ZEZ2T = Zechstein 2 Dakanhydriet
ZEZ3A = Zechstein 3 Hoofd-Anhydriet
ZEZ3H = Zechstein 3 Zout
ZEZ4A = Zechstein 4 Pegmatiet-Anhydriet
ZEZ4H = Zechstein 4 Zout

4.1.5 Upper Zechstein Claystone Formation

The Upper Zechstein Claystone Formation is an anhydritic claystone succession between the Pegmatite Anhydrite and the base of the Lower Germanic Trias Group. For practical reasons NAM & RGD (1980) group this argillaceous transitional succession with the Lower Germanic Trias. In the revised nomenclature of RGD & NOGEPA (1993) this formation is considered as the uppermost part of the Zechstein. This claystone succession of the Upper Zechstein is present throughout the map sheet area, with the exception of the crest of the Texel-IJsselmeer High.

In the map sheet area the Upper Zechstein in the extreme north and south comprises a thin series of anhydritic claystones with a low acoustic velocity. The thickness varies from 35 m in the east of the map sheet area to 8 m in the Central Netherlands Basin.

The abovementioned anhydritic claystone succession at the top of the evaporitic Zechstein Group is informally referred to as Upper Zechstein Claystone Formation and is not regarded as a new Zechstein cycle. In fact the limited lithological development (only clay and anhydrite) makes reference to a complete, new cycle inappropriate.

4.2 Sedimentary development and palaeogeography

During the deposition of the Zechstein Group a precursor of the present Texel-IJsselmeer High was formed, surrounded by two basins. The Central Netherlands Basin originated in the south as a subbasin of the Southern Permian Basin. The main basin was situated to the north of the high and deepened rapidly towards the north. This continental basin may have filled up with water under catastrophic circumstances (Glennie & Buller, 1983) at the end of the Early Permian. The proto-Texel-IJsselmeer High was somewhat larger than the present Texel-IJsselmeer High and situated slightly more to the north.

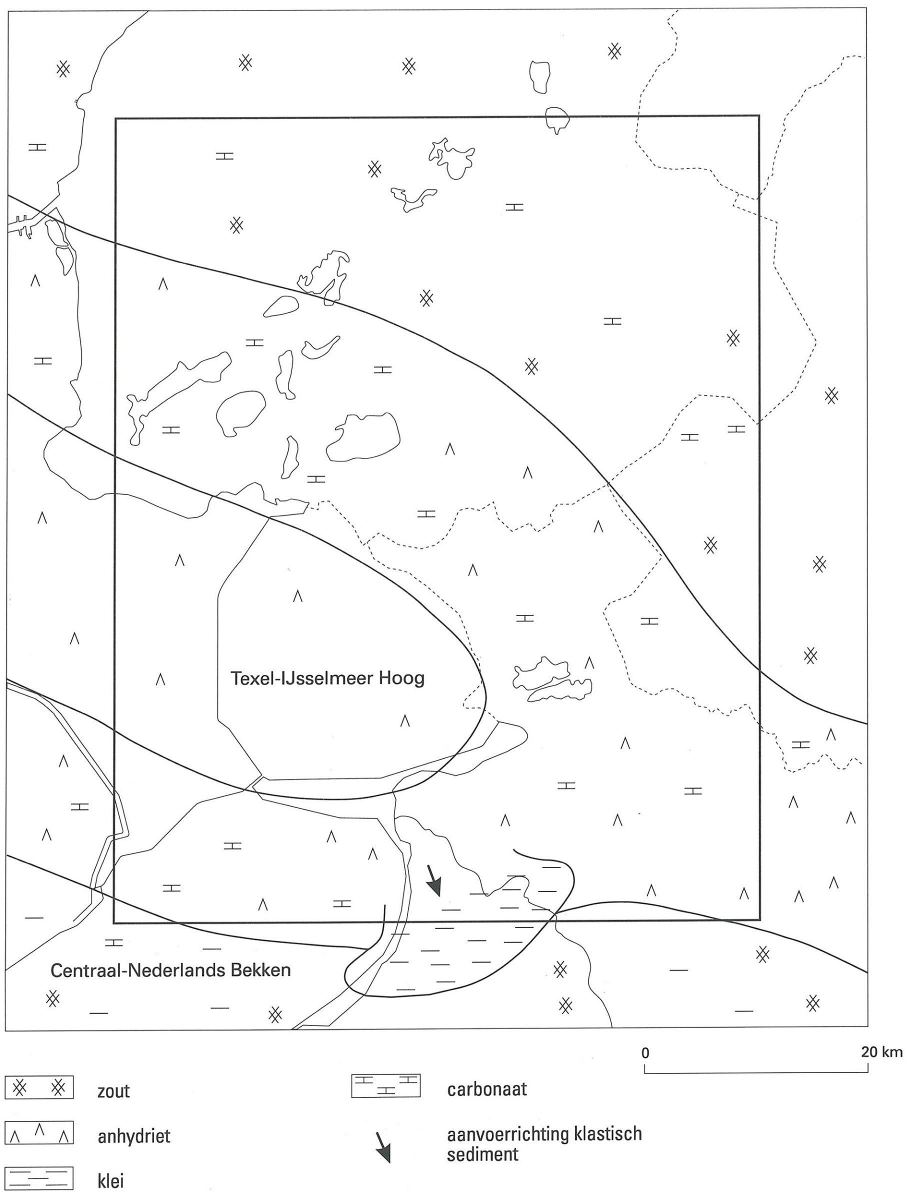
The map sheet area is located on the southern margin of the Southern Permian Basin and both the evaporitic central basin facies and the argillaceous marginal facies developed. The influence of the facies at the margin can be recognised easily, particularly to the south of the Texel-IJsselmeer High. A predominantly carbonate/anhydrite platform facies developed on the High. During deposition of the Zechstein Group the Central Netherlands Basin, the Texel-IJsselmeer High and the main basin in the north of the map sheet (of the Southern Permian Basin) are the principal structures in the area. The lithological units of the Zechstein cycles can be easily traced over the Texel-IJsselmeer High, indicating that the basins bordering the Texel-IJsselmeer High were regularly inter-connected (fig. 4.3a t/m d).

Despite the fact that considerable erosion took place during the Late Kimmerian tectonic phase, it is clear that a certain relief (including the Texel-IJsselmeer High) was present during deposition of the Zechstein (fig. 4.4). The high clastic influx on the southern edge of the Texel-IJsselmeer High during different Zechstein cycles, confirms this interpretation. The clay-dominated limestone successions occur in a zone immediately to the south of the Texel-IJsselmeer High. Further to the south, evaporites were deposited. Van Adrichem Boogaert & Burgers (1983) also report that the basin margin, dominated by clastic sediments, lies further to the south. The relatively high clastic influx in the Doornspijk-2 well can be accounted for assuming a part of the Texel-IJsselmeer High to have been the northern source area (fig. 4.4).

The sedimentary succession of the Zechstein Group starts with the Coppershale, deposited in a euxinic basin (Taylor, 1986). During deposition of the Zechstein sediments, periodical influx and evaporation took place. Each new influx of fresh sea water is manifested in the form of an evaporitic cycle.

A complete series of evaporites was deposited in the Central Netherlands Basin during the first evaporite cycle. The carbonates were formed in an open marine environment. A decreasing quantity of sea water in combination with high evaporation and consequent drop in sea level resulted in an increase in salinity. Sulphates were the first to be precipitated from this hypersaline brine. The Zechstein 1 Anhydrite on the southern flank of the Texel-IJsselmeer High is remarkably thick (fig. 4.2). The shallow water level was favourable for a high sedimentation rate of sulphur crystals (Van der Baan, 1990). After dehydration, the gypsum was later altered into anhydrite. Consequently, platforms of anhydrite were formed on and around the palaeohighs which arose

Figure 4.4 Palaeogeography during the Late Permian in and immediately surrounding the map sheet area. The development of carbonate and anhydrite facies on the Texel-IJsselmeer High and the argillaceous sedimentation in the extreme south are pronounced features.



during the Variscan orogeny (Richter - Bernburg, 1986). In the map sheet area anhydrite platforms are present along the edges of the Texel-IJsselmeer High during the Zechstein 1, 2 and 3 cycles. Carbonate platforms and barrier systems were formed on these shallow anhydrite platforms during subsequent Zechstein cycles. In addition to anhydrite/gypsum, halite was also deposited in the Central Netherlands Basin.
The evaporitic sequence of the Zechstein 2 Formation displays a great similarity with that of the Zechstein 3 Formation. Both formations show a relatively thick development of carbonates and anhydrites on the edges of the IJsselmeer High and a thick halite development in the basins. An important difference is the greater thickness of the Zechstein 3 Anhydrite to the north of the Texel-IJsselmeer High in comparison with the Zechstein 2 cycle (fig. 4.2), and the occurrence of polyhalite layers in the main basin. The rapid increase in lateral thickness of the Zechstein 3 sequence in the Central Netherlands Basin and to the north of the Leeuwarden – Allardsoog line points to synsedimentary fault tectonics.

After the transgression at the beginning of the fourth cycle, the Red Salt Clay and Pegmatite-Anhydrite were deposited under prolonged hypersaline conditions. Whereas the carbonates of this evaporite cycle do not occur throughout the map sheet area, sediments of the Red Salt Clay and Zechstein 4 Pegmatite-Anhydrite can be identified at a very constant thickness. A further halite succession of several metres was deposited in the Central Netherlands Basin. The last differences in relief were levelled out at the end of the Permian. The deposits of the Zechstein 4 Formation and the Upper Zechstein may be assumed to have taken place on an alluvial plain bordering the Southern Permian Basin, illustrative of a playa-type environment. The sedimentation decreased under regressive conditions.

4.3 Salt pillows

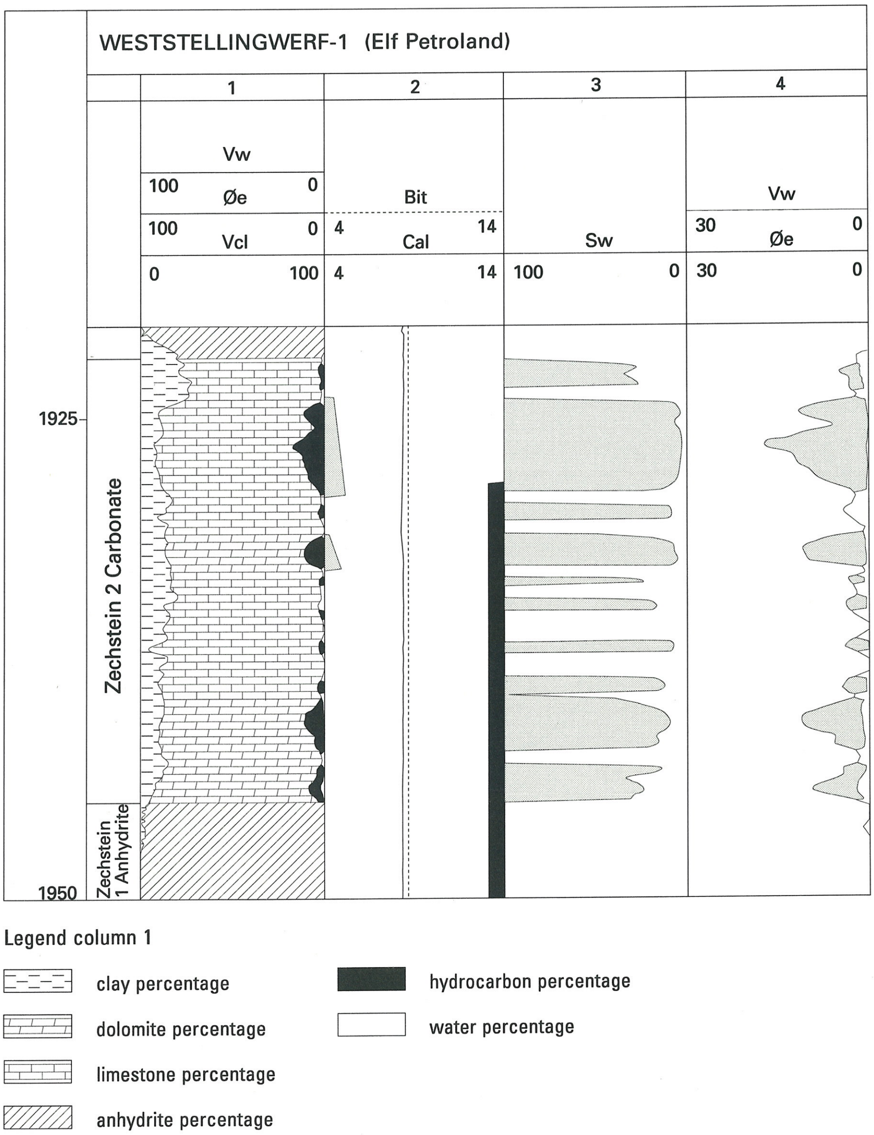
In the east and northeast of the map sheet area there are salt pillows at De Wijk, Dwingeloo and Steenbergen (Rijks Geologische Dienst, 1988; fig. 9.2). The great thickness of the Zechstein at the abovementioned sites only occurs as a growth of the Zechstein salt as a consequence of halokinesis. These Zechstein structures achieve a thickness of over 1000 m (Map 4).

The salt pillow De Wijk (Map 4) lies for the greatest part in the map sheet area and on the border of the North Netherlands salt province. The top of the structure lies at a depth of 1400 m. Above the salt pillow are the Lower Buntsandstein and part of the Main Buntsandstein present. Sediments of the Upper Germanic Trias are present on the eastern flank of the structure and are unconformably overlain by the sediments of the Rijnland, the Chalk Group and the North Sea Supergroup. Visser & Sung (1958) and Gdula (1983) have found that the salt doming began in the North Netherlands already during the Triassic. During the Cretaceous, the salt pillow was comparatively inactive. The base of the Tertiary lies above the salt pillow, approximately 100 – 150 m above the regional level. As a consequence of halokinesis during the Late Cretaceous, the entire Cretaceous succession of sediments has a very weak antiformal structure above the salt pillow. The base of the Breda Formation lies 60 – 110 m higher than the regional level, from which one may conclude that growth of the salt pillow continued into the Miocene.

The Dwingeloo salt pillow (Map 4) is situated at the eastern boundary of the map sheet area. The total thickness of the sediments of the Zechstein Group in this salt structure is 1050 m. The top of the structure lies at a depth of 1350 m. The salt structure forms part of an E-W trending structure, which extends in an easterly direction possibly as far as the German border. Under the Dwingeloo salt structure there is a normal fault which may have initiated the halokinesis. The depth of the base of the Tertiary is approximately 200 – 300 m less than might have been expected for the region. To the west of the Dwingeloo salt pillow, salt tectonic movements generated normal faults, as a result of which the superimposed Lower Tertiary sediments are substantially thicker. Above the pillow, the base of the Breda Formation lies a maximum of 40 m above its regionally expected depth. The greatest salt rise of the Dwingeloo structure took place during the Early Tertiary. Salt movements during the Triassic are of less importance.

The Steenbergen salt pillow (Map 4) is situated in the extreme northeast of the map sheet area, near a fault structure which proceeds predominantly in a NNW direction (the Hantum Fault; fig. 1.7). The total thickness of the Zechstein sediments is 1100 m. The top of the salt structure lies at a depth of 1600 m. The growth of the Zechstein salt and the normal fault in the basement near the Hantum fault are shown in section 3 (Map 18). The fault in the basement, with an overlying sediment succession tending to be brittle, caused the graben structure directly above the normal fault (Rijks Geologische Dienst, 1991b; Richards, 1991). The sediments of the Rijnland Group and of

Figure 4.5 Petrophysical evaluation of the Zechstein 2 Carbonate interval in the Westellingwerf-1 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained using the complex porosity model (density, neutron and sonic logs), for which the calculated log porosity was corrected for the clay and hydrocarbons present. Column 2: drill hole diameter (Cal) and bit diameter, both in inches; furthermore the tested intervals (appendix F) are indicated by trapezia signs, and the cored interval by a black bar. Column 3: water saturation Sw %. The Archie formula, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe (left curve) and the volume of water in the pores Vw (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the actual depths.



the Chalk Group as well as of the North Sea Supergroup formed synthetic and antithetic faults in this brittle overlying sediment succession, probably as the result of a Tertiary dextral strike-slip movement (Rijks Geologische Dienst, 1991b). The plastic behaviour of the Zechstein salt caused decoupling of the basement and the sedimentary cover when these transverse fault tectonics occurred. Halokinesis produced a pronounced graben.

4.4 Petrophysical evaluation

Commercial quantities of natural gas in Zechstein carbonate reservoirs were discovered by NAM in the south of the province of Drenthe in 1948, since when the Zechstein 2 Carbonate has been a

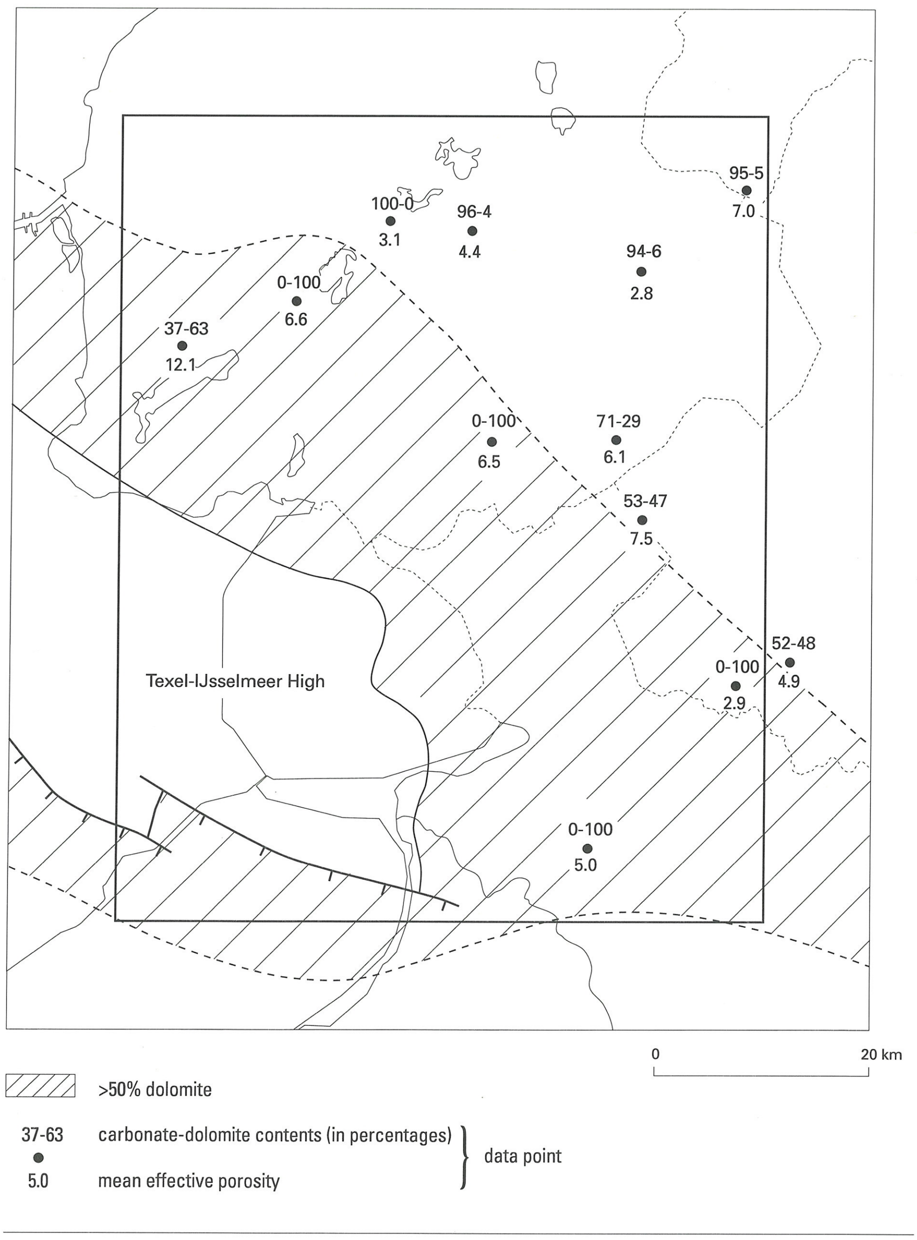


Figure 4.6 The Zechstein 2 Carbonate effective porosity Øem (in percentages) and carbonate-dolomite ratio. The area with more than 50% dolomite is indicated in the figure by hatching. The carbonate-dolomite ratio has been included in the reservoir evaluation (RDG, 1993a). The effective porosity values are also given in appendix E. The Zechstein 2 Carbonate has been eroded on the Texel-IJsselmeer High.

successful exploration target in The Netherlands. Five gasfields in the Zechstein 2 Carbonate have been identified in the map sheet area (fig. 1.2).

An evaluation has been carried out of the Zechstein 2 Carbonate of twelve boreholes in the map sheet area (appendix E), four of which have encountered hydrocarbons (appendix F). The result of the Weststellingwerf-1 well is shown in figure 4.5 as an example of a log evaluation of the Zechstein 2 Carbonate reservoir interval.

The limestone/dolomite ratio from twelve boreholes has been calculated and is shown in figure 4.6, which also indicates the average effective porosities of the borehole studies. These effective reservoir porosities vary considerably in the Zechstein 2 Carbonate (RGD, 1993a).

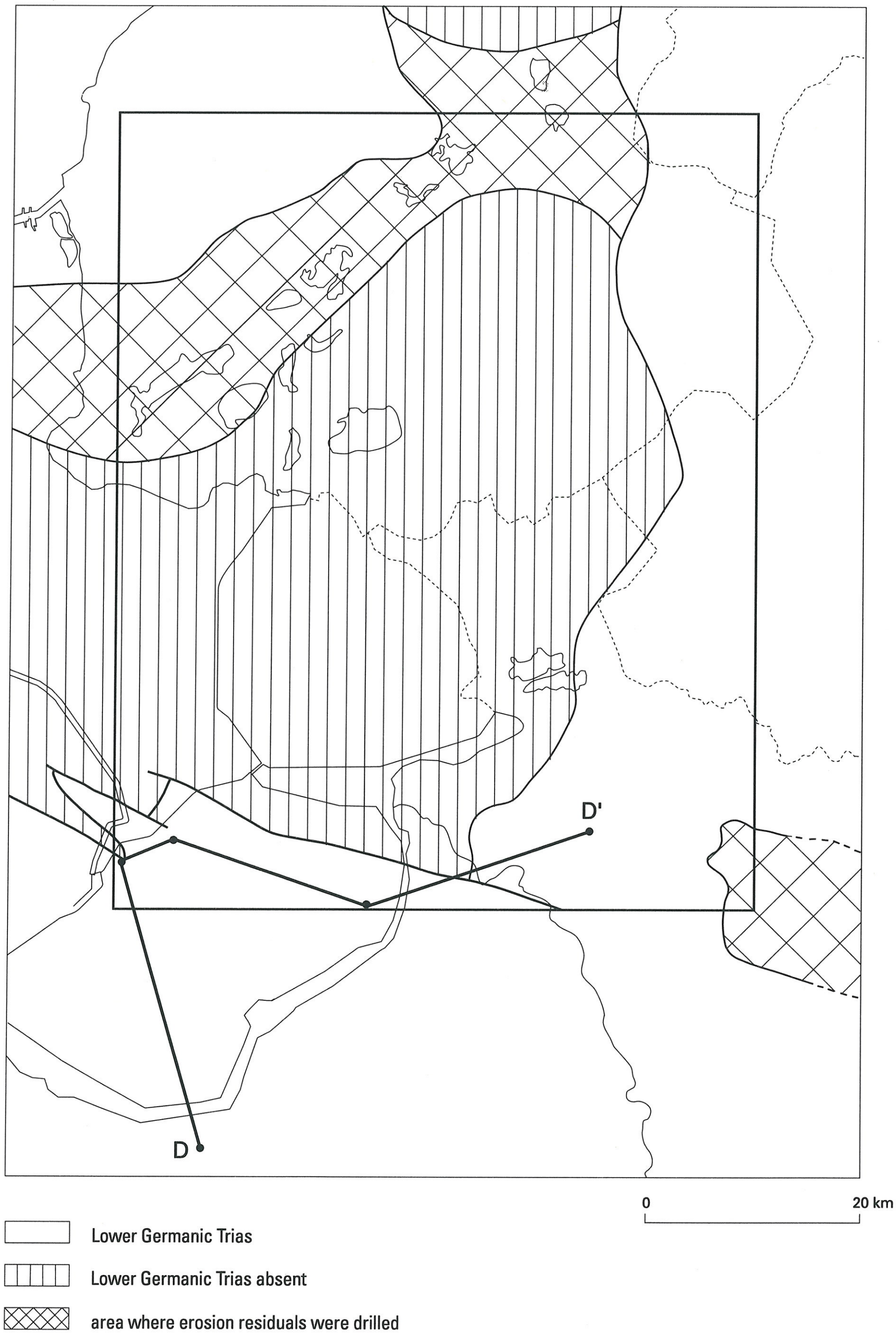
The Zechstein 2 Carbonate in map sheet V was deposited in different depositional environments (platform, slope and basin facies). Dolomitisation took place particularly within the extent of the platform facies (fig. 4.4 & 4.6) and, on the northern flank of the Texel-IJsselmeer High, occurred during an early diagenetic phase (Van der Poel, 1987). The porosity of the Zechstein 2 Carbonate is the consequence of diagenetic processes and in particular of leaching of the carbonates of the Texel-IJsselmeer High and the Friesland Platform, during the uplift of the Middle and Late Jurassic (Van der Baan, 1990).

5 Lower and Upper Germanic Trias Group

5.1 General

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

Figure 5.1 Distribution map of the Lower Germanic Trias Group in the map sheet area and the position of stratigraphic correlation section D-D′. In the figure, a zone is indicated where, although the Lower Buntsandstein Formation has not been seismically identified, thin erosion remnants have nevertheless been proved to be present by drilling.



The Triassic is not represented on the Texel-IJsselmeer High and the Friesland Platform. Deposits of the Lower Germanic Trias occur in the north, east and south of the map sheet area. On the contrary, deposits of the Upper Germanic Trias Group are only present to the south of the Texel-IJsselmeer High and in the east of the map sheet area (fig. 5.1). The greatest thicknesses occur in the southeast of the map sheet area (Map 6).

The stratigraphic succession of Triassic deposits is illustrated by a log correlation section (fig. 5.2) and a lithostratigraphic diagram (5.3) of the Triassic deposits, directly south of the Texel-IJsselmeer High.

5.2 Lower Germanic Trias Group

5.2.1 Stratigraphy

The Lower Germanic Trias Group consists of the Lower Buntsandstein and the Main Buntsandstein Formation. The Lower Germanic Trias Group is mainly composed of continentally deposited reddish-brown claystones, siltstones and sandstones. The Lower Germanic Trias Group was deposited during the latest Late Permian and the Early Triassic (Scythian).
The Lower Germanic Trias in the study area is present to the south of the Texel-IJsselmeer High (Map 5). The entire Lower Buntsandstein Group is absent on the Netherlands Swell (fig. 11.1) and the Texel-IJsselmeer High. The Netherlands Swell is a NNE-SSW trending rise in The Netherlands, developing during the Triassic, above which erosion of the Lower Germanic Trias occurred (fig. 11.1).

The Lower Germanic Trias Group in the map sheet area reaches thicknesses of over 400 m. Figure 5.1 shows the local extent of the Lower Germanic Trias Group in the map sheet area, and also a zone in the north in which erosion remnants of this group appear, but were unable to be mapped owing to the insufficiency of the available seismic records. The boundary of this zone is shown on map 5 and 6.

The Lower Germanic Trias Group rests conformably upon the Zechstein Group. In the map sheet area the Lower Germanic Trias Group is overlain unconformably by different formations. In the Central Netherlands Basin this is the Upper Germanic Trias Group; in the north and east of the map sheet area, the Rijnland Group (Map 16).

5.2.1.1 Lower Buntsandstein Formation.

The Lower Buntsandstein Formation consists of the Basal Buntsandstein, the Main Claystone and the Rogenstein Members. The formation exhibits thicknesses in the map sheet area varying between 350 and 425 m.

The Lower Buntsandstein Formation rests conformably upon the sediments of the Zechstein Group. The area of extent of the Lower Buntsandstein, including the Lower Germanic Trias Group, is shown in figure 5.1. In the majority of the map sheet area the succession is not complete as a consequence of erosion. The Lower Buntsandstein Formation does not occur (Map 5) in a large part of the map sheet area.

The *Basal Buntsandstein* consists of a thin sandstone layer and a superimposed claystone member. The whole succession, less than 15 m thick, displays an upwardly progressively positive reading on the gamma-ray log. The succession is silty and cemented by anhydrite.

A sedimentological study of the Lower Buntsandstein and the Main Claystone in Northwest Germany has shown that these are built up of fining-upward, repetitive cycles (Wolburg, 1961; Brüning, 1986). The lithostratigraphic boundary defined by NAM & RGD (1980) between these two successions in fact appears to lie in the middle of one such sedimentary cycle. According to the same definition by NAM & RGD (1980), the Basal Buntsandstein also comprises equivalents of higher Zechstein cycles. The lower boundary of the Basal Buntsandstein has been readjusted in this explanation so that it correlates with the lowest clastic cycle of the Triassic (Rijks Geologische Dienst, 1991a). The description of the basal Buntsandstein then correlates with the "Obere Bröckelschiefer" in Germany, as described by Best (1989).

The *Main Claystone* is built up of cyclic, repetitive fining-upward sequences, with thin, fine-grained sandstone beds at the base. The sediments of the succession are silty and anhydritic. Anhydrite usually occurs as lenticles in the reddish-brown claystone.

From the evolution of different, clearly recognisable cycles in the sediment layer of the Main Claystone in the wells round the Texel-IJsselmeer High, it may be concluded that there are few differences in true thickness (RGD, 1989). The thickness of the Main Claystone is fairly constant in the map sheet area and varies between 120 m in the Central Netherlands Basin and 160 m in the southeast of the map sheet area.

The *Rogenstein* rests conformably on the Main Claystone and consists of red and green anhydrite-bearing shales alternated by oolite beds. The oolite beds are clearly identifiable by the low gamma-ray, the high resistivity, and the increased acoustic velocity readings. The number of oolite beds varies from 5 to 10 and they do not exceed a few metres in thickness. The entire Rogenstein Member in the Central Netherlands Basin comprises a maximum thickness of 190 m (Langenholte-1; fig. 5.2).

In the map sheet area the Rogenstein is usually overlain conformably by the Volpriehausen Sandstone of the Main Buntsandstein Formation. Locally, the Solling Claystone of the Röt Formation rests unconformably on the Rogenstein Member as a consequence of the erosion related to the Hardegsen tectonic phase (fig. 5.3).

5.2.1.2 Main Buntsandstein Formation

In the map sheet area only the two lowest members of the Main Buntsandstein Formation can be identified namely, from old to young, the Volpriehausen Sandstone and the Volpriehausen Clay-Siltstone (fig. 5.3). The complete succession of the Main Buntsandstein can be found in the areas east of the map sheet area, where the Volpriehausen Clay-Siltstone is superimposed by the Detfurth Sandstone, the Detfurth Claystone, and the Hardegsen Member.

The Main Buntsandstein Formation is composed of sandstones and claystones. The sandstone bodies are massive and comprise few claystone interbeds. The claystones are of a clear reddish-brown colour and comprise a variable quantity of silt and sand.

The formation rests conformably upon the Lower Buntsandstein Formation, and is unconformably overlain by the Solling Member of the Röt Formation. Where the Solling Claystone lies directly on the claystones of the Lower Buntsandstein (fig. 5.2) its base is hard to detect on the logs. A clay layer may occur in the Main Claystone or in the Rogenstein, recognisable by a characteristically high gamma ray, possibly indicating a palaeosol, which would then be the time equivalent of the hiatus and the unconformity at the base of the Röt Formation.

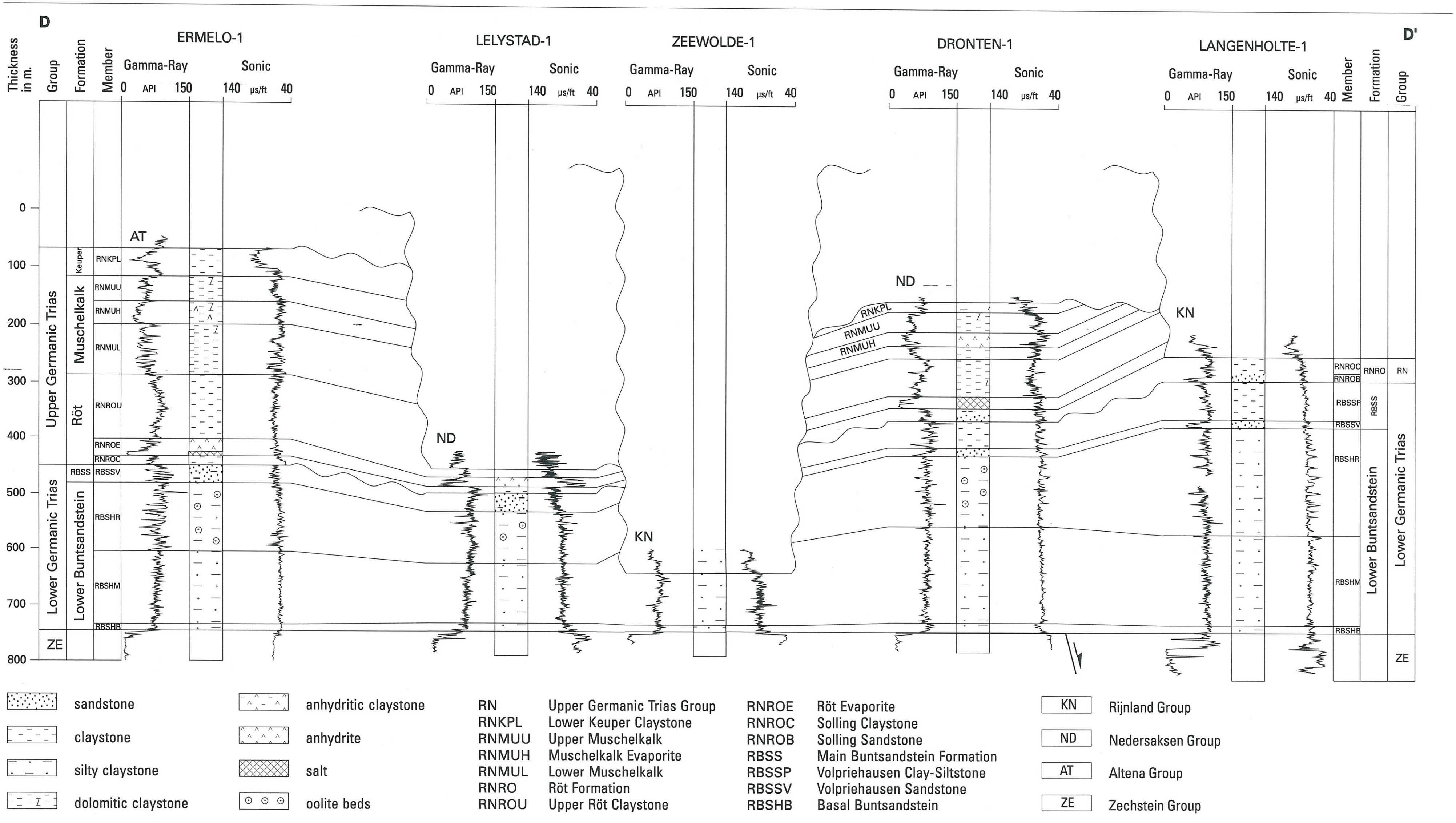


Figure 5.2 Stratigraphic correlation section D-D' of the Triassic deposits in the south of the map sheet area. The level of reference is the base of the Lower Buntsandstein Formation. Keuper and Muschelkalk sediments occur in the Ermelo-1 and Dronten-1 wells. The position of D-D' is indicated in figure 5.1

During the Hardegsen and the Kimmerian tectonic phase, the sediments of the Main Buntsandstein Formation underwent widespread erosion in the map sheet area, giving rise to local differences in thickness of the deposits. No more than 85 m of the Main Buntsandstein Formation has remained.

The *Volpriehausen Sandstone* is the lowest member of the Main Buntsandstein Formation and has only been identified in the south of the map sheet area. The grains of the reddish-brown coloured, pure sandstones are fine to medium in size and are moderately to well rounded.

The sandstones clearly display a low, block-like reading on the gamma-ray log. The thickness of the Volpriehausen Sandstone in the map sheet area is up to 15 m (Langenholte-1; fig. 5.2).

The *Volpriehausen Clay-Siltstone* consists of a thick level of reddish-brown to green claystone, thin sandstone lenses and anhydrite nodules. The sediments are very argillaceous at the base, in sharp contact with the Volpriehausen Sandstone. The sediments of this member are coarsening upward. The thickness of the Volpriehausen Clay-Siltstone ranges from 85 m in the east to 50 m in the south of the map sheet area (fig. 5.2).

5.3 Upper Germanic Trias Group

5.3.1 Stratigraphy

This group in the map sheet area comprises the Röt Formation, the Muschelkalk Formation and the Keuper Formation. These formations are built up of clastic sediments, limestones, marls and evaporites. The group was deposited during the Middle and Late Triassic (Late Scythian to Norian age).

In the map sheet area the sediments of the Upper Germanic Trias Group are restricted to the Central Netherlands Basin. Dronten-1, one of the few wells besides Lelystad-1 and Langenholte-1 to contain Upper Germanic Trias sediments in the map sheet area, comprises a 210 m sequence. The extent of the Triassic is cut off in this area by the southern boundary fault of the Texel-IJsselmeer High, which runs immediately to the north of the Dronten-1 well (Map 6 and figure 5.1). South of the map sheet area, towards the axis of the Central Netherlands Basin, the total thickness of the section increases to approx. 400 m.

In the map sheet area the Upper Germanic Trias Group rests unconformably upon the Lower Germanic Trias Group and is, in its turn, overlain unconformably by the sediments of the Altena Group, the Rijnland Group or the North Sea Supergroup.

5.3.1.1 Röt Formation

The Röt Formation, Late Scythian to Anisian, is built up of the Solling Sandstone, the Solling Claystone, the Röt Evaporite and the Upper Röt Claystone. The formation rests unconformably upon the Main Buntsandstein and reaches a thickness of 115 m at the Dronten-1 well. The axis of maximum depositional thickness of the Röt Formation lies to the south of the Texel-IJsselmeer High in the Central Netherlands Basin.

The *Solling Sandstone* is composed of fine to coarse-grained sandstones a few metres thick, highly appropriate for well-log correlation. The Solling Sandstone in the map sheet area is very thin, and only present in the south of the map sheet area (Langenholte-1, fig. 5.2).

The *Solling Claystone* is a greyish-green and red argillaceous deposit, reaching a thickness of 28 m in the map sheet area (Dronten-1). Several members of the Lower Germanic Trias Group are overlain unconformably by the Solling Claystone. This unconformity has been named the Base Solling Unconformity (or Hardegsen Unconformity; fig. 1.6). The Solling Claystone lies unconformably on the Rogenstein or on the Main Claystone, depending on the depth of incision of the unconformity. In the east of the map sheet area, the Solling Claystone is overlain by sediments of the Rijnland Group (fig. 5.2).

The *Röt Evaporite* overlies the Solling Claystone, with a sharp boundary, and is 20 m thick in the map sheet area. The succession is composed of claystone, anhydrite and rock salt. Two Röt salt layers, separated by a thin clay layer a few metres thick, have been identified in the well logs of Ermelo-1 and Lelystad-1 (fig. 5.2).

The *Upper Röt Claystone* is mainly composed of reddish-brown, silty and anhydrite-bearing claystone and also comprises small white and light-green coloured sand beds. The succession is 65 m in thickness immediately to the south of the map sheet area (Ermelo-1; fig. 5.2) and the thickness increases up to 110 m in the west of the map sheet area.

5.3.1.2 Muschelkalk Formation

The Muschelkalk Formation, in the centre of the Permo-Triassic Basin of Northwest Europe, comprises the Lower Muschelkalk, the Muschelkalk Evaporite, the Middle Muschelkalk Marl and the Upper Muschelkalk. The Muschelkalk Formation in the map sheet area is only present in the extreme south (fig. 5.2 & 5.3).

The Muschelkalk in the Central Netherlands Basin reaches a thickness of 115 m (Oost-Flevoland-1). In the Dronten-1 well, the thickness reached is 80 m (fig. 5.2), indicating a possible thinning towards the Texel-IJsselmeer High. Towards the south the thickness of this formation rapidly increases. In the middle of the Muschelkalk interval an increase of dolomite and limestones can be perceived (fig. 5.2).

The formation rests conformably on the Röt Formation and is covered by the Keuper Formation, likewise conformably. The lithology consists mainly of light-grey and green claystones and dolomitic limestones which were deposited in a marine environment. The Muschelkalk Formation was deposited during the Anisian and the Ladinian.

The *Lower Muschelkalk* consists mainly of grey marls in the basal part and shows an upward increase in limestone and dolomite. There are also a few occurrences of claystone beds.

The *Muschelkalk Evaporite* is a 20 m thick layer composed of anhydrite and halite. High acoustic velocity facilitates identification on well logs.

The other Muschelkalk members are composed of marls, dolomites rich in clay, carbonates and anhydritic claystones.

5.3.1.3 Keuper Formation

The Keuper Formation, deposited during the Carnian, rests conformably upon the sediments of the Muschelkalk Formation. In the map sheet area the formation consists of green, grey or reddish-brown, silty clays and anhydrite beds.

Keuper deposits are presumed to occur in the extreme south and east of the map sheet area but have not been drilled there. The Lower Keuper Claystone sequence in the Ermelo-1 well (fig. 5.2 & 5.3) is just beyond the limits of the map sheet area.
In Northwest Europe the general succession of the Keuper Formation consists of different claystones and sandstones with rhythmic alternations of evaporite deposits (Warrington, 1974; Beutler & Schüler, 1979; Bertelsen, 1980). The Keuper succession exceeds a thickness of 500 m in the centre of the Northwest European Permo-Triassic Basin. In the map sheet area the thickness is much less with presumably no evaporite deposition (Ziegler, 1990). Owing to the very limited amount of well data on the Keuper Formation in the map sheet area, a more precise subdivision of the Keuper Formation has not been made.

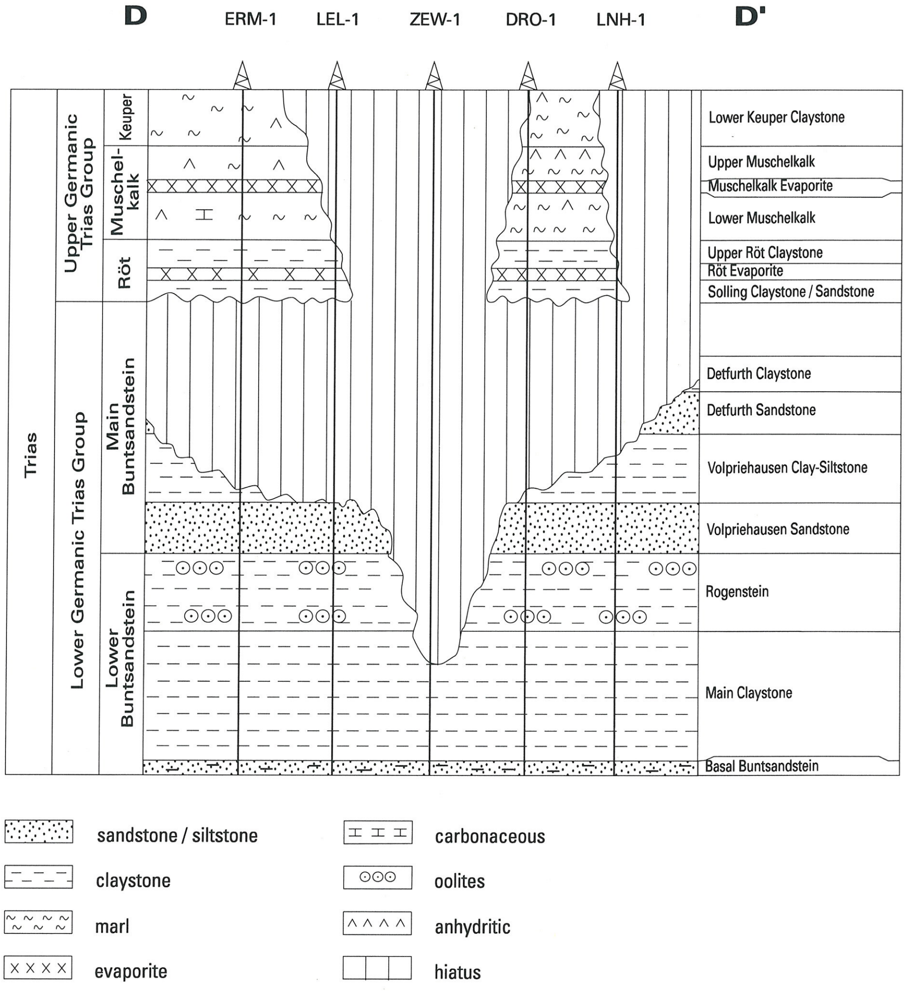


Figure 5.3 Lithostratigraphic diagram of the Triassic deposits situated directly south of the Texel-IJsselmeer High (section D-D'). The figure shows the lithological succession of the Lower and Upper Germanic Trias Groups and the Base Solling Unconformity. In the Lelystad-1, Zeewolde-1 and Langenholte-1, Late Kimmerian erosion has (partially) removed the Upper Germanic Trias deposits. The position of D-D' is indicated in figure 5.1.

5.4 Sedimentary development and palaeogeography

At the beginning of the Triassic, owing to sediment accumulation the relief of the Texel-IJsselmeer High was almost completely reduced. This was already noticeable during deposition of the Zechstein 4 Formation.

The regional, homogeneous composition of the Lower Buntsandstein Formation points to a uniform subsidence of the Permo-Triassic Basin. The sediments are interpreted as lacustrine deposits. The sediments were deposited in a vast lake and occasionally became exposed. According to Walker (1967), homogenisation and mixing of the red coloured oxides through the sediment took place in conditions of a fluctuating groundwater table and the arid climate. The oolites, which occurred predominantly in the Rogenstein and to a lesser extent in the Main Claystone, were formed in a lacustrine or shallow environment with saline conditions. The different oolite beds facilitate regional correlation. Because correlation across the Netherlands Swell proved to be difficult, it would appear that this swell affected the depositional environment during this early period of the Triassic.

The sandy deposits of the Main Buntsandstein Formation northwards represent prograding distal fan systems and fluvial systems. The argillaceous deposits indicate lacustrine conditions which predominated within the distal range of the fluvial systems (Brennand, 1975). Uplifts in the hinterland, or rising of the groundwater table, for example as a consequence of local basin subsidence, had an influence on this. In the map sheet area the occurrence of deposits of the Main Buntsandstein Formation demonstrates the tectonic influence of the Netherlands Swell and the different areas of subsidence which were situated to the west and east (fig. 11.1). On the Texel-IJsselmeer High the sediments of the Lower Germanic Trias have not been found but are presumed to have been deposited originally. After deposition of the Main Buntsandstein the uplift of the Netherlands Swell began, which was manifested in the Hardegsen tectonic phase (Wolburg, 1962; Schröder, 1982). The subcrop map below the Base Solling Unconformity displays NE-SW trending of the Netherlands Swell (NAM & RGD, 1980; fig. 11.1). The Hardegsen tectonic phase removed the greatest part of the Lower Germanic Trias.

After the Hardegsen tectonic phase, claystones were deposited in a lacustrine environment and rock salt in a marine environment. The thickening of the Röt Evaporite in the direction of the Central Netherlands Basin is remarkable. Two Röt evaporite cycles were deposited in a restricted marine, playa-like environment indicating that the differences in relief around the Texel-IJsselmeer High cannot have been very large. The Upper Röt Claystone represents a transgressive phase after a period of relative low stand. After the lacustrine and sabkha-like environment of the Scythian, marine conditions predominated during the Anisian and Ladinian. The transgression caused a change-over from clastic to carbonate (dolomite-rich) deposits.

The strong influence of structural highs and lows on the thickness of the Röt, Muschelkalk and Keuper Formation is illustrated by the different trends in thickness development. The total thickness of the Middle and Late Triassic sediments deposited on the Texel-IJsselmeer High will probably range from 100 to 300 m (RGD, 1989). This is in contrast to the 600 m thickness in the deeper parts of the Permo-Triassic Basin.

5.5 Reservoir-geological aspects

The gasfields of Wanneperveen and De Wijk (fig. 1.2) comprise a unique series of stratigraphic units from which gas is exploited. In these fields, the Tubbergen Sandstone, the Zechstein 2 Carbonate, the Rogenstein, the Volpriehausen Sandstone, the Vlieland Sandstone and the Basal Dongen Tuffite are gas-bearing. The gasfields occupy a geographical position between the Texel-IJsselmeer High and the Lower Saxony Basin and were discovered by the NAM in 1949.

In the major part of the gasfields, the Triassic is overlain unconformably by claystones of the Lower Cretaceous, which act as a vertical seal of the reservoir. Of the total thickness of 165 m of Rogenstein, 40 m consists of reservoir rocks (Gdula, 1983) which are for the most part built up of calcite ooliths partially composed of quartz sand. The remainder of the Rogenstein succession consists of sandy and silty claystones. The porosity of the pure, calcite oolite layers may reach 30%; the permeability may be as high as 1 Darcy. The porosity of the quartz sand present in the reservoir is approximately 25% and the permeability varies from 10 to 100 mD. Porosity in the Rogenstein developed mainly during the Kimmerian erosive period. Total solution of the cement took place above the Kimmerian palaeo-water level, whereas below it, the entire intergranulary porosity was lost through anhydritic pore filling (Gdula, 1983).

6 Altena Group

6.1 Stratigraphy

The Altena Group in the map sheet area, deposited during the Rhaetic and the Lias, is composed of dark claystones, belonging to the Sleen Shale Formation, the Aalburg Shale Formation and the lowest part of the Werkendam Shale Formation. In the map sheet area the first two formations have been penetrated and the Werkendam Formation has been seismically identified.

In the map sheet area, the sediments of the Altena Group were only preserved in large-scale synformal structures, such as the Central Netherlands Basin (Map 7). The greatest thicknesses have been identified in a deep synformal structure, immediately to the southwest of the map sheet area: the Gouwzee Trough.

The deposits of the Altena Group overlie the sediments of the Upper Germanic Trias Group. The deposits are overlain by sediments of the Lower Saxony Group and by the Rijnland Group, from which they are divided by the Late Kimmerian unconformities. The Altena Group is likewise unconformably overlain by the North Sea Supergroup.

Drillings in the Central Netherlands Basin were often carried out on high structures, where relatively little of the Jurassic sediments remained. The seismically recovered thickness of the Altena Group sometimes exceeds 400 m, while in the wells on the high structures, a maximum thickness of only 80 m is found. The variation in thickness of the Altena Group is to a large extent attributable to erosion (Map 8).

6.1.1 Sleen Shale Formation

The Sleen Shale Formation consists of a sequence of light grey claystones, with thin interbedded layers of dolomite and sandy claystones. A lithological tripartition can be made on the basis of the intercalated sands. Deposition took place in a marine basin with prevailing anoxic conditions.

The age of the Sleen Shale is Rhaetic, established by biostratigraphic studies on the Dronten-1 well (RGD, 1990a). In this well the Sleen Shale Formation covers an interval of 20 m thick.

The Sleen Shale Formation is conformably overlain by the Aalburg Shale Formation and unconformably overlain by deposits of the 'Upper Jurassic' Group, the Rijnland Group or the North Sea Supergroup.

6.1.2 Aalburg Shale Formation

The Aalburg Shale Formation is composed of dark grey and dark brown claystones, in silty occurrences locally. Thin dolomitic limestone beds occur within the claystones. The formation has constituents of pyrite, siderite, coal fragments and belemnites. The Aalburg Formation was not fully penetrated by drilling, but the seismically inferred thickness ranges from 350 to 400 m.

The Aalburg Shale Formation rests conformably upon the Sleen Shale Formation. In the map sheet area the formation is conformably overlain by the Werkendam Shale Formation, or unconformably by Upper Jurassic deposits, the Rijnland Group or the North Sea Supergroup.

The sediments of the Aalburg Formation were deposited during the Hettangian up to the Pliensbachian. The determinations of foraminifera and ostracods allow a biostratigrahical subdivision of different stages of the Lias.

6.1.3 Werkendam Formation

The sediments of the Werkendam Formation in the map sheet area have not been penetrated. The presence of the lowest part of the formation, the Posidonia Shale Member can be inferred from seismics.

The Werkendam Formation comprises claystones deposited in a marine environment. The Posidonia Shale, at the base of the formation, consists of blackish-brown, bituminous claystones, deposited in a euxenic environment. The high marine organic component content makes this member an important oil-source rock in other regions. The Posidonia Shale was deposited during the Toarcian.

The sediments of the Werkendam Formation are overlain unconformably by the Upper Jurassic deposits and the sediments of the Rijnland Group or the North Sea Supergroup.

6.2 Sedimentary development and palaeogeography

The claystones of the Altena Group were deposited under marine conditions. The fine-grained character of the deposits points to the absence of land in the immediate vicinity. Although, from a regional perspective, there was probably intensified tectonic activity at the end of the Triassic (Early Kimmerian phase) no stratigraphic indications are present in the map sheet area. There is no evidence of a large-scale regressive trend, nor of an unconformable depositioning.

The claystones of the Sleen and of the Aalburg Formation were deposited in a deep marine environment. A transgression caused the development of a connection between the Tethys and the Arctic Ocean, indicated by mixing of the different faunas. The deposition of the Werkendam Shale Formation is characterised by a stagnating water circulation in the basin, in which the organically rich material of the Posidonia Shale was deposited under anoxic conditions. During a high stand, the shale originated in the deepest part of the basin where the vertical water circulation stagnated as a result of stratified density inversion.

The reconstruction of the subsequent depositional history of the Altena Group is seriously hampered by the lack of deposits in large areas as a consequence of younger tectonic uplift and associated erosion. However, the development of the sediments of the Altena Group in the West Netherlands Basin may indicate that the sedimentation was mainly restricted to the deeper parts of the Central Netherlands Basin. Progressively less deposition occurred towards the margins and erosion became active (Haanstra, 1963a, 1963b; Van Wijhe, 1987a).

During the Early Jurassic a period of extensional tectonic conditions and basin subsidence developed in Northwest Europe, to which a large part of the region was subjected. Differential basin subsidence caused a variety of depositional thicknesses in the different subbasins of the Jura sea. The Texel-IJsselmeer High probably subsided less in comparison with the Central Netherlands Basin.

7 'Upper Jurassic' Group

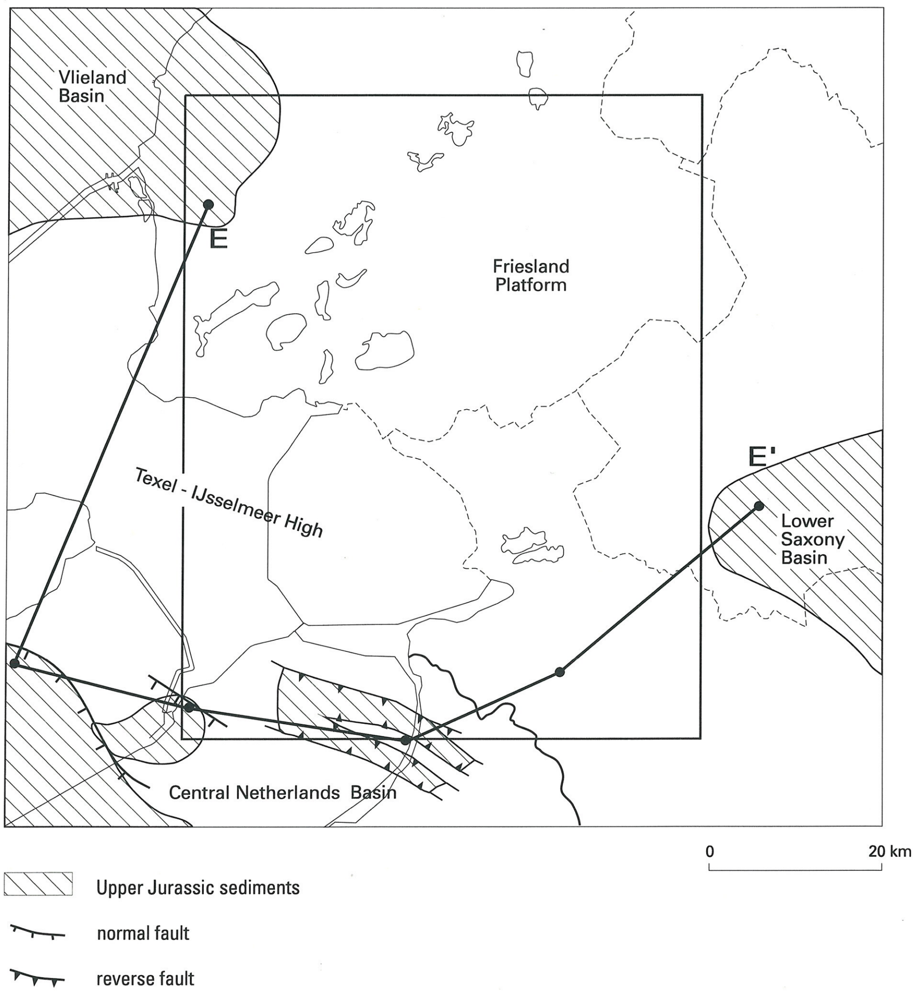
7.1 General

The sediments in the map sheet area of a Late Jurassic to earliest Cretaceous age (Kimmeridgian – Ryazanian) are discussed in this explanation as the Upper Jurassic deposits.

Upper Jurassic deposits are found in the Central Netherlands Basin, in the Vlieland Basin and also immediately to the east of the map sheet area, in the Lower Saxony Basin (Map 9 & fig. 7.1). The Upper Jurassic deposits in the Lower Saxony Basin belong to the Lower Saxony Group. The Lower Saxony Basin extended over a part of the east of The Netherlands and the central part of the former Federal Republic of Germany (Bischoff & Wolburg, 1963; 't Hart, 1969). The map sheet area is situated just outside the most westerly margin of the Lower Saxony Basin (fig. 7.1).

The Upper Jurassic deposits to the west of the map sheet area and in the Vlieland Basin have been designated by Herngreen et al. (1989) as belonging to the Delfland Formation of the Central Graben Group. The Upper Jurassic deposits which were recovered in the south of the map sheet area in the Central Netherlands Basin are comparable with the deposits of the Central Graben Group as well as with those of the Lower Saxony Group and consequently both are discussed in this

Figure 7.1 Upper Jurassic basins situated in the map sheet area and the position of section E-E' of figure 7.3.



chapter. In the central part of the map sheet area, on the Texel-IJsselmeer High and the Friesland Platform, no Upper Jurassic deposition occurred.

A seismic section transecting the southern boundary fault of the Texel-IJsselmeer High illustrates onlap structures (fig. 11.2). The interval containing these features was not drilled but their stratigraphical position and seismic character point to Upper Jurassic deposition.

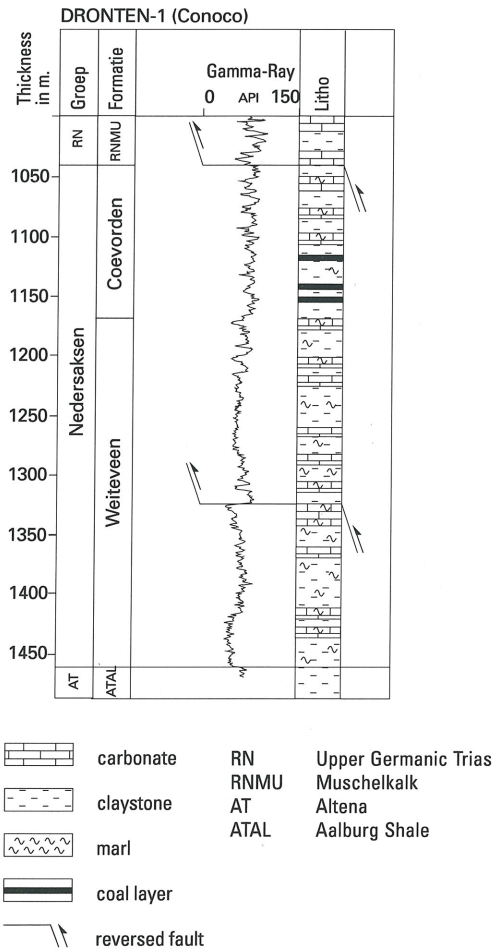
Lithostratigraphic and chronostratigraphic aspects of the Upper Jurassic deposits are explained by well correlation sections on and in the immediate vicinity of the map sheet area (fig. 7.2 & 7.3).

7.2 Central Graben Group

7.2.1 Stratigraphy

Deposits of the Central Graben Group consist of clastic sediments and coal seams. In this map sheet area the Central Graben Group only comprises the Delfland Formation. In the Dronten-1 well a mixed lithology of both the Central Graben and the Lower Saxony Group appears to be present.

Figure 7.2 Upper Jurassic interval in the Dronten-1 well. The coal seams have been determined by sonic logs, but which are not shown in this figure owing the poor quality. The well passes through a series of faults. The uppermost fault is a reverse fault which has effected the overlap of the Muschelkalk (Triassic) above Coevorden (Upper Jurassic). The bottommost fault is also a reverse fault and caused the stratigraphic heave of the Weiteveen Formation.



7.2.1.1 Delfland Formation

The Delfland Formation is mainly built up of grey, green or brown siltstones, with light to dark brown intercalated sandstones. Plant debris and coal seams are usually present in the topmost part of the formation. The sediments of the Delfland Formation were predominantly deposited in a continental environment.

According to Herngreen et al. (1991), the Delfland Formation in the Vlieland Basin dates from Late Kimmeridgian to Ryazanian. The Delfland sediments recovered immediately to the west of the map sheet area (IJsselmeer-1) date from the Portlandian (RGD, 1974). In the Central Netherlands Basin, the Delfland Formation has been demonstrated to be Late Portlandian to Ryazanian (RGD, 1990). Consequently the base of the formation in the Vlieland Basin is older than its base in the Central Netherlands Basin (fig. 7.3).

In the map sheet area the Delfland Formation rests unconformably upon the Altena Group, separated by the Late Kimmerian I unconformity. The Upper Jurassic deposits are conformably overlain by deposits of the Rijnland Group (Map 17).

The thickness of the Delfland Formation slightly exceeds 100 m in the Bolsward-1 well (Herngreen et al., 1991), but in the centre of the Vlieland Basin, to the northwest of the map sheet area, thicknesses up to 500 m were deposited (Map 10).

7.3 Lower Saxony Group

7.3.1 Stratigraphy

The Lower Saxony Group consists of marls, limestones, claystones and evaporites and is subdivided into the Weiteveen and the Coevorden Formation (NAM & RGD, 1980). Evaporites have not been found in the map sheet area, but towards the Lower Saxony Basin evaporites occur with increasing frequency. The Lower Saxony Group in the map sheet area was deposited during the Portlandian and the earliest Ryazanian (RGD, 1990; fig. 7.3).

The Upper Jurassic deposits occur in this map sheet area to the south of the Texel-IJsselmeer High (Map 9) and also immediately to the east of the map sheet area. The description of the deposits of the Lower Saxony Group is restricted to the occurrences in the south of the map sheet area. Here they overlie the Altena Group unconformably. Furthermore, the Lower Saxony deposits in the map sheet area are overlain unconformably by the North Sea Supergroup. A total thickness of over 400 m of Upper Jurassic deposits has been recovered in the well Dronten-1. In a westerly direction the thickness decreases rapidly. Progressive thickening occurs towards the east to over 600 m in the Lower Saxony Basin situated outside the map sheet area.

7.3.1.1 Weiteveen Formation

The Upper Jurassic deposits from the Dronten-1 well exhibit a greater lithological resemblance to the marine and lacustrine sediments of the Lower Saxony Basin in contrast to the clastic sediments of the Delfland Formation in the Vlieland or the Central Netherlands Basin, reflecting a predominantly continental deposition (fig. 7.3). Biostratigraphic research has determined that in the well Dronten-1, the interval range from 1175 m to 1464 m encompasses the Portlandian (RGD, 1990). No subdivision of the Weiteveen Formation has been made owing to the absence of evaporites (fig. 7.2).

The Weiteveen Formation, Portlandian, is composed of calcareous claystones and argillaceous limestones and dolomite. The claystones are dark grey/light grey to green. The dolomite layers are frequently brown and coarse-grained. Massive limestone beds reach a maximum thickness of 5 m. Thin beds of marl and limestone frequently alternate.

Towards the west and the south there is presumed to be a transition from the Weiteveen Formation into the continental and fluvial sediments of the Delfland Formation. In the map sheet area the Weiteveen Formation exhibits marine or lacustrine elements, such as ostracods. In this Weiteveen interval some levels contain organic material. A low energetic and terrestrial to brackish environment is inferred from the fossil content, in particular the presence of thin-walled ostracods.

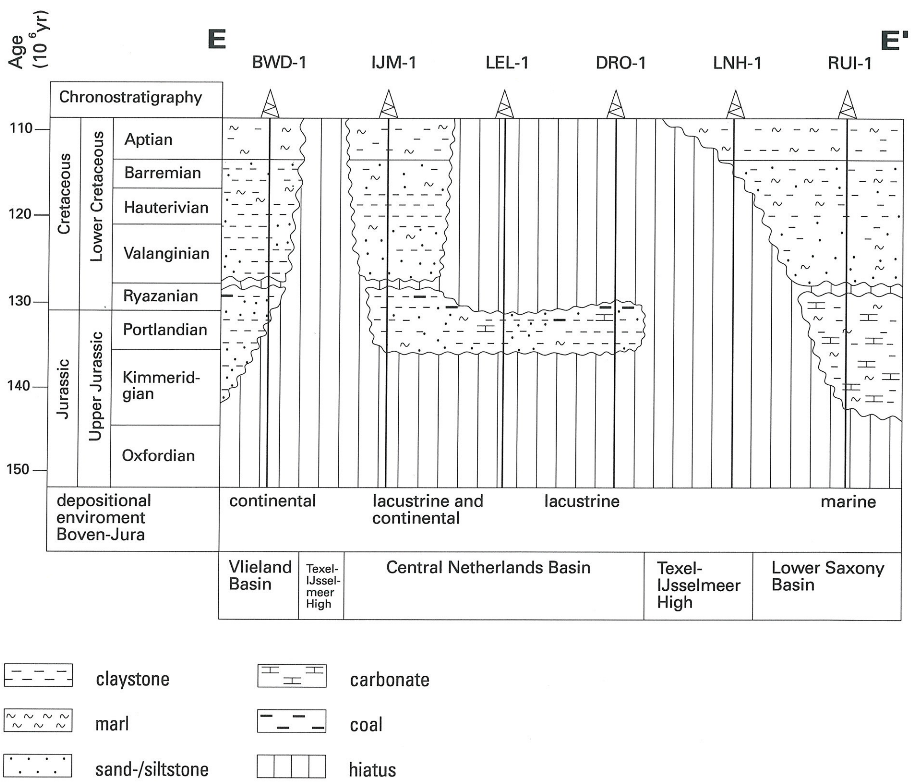
The thickness of the Weiteveen Formation in the Dronten-1 well is 285 m and 150 m in the Ruinen-1 well. In the Dronten-1 well the thickness of this formation may have doubled through reverse faulting at a depth of approx. 1325 m (RGD, 1990), caused by Sub-Hercynian or Laramide compressive inversional tectonics.

The Weiteveen Formation rests unconformably upon the Altena Group and is conformably overlain by the Coevorden Formation.

7.3.1.2 Coevorden Formation

The Coevorden Formation consists of marly claystones, limestone beds and small coal seams and in addition comprises a number of characteristic elements of the Delfland Formation (see section 7.2.1.1). The formation was deposited in fresh to brackish water (RGD, 1990). Within the map sheet

Figure 7.3 Lithostratigraphic diagram of the Upper Jurassic and the Lower Cretaceous deposits showing the position within the map sheet area. Section E-E' demonstrates the chronostratigraphic relation between the sediments of the Delfland Formation and the Lower Saxony Group. The position of the section is indicated in figure 7.1.



area the Coevorden Formation was penetrated only in the well Dronten-1. The formation there covers an interval of 140 m with a presumed age dating of Early Ryazanian.

7.4 Sedimentary development and palaeogeography

Sedimentation in the Lower Saxony Basin commenced during the Kimmeridgian, as in the case of the Vlieland Basin. The Lower Saxony Basin extended from the east of The Netherlands far into Germany. In this basin, lacustrine, evaporitic and shallow marine conditions prevailed. In the south of the map sheet area, during the Portlandian, lacustrine restricted marine) to continental depositional conditions were dominant. A kind of inland lake or bay existed here, probably interconnected with the Lower Saxony Basin. This bay underwent deposition of clays and marls under low energetic conditions. During the Ryazanian peat developed in this area.

The Central Netherlands Basin and the Vlieland Basin were separated by the Texel-IJsselmeer High. In the Central Netherlands Basin sedimentation of the Delfland Formation began during the Portlandian, in contrast to the Vlieland Basin where sedimentation had already started during the Kimmeridgian. The Portlandian transgression effected lagoonal-clay deposition in a brackish-water environment. These clays are covered by sediments indicative of a relative low stand and were probably even deposited under continental conditions during the Ryazanian. This can be interpreted from the coarsening-upward sequence and the intercalated coal seams (Rijks Geologische Dienst, 1991a). The area of provenance for the Upper Jurassic deposits lay on the surrounding structural highs, such as the Texel-IJsselmeer High (RGD, 1974) and the Friesland Platform.

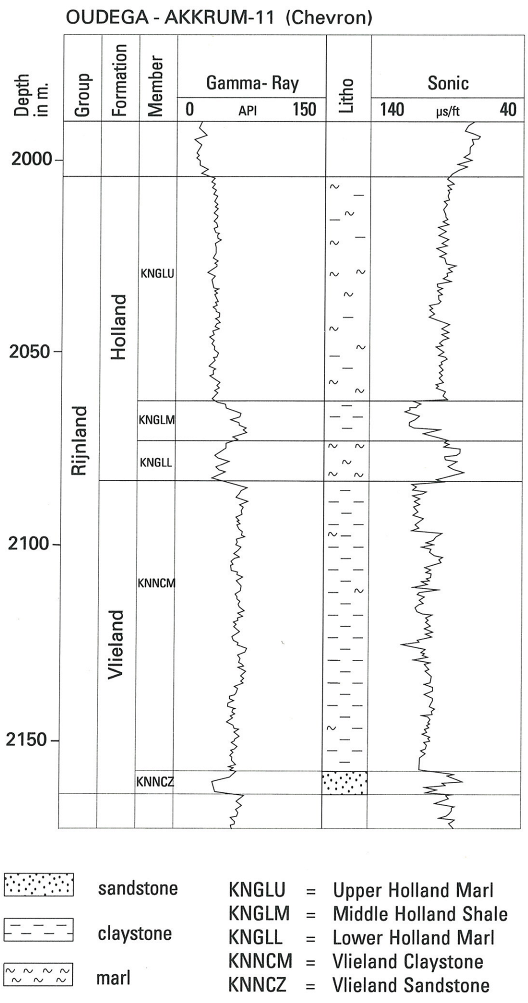
8 Rijnland Group

8.1 Stratigraphy

The Rijnland Group, subdivided into the Vlieland Formation and the Holland Formation (fig. 8.1), consists of greyish-brown to green basal sandstones and grey to brown coloured siltstones, claystones and marls. The Rijnland Group was deposited in an initially shallow-marine environment which became gradually more open marine. The Rijnland Group was deposited during the Early Cretaceous.

The Rijnland Group unconformably overlies the Altena, the Upper and Lower Germanic Trias, the Zechstein, the Upper Rotliegend and the Limburg Group (Map 16). In the Vlieland Basin and the Lower Saxony Basin the Rijnland Group covers the Upper Jurassic deposits. In the map sheet area the Rijnland Group is overlain conformably by the Chalk Group. The sediments of the Rijnland Group occur on the Friesland Platform and the Texel-IJsselmeer High (Map 11). Deposits of the Rijnland Group are not present in the southernmost part of the map sheet area.

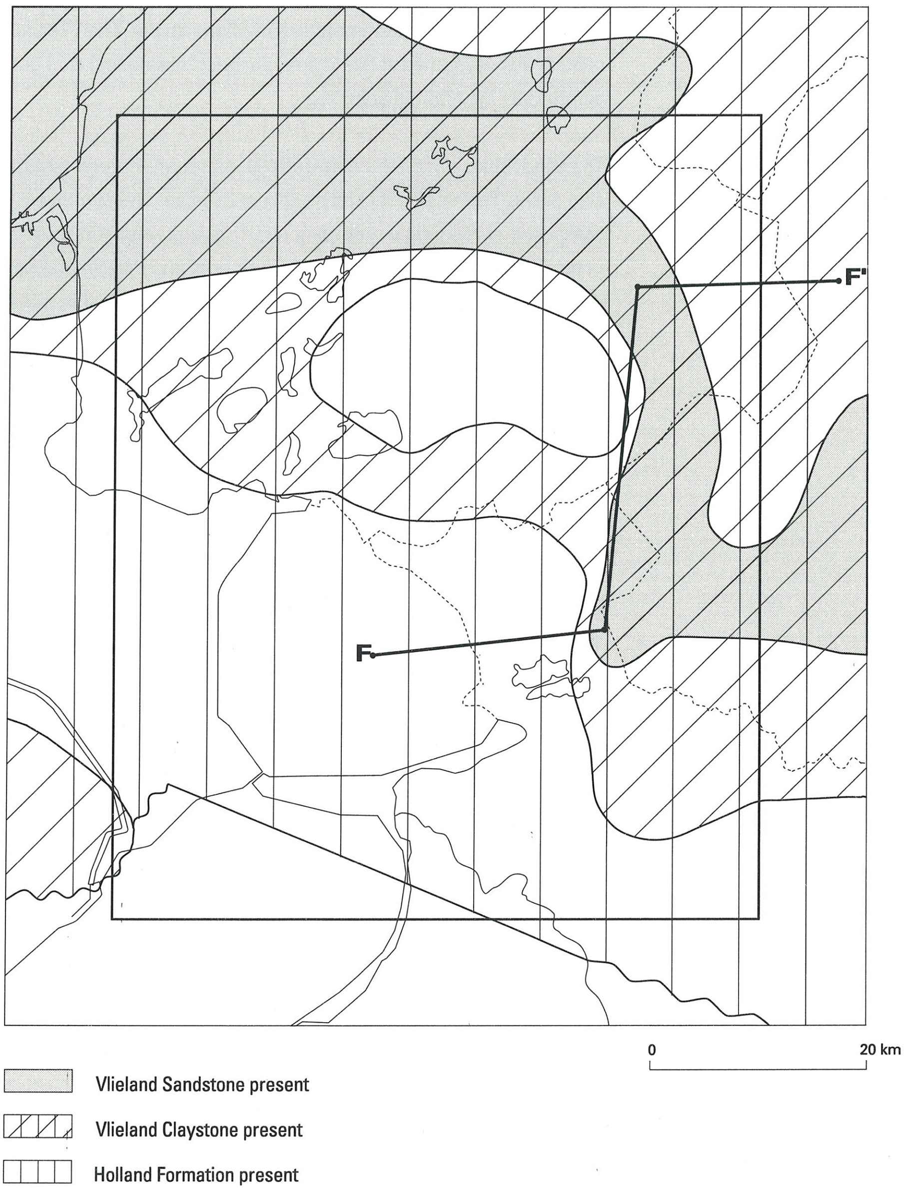
Figure 8.1 Lower Cretaceous interval in the Oudega-Akkrum-11 well.



The thickness of the Rijnland Group ranges in the map sheet area from 50 m in the centre to 450 m in the northwest (Map 12). Depocentres of the sandy basal Rijnland deposits, the Vlieland Sandstone, are located in the north and the east of the map sheet area (fig. 8.2). The thicknesses increase from outside the map sheet area towards the centre of the Vlieland Basin and the Lower Saxony Basin to over 750 m.

The development of the sediment sequence of the Rijnland Group is illustrated by the Oudega-Akkrum-11 well (fig. 8.1), a distribution map (fig. 8.2) and a correlation section (fig. 8.4).

Figure 8.2 Distribution map of Lower Cretaceous deposits in map sheet V and section F-F' (based on wells and seismics). A distinction has been made between the Vlieland Sandstone and the Vlieland Shale. The presence of the Vlieland Sandstone Formation on the northeastern part of the Friesland Platform reflects the feature referred to as the 'corridor' which lay in between the Texel-IJsselmeer High and the Groningen High during the Early Cretaceous (8.1.1)..



8.1.1 Vlieland Formation

The Vlieland Formation (NAM & RGD, 1980), Late Ryazanian up to Barremian, comprises the basal Vlieland Sandstone Member and the overlying Vlieland Shale Member in the map sheet area. The Vlieland Formation was deposited in a shallow-marine to open-marine environment under transgressive conditions. In the Vlieland Basin and the Lower Saxony Basin the formation rests unconformably (with a small time hiatus) upon the underlying sediments of the Central Graben Group and the Lower Saxony Group respectively. The formation, separated by a hiatus, is overlain by deposits of the Holland Formation. The Vlieland Formation does not occur in the south of the map sheet area and was most probably not deposited here either. The thickness ranges from 8 m in the southeast to 410 m in the northwest.

The *Vlieland Sandstone* comprises an alternation of light grey and green medium-fine sandstones, dark siltstones and silty claystones. There are very local occurrences of intercalations of coarsening-upward conglomeratic sandstone layers. The Vlieland Sandstone overlies with a sharp contact the claystones of the 'Upper Jurassic' Group and is in general clearly demonstrated on the gamma-ray log and the sonic log.

The sandstones are often cross-bedded, although through bioturbation, homogeneous sandstones also occur. The small silty and argillaceous layers are laminated. The sandstones are mainly composed of moderately rounded quartz grains, with constituents of mica, pyrite and glauconite. In the Oudega-Akkrum-2 well, coal fragments and Pelecypoda have been found in the sandy intervals. A thin section of the Vlieland Sandstone from this well demonstrates that besides quartz grains (up to 0.08 mm), detrital mica and calcite pore fillings are also present (appendix I; photo 3). Cross stratification and bioturbation reflect a nearshore, shallow-marine depositional environment, as in shore-face systems. In the area of the well Wanneperveen-1 the coarse and poorly sorted sands were deposited by a combined alluvial fan/fluvial system (Dorsman, 1954), which protruded into the sea.

Three subbasins can be identified, the Southern Vlieland Basin, the Leeuwarden Subbasin and the Wanneperveen Subbasin, characterised by deposition of relatively thick sand bodies (fig. 8.3). In the map sheet area the thickest succession of the Vlieland Sandstone Member lies in the Southern Vlieland Basin, and the thickness even exceeds 100 m immediately to the west of the map sheet area (fig. 8.3).

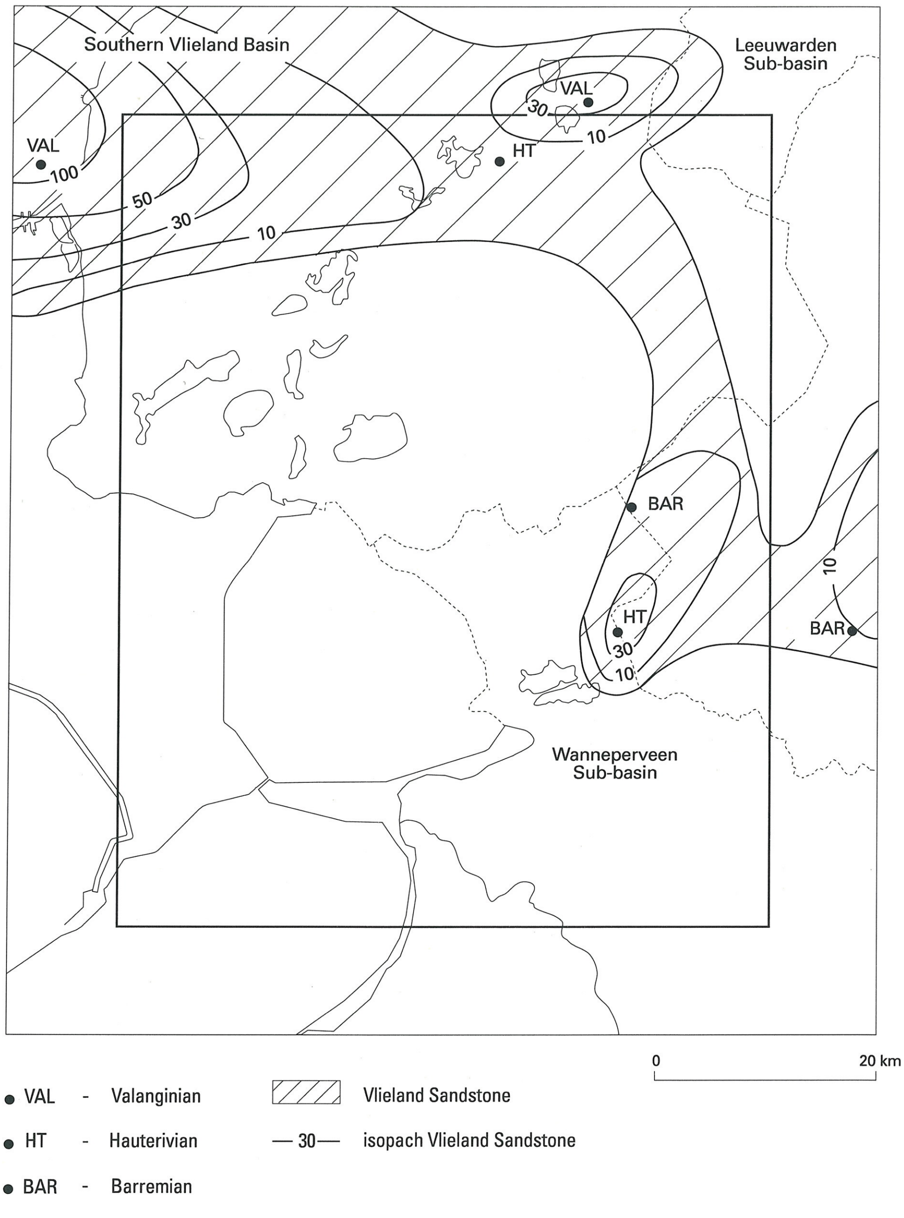
Within the map sheet area the Vlieland Sandstone occurs in the Vlieland Basin, the Lower Saxony Basin, and in the 'corridor' interconnecting the two basins, via the Leeuwarden and Wanneperveen Subbasins (fig. 8.3). In the Vlieland Basin the age of the Vlieland Sandstone Formation ranges from Late Ryazanian up to Early Valanginian (Herngreen et al., 1991; RGD, 1991a). The biostratigraphic age datings of the Vlieland Sandstone in the 'corridor' reveal a younger age, namely Hauterivian (RGD, 1991c, 1991d), and in the Nijensleek-1 well the Vlieland Sandstone is of an even younger age, namely Barremian (RGD, 1992d). Consequently, the basal sands of the Vlieland Formation in the map sheet area are diachronous (fig. 8.3).

In the map sheet area the Vlieland Sandstone is gas-bearing in the vicinity of Leeuwarden/Akkrum and of Wanneperveen (fig. 1.2). Locally, these porous, permeable sandstones reach relatively great thicknesses of up to 25 m (fig. 8.4), which makes these sands a suitable target for exploration. The greatest thicknesses were probably deposited in palaeo-depressions.

The *Vlieland Shale* consists of dark brown and dark grey, silty claystones. The succession ranges in thickness from 16 m in the 'corridor' (fig. 8.4) to over 320 m in the Vlieland Basin. During the Valanginian the claystones were deposited in a shallow-marine basin which deepened during the Hauterivian and the Barremian.

The Vlieland Claystone Member is unconformably overlain by claystones of the Holland Formation. The thick claystones of the Vlieland Shale evidently form a good seal for the gas-bearing reservoir sands of the Vlieland Sandstone in the Leeuwarden/Akkrum and the Wanneperveen gas field.

Figure 8.3 Highly simplified isopach map of the Vlieland Sandstone and age of the base. Deposition of the sands occurred in the Vlieland Basin during the Valanginian, which only started in the 'corridor' (between the basins) during the Hauterivian and the Barremian.



8.1.2 Holland Formation

The Holland Formation consists of a succession of light to dark grey, sometimes purple coloured, marly claystones. The formation is the upper unit of the Rijnland Group and well logging enables tripartition into members, which can be identified in large parts of The Netherlands: the Lower Holland Marl, the Middle Holland Shale and the Upper Holland Marl. The formation was deposited in a shallow to deep marine environment during the Late Aptian and the Albian.

In the major part of the map sheet area, the Holland Formation rests unconformably upon the claystones of the Vlieland Formation. The hiatus between the two formations covers almost the complete Early Aptian (Herngreen et al., 1991). On the Texel-IJsselmeer High and the Friesland Platform the Limburg, the Upper Rotliegend, the Zechstein or the Lower Germanic Trias Group are overlain unconformably by the Holland Formation which in its turn is conformably overlain by deposits of the Chalk Group.

The Holland Formation occurs throughout the map sheet area with the exception of the Central Netherlands Basin, where the formation has been eroded. The thickness ranges from 34 m in the centre to over 190 m in the east of the map sheet area.

The *Lower Holland Marl* is composed of light grey and dark grey marly claystones. Occasionally these sediments are reddish-brown or ochre yellow in colour.

The Lower Holland Marl overlies the Vlieland Shale Member with a hiatus covering nearly the complete Early Aptian (Herngreen et al., 1991). The Lower Holland Marl was deposited during the Middle and Late Aptian. The thickness ranges from 2 m in the northwest up to 20 m in the east of the area. This succession does not occur on the Texel-IJsselmeer High.

The Middle Holland Shale in the map sheet area consists of dark grey claystones which prove to be highly suitable for well-log correlation in the north of the map sheet area. This succession does not occur on the Texel-IJsselmeer High.

The *Middle Holland Shale* clearly displays a high gamma-ray reading and a low acoustic velocity with respect to the underlying and overlying marl successions of the Holland Formation (fig. 8.1). The member ranges in age from Early Albian up to Middle Albian.

The Middle Holland Shale in the map sheet area rests upon the Lower Holland Marl, separated by a hiatus (Herngreen et al., 1991). This hiatus, in the north of the map sheet area in particular, covers the transition of the Aptian-Albian. To the northeast of the map sheet area the shale series reaches a maximum thickness of 39 m.

The *Upper Holland Marl*, Late Albian, is composed of light grey and light purple coloured marly and silty claystones. According to Herngreen et al. (1991) a few small hiatuses occur within the Upper Holland Marl succession.
On the Texel-IJsselmeer High, the Upper Holland Marl rests unconformably upon the deposits of the Limburg, the Upper Rotliegend or the Zechstein Group (fig. 8.4; RGD, 1992b). On the northern flank of the Texel-IJsselmeer High the Upper Holland Marl lies conformably on the Middle Holland Shale. The Upper Holland Marl is conformably overlain by the Texel Chalk Formation. The thickness of the marl increases in a southeasterly direction, from over 20 m in the north of the area to 95 m in the southeast.

8.2 Sedimentary development and palaeogeography

During the Ryazanian the north of The Netherlands was completely submerged as a consequence of a gradual sea-level rise. During the deposition of the Rijnland Group synsedimentary faulting occurred in the northern part of the map sheet area. The sandy, marine sediments deposited in the map sheet area from the Ryazanian to the Barremian form the base of a transgressive series. The complete Rijnland Group can be considered as a transgressive megasequence. The Late Kimmerian palaeorelief is overlain diachronously by the sands of the Lower Cretaceous. Finally, the sea also flooded the Texel-IJsselmeer High, as a consequence of a regional transgression which persevered until Late Cretaceous (Crittenden, 1987).

The sandstones of the Vlieland Formation were initially deposited in the centre of the Vlieland Basin and the Lower Saxony Basin, in a shallow-marine environment. The thickness and the

Figure 8.4 Lithostratigraphic schematic section F-F' of the Lower Cretaceous deposits. The section transects the 'corridor' which has connected the Vlieland Basin with the Lower Saxony Basin since the Hauterivian. The position of F-F' is indicated in figure 8.2.

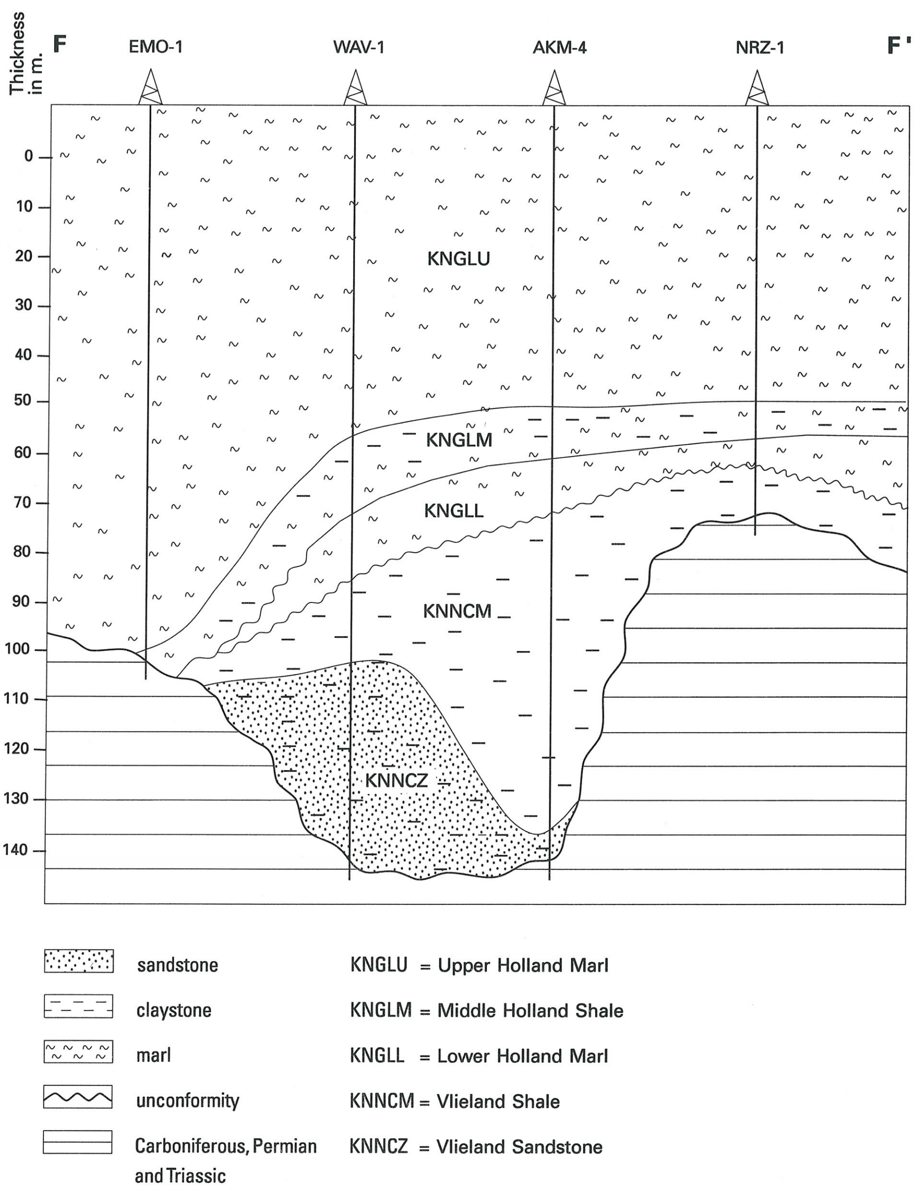
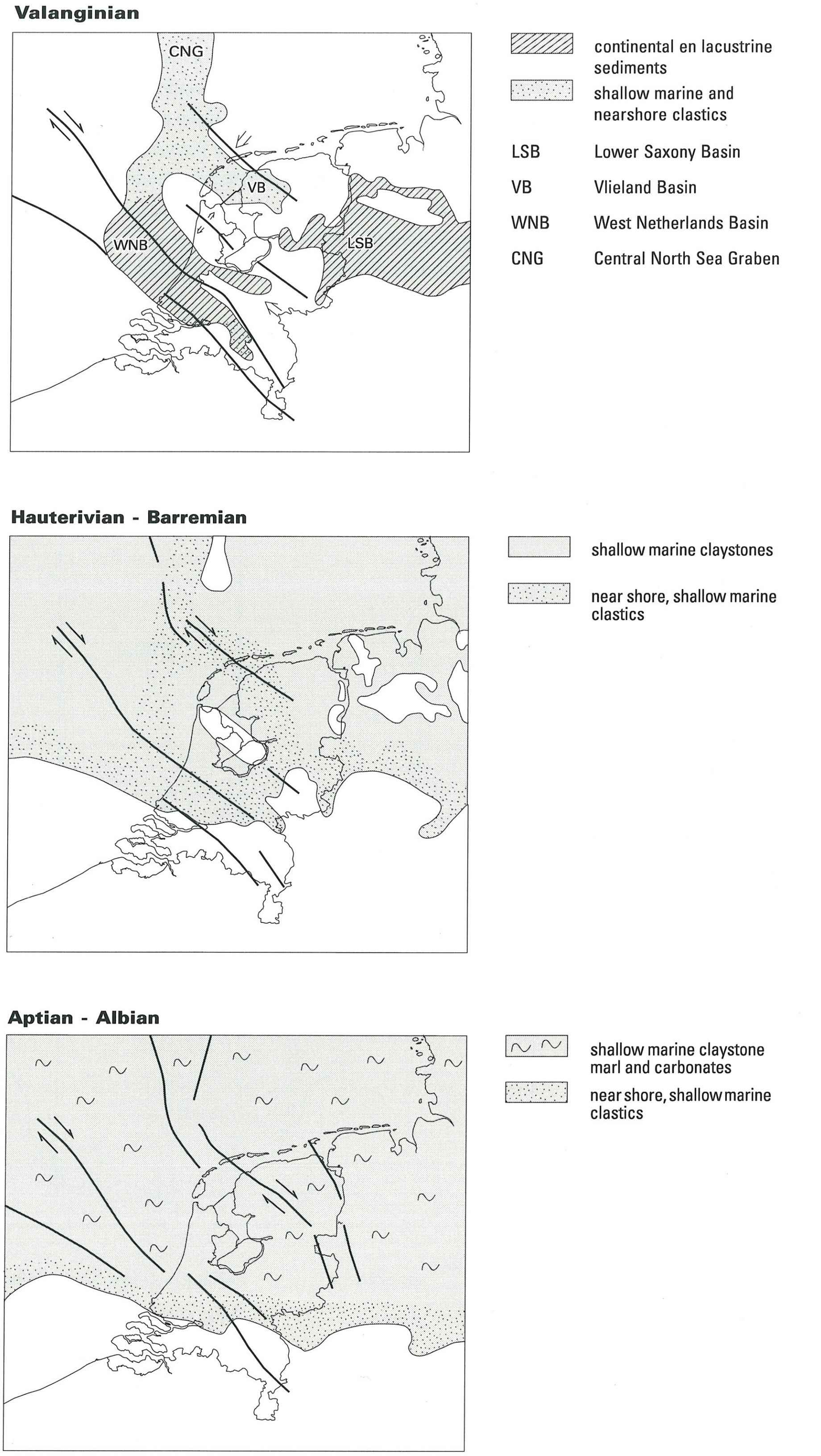
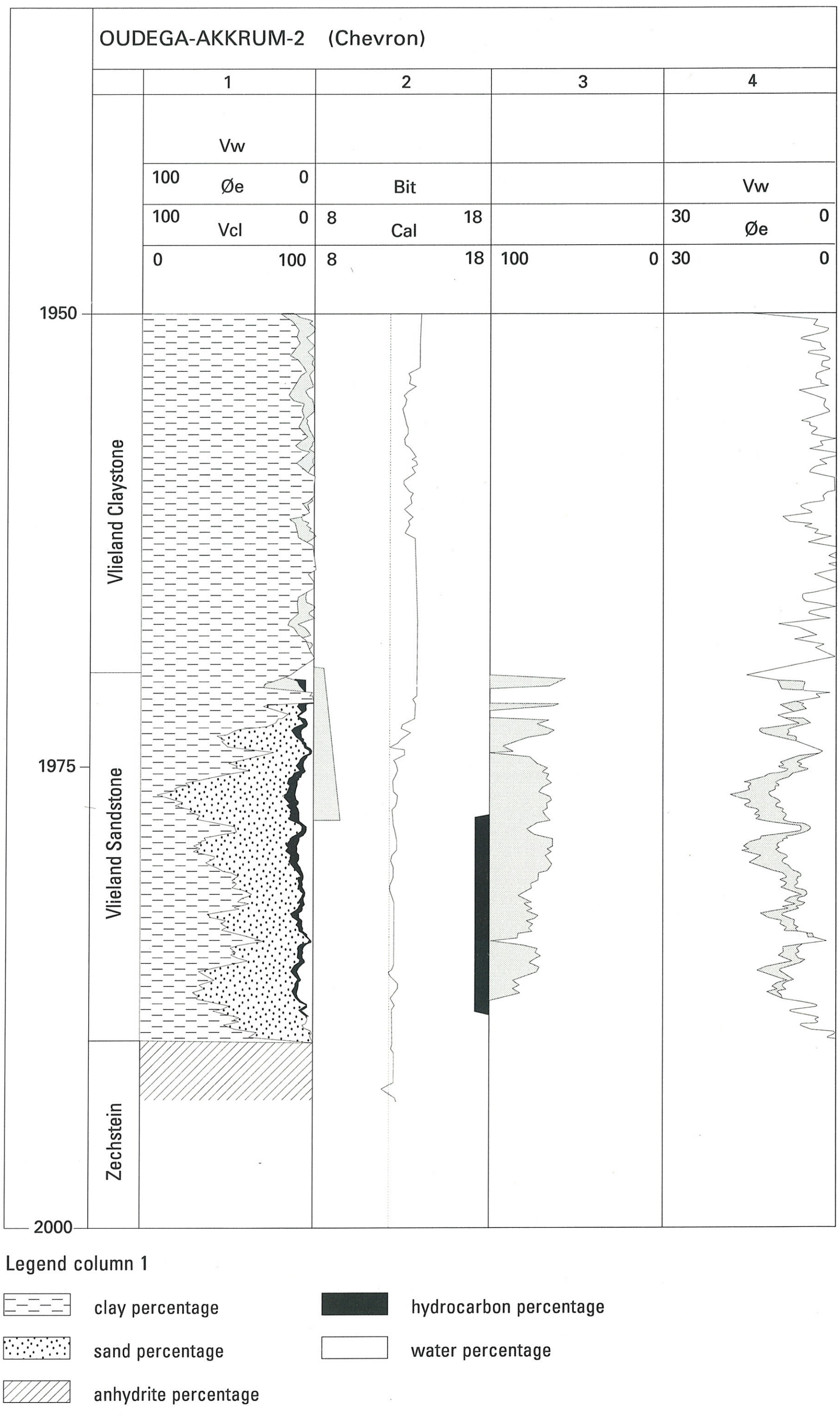


Figure 8.5 Palaeogeography of the Lower Cretaceous in The Netherlands (after Ziegler, 1990).



occurrence of the sandstones were mainly determined by the palaeorelief evolving at the end of the Late Kimmerian tectonic phase. The coarse conglomeratic intercalations are presumed to have been deposited within the distal range of fans which protruded into the sea.

Figure 8.6 Petrophysical evaluation of the Vlieland Sandstone interval in the Oudega-Akkrum-2 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw, all given in percentages. Owing to the glauconite content of the Vlieland Sandstone Formation, the gamma-ray log reading is not suitable as a clay indicator. The clay content was determined with the use of the density-sonic indicator (Fertl, 1987). The effective porosity was obtained using the single porosity model by the density log (sonic log) taken as porosity log, for which the calculated log porosity was corrected for the clay and hydrocarbons present. Column 2: drill hole diameter (Cal) and bit diameter, both in inches; furthermore the tested intervals (appendix H) are indicated by trapezia signs, and the cored interval by a black bar. Column 3: water saturation Sw %. The Indonesia formula, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe (left curve) and the volume of water in the pores Vw (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated. The depths are the actual depths.



During the Hauterivian and the Barremian clay was deposited in the Vlieland Basin and the Lower Saxony Basin. The age dating of the basal Vlieland Sandstone in the Wanneperveen-1 well (RGD, 1991c) indicates that the 'corridor' between the Vlieland Basin and the Lower Saxony Basin was not achieved before the Hauterivian/Barremian. In the Hauterivian and the Barremian the sedimentation of clays extended over the highs. The transgression approached from the Atlantic Ocean, via the Central North Sea Graben and migrated from the north into the Vlieland Basin, while the transgression in the Lower Saxony Basin approached from the eastern Tethys and migrated from the Polish Trough.

The palaeogeography of the Lower Cretaceous, during and after the Late Kimmerian phase, accounts for the local occurrences of the Vlieland Sandstone in the map sheet area (fig. 8.5). The sands in the Southern Vlieland Basin and in the Leeuwarden and Wanneperveen Subbasins were

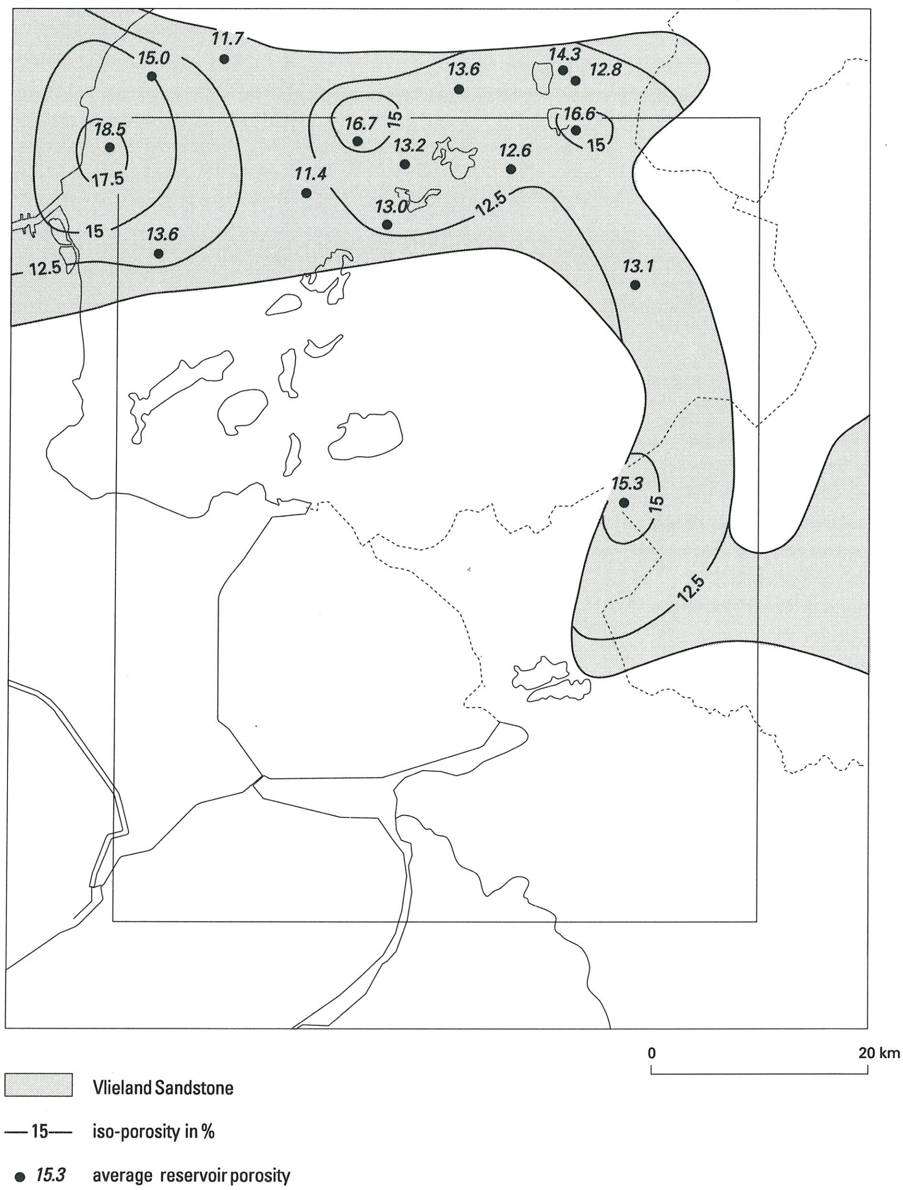


Figure 8.7 Schematised contour map of the reservoir-average effective porosity Øem of the Vlieland Sandstone Formation (in percentages). The values of the marked data points are also given in appendix G. For the porosities not given, reference should be made to Rijks Geologische Dienst 1991a and 1991b.

deposited in a nearshore marine depositional environment, while coarse-grained sediments derived from the structural highs were discharged into the basins via rivers and alluvial fan systems. With the transgression throughout the Lower Cretaceous, the Vlieland sands diachronously covered the Late Kimmerian palaeorelief.

At the end of the Barremian only the Texel-IJsselmeer High was still elevated above sea level. During the Aptian and the Albian very few structures with a minimum of relief still protruded above the water. The coastline during the Aptian and Albian was situated south of the map sheet area; consequently the clastic influx was low and the sediments of the Holland Formation became marly. However, the sea did not reach the highest part of the Texel-IJsselmeer High until the Late Albian when the Upper Holland Marl was deposited (RGD, 1992b).

8.3 Petrophysical evaluation

In the north and east of the map sheet area there are a number of small gasfields producing gas from the Vlieland Sandstone (fig. 1.2). Seven boreholes have been selected for the petrophysical evaluation of the Vlieland Sandstone in map sheet area V (appendix G). In two of these boreholes, the Vlieland Sandstone has been proved to be gas-bearing (appendix H). The log evaluation of the Vlieland Sandstone in particular illustrates the result of the Oudega-Akkrum-2 borehole (fig. 8.6).

Figure 8.7 gives the schematic distribution of the reservoir-average effective porosity of the Vlieland Sandstone. The lateral extent of the Vlieland Sandstone is based on well data. A comparison of the data illustrated by this figure with the thickness map of the Vlieland Sandstone (fig. 8.3) shows that the maximum porosity readings match the depocentres of the Vlieland Sandstone.

9 Chalk Group

9.1 Stratigraphy

The Chalk Group, Late Cretaceous, is divided into the Texel Chalk and the Ommelanden Chalk Formation (fig. 9.1). The boundary between these two formations has been drawn at the top of a prominent dark claystone-rich marl layer (Plenus Marl). The Chalk Group in the map sheet area consists of a thick succession of marly limestones and well-cemented, light coloured chalk. The sediments contain little terrigenous material and are built up of the calcareous fragments of planktic and benthic organisms (coccoliths, foraminifera, bryozoa, echinoderms). Depositional hiatuses in the Chalk Group are frequently manifested in the succession as hardgrounds.

The Chalk Group has been completely eroded in the Central Netherlands Basin but, however does occur throughout the rest of the map sheet area (Map 13). From the northern margin of the Central Netherlands Basin, the thickness gradually increases towards the northeast of the map sheet, exceeding 950 m (Map 14).

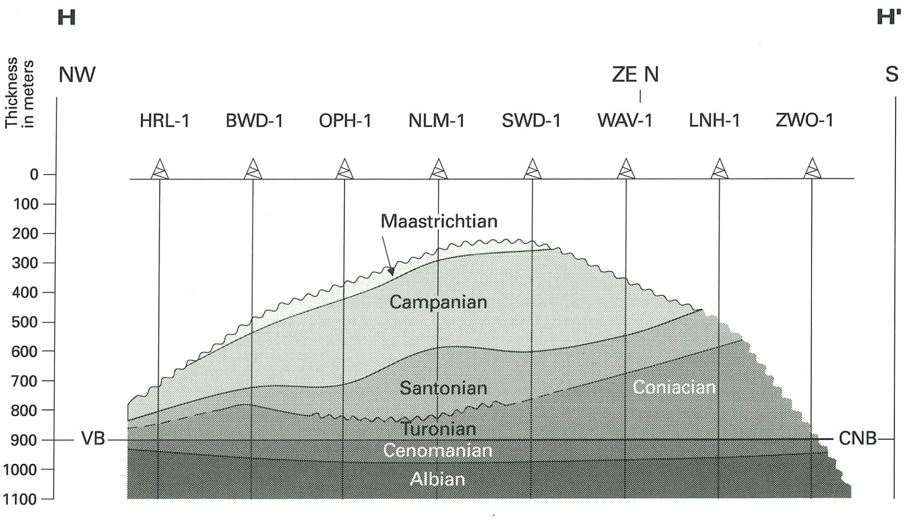
9.1.1 Texel Chalk Formation

The Texel Chalk Formation consists largely of light grey marly chalk, which becomes purely calcareous upwardly. The top of the formation exhibits a prominent marl layer, the Plenus Marl, a few metres thick, which can be correlated over great distances.

The Plenus Marl can be clearly identified from well logging by a relatively low acoustic velocity, high gamma-ray reading and high resistivity. The Plenus Marl derives its name from its prolongation in the southern part of the Chalk sea, of which deposits in England in particular are characterised by the abundance of the belemnite *Actinocamax plenus.*

The Texel Chalk Formation displays a uniform composition in the map sheet area. The thickness here varies from 50 m in the north to 85 m in the south. The formation is of a Cenomanian to earliest Turonian age.

Figure 9.1 Chronostratigraphic correlation section H-H' of the Chalk Group in map sheet area V. The position of the section is indicated in figure 9.2.



VB Vlieland Basin
CNB Central Netherlands Basin

9.1.2 Ommelanden Chalk Formation

The Ommelanden Chalk Formation is mainly composed of a white to light grey chalk. In the succession several bands of flint concretions parallel to the bedding are found.

The formation rests unconformably on the Texel Chalk Formation and is overlain unconformably by the clastic deposits of the North Sea Supergroup.

The formation is Turonian up to Maastrichtian in age. A number of intraformational hiatuses has been determined biostratigraphically (RGD, 1991b). Part of these can be correlated by well-log data (RGD, 1988b).

The Ommelanden Chalk Formation is mainly composed of fine-grained, micritic limestone, which was formed by the accumulation of planktic marine algae remains, mainly representatives of the phylum *Haptophyceae* (Hancock, 1984; Christensen, 1962) and of planktic and benthic foraminifera. When the Haptophyta skeletons are tablet-like grains in a ring-shaped arrangement, these are referred to as coccoliths (Hancock & Scholle, 1975). In the Ommelanden Formation, however, very little of this texture has been preserved. From a chemical perspective, the basic difference of the Chalk from normal limestone is determined by the low-magnesium content of the chalk.

Within the map sheet area erosion has caused internal thickness variations of the formation. The Laramide uplift (inversion) initiated the erosion of the Ommelanden Chalk Formation in the Vlieland and the Central Netherlands Basin. The uplift and erosion caused the disappearance of the entire Chalk Group in the Central Netherlands Basin (fig. 9.1).

Figure 9.2 shows the thickness map of the Ommelanden Chalk Formation in the northern Netherlands. In the northeastern part of the map sheet the thickness of the Ommelanden Chalk Formation locally exceeds 800 m. In the extreme northwest the preserved thickness of the Ommelanden Formation is ca. 200 m. The centre of the area represents a saddle (fig. 9.2), and in the south the entire Chalk Group is cut off by the southern boundary fault of the Texel-IJsselmeer High (Map 14 and section 2). The upper part of the Ommelanden Chalk Formation has been eroded in the south of the map sheet area (fig. 9.1).

In the area to the east of the map sheet area, the thickness of the Ommelanden Chalk Formation was influenced by halokinesis during the Late Cretaceous. There is a causal link between the thickness of the Ommelanden Formation and the growth of salt pillows, in particular in the vicinity of Dwingeloo in the east of the map sheet area. Immediately above the salt pillow, the formation has been reduced, while in the rim synclines immediately around the structure the formation thickens (Map 14 & fig. 9.2).

9.2 Sedimentary development and palaeogeography

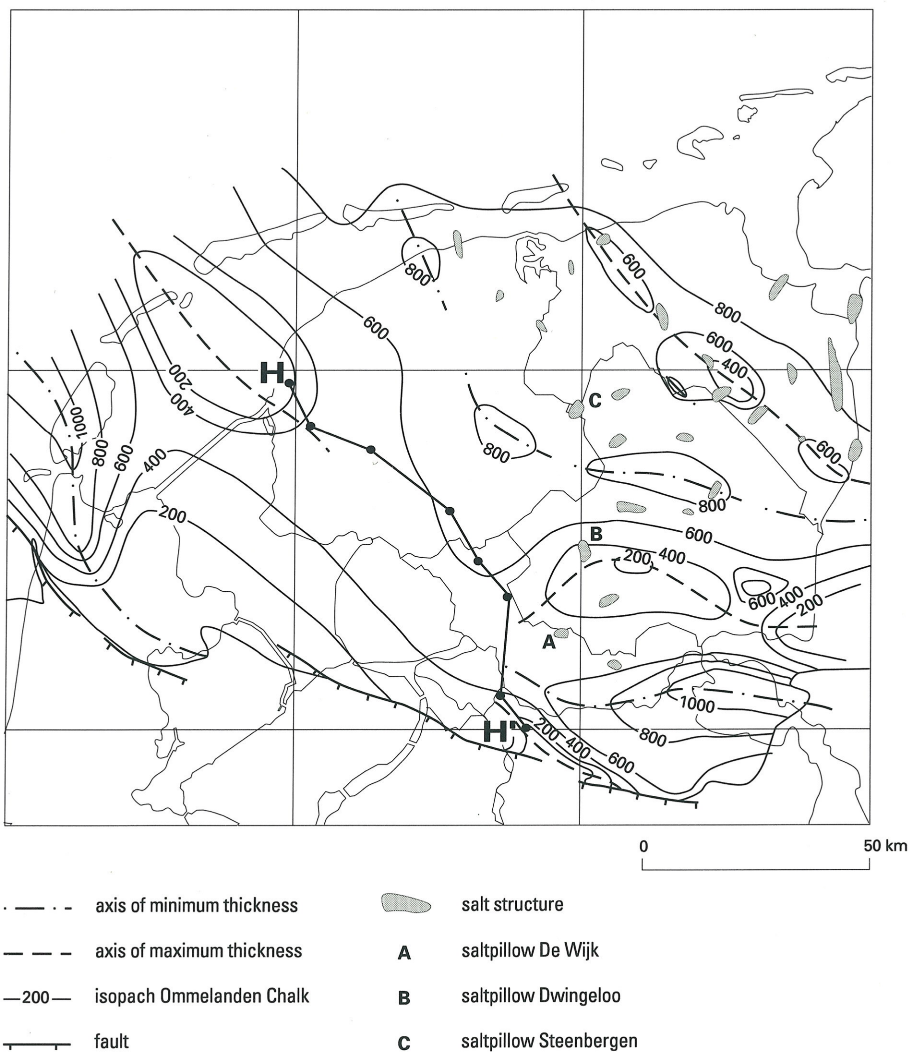
Within the map sheet area the remaining landmasses had already become flooded during the Albian. The transgression continued into the Late Cretaceous and developed into a global phenomenon (Pitman, 1978; Donovan & Jones, 1979; Haq et al., 1987). The coastline migrated to the south of The Netherlands and the influx of terrestrial sediments diminished.

The sediments of the Chalk Group reflect a depositional environment which increasingly became characterised by pelagic sedimentation. In contrast, the Holland Formation is still composed of shales and marls. The great thickness of the Ommelanden Chalk Formation (a thickness of over 950 m is present in the map sheet area) is due to the prolonged and continuous rain of pelagic coccoliths. A maximum depositional depth in the Chalk sea has been estimated at 150 – 200 m (Hancock & Scholle, 1975).

The Plenus Marl was assumed to have been deposited in a period of low oxygen content of the sea water, as a consequence of poor circulation (Schlanger et al., 1987). This model was based on a minimal and constant sedimentation of clay, while the quantity of organic pelagic material reduced, giving a highly condensed deposit. Recent geochemical research on the Plenus Marl from England indicates a $\delta^{13}C$ anomaly which matches a maximum regression and an increased supply of terrestrial material (Jeans et al., 1991).

During the Cenomanian and the Turonian there are few indications of tectonic movements in the map sheet area. This period of tectonic quiescence ended at the start of the Coniacian as demonstrated in the Vlieland Basin (Rijks Geologische Dienst, 1991a). The extensional regime gave

Figure 9.2 Isopach map of the Ommelanden Chalk Formation in the North Netherlands with axes of maximum and minimum thicknesses based on wells. The position of the salt pillows Steenbergen, Dwingeloo and De Wijk and the position of section H-H' are also indicated.



way to a compressional stress field, which resulted in inversion of the different sedimentary basins (Sub-Hercynian phase). During the Santonian and the Campanian inversion movements were at a maximum, resulting in antiformal structures elevated above the base level of erosion (Betz et al., 1987; Van Wijhe, 1987a). Redeposition of the calcareous material is likely to have occurred in the synformal basin structures. To the west of the map sheet area large intraformational hiatuses are present of Coniacian age (Rijks Geologische Dienst, 1993a).

As a consequence of the inversional tectonics, the entire Chalk Group is not present to the south of the southern Texel-IJsselmeer boundary-fault. Immediately to the north of this fault, the sediment sequence of the Chalk Group is considerably reduced as a result of erosion.

9.3 Reservoir-geological aspects

The Harlingen gasfield, which is productive from the uppermost part of the Chalk succession (Campanian and Lower Maastrichtian), is only partly situated within map sheet V (fig. 1.2). The field was discovered in 1964 by Elf Petroland B.V. and up to now is the only gasfield in the Chalk in The Netherlands. The reservoir is enclosed in an antiformal structure which is sealed by angular unconformably overlying claystones of the Lower North Sea Group. The antiformal doming was caused by salt movements and inversion tectonics at the end of the Cretaceous. The intergranulary porosity, averaging 28 to 30% (Van den Bosch, 1983), is almost entirely formed by the inter-particle space of complete, undamaged coccoliths or fragments of these.

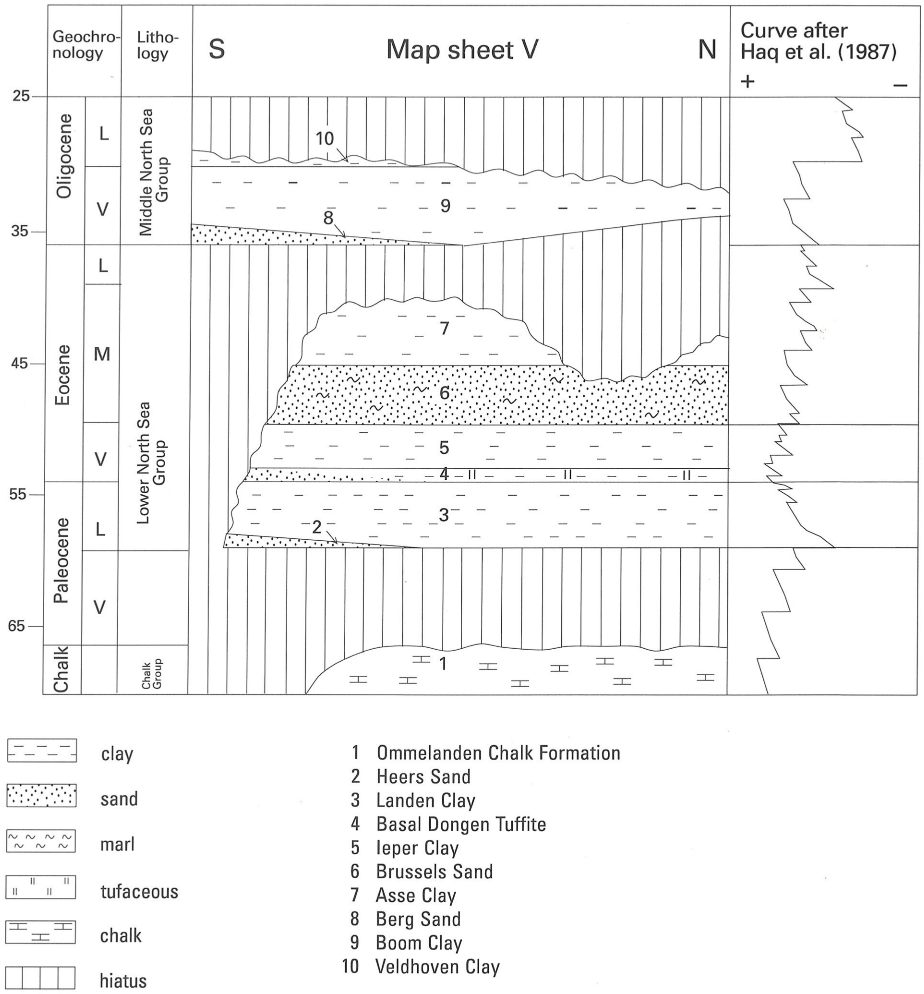
10 North Sea Supergroup

10.1 Stratigraphy

The North Sea Supergroup mainly consists of claystones and sandstones which were deposited in a shallow marine to continental environment. The Supergroup is subdivided into the Lower, Middle and Upper North Sea Groups which are separated by unconformities. In the map sheet area, the sediments of the North Sea Supergroup for the most part overlie the sediments of the Chalk Group. In the Central Netherlands Basin, however, the North Sea Supergroup rests unconformably upon the Rijnland Group, the 'Upper Jurassic' Group, the Altena Group, and in very few places, the Lower and Upper Germanic Trias Group, the Zechstein Group and the Rotliegend Group (Map 17).

The North Sea Supergroup is present throughout the map sheet area (Map 15 & fig. 10.1). In the extreme southwest the thickness of the Supergroup reaches 1300 m (Map 15). This thickness further increases outside the map sheet area to over 1500 m in the Zuiderzee Low (fig. 11.1). The minimum thickness occurs above salt pillows in the east of the map sheet area.

Figure 10.1 Lithostratigraphic diagram of the Lower and Middle North Sea Group of the map sheet area and curve after Haq et al. (1987).



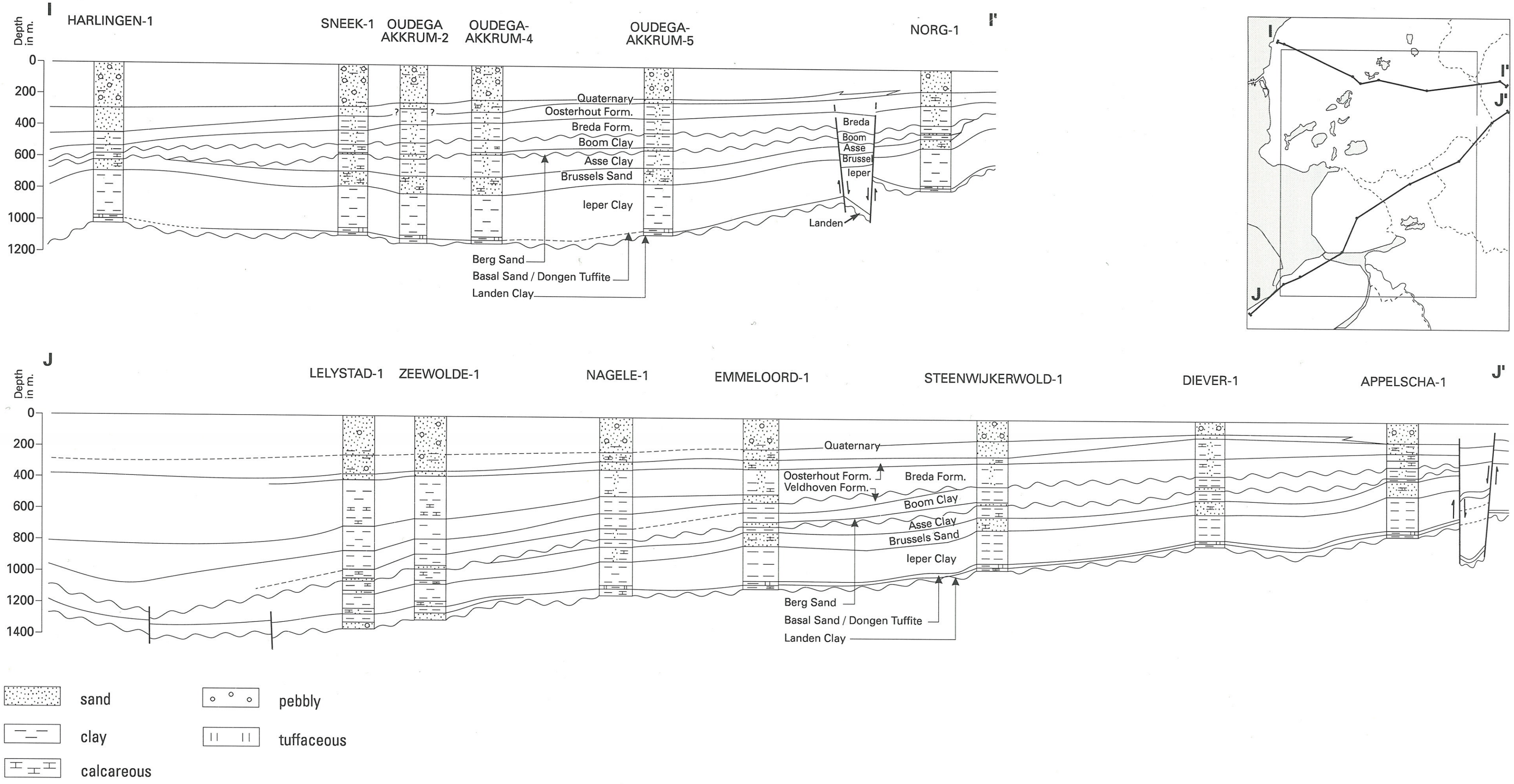


Figure 10.2 Schematic sections I-I' and J-J' through the Cenozoic (after Rijks Geologische Dienst, 1983 and 1984). The Hantum Fault in the northeast and the Zuiderzee Low in the southwest of the map sheet area are notable.

The composition of the Lower and Middle North Sea Group in the map sheet area is illustrated in figure 10.1 and, on the whole, shows a regressive trend. The geology of the whole North Sea Supergroup is demonstrated by two sections through the Cenozoic sedimentary cover of the map sheet area (fig. 10.2).

The description of the deposits of the North Sea Supergroup is mainly based on reports by the Geological Survey of The Netherlands (Rijks Geologische Dienst, 1983, 1984). The deposits are of the Tertiary and the Quaternary. The Quaternary sediments are only mentioned briefly in this explanation, as they are fully explained in the 'Explanation of the Geological map of The Netherlands, 1:50.000' of the shallow subsurface of The Netherlands by the Geological Survey of The Netherlands.

10.1.1 Lower North Sea Group

The Lower North Sea Group is the lowest unit of the Tertiary and throughout the map sheet area unconformably overlies older formations (fig. 10.1), and is unconformably superimposed by the Middle North Sea Group. The Lower North Sea Group comprises the Landen Formation and the Dongen Formation (fig. 10.1). The Lower North Sea Group was deposited during the Palaeocene and the Eocene.

The *Landen Formation* is composed of claystones and sands (fig. 10.1) and is present nearly throughout the map sheet area (fig. 10.2). The formation was deposited during the Palaeocene and is subdivided into the Heers Sand and the Landen Clay. The Heers Sand consists of green-grey, very fine-grained sands, slightly cemented with carbonate, with glauconite and shells as constituents. In the Central Netherlands Basin the formation reaches a thickness of 20 m. The Landen Clay is a 10 to 50 m thick green-grey clay layer, which contains glauconite, mica and pyrite. To the east of the map sheet area the thickness of the clay layer decreases slightly. Locally, the argillaceous sediments have been hardened by carbonate. At the time of the sedimentation of the Landen Clay, the coastline was situated in the east of The Netherlands.

The *Dongen Formation*, deposited during the Eocene, consists of the Basal Dongen Tuffite, the Ieper Clay, the Brussels Sand and the Asse Clay. The total thickness of the formation in the map sheet area ranges from 150 m in the south to over 450 m in the north (fig. 10.1). This increase in thickness towards the north is both the result of erosion in the south and of a greater subsidence of the area in the north of the map sheet (Rijks Geologische Dienst, 1984). Great thicknesses occur in the fault structure of the Hantum Graben in the extreme northeast of the map sheet area. The Dongen Formation has been eroded in part of the Central Netherlands Basin. The Dongen Formation rests conformably upon the Landen Formation and is unconformably overlain by the deposits of the Middle North Sea Group.

The *Basal Dongen Tuffite* is composed of green-grey glauconitic sandy clays and dark tuffaceous intercalations. The thickness ranges from 16 m in the north to 25 m in the south. The Ieper Clay exhibits clay at the base and sandy clay at the top. The argillaceous succession at the base is brown-grey and contains pyrite, coalified plant remains, and benthic foraminifera. The fat clay contain sandy and silty intercalations. The upper part of the Ieper Clay exhibits green-grey, glauconitic, and marly, silty intercalations of sand. Pockets of sand reflect bioturbation. This formation progressively thickens from nearly 90 m in the south to over 250 m in the north. The Brussels Sand mainly comprises very fine-grained micaceous sands and substantial shell debris, echinoderm fragments and glauconite. Upwardly the carbonate content increases and simultaneously the glauconite content decreases. The thickness rapidly increases towards the north reaching an average thickness of 112 m in the centre of the map sheet area. Greater thicknesses occur around salt structures (section 4.3) and in areas subjected to synsedimentary faulting (Hantum Fault). In this latter area, thicknesses of over 250 m are attained. The Asse Clay is a plastic green-grey to blue-grey calcareous clay. The clay contains a considerable amount of pyrite and glauconite. The entire succession contains pockets of sand as a result of bioturbation. Major differences in thickness in the Asse Clay occur as a result of erosion in the south and salt movements in the north. The average thickness of the succession is 70 m.

10.1.2 Middle North Sea Group

The Middle North Sea Group, deposited during the Oligocene, rests unconformably upon the Lower North Sea Group and is unconformably superimposed by the Upper North Sea Group (fig. 1.5). Within the map sheet area, the group is subdivided into the Rupel Formation and the Veldhoven Formation (fig. 10.1).

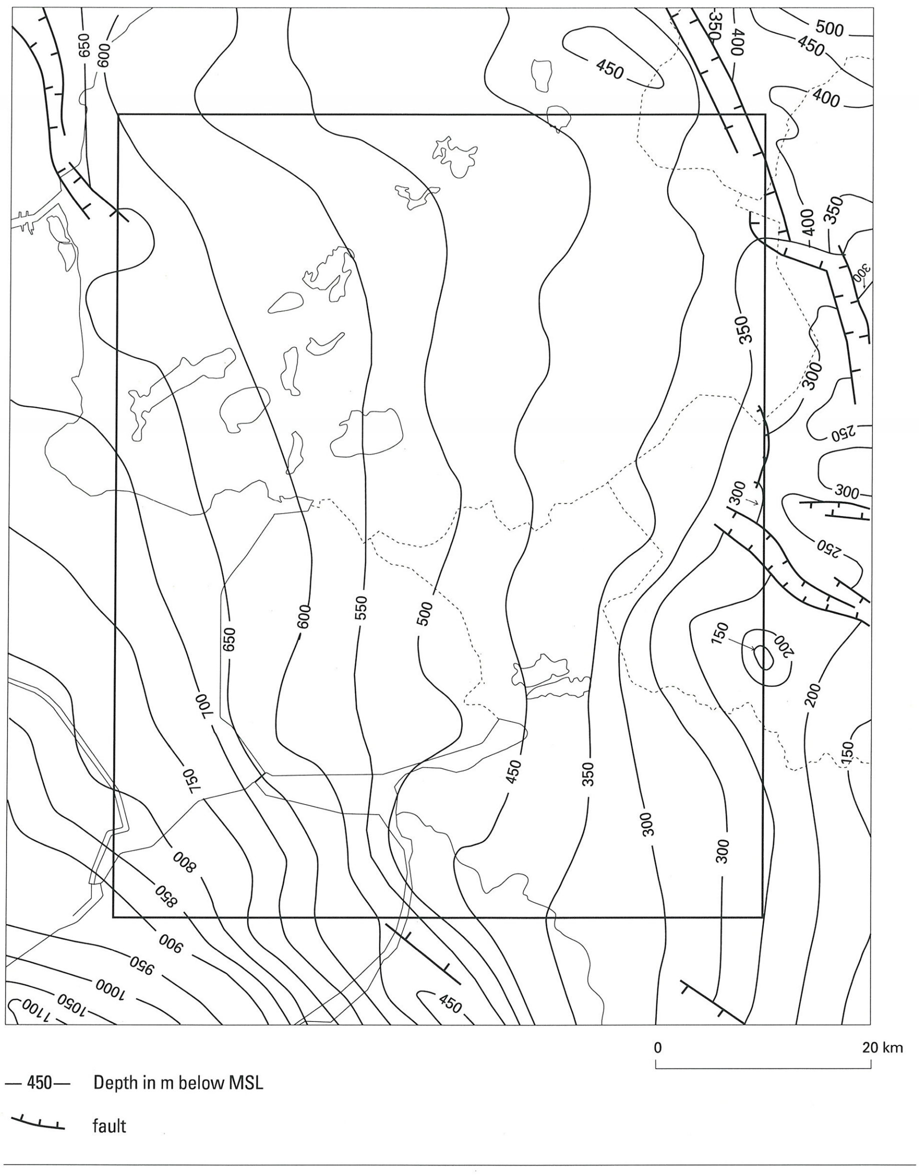


Figure 10.3 Depth map of the Savian unconformity or depth map of the base of the Upper North Sea Group (= base Breda Formation) shows a great increase in thickness towards the west and the southwest: the Zuiderzee Low (after RGD 1983, 1984).

The *Rupel Formation* comprises the Berg Sand and the Boom Clay. The formation has an Early to Middle Oligocene age. The Berg Sand is a thin, glauconitic and pyritic sand succession with a maximum thickness of 25 m, covering almost the total map sheet area. In areas where intense halokinesis took place (to the north and west of the map sheet area) the Berg Sand is absent. The Boom Clay consists of stiff, fat, pyritic green-grey clay and was deposited as a clay succession 20 to 60 m thick in the map sheet area. In the graben of the Hantum Fault, the Boom Clay reaches a thickness of 111 m.

The *Veldhoven Formation,* deposited during the Late Oligocene, is represented only by the Veldhoven Clay in the map sheet area. This succession consists of grey-green, silty and sandy sequences and of clay with glauconitic, micaceous and pyritic constituents. The Veldhoven Clay is not found in the north of the map sheet area (fig. 10.1 & 10.2). The formation reaches a thickness of over 100 m in the south of the map sheet area.

10.1.3 Upper North Sea Group

The Upper North Sea Group is subdivided into the Breda Formation (Middle/Late Miocene), the Oosterhout Formation (Pliocene), the Maasluis Formation (Quaternary), and exhibits continental deposits at the top. The group rests unconformably upon the Middle North Sea Group. The hiatus between the Middle North Sea Group and the Upper North Sea Group covers the Early Miocene. The thickness is minimum above the Dwingeloo salt pillow, where it is approx. 150 m. To the west, the thickness of the Upper North Sea Group increases to 650 m; in the southwest, towards the Zuiderzee Low, to over 900 m (fig. 10.3).

The Breda Formation, deposited during the Middle and Late Miocene, consists of green-black, glauconite-rich sandy clays, clays and sands. The sandy clays at the base of the formation give a relatively high gamma-ray reading. Towards the top of the formation the glauconite content decreases. In the Zuiderzee Low the succession reaches a maximal thickness of 570 m, immediately to the south of the map sheet area. The upper sequences of the Zuiderzee Low are sandy and contain a large number of shell debris. In the northwestern part of the map sheet area the thickness diminishes to 52 m. The differences in thickness are caused by a greater basin subsidence in the Zuiderzee Low.

The Oosterhout Formation, Pliocene in age, consists of alternating argillaceous sands and arenaceous clays. The lower and upper part of the formation, in particular, exhibit a sandy appearance. In the Zuiderzee Low the sandy basal layer is rich in shell debris, echinoderm fragments and fish remains. In the map sheet area the thickness ranges from 35 m in the north to 110 m in the south.

The Maasluis Formation, Early Pleistocene in age, comprises an alternation of sand and clay layers. In the Zuiderzee Low the development of the base of the formation is sandy and rich in shell debris. The top exhibits alternating layers of sand and claystone, containing many plant and wood remains. The thickness of the formation ranges between 20 m and 180 m and decreases in an easterly direction.

The younger Quaternary formations comprise clay, sand and gravel and were deposited under shallow-marine and continental conditions. The thickness of these deposits ranges from 25 m in the north to 300 m in the south.

10.2 Sedimentary development and palaeogeography

After a period of erosion, the sedimentation resumed during the course of the Palaeocene. Arenaceous and argillaceous sediments alternate irregularly showing a certain cyclicity (fig. 10.1) and were usually deposited in a shallow-marine environment. According to Zagwijn (1989), during the Tertiary the effects of relative subsidence and the amount of sedimentation were, in general, neutralised, but sea level fluctuations caused some not insignificant hiatuses. The maximum fall in sea level occurred between the Early and the Late Oligocene (fig. 10.1; Haq et al., 1987). From the Miocene onwards, a subbasin began to develop in the southwest of the map sheet area, the Zuiderzee Low (fig. 11.1 & 10.3) where shallow marine and littoral sediments were initially deposited.

The extension of the formations of the Lower and Middle North Sea Group in the northern part of The Netherlands are given in figure 10.2. The absence of the Landen and the Dongen Formations in the map sheet area is caused by erosion during the Pyrenean phase. The Veldhoven Formation is not present in the extreme north of The Netherlands owing to erosion during the Savian phase. Halokinesis in the northeast of the map sheet area made a highly significant contribution to the sedimentation pattern during the Tertiary. Moreover, the Dongen Formation is locally completely absent above salt structures.

During the Pliocene, the coastline was situated immediately to the east of the map sheet area. The depositional environment increasingly became subjected to continental conditions. The regression continued and the depocentre migrated towards the north (Zagwijn, 1989). Finally, during the remainder of the Quaternary, the preexisting marine depositional conditions were superseded by the deposition of continental sediments with a few marine intercalations.

10.3 Reservoir-geological aspects

One of the gas-producive stratigraphic units of the De Wijk gasfield is the Basal Dongen Tuffite. The average porosity of this reservoir is 30% and the permeability ranges from 10 to 100 mD. These favourable reservoir qualities of the well sorted siltstones are mainly due to the absence of detrital clay and diagenitic products, such as authigenic quartz (Gdula, 1983).

11 Geological History

11.1 Introduction

This chapter gives an overview of the geological history from the Late Carboniferous up to and including the Quaternary and has been divided into three parts. Section 11.2 discusses the structural geology of the map sheet area, section 11.3 deals with the burial history of the different structural units and section 11.4 discusses the general basin development and the sedimentation in relation to the tectonic events for each separate period. Figures 1.5, 1.6 and 1.7 provide an overview of the names used for stages and tectonic phases and illustrate the locations of the structural elements. The main structural units referred to in this chapter are outlined in figure 11.1.

11.2 Structural geology

The structural geology is explained by means of an interpreted seismic profile (fig. 11.2), a fault map (fig. 11.3) and rose diagrams of the various generations of faults (fig. 11.4).

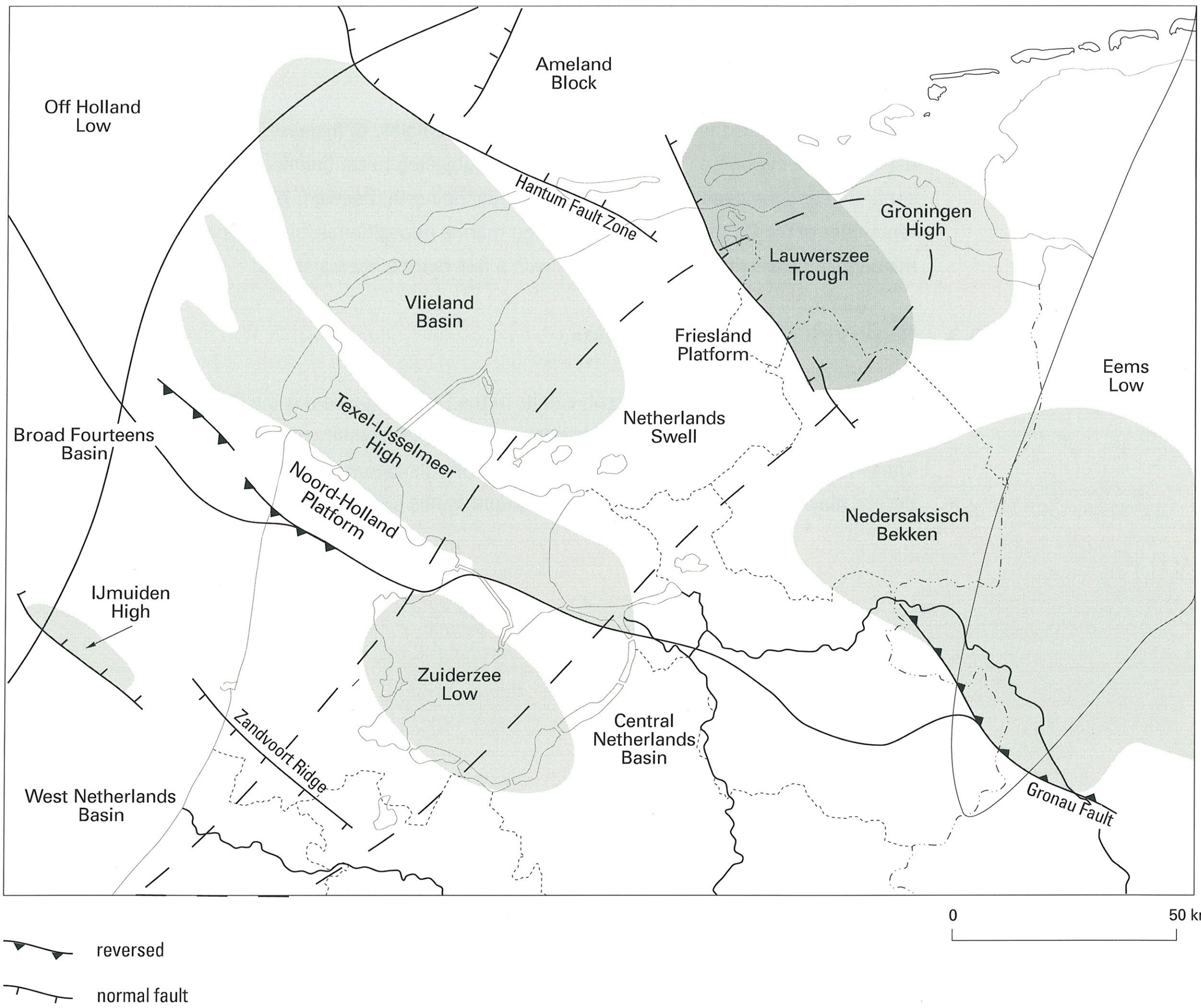


Figure 11.1 Schematic overview of structural elements in the northern Netherlands relevant to this explanation.

The NW-SE trending Texel-IJsselmeer High is of major importance to a discussion of the structural geology of the map sheet area. The southern boundary of the high is defined by normal faulting with an offset of at least 1000 m from the base of the Zechstein (fig. 11.2), while the northern and eastern limits of the high are less sharp, being defined by the absence of Upper Rotliegend sediments. The Texel-IJsselmeer High is a tilted NW-SE trending fault block. The tilting, which was most deeply incised on the southern boundary (Map 18: section 2 and 3), mainly took place during the Kimmerian tectonic phases and is responsible for the northwardly inclined extended flank and the southern boundary delimited by faults.

Faulting took place in the map sheet area during the Late Variscan, Saalian tectonic phase. The NW-SE trending extremely open folds originated in this period. The orientation pattern of the Variscan fault system varies from WNW to NNW (fig. 11.4). The minimal age, Late Variscan, of the Texel-IJsselmeer High is inferred from the thickness pattern of the Permian sediments (Rotliegend and Zechstein) which surround the Texel-IJsselmeer High (fig. 3.4 & 4.2). Synsedimentary fault tectonics and the development of the Central Netherlands Basin occurred during the deposition of the Zechstein sediments (Late Permian).

During the break-up of the supercontinent Pangaea in the Jurassic, faults originated in an extensional stress field (Kimmerian phase). Faulting occurred during the Early, Mid- and Late Kimmerian phase. Differentiation between faults from the Late Kimmerian I and II pulses has not been indicated because the severe erosion in this area at the end of the Jurassic made them mutually indistinguishable. Late Kimmerian tectonics created a network of faults in the Permian, Triassic and Lower Jurassic sediments (fig. 11.3). The trend of the Late Kimmerian normal faults varies from W to NNW, with a N-S to WSW-ENE minimal principal stress direction $\sigma 3$ (perpendicular to the strike of the normal faults) during the Late Kimmerian phases (fig. 11.4).

The basins which developed during the Jurassic in the map sheet area, were filled with Upper Jurassic and Lower Cretaceous sediments. In the northern part of the Central Netherlands Basin contemporaneous sedimentation and faulting developed. A unit with onlap structures was observed on the seismic line of figure 11.2 at shotpoint nr. 1500. The deposition of this succession is presumed to have occurred during the Late Jurassic.

After the extensional tectonics during the Jurassic and the Early Cretaceous, an compressional regime was active during the Sub-Hercynian and Laramide phases of the Late Cretaceous. The Central Netherlands Basin became inverted; the faults along which normal faulting had occurred during the Kimmerian phases were reactivated during the inversion as a reverse fault (fig. 11.3). In the extreme south of the map sheet area, owing to this compressive phase, so-called 'pop-up' structures developed which appear as a positive flower structure on a seismic profile (fig. 11.1). The uplift was so extreme in the Central Netherlands Basin that the entire Upper Cretaceous was elevated and was removed by erosion. The orientation of the faults along which these movements occurred is WNW-ESE (fig. 11.4). The maximal principal stress direction ($\sigma 1$) is oriented SSW-NNE during this compressive tectonic phase. During this period, in the northwest of The Netherlands, the Upper Cretaceous succession underwent minor folding displaying NW-SE trending fold axes.

Post-Laramide fault tectonics (fig. 11.4) were active in the east and northeast of the map sheet area. Here graben structures were detectable which occur in the Tertiary coverage of the map sheet area, attributable both to halokinesis and to movements of reactivated Variscan fault blocks (Rijks Geologische Dienst, 1991b). For example, movements of the Dwingeloo salt pillows caused the development of a graben structure on the western side of this salt culmination (fig. 11.2). The other faults in the Tertiary cover of the map sheet area developed through activation of fault blocks in the basement. Such fault block movements were responsible for normal faulting with a NNW trend in the northeast of the map sheet area (Hantum Graben). In conjunction with these normal faults in the north of the map sheet area, dextral strike-slip movements of basement blocks during the Tertiary are presumed to have occurred (Rijks Geologische Dienst, 1991b).

The trending of the faults in the Variscan, Kimmerian and Laramide phases show considerable similarities and even match in places (fig. 11.4), which is a consequence of different tectonic phases reactivating the same basement blocks.

11.3 Geochemical evaluation and burial history.

11.3.1 General

The burial depth history of an area can be determined from the relation between the measured coalification of organic material from sediments and theoretically calculated coalification values. This is based on the geothermal gradient which determines the changes in the physical-chemical composition of organic material. The actual coalification rank is dependent on the temperature, the duration of the reaction temperature and the type of organic material (Arrhenius Law). The reflectivity of the organic material also changes in direct proportion to the increase in coalification. The reflection value under standard conditions is measured by means of a reflection microscope and expressed as a percentage of the incident ray of light (vitrinite reflection %Rm). For humic matter (Stach et al., 1982) the reflectivity varies from 0.2% (peat) via 0.6% (brown coal) to over 2% (anthracite).

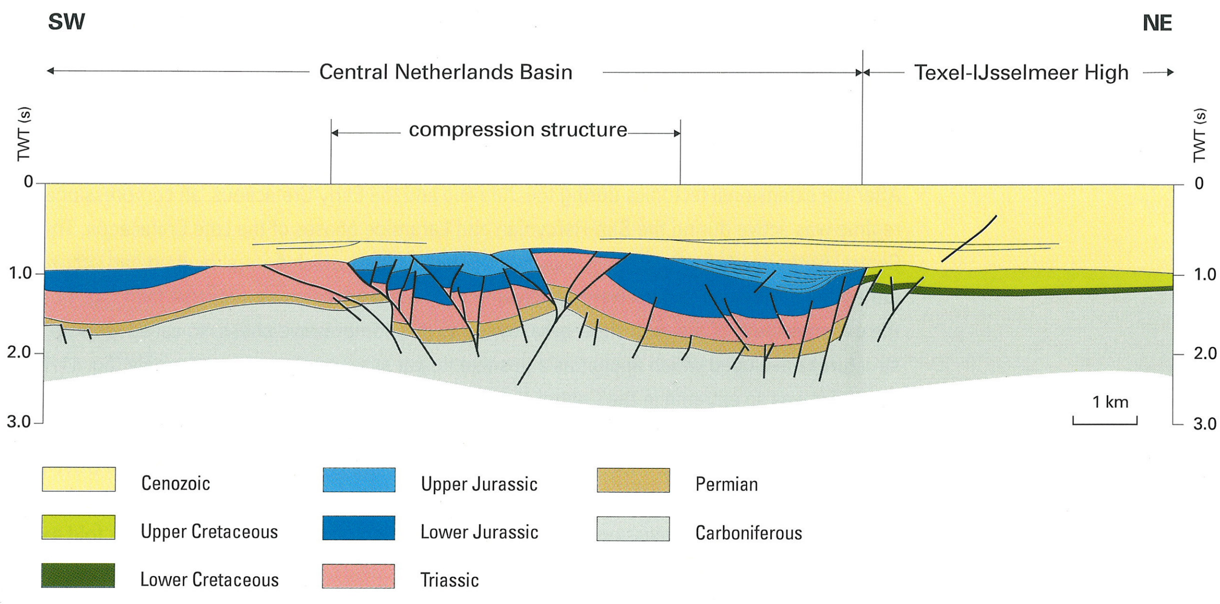
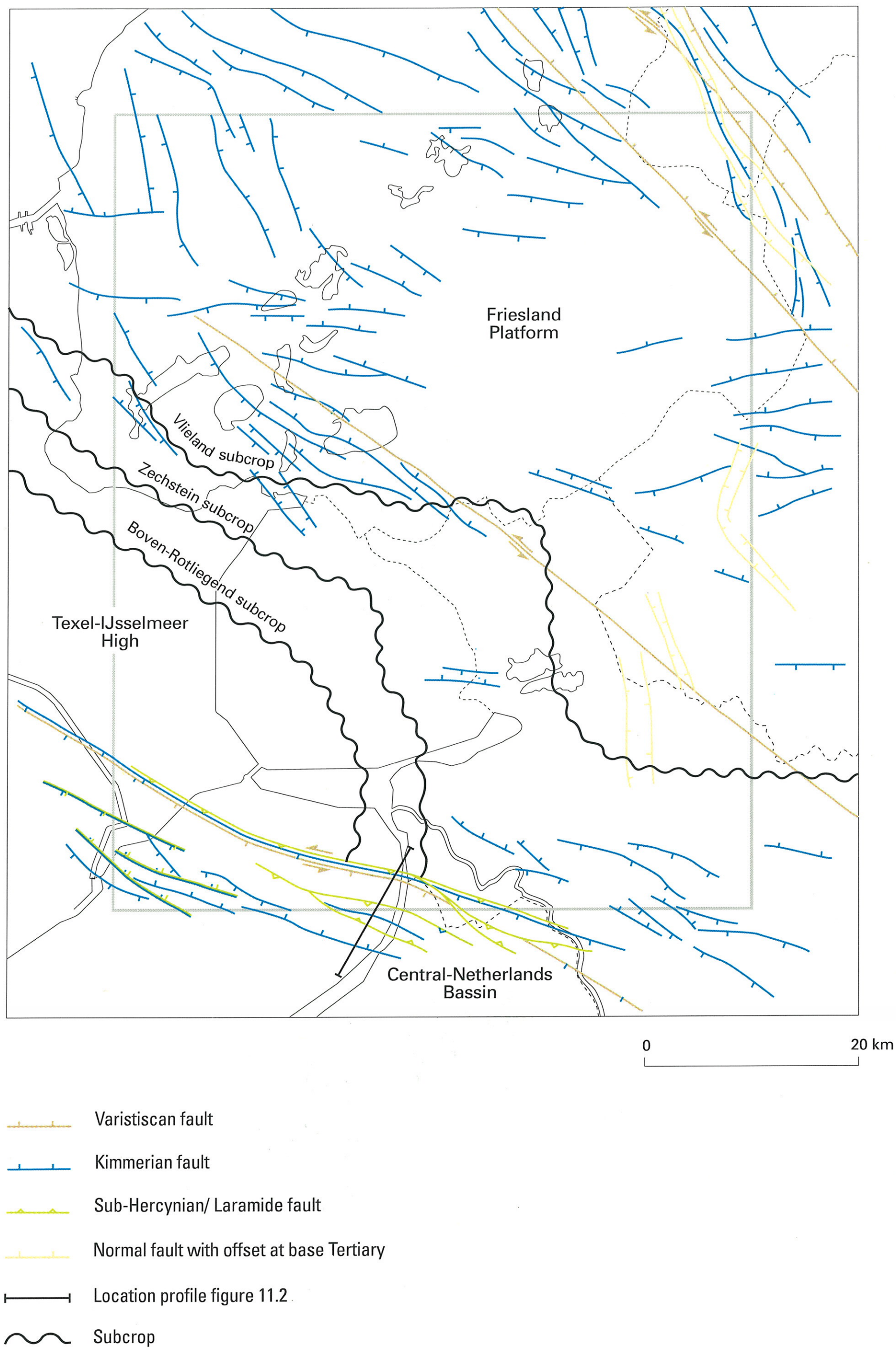


Figure 11.2 Interpreted seismic section 813401. The position of the section is indicated in figure 11.3. The section shows a Sub-Hercynian/Laramide compressional structure south of the Texel-IJsselmeer High. Here, the offset of the base of the Zechstein reaches at least 1800 m.

In order to verify the burial depth history in the geological model studies, various parameters were entered which are in indirect proportion to these time-temperature relations.

Figure 11.3 Structural-geological overview of map sheet V. Mapped faults are grouped according to tectonic phases.

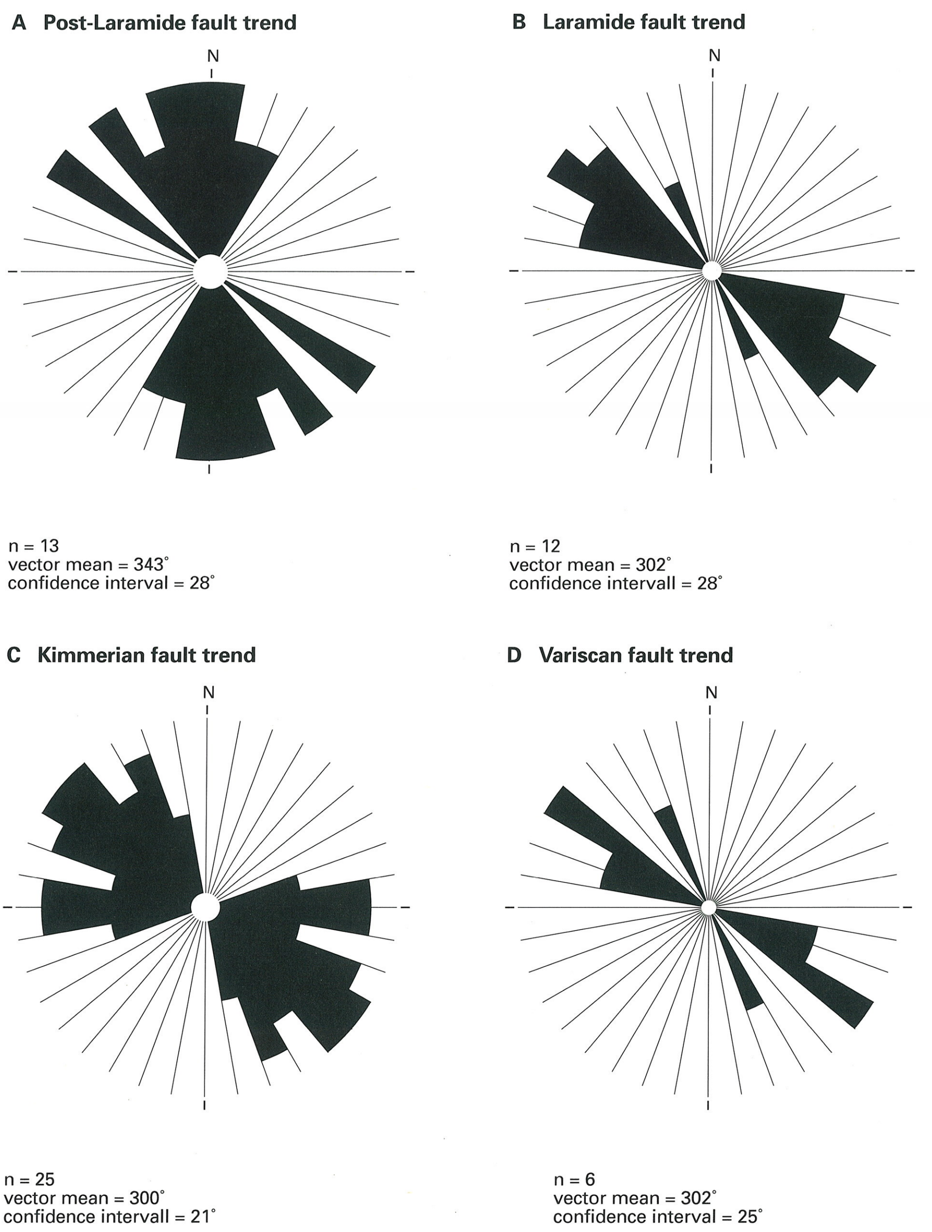


Stratigraphic and geochronological data determine the burial depth history of the sediment succession. The lithological information provides the boundary conditions for compaction, thermal conductivity and heat capacity of rock. This, combined with palaeo-surface temperature, enables modelling of the vertical heat flow.

11.3.2 Results

Six wells were selected for the modelling (fig. 11.5): Dronten-1, Nagele-1, Nijensleek-1, Oudega-Akkrum-2, West-Harlingen-1 and Zeewolde-1.

Figure 11.4 Rose-diagrams of fault directions in the map sheet area, grouped according to tectonic phases.



The maceral material of the Carboniferous (Limburg Group) from all these wells was determined for reflectivity. In addition, the Coppershale (Zechstein Group), from the Dronten-1, Nijensleek-1 and Oudega-Akkrum-2 wells and the maceral material from the Delfland Formation (Central Graben Group) and from the West-Harlingen-1 well were analysed. The measured reflective values (table 2) were used as calibration points in the model studies. By varying the heat flow and the maximum burial depth, different models were able to be tested to obtain an optimum correlation between the measured and calculated values (fig. 11.6).

Figure 11.7 shows the optimised burial history diagrams of two modelled wells. The horizontal axis represents the geological timetable (Harland et al., 1990), the vertical axis represents the burial depth of the deposits. Calculated iso-vitrinite reflection lines have also been included in the diagrams. The estimates of the maximum burial depth are based on the algorithms used for the modelling (GAPS, 1991). The lack of organic material in the Jurassic/Cretaceous time interval in five of the six wells precludes reliable conclusions on the basin development during this interval.

Figure 11.5 Location map of modelled wells and structural units.

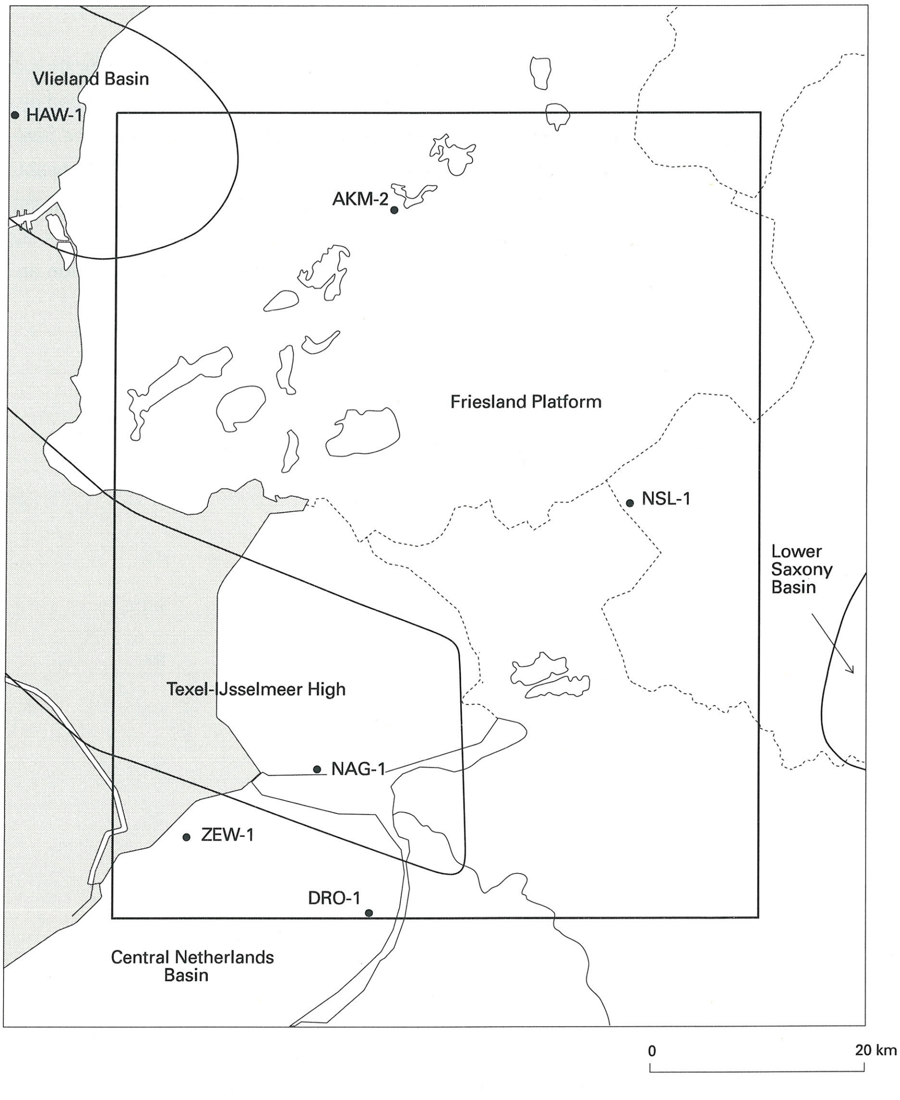


Figure 11.8 gives the burial history diagrams of the base of the Upper Rotliegend Group of the modelled wells, clearly illustrating the differences in subsidence history between the structural units. Several wells have been taken to illustrate the subsidence history of different areas: the West-Harlingen-1 well for the Vlieland Basin, the Nijensleek-1 and Oudega-Akkrum-2 wells for the Friesland Platform, the Nagele-1 well for the Texel-IJsselmeer High and the Zeewolde-1 and Dronten-1 wells for the Central Netherlands Basin.

The coalification of the upper part of the Carboniferous (all investigated wells have been age dated as Westphalian A; fig. 2.2) varied at the beginning of the Permian from 0.71 %Rm (Nijensleek-1) to 1.85 %Rm (Nagele-1). In the map sheet area, a good correlation between the calculated and the measured reflection values is achieved by taking a regional heat flow of 75-85 mW/m^2 for a thickness of 2000 ± 200 m eroded Upper Carboniferous sediments. This means that the Westphalian (and possibly the Stephanian) succession in the map sheet area must have had a total thickness of approx. 3000 m. All the wells demonstrate a significant coalification originating during the Late Carboniferous, followed by erosion of different Westphalian successions. Nagele-1 forms an exception. The heat flow of 120 mW/m^2 in this well shown by the model study is exceptionally high compared with the surrounding wells and is likely to be related to the intrusives found in this well (section 2.2).

The processed coalification data of the modelled wells indicate that a discontinuity in coalification occurs at the Saalian unconformity. This can only be explained by assuming erosion of a significant succession of Carboniferous sediments during the Saalian uplift. This discontinuity in coalification is extreme in the Nagele-1 well, but is also significant in the Dronten-1 (fig. 11.7a), Nijensleek-1 and Zeewolde-1 wells. These models show that in the Oudega-Akkrum-2 (fig. 11.7b) and West-Harlingen-1 wells recent active coalification has been occurring to post-Carboniferous sediments as a result of which the discontinuity in coalification on the Saalian unconformity

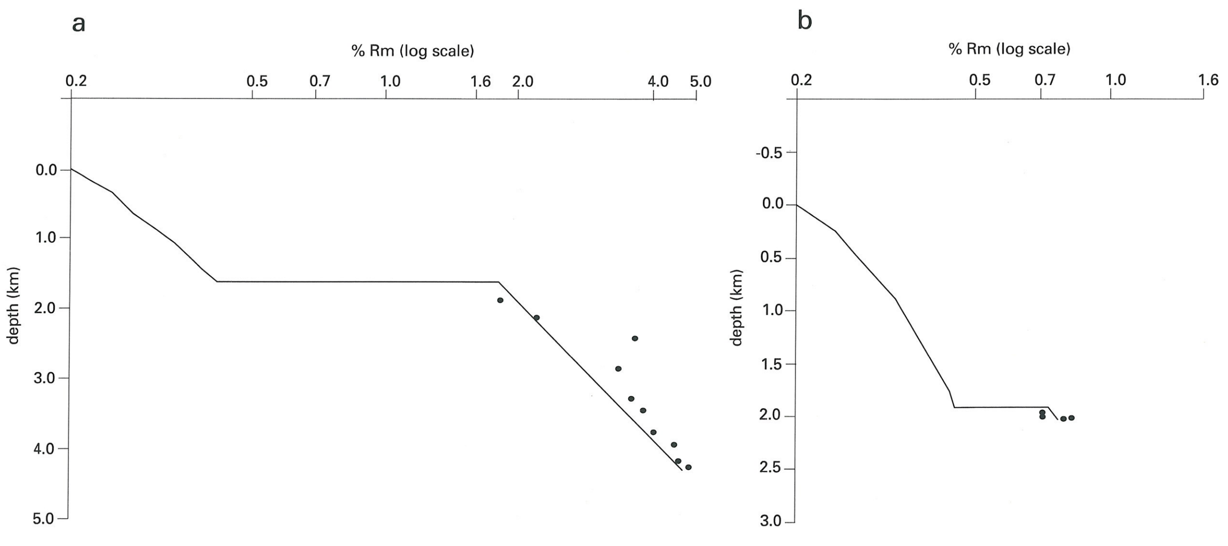


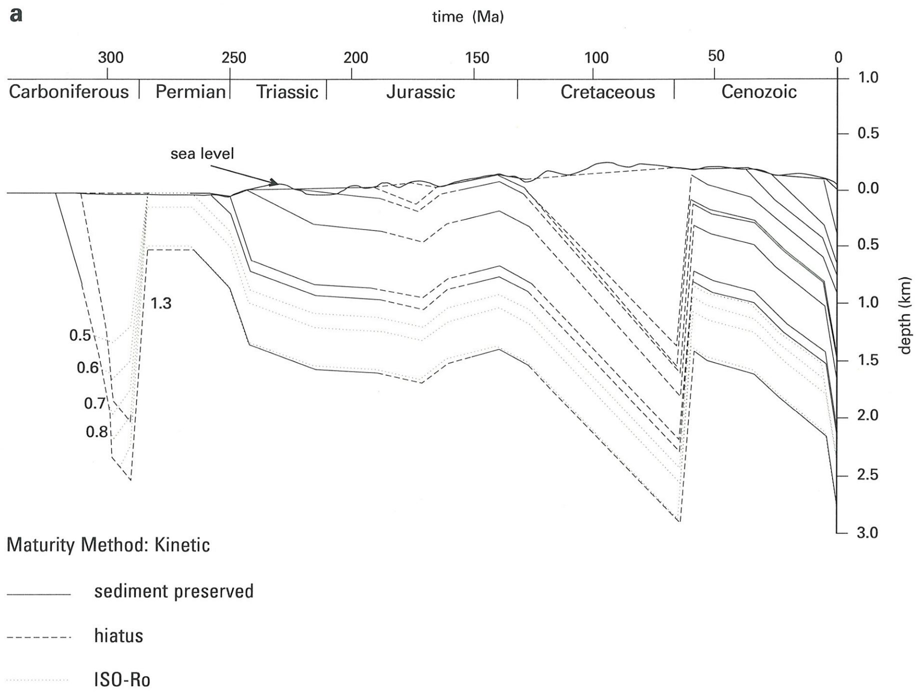
Figure 11.6 Correlation of vitrinite measurements (calibration points) and the modelled coalification curves of two wells; see section 11.3.2.

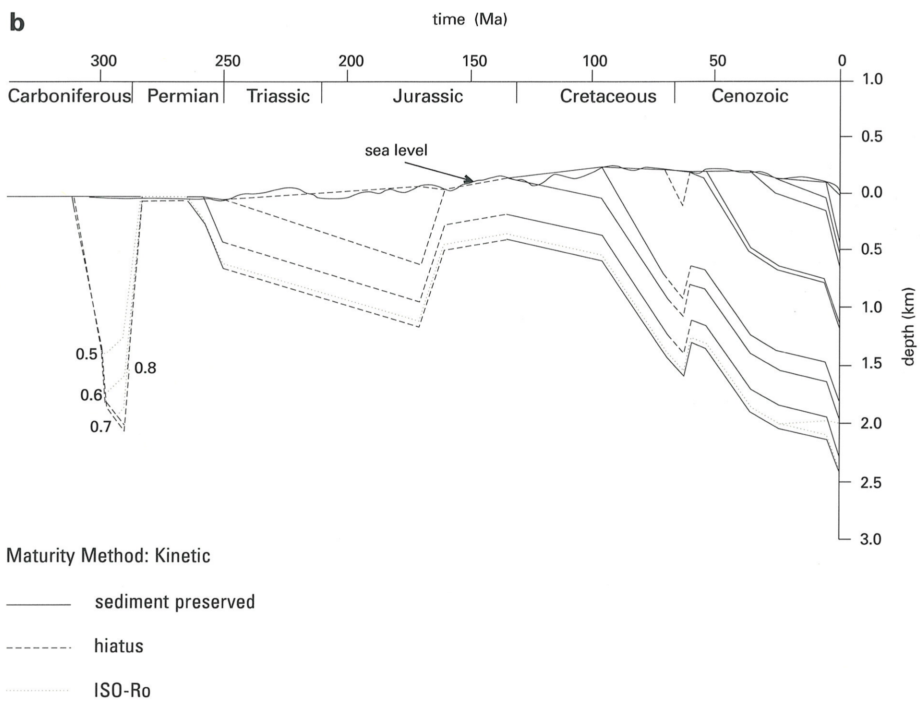
a Nagele-1; model on the basis of a heat flow of 120 Mw/m^2 during the Carboniferous.

b Nijensleek-1; model on the basis of a heat flow of 80 Mw/m^2 during the Carboniferous.

Figure 11.7 Burial analysis diagrams and iso-vitrinite reflection lines of two modelled wells in map sheet area V. The regional discontinuity of coalification coinciding with the Saalian unconformity surface (table 2) can only be explained by the assumption of the erosion of a significant succession of Carboniferous sediments. In the Oudega-Akkrum-2 well coalification of the Coppershale occurs during the Cenozoic.

a Dronten-1
b Oudega-Akkrum-2





horizon is being reduced. The modelling reveals that no coalification of post-Carboniferous rocks is present in the southern part of the map sheet area. The youngest coalification of post-Carboniferous rock would appear to be intensifying in a northwesterly direction.

Figure 11.8 Burial history diagram of the base of the Rotliegend of all modelled wells. Owing to the absence of the Rotliegend in Nagele-1 well, a hypothetical layer of 1 m Rotliegend has been modelled. There is a notable difference in the appearance of sedimentation after the Late Kimmerian (Late Jurassic) erosion on the various structural units.

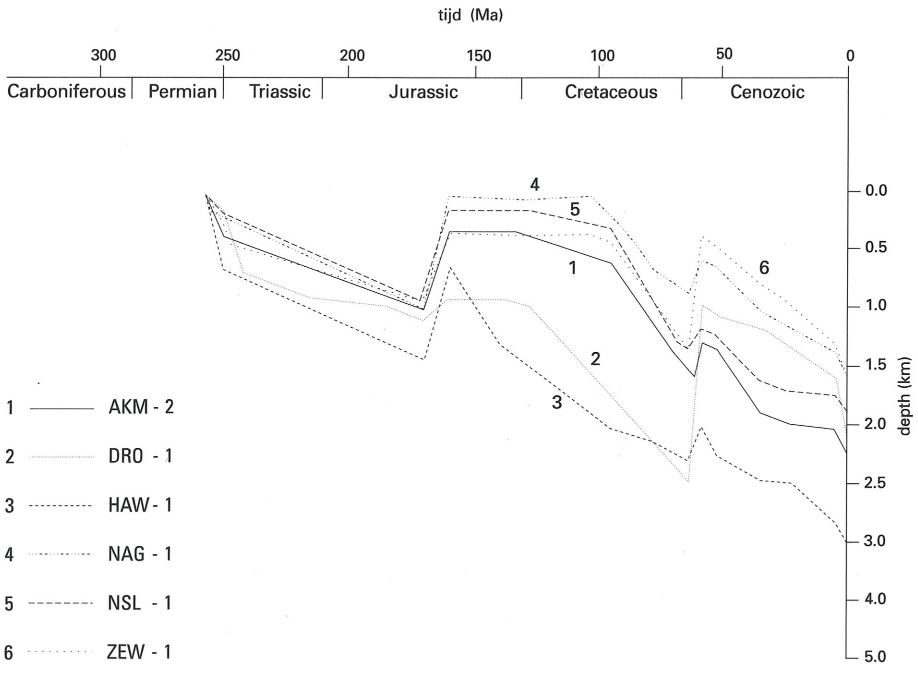


Table 2: Measured vitrinite reflectance values used in the modelling of the burial history (RGD, 1993b).

Well	*Depth (m)*	*Sample*	*%Rm*
Dronten-1	2186	Coppershale	0.50
	2393	Limburg	0.87
	2440	Limburg	0.95
	2479	Limburg	1.13
	2526	Limburg	1.11
Nagele-1	1896	Limburg	1.85
	2158	Limburg	2.24
	2412	Limburg	3.68
	2866	Limburg	3.38
	3276	Limburg	3.16
	3416	Limburg	3.84
	3778	Limburg	4.01
	3930	Limburg	4.49
	4170	Limburg	5.41
	4254	Limburg	4.82
Nijensleek-1	1927	Coppershale	0.38
	2012	Limburg	0.71
	2037	Limburg	0.71
	2061	Limburg	0.82
	2070	Limburg	0.79
Oudega-Akkrum-2	2321	Coppershale	0.56
	2460	Limburg	0.83
West-Harlingen-1	2002	Delfland	0.57
	2029	Delfland	0.45
	2081	Delfland	0.45
	3213	Limburg	0.81
	3286	Limburg	0.78
	3286	Limburg	0.82
	3323	Limburg	0.94
	3326	Limburg	0.83
	3343	Limburg	0.78
	3345	Limburg	0.82
Zeewolde-1	1797	Limburg	0.99
	1903	Limburg	1.10
	1975	Limburg	1.14

11.4 Basin development, sedimentation and tectonics

11.4.1 Late Carboniferous

The Variscan orogeny, also called the Hercynian orogeny, comprises three phases of deformation in the map sheet area: the Sudetic, the Asturian and the Saalian. The entire orogeny characterises the end of the proto-Tethys and the development of the supercontinent Pangaea. The Northwest European Variscan geosynclinal system was active from the Middle Devonian up to and including the Late Carboniferous, and was determined by alternating compressive and extensive tectonic cycles (Ziegler, 1990). From the Early Carboniferous, a compressive tectonical regime was active for 45 Ma. During the Early Permian, the Variscan orogeny ceased.

The Sudetic phase reflects the collision between Gondwana and Laurussia. This continent-collision was characterised by a N-S trending compressive stress field and initiated the development of an E-W trending orogenic belt extending right across Europe from Cornwall to Poland. In response to the tectonic stress of the lithosphere caused by the piled-up Variscan overthrusts, a foreland basin was formed to the north of these mountains. The map sheet area covers part of the basin and was filled with the detritus from the Variscan mountains lying further to the south (fig. 11.9). Sedimentation occurred under predominantly paralic conditions. Vast areas, including the map sheet area, were flooded by transgressions during the Carboniferous, caused by glacio-eustatic sea-level rises (Ziegler, 1990). During the Westphalian, the fluvial influence on the sedimentation gradually increased and more (fluvial) sands were deposited. Widespread peat formation occurred in the areas located between the rivers and in the delta plains.

During the Asturian phase at the end of the Westphalian, the sediments in the foreland basin became slightly folded and E-W trending folds developed (fig. 2.2), as a reaction to the movements of tectonic highs in the basement (Read & Watson, 1975; Ziegler, 1988). The maximum principal stress direction ($\sigma 1$) was N-S. The map sheet area is presumed to have been elevated and eroded during this tectonic phase (Bless et al., 1977).

During the Saalian phase (Late Carboniferous/Early Permian) the relative movement direction of the colliding mega-continents changed from N-S to E-W (Ziegler, 1989, 1990). These movements reflect SW-NE trending fold axes in the map sheet area (fig. 2.2), possibly caused by the movement of old, NNE-SSW trending Caledonian fault blocks. Rotation of the continents led to NW-SE trending wrench faults, thus forming the southern boundary of the Texel-IJsselmeer High (fig. 2.2). The entire Late Carboniferous basin of Northwest-Europe was intersected by a conjugate set of dextral and sinistral strike-slip zones (Arthaud & Matte, 1975, 1977). A gabbroid plutonic body is presumed to have intruded in the Wanneperveen area during this phase (approx. 300 – 280 Ma).

The area with the oldest deposits at the top of the Carboniferous (Westphalian A) is seen as a precursor of a structural element: the Texel-IJsselmeer High. Through reactivation of old (Variscan) faults, subsequently developing faults exhibit approximately the same NW-SE trend as the high.

11.4.2 Permian

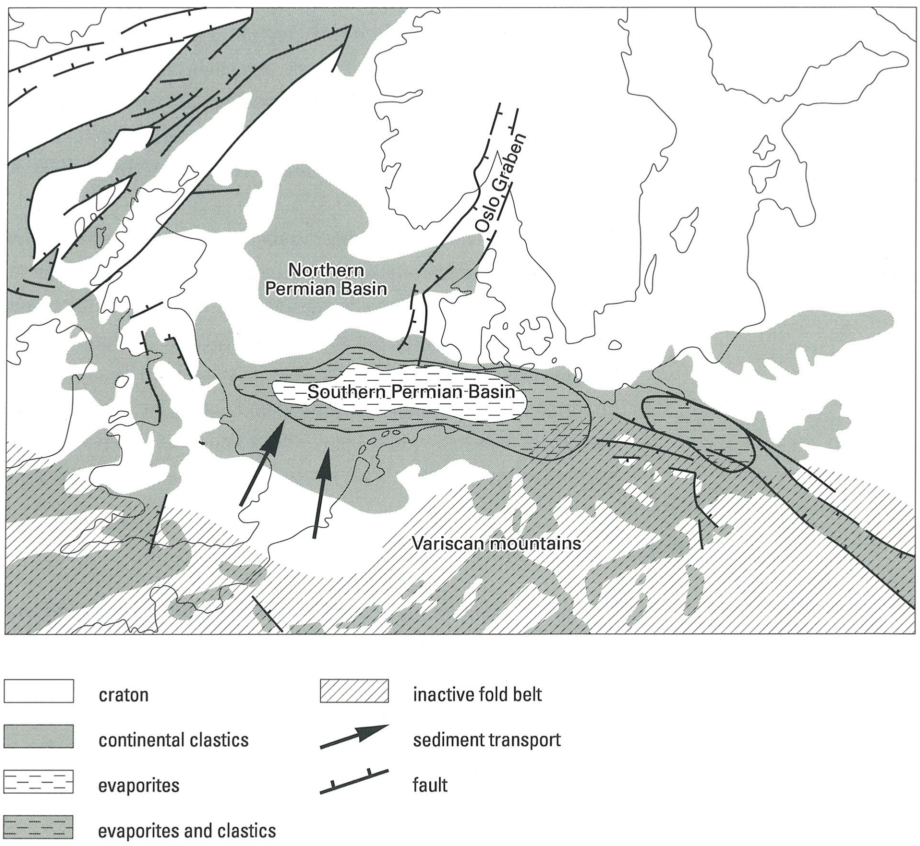
During the Early Permian, a primary peneplain was formed in Northwest Europe, caused by erosion resulting from the Saalian phase of the Variscan orogeny.

Cooling of the lithosphere from the Late Permian onwards generated a vast, relatively low-lying intracratonic basin, the Permo-Triassic Basin, extending over a large part of Northwest Europe and separated by the Middle North Sea/Ringkøbing-Fyn High in the Northern and Southern Permian Basin (fig. 11.9). On the southern margin of the Southern Permian Basin, arid conditions gave rise to a desert plain. In the map sheet area, the precursor of the Texel-IJsselmeer High formed a barrier between the Southern Permian Basin and a subbasin, the Central Netherlands Basin (fig. 11.1).

Sedimentation during the Early Permian commenced with fluvial and lacustrine deposits in the deeper part of the basin and with alluvial fan deposits along the basin margins. During the Permian, sedimentation extended over the higher parts. Cyclical fluctuations of the water-level in the central desert lake caused the basin to extend right up to the top of the Texel-IJsselmeer High. The internal relief differences within the map sheet area gradually decreased and extensive sand plains formed along the margins of the Southern Permian Basin. Here, drifted sand accumulated as sand dunes, under the influence of the prevailing dry climate and northeasterly trade winds (Glennie, 1972, 1983).

In the southeast of the map sheet area, there was a NW-SE trending prolongation of the Variscan mountain chain (fig. 3.4). Coarse-grained and brecciated material was deposited on the flanks in the form of alluvial fan systems. Towards the centre of the basin, conglomeratic intercalations

Figure 11.9 Palaeogeography of Northwest Europe during the Early Permian (after Ziegler, 1982).



were intermittent in the fluvial aeolian sediments. At the end of the Early Permian an increased influx of coarse-grained sediment appeared.

A transgression at the beginning of the Late Permian brought an end to the aeolian and fluvial sedimentation in most of the map sheet area. Rifting in the North Atlantic/Arctic area, together with a eustatic sea-level rise owing to the deglaciation of Gondwana, initiated an open connection between the Barentsz Sea in the north and the continental Permo-Triassic Basin (Ziegler, 1987).

At the end of continental sedimentation in the map sheet area, the deposition of the Zechstein evaporite cycles started. Cyclical glacio-eustatic sea-level fluctuations were responsible for four evaporite cycles in the map sheet area. Evaporation gave rise to an increase in salinity and precipitation of the less soluble salts. Continuing basin subsidence and contemporaneous synsedimentary faulting had an important influence on the thickness development of the evaporites and determined the palaeogeography of the northern part of The Netherlands.

Pronounced differences in rate of basin subsidence occurred during the Late Permian in the map sheet area, clearly demonstrated by the facies development of the Zechstein Group. Evaporites were deposited in the deeper parts of the basin. The thickness in the northeast of the map sheet area is indicative of greater subsidence than in the western and central parts of the map sheet area. Pronounced synsedimentary faulting is evidenced by the thickness increase (Map 4) and the palaeogeographical reconstruction of the southwest and north of the map sheet area (fig. 4.1). The maps showing the extent of the salt deposits also indicate that the salinities in the Central Netherlands Basin in the extreme southwest of the map sheet area and the main basin differed during various periods of the Late Permian. The Texel-IJsselmeer High subsided to a lesser extent and was only flooded during periods of relative high stand. Large quantities of anhydrite were deposited in a shallow water environment on and near this palaeohigh (fig. 4.1 & 4.3). The Central Netherlands Basin underwent continental depositional conditions, which had a progressively stronger influence in a southerly direction (Plomp & Geluk, 1988; Rijks Geologische Dienst, 1993a).

The differences between the basin subsidence in the Central Netherlands Basin and the main basin diminished progressively during the Late Permian, which can be inferred from the increasing uniformity in facies and the decreasing differences in the thickness of the deposits. The synsedimentary faulting had almost entirely ceased before the beginning of the Triassic. Therefore, the Texel-IJsselmeer High and the basins situated to its south and north were no longer of importance at the end of the Permian and during the Early Triassic. The differences in relief in the map sheet area had virtually smoothened out. The last evaporite cycle in the map sheet area finally resulted in the transition from a restricted marine to a continental basin.

11.4.3 Triassic

The development of the Scythian indicates highly uniform and large-scale basin subsidence and points to the absence of any substantial relief. Sediments came in from the south and were deposited in a fluvial and lacustrine environment, with minor marine influences. The sediments display a cyclical development which can most probably be attributed to variations in meteoric water, and the related periodical changes in the supply of coarse clastic material, which was transported across a flood plain to a large continental lake in the centre of the Permo-Triassic Basin.

The uniform subsidence pattern terminated before the end of the Scythian, with extensive tectonic movements which accentuated the NNE-SSW trending structures of the Off-Holland Low and the

Ems Deep. In between these depressions, a structural high developed, the Netherlands Swell (fig. 11.1). The geological expression of this high was, however, overshadowed by erosion of later Kimmerian erosion on the Texel-IJsselmeer High and the Friesland Platform. The Netherlands Swell in the map sheet area partially corresponds with the NW-SE trending Texel-IJsselmeer High (fig. 11.1). The Main Buntsandstein Formation was predominantly deposited in the Off Holland Low and the Ems Deep (fig. 11.1), while on the Netherlands Swell only a thin and incomplete succession was accumulated (RGD, 1989). At sea-level low stands, braided rivers dominated the sedimentary pattern, while during periods of high stand, lacustrine conditions prevailed. During high stand, playa clays and silts were deposited. At the end of the Scythian, a combination of eustatic sea-level fall and epeirogenic uplift, the Hardegsen tectonic phase, caused a regional unconformity (Base Solling Unconformity). Erosion as a result of the Hardegsen tectonic activity resulted in absence of the Main Buntsandstein in the Netherlands Swell.

During the Anisian, a new transgression brought a return of marine conditions to the map sheet area and resulted in the deposition of Röt evaporites in the Central Netherlands Basin. During the Early Ladinian, the transgression intensified which resulted in deposition of shallow-water carbonates (Lower Muschelkalk) and rock salt (Muschelkalk Evaporite) in the Central Netherlands Basin. After this transgression, the influx of clastic sediments increased again and clays and marls were deposited in the map sheet area.

At the beginning of the Late Triassic (Carnian), a regression brought an end to marine sedimentation in the Permo-Triassic Basin. A complex of lagoons, sabkhas and tidal-flat areas was formed in and around the map sheet area. The greater part of the map sheet area was occupied by a relative high (Netherlands Swell) during the Carnian and the Norian. For this area, the relative low stand caused the interruption of the sedimentation at the end of the Norian.

From the beginning of the Rhaetic, the Early Kimmerian phase was active but demonstrated no faulting of any significance in the map sheet area. The consequences of this tectonic phase were much greater in the east of The Netherlands and in Germany (Haanstra, 1963a; Schröder, 1982). The Early Kimmerian phase was accompanied by an extensive stress regime which resulted in the intrusion of some dolorites in the area of Wanneperveen.

11.4.4 Jurassic

At the end of the Triassic, the disintegration of Pangaea began and continued during the Jurassic. This process can be divided into a number of phases: the Early Kimmerian phase (Late Triassic), the Mid-Kimmerian phase (Middle Jurassic) and the Late Kimmerian phase (Late Jurassic). For practical reasons, the Late Kimmerian I and II pulses have been related to the principal interruptions in the stratigraphic succession: resp. base 'Upper Jurassic' Group and base Vlieland Formation. In reality, the separation between these pulses cannot be sharply defined time-wise (Stille, 1924; Heybroek, 1974; Ziegler, 1978, 1982). The Kimmerian phase was active throughout Northwest Europe and consisted of a number of large-scale extensional pulses, which significantly determined the geological development of the map sheet area.

The extensional tectonics of the Early Kimmerian phase can best be described as 'regional extension', a term chosen because the uniform basin subsidence was similar in vast areas during the Early Jurassic. This is in contrast to the extensional tectonics of the Late Kimmerian phase which can best be termed 'local extension'. During this phase, basin subsidence also occurred, but this was more local in character and was controlled by fault movements.

During the Kimmerian phases, normal faults were present along the southern boundary fault zone of the Texel-IJsselmeer High, with a possible strike-slip component. These extensive movements, occurring in the extreme south and immediately to the south of the map sheet area along WNW-ESE trending faults, were the superficial manifestations of large-scale listric faults which are presumed to have extended far down into the basement.

The present extent of the Lower Jurassic sediments is confined to the various Late Jurassic basins (fig. 7.1). The high degree of uniformity in the lithology makes it highly probable that the marine sediments were originally deposited in an undivided basin. The Toarcian sediments (Posidonia Shale) are indicative of an anoxic environment as a consequence of limitations in or stagnations of sea-water circulation.

The Middle Jurassic sediments are not found in the northern Netherlands High but do, however, occur in the Lower Saxony Basin and the West Netherlands Basin. The sedimentation in the Middle Jurassic increasingly confined itself to the deeper basin parts (Betz et al., 1987; Van Wijhe, 1987a, 1987b). The Mid-Kimmerian phase occurred at the beginning of the Middle Jurassic. The effect of this in the map sheet area can no longer be ascertained because the Late Kimmerian erosion overprinted the former erosion as deeply, if not more deeply in the map sheet area. The alternation of carbonates and fine-grained clastic sediments in the Lower Saxony and West Netherlands Basins points to a relatively shallow marine environment.

The Late Kimmerian tectonic phase initiated the formation of the Vlieland Basin and renewed subsidence of the Central Netherlands Basin and the Lower Saxony Basin. During a regional sea-level fall in the Oxfordian, large parts of the map sheet area probably became exposed (Texel-IJsselmeer High and the Friesland Platform).

Beyond the basins, the Late Kimmerian pulses were responsible for strong uplift and deeply incisive erosion on the crest of the Texel-IJsselmeer High down into the Carboniferous. The Texel-IJsselmeer High was tilted towards the NNE with a gentle dip (Map 16 & Map 18, section 2).

Since the Late Kimmeridgian the Delfland Formation accumulated in the Vlieland Basin in a predominantly lacustrine depositional environment and comprised the erosion products from the surrounding highs. More continental conditions occurred later, during the Ryazanian, when peat was formed in the basins as a result of drainage stagnation.

The Upper Jurassic deposits in the Vlieland Basin and the Central Netherlands Basin were deposited under lacustrine and fluvial conditions, while limited shallow marine conditions prevailed in the Lower Saxony Basin. The calcareous appearance of the Upper Jurassic deposits in the Central Netherlands Basin may indicate the existence of a connection with the Lower Saxony Basin.

At the end of the Jurassic and the beginning of the Cretaceous, sedimentation was confined to the deeper basin parts, situated just outside the map sheet area. The results of the different Late Kimmerian phases are difficult to distinguish and can only be studied in each separate basin. Sedimentation in the Vlieland Basin and the Lower Saxony Basin began as early as the Kimmeridgian, and during the Portlandian subsequent sedimentation occurred in the Central Netherlands Basin.

11.4.5 Cretaceous

In the Early Cretaceous, the differential basin movements of the Jurassic changed to a period of relative tectonic rest. Isostatic compensation following the Jurassic tectonic uplift led to regional subsidence. Independently of this, a new eustatic transgressive phase began in the Valanginian, culminating in flooding of the high structures within the map sheet area. The transgression continued into the Late Cretaceous, enabling the open marine depositional environment throughout the map sheet area to be sustained. From the Hauterivian onwards, the Cretaceous series in the map sheet area was deposited in a marine environment. The gradual sea-level rise was only interrupted by a few brief regressions.

In the Vlieland Basin and the Lower Saxony Basin the sedimentation started in the Valanginian, while the transgression migrating westwardly around the Texel-IJsselmeer High, did not reach the Central Netherlands Basin until during the Hauterivian. Sedimentation took place in a shallow marine environment (Perrot & Van der Poel, 1987). The transgression in the Vlieland Basin came from the north, whereas in the Lower Saxony Basin it migrated from the east (Ziegler, 1990). The connection between these two basins (fig. 8.2) was established during the Late Hauterivian. Sands and clays were deposited in a nearshore environment in a relatively narrow zone, a 'corridor'. The sandy sediments were fed by fluvial fan systems protruding into the sea. The area of provenance for the Vlieland Sandstone was the Texel-IJsselmeer High where, as a result of Kimmerian uplift, even the Slochteren Sandstone (Upper Rotliegend) finally was elevated above the base level of erosion. Because the relief was smoothened during the Kimmerian phases, even small eustatic sea-level fluctuations had a great effect on the extent of the sea over the area. During the Barremian, clay was mainly deposited in the map sheet area.

During the Aptian and the Albian, ongoing sedimentation occurred in the map sheet area and was only interrupted by a few eustatic sea-level fluctuations, with the consequent occurrence of a few intraformational hiatuses on the Friesland Platform during the latest Early Cretaceous. The transgression flooded the greater part of the map sheet area only at the beginning of the Aptian, while the Texel-IJsselmeer High was not flooded until the Late Albian (fig. 8.2).

The coastline during the Albian was situated over a hundred kilometres further to the south, causing the proportion of terrigenous, clastic material to gradually diminish, resulting in the Upper Cretaceous deposits being predominantly built up of marine bioclasts.

In the Cenomanian, no separate basins can be differentiated in the map sheet area. The marly succession which was deposited during this period has a consistent thickness, but the shale layer at the top of the Texel Formation (Plenus Marl), which is generally well correlatable, is poorly developed. The south of the map sheet area would appear to have subsided more rapidly in the Turonian and the Coniacian. The great thickness of the Turonian and the Coniacian sediment succession can be seen in the thickness section of the Chalk Group (fig. 9.1). This is also observed to the west of the map sheet area (Rijks Geologische Dienst, 1993a).

A number of basins in Northwest Europe became inverted during the Late Cretaceous, which Ziegler (1982) attributes to the collision of the African and the European continents and a consequent compressive stress field which extended over large areas of the Alpine foreland (Northwest Europe) during the Late Cretaceous. Although the orogenic front lay over 1000 km further south, the tectonic phases of the Alpine orogeny are contemporaneous with the tectonic active periods in Northwest Europe. The inversion occurred in Northwest Europe during two phases: the Sub-Hercynian (during the Santonian and Campanian) and the Laramide phase (during the Late Cretaceous/Early Tertiary). As far as this area is concerned, the compression resulted in the uplift of the Vlieland Basin (Rijks Geologische Dienst, 1991a), the Lower Saxony Basin (Betz et al., 1987) and the Central Netherlands Basin.

Tectonic uplift and tilting commenced in the Vlieland Basin during the Sub-Hercynian phase, indicated by intraformational hiatuses and angular unconformities (Rijks Geologische Dienst, 1991a). Sedimentation occurred during all the stages of the Late Cretaceous, but were demonstrated as condensed deposits, in contrast to the sedimentation on the relatively high, non-inverted areas. The Chalk in the Vlieland Basin represents a condensed succession with respect to the similar sedimentary series on the Friesland Platform and the Texel-IJsselmeer High (Rijks Geologische Dienst, 1991a, 1991b).

The relatively great thickness of the Santonian and Campanian sediments immediately to the north of the Central Netherlands Basin indicates the probability that inversion in the northern part of the Central Netherlands Basin mainly occurred during the Laramide tectonic phase. Owing to compressive stresses of the inversion, the southern boundary fault zone of the Texel-IJsselmeer High was reactivated and the area to the south (the Central Netherlands Basin) was strongly uplifted. Immediately to the south of this boundary fault zone, reverse fault structures developed during this compressive phase (fig. 11.1). To the south of the boundary fault zone, the entire succession of the Upper Cretaceous was eroded.

The inversion had little effect on the central part of the map sheet area. On the thickness map of the Ommelanden Chalk Formation (fig. 9.2) this area forms a saddle structure and the sediments of the Maastrichtian are present here. To the east of this saddle lies the western prolongation of the Lower Saxony Basin where the inversion had already commenced during the Turonian and the Coniacian (Betz et al.,1987; Baldschun et al., 1991).

In the Central Netherlands Basin, as a result of the Laramide tectonic phase, the erosion mostly cut into the Lower Jurassic and the Triassic, even reaching the Permian and the Upper Carboniferous in places. The uplift ranged from approx. 1400 m (North Sea Supergroup unconformable upon Delfland) to approx. 2000 m (North Sea Supergroup unconformable upon the Germanic Trias Groups, the Zechstein and the Rotliegend Group: Map 17).

The Kimmerian phase during the Jurassic, the Sub-Hercynian phase during the Late Cretaceous and the Laramide phase in the Early Tertiary, together with the Pyrenean (Eocene/Oligocene) and the Savian phase (Miocene), belong to the Early and Middle Alpine orogenic phases.

11.4.6 Cenozoic

At the beginning of the Tertiary, the North Sea Basin formed, which has determined the sedimentation pattern up to the present time. The sediments consist mainly of erosion products derived from the areas uplifted during the Late Cretaceous and Early Tertiary. Major relative sea-level fall also created hiatuses in the sedimentary succession. The Late Eocene/Early Oligocene relative sea-level fall is related to the Pyrenean tectonic phase. The Early Miocene hiatus is linked to the Savian tectonic phase.

During the Tertiary and the Quaternary, the rate of subsidence of the North Sea Basin increased spectacularly and in the centre of the basin over 3000 m of sediment was deposited in approx. 65 million years. The map sheet area is situated on the southern margin of the North Sea Basin, where the thickness of the sediment succession ranges from approx. 600 m in the east to approx. 1300 m in the southwest.

Early Tertiary halokinetic movements generated salt structures in the east and the northeast of the map sheet area. A pillow structure is present near the Hantum Fault, in the northeast of the map sheet area. The Hantum Fault was active from the Paleocene up to the end of the Miocene and formed a large graben structure which developed as a result of a combination of salt flow and reactivation of faults in the basement (Rijks Geologische Dienst, 1991b; Richards, 1991). The southern prolongation of this structure extends right into the extreme northeast of the map sheet area.

In the Paleocene, influx of clastic material displaced the predominantly bioclastic sedimentation of the Late Cretaceous in the map sheet area; clays were deposited during transgressions and sands during regressions. Locally, Eocene sediments are absent in the east of The Netherlands owing to salt flow which mainly occurred during the Paleocene and the Eocene. The basin margin was situated a few hundred kilometres to the south of the map sheet area.

Late Eocene compression (Pyrenean phase) was responsible for the uplift of the former Central Netherlands Basin and the east of The Netherlands. It is probable that during this movement an old fault system was reactivated. Alpine inversion tectonics were still active until the end of the Eocene (Pyrenean phase), as is demonstrated by the uplift and the entire or partial erosion of the Landen and Dongen Formations in the Central Netherlands Basin (fig. 10.2).

During the Oligocene, sedimentation occurred in a uniformly subsiding basin. Renewed uplift and erosion took place as a result of the Savian tectonic phase in the north and east of the map sheet area. In the Miocene, a new basin developed in the southwest of the map sheet area, the Zuiderzee Low. During the Middle and Late Miocene, substantial subsidence occurred (Zagwijn, 1989), as a result of which the map sheet area was subjected to open marine environmental conditions. The Zuiderzee Low formed part of the Cenozoic rift system which continued further to the south in the Roer Valley Graben and to the north in the North Sea Basin (Fuchs et al., 1983; Zagwijn, 1989). The open marine environment persisted into the Pliocene, after which a regressive sea-level fluctuation commenced. The coastline, formerly situated to the east and the south, migrated to the west and the north, while sedimentation occurred in a very shallow-marine environment.

In the Quaternary, substantial basin subsidence occurred in the southwest and west of the map sheet area, in particular in the Zuiderzee Low. Continental sedimentary depositional conditions characterised a major part of the Quaternary.

Appendices

Appendix A

Overview of seismic data used

Survey	*Year*	*Owner*
30**	1961	NAM
7050**	1970	NAM
7150**	1971	NAM
7170**	1971	NAM
7250**	1972	NAM
7270**	1972	NAM
7271**	1972	NAM
7311**	1973	NAM
7411**	1974	NAM
7514**	1975	NAM
76-**	1976	Chevron
77-**	1977	Chevron
78-**	1978	Chevron
79-**	1979	Chevron
7911**	1979	NAM
8021**	1980	NAM
8030**	1980	NAM
8042**	1980	NAM
8132**	1981	NAM
8134**	1981	NAM
8232**	1982	NAM
8234**	1982	NAM
8260**	1982	NAM
82-**	1982	Chevron
84-*	1984	Chevron
8420**	1984	NAM
9030**	1973	NAM
ANE79-2**	1979	Amoco
ANE80-2**	1980	Amoco
FR-***	1964	Elf Petroland
FR75-**	1975	Elf Petroland
FR76-**	1976	Elf Petroland
FR77-**	1977	Elf Petroland
FR78-**	1978	Elf Petroland
FR80-**	1980	Elf Petroland
FR81-**	1981	Elf Petroland
FR83-**	1983	Elf Petroland
FR83-HR**	1983	Elf Petroland
GK78-**	1978	Elf Petroland
GK80-**	1980	Elf Petroland
GK81-**	1981	Elf Petroland
GK84-**	1984	Elf Petroland
SU-**	1966	Chevron
Y-5**	1968	Chevron

*/**/*** refer to specific line numbers

Overview of wells used[1]

No.	Well	Code	Owner	Final depth log depth in metres	Year completed
1	Allardsoog-1	ALO-1	NAM	3180	1984
2	Appelscha-1	APS-1	NAM	3000	1971
3	Boerakker-1	BRA-1	NAM	3262	1984
4	Bolsward-1	BWD-1	NAM	2679	1971
5	Bozum-1	BOZ-1	Elf Petr.	1963	1982
6	Diever-1	DIV-1	NAM	2260	1961
7	Doornspijk-1	DSP-1	NAM	2406	1964
8	Doornspijk-2	DSP-2	NAM	1832	1966
9	Dronrijp-1	DRP-1	Elf Petr.	3019	1984
10	Dronten-1	DRO-1	Conoco	2532	1965
11	Dwingelo-1	DWL-1	NAM	938	1949
12	Dwingelo-2	DWL-2	NAM	3797	1955
13	Eernewoude-1	ERW-1	Elf Petr.	2479	1965
14	Emmeloord-1	EMO-1	Elf Petr.	2548	1969
	Ermelo-1	ERM-1	NAM	2650	1969
15	Gorredijk-1	GRD-1	Chevron	2292	1971
16	Grootegast-102	GGT-102	NAM	3244	1976
17	Harlingen-1	HRL-1	Elf Petr.	3103	1965
18	Harlingen-2	HRL-2	Elf Petr.	1870	1965
19	Harlingen-3	HRL-3	Elf Petr.	2003	1965
20	Harlingen-6	HRL-6	Elf Petr.	1117	1985
21	Heegermeer-1	HGM-1	Chevron	2144	1973
22	Hessum-1	HES-1	Conoco	2223	1968
23	Hijken-1	HIJ-1	Elf Petr.	1925	1965
	IJsselmeer-1	IJM-1	Superior	2892	1966
24	Kampen-1	KAM-1	Chevron	2154	1969
25	Knardijk-1	KRD-1	Amoco	1524	1978
26	Langenholte-1	LNH-1	NAM	2386	1977
27	Leeuwarden-1	LEW-1	Elf Petr.	1971	1968
28	Leeuwarden-2	LEW-2	Elf Petr.	1947	1968
29	Leeuwarden-3	LEW-3	Elf Petr.	1973	1968
30	Leeuwarden-4	LEW-4	Elf Petr.	1952	1969
31	Leeuwarden-6	LEW-6	Elf Petr.	1956	1969
32	Leeuwarden-7	LEW-7	Elf Petr.	1952	1970
33	Leeuwarden-9	LEW-9	Elf Petr.	2440	1969
34	Leeuwarden-12	LEW-12	Elf Petr.	1950	1980
35	Leeuwarden-13	LEW-13	Elf Petr.	2137	1981
36	Lelystad-1	LEL-1	Conoco	2057	1970
37	Marum-2	MAR-2	NAM	2737	1978
38	Marumerlage-1	MAL-1	NAM	3152	1984

continued on p. 107

Continuation of Appendix B

No.	Well	Code	Owner	Final depth log depth in metres	Year completed
39	Middelburen-1	MBN-1	Elf Petr.	2690	1979
40	Nagele-1	NAG-1	Elf Petr.	4304	1970
41	Nijega-1	NGA-1	Elf Petr.	2500	1965
42	Nijega-7	NGA-7	Elf Petr.	1937	1978
43	Nijega-9	NGA-9	Elf Petr.	2180	1982
44	Nijensleek-1	NSL-1	NAM	2327	1987
45	Nijlamer-1	NLM-1	NAM	2055	1972
46	Noord-Bergum-1	NBG-1	NAM	2640	1965
47	Norg-1	NOR-1	NAM	3329	1965
48	Norg-3	NOR-3	NAM	3224	1977
49	Norg Zuid-1	NRZ-1	NAM	3956	1984
50	Oost-Flevoland-1	OFL-1	NAM	2390	1965
51	Opeinde-1	OPE-1	Elf Petr.	1991	1976
52	Opeinde-2	OPE-2	Elf Petr.	1955	1979
53	Opende Oost-1	OPO-1	NAM	3100	1979
54	Oppenhuizen-1	OPH-1	NAM	2190	1972
55	Oudega-Akkrum-1	AKM-1	Chevron	2492	1965
56	Oudega-Akkrum-2	AKM-2	Chevron	2487	1965
57	Oudega-Akkrum-3	AKM-3	Chevron	2362	1966
58	Oudega-Akkrum-4	AKM-4	Chevron	2362	1966
59	Oudega-Akkrum-5	AKM-5	Chevron	2412	1969
60	Oudega-Akkrum-6	AKM-6	Chevron	1945	1976
61	Oudega-Akkrum-7	AKM-7	Chevron	2095	1980
62	Oudega-Akkrum-9	AKM-9	Chevron	2603	1980
63	Oudega-Akkrum-11	AKM-11	Chevron	2513	1978
64	Oudega-Akkrum-13	AKM-13	Chevron	2400	1980
65	Oudega-Akkrum-15	AKM-15	Chevron	2144	1981
66	Punthorst-1	PTH-1	NAM	1922	1984
67	Rauwerd-1	RWD-1	Elf Petr.	1979	1981
68	Rauwerd-2	RWD-2	Elf Petr.	1981	1982
69	Ried-1	RID-1	NAM	3039	1952
70	Ruinen-1	RUI-1	NAM	1489	1950
71	Ruinen-2	RUI-2	NAM	1287	1954
72	Sloten-1	STN-1	Elf Petr.	2193	1969
73	Smilde-1	SML-1	NAM	2550	1974
74	Sneek-1	SNK-1	Elf Petr.	2005	1969
75	Sonnega-Weststellingwerf-1	SOW-1	NAM	1983	1963
76	Staphorst-1	STA-1	NAM	1495	1950
77	Staphorst-2	STA-2	NAM	1635	1950
78	Staphorst-3	STA-3	NAM	1485	1950

continued on p. 108

Continuation of Appendix B

No.	Well	Code	Owner	Final depth log depth in metres	Year completed
79	Steenwijkerwold-1	SWD-1	NAM	3649	1966
80	Suawoude-2	SUW-2	NAM	3161	1980
81	Tietjerksteradeel-105	TID-105	NAM	3055	1986
82	Tietjerksteradeel-401	TID-401	NAM	2300	1978
83	Ureterp-1	URE-1	NAM	2188	1950
84	Ureterp-101	URE-101	NAM	2597	1966
85	Vledder-1	VLR-1	NAM	2518	1981
86	Wanneperveen-1	WAV-1	NAM	2070	1951
87	Wanneperveen-6	WAV-6	NAM	1519	1952
88	Wanneperveen-12	WAV-12	NAM	1575	1983
89	Warga-1	WRG-1	Elf Petr.	2501	1965
	West-Harlingen-1	HAW-1	Placid	3348	1965
90	Weststellingwerf-1	WSF-1	Elf Petr.	2086	1983
91	De Wijk-1	WYK-1	NAM	1174	1949
92	De Wijk-4	WYK-4	NAM	1204	1951
93	De Wijk-7	WYK-7	NAM	2696	1954
94	De Wijk-13	WYK-13	NAM	2700	1973
95	De Wijk-15	WYK-15	NAM	3380	1977
96	De Wijk-17	WYK-17	NAM	1622	1978
97	De Wijk-19	WYK-19	NAM	1526	1978
98	De Wijk-20	WYK-20	NAM	1560	1981
99	De Wijk-21	WYK-21	NAM	2970	1982
101	Wirdum-1	WRM-1	Elf Petr.	1916	1972
101	Wirdum-2	WRM-2	Elf Petr.	1935	1980
102	Zeewolde-1	ZEW-1	Conoco	2000	1966
103	Zuidwolde-1	ZUW-1	NAM	2912	1954
104	Zurich-Waddenzee-1	ZUR-1	Placid	2164	1965
105	Zevenhuizen-1	ZVH-1	NAM	3270	1983
106	Zwolle-1	ZWO-1	NAM	1058	1965

[1] The locations of the numbered wells are shown in figure 1.4. For the locations of the non-numbered wells Ermelo-1, IJsselmeer-1 and West-Harlingen-1 reference should be made to figures 5.1, 7.1 and 11.5 respectively.

Reservoir calculations Upper Rotliegend Group

The calculations in the three tables below were carried out for the entire Upper Rotliegend Group, the Slochteren Sandstone Formation and the Akkrum Sandstone resp. Cut-off values applied: clay content Vcl(co) = 50%; effective porosity Øe(co) = 6%. The cut-off value of the effective porosity is based on core data. Wells in which only a part of the Upper Rotliegend Group sequence was evaluated are marked with an *.

Gross, net in metres
Øem = average effective porosity (in percentages)
Vclm = average clay content (in percentages).

Upper Rotliegend Group

Well	*Gross*	*Reservoir*		
		Net	*Øem*	*Vclm*
AKM-1	156.0	115.3	20.7	15.9
AKM-11	118.9	109.5	20.2	10.6
AKM-13	100.6	75.4	20.4	22.0
EMO-1	44.0	43.7	25.8	12.8
HGM-1	92.3	91.2	23.9	19.7
KAM-1	123.2	117.7	18.1	6.8
LEL-1	144.0	143.2	21.1	8.6
MAL-1	182.6	134.3	21.0	16.8
MAR-2	168.2	121.2	17.6	24.3
MBN-1	166.2	126.5	20.5	13.6
NOR-1 *	137.2	111.2	16.0	17.3
NSL-1	29.6	29.2	18.3	19.3
OPH-1	65.3	33.7	11.7	41.4
OPO-1	201.2	149.2	18.2	22.7
STN-1	95.7	95.0	25.6	21.0
SUW-2 *	158.3	112.8	18.7	16.3
URE-101	159.0	117.3	17.1	10.8
VLR-1	40.4	31.6	19.9	4.1
WYK-15	15.8	15.4	16.7	22.1

Slochteren Sandstone Formation

Well	*Gross*	*Reservoir*		
		Net	*Øem*	*Vclm*
AKM-1	114.9	113.9	20.9	15.8
AKM-11	97.6	97.6	20.9	8.8
AKM-13	80.8	73.8	20.5	21.8
EMO-1	44.0	43.7	25.8	12.8
HGM-1	92.3	91.2	23.9	19.7
KAM-1	123.2	117.7	18.1	6.8
LEL-1	144.0	143.2	21.1	8.6
MAL-1	136.2	133.5	21.1	16.8
MAR-2	121.1	119.4	17.6	24.1
MBN-1	125.8	125.4	20.6	13.7
NOR-1 *	118.5	106.6	16.2	16.9
NSL-1	29.6	29.2	18.3	19.3
OPH-1	65.3	33.7	11.7	41.4
OPO-1	155.5	148.4	18.2	22.5
STN-1	95.7	95.0	25.6	21.0
SUW-2 *	111.7	109.8	18.7	16.1
URE-101	120.3	116.1	17.2	10.6
VLR-1	26.6	26.0	20.1	11.9
WYK-15	15.8	15.4	16.7	22.1

Akkrum Sandstone

Well	*Gross*	*Reservoir*		
		Net	*Øem*	*Vclm*
AKM-1	1.3	1.0	12.0	22.9
AKM-11	1.4	1.4	13.9	16.7
AKM-13	1.3	0.0	--	--
VLR-1	5.8	5.6	18.7	24.2

Show, status and test data Upper Rotliegend

Put	Show	Status	Test	Interval	Yield	Flow	Unit
AKM-1	gas	GAS	PRP 1	2342-2348	G	470	ROSL
AKM-11	gas	GAS	PRP 1	2398-2402	G	400	ROCLT/ROSL
					W	26.6	
			PRP 3	2377-2378	G	780	ROSLA
					C	6.2	
					(W)		
AKM-13	gas	GAS	PRP 2	2230-2245	G	285	ROCLT/ROSL
					W	200	
EMO-1	–	D&A	DST 1	1686-1696	SW	10300	ROSL
			FIT 1	1681	SW	20	ROSL
KAM-1	gas	D&A	DST 1	1785-1829	GCSW	2400	ROSL
					GCM	1900	
					C		
			FIT 1	1785-1829	G	0	ROSL
					FW + MF	2	
LEL-1	gas	D&A	DST 1	1850-1950	G + SW		ROSL
MAL-1	gas	SUS	RFT 6	2899			ROCLT
			RFT 7	2930	G + W (u)	3.8	ROSLU
					G + W (l)	10.4	ROSLU
			RFT	2930-3079			ROSL
MAR-2	gas	GAS	PRP	2580-2616	G	680	ROSL
					W	2.7	
					C	7.3	
MBN-1	gas	SUS	PRP	2493-2499	G	170	ROCLT
					W	10	
NOR-1	gas	SUS	PRP	2838-2844	G	350	ROSL
					C	5.9	
					(W)		
OPH-1	–	D&A	FIT	2068	SW + MF	10	ROSL
STN-1	–	D&A	DST 2	1998-2020	SW	11500	ROSL
SUW-2	gas	GAS	PRP	2957-2990	G	2400	ROCLT/ROSL
					W	8.4	
					C	0.7	
URE-101	gas	GAS	PRP 1	2431-2437	G	345	ROSL
					W	1.1	
					C	0.4	
VLR-1	–	D&A	RFT	2411	MF + FW (u)	3.8	ROSL
					MF + FW (l)	10.4	ROSL
WYK-15	–	D&A	RFT 1	3017			ROSL

Legend to appendices D, F and H

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

test interval in metres

FIT	=	formation interval test (flow in litres)
RFT	=	repeat formation test (flow in litres)
DST	=	drill stem test (flow in litres)
PRP	=	production test (flow gas (Q50) in 1000 m^3/d, flow water and condensate in m^3/d)

G	=	gas
O	=	oil
C	=	condensate
FW	=	formation water
SW	=	salt water
W	=	water
MF	=	mud filtrate
GCM	=	gas cut mud
GCSW	=	gas cut salt water

(u)	=	in uppermost chamber of RFT
(l)	=	in bottommost chamber of RFT
pa	=	post acidity
ns	=	no stabilisation

ROSL	=	Slochteren Sandstone Formation
ROSLA	=	Akkrum Sandstone
ROCLT	=	Ten Boer Claystone
ROSLU	=	Upper Slochteren Sandstone

Reservoir calculations Zechstein 2 Carbonate

Cut-off values applied: clay content Vcl(co) = 50%; effective porosity Øe(co) = 2%. The cut-off value of the effective porosity is based on core data.

Gross, net in metres
Øem = average effective porosity (in percentages)
Vclm = average clay content (in percentages)

Well	*Gross*	*Reservoir*		
		Net	*Øem*	*Vclm*
AKM-2	18.5	13.6	3.1	10.9
AKM-11	13.6	3.6	2.8	31.7
AKM-13	19.0	6.6	4.4	8.5
ALO-1	12.2	4.0	7.0	14.9
HGM-1	42.0	41.6	12.1	4.1
LNH-1	40.9	29.6	5.0	4.2
NLM-1	23.5	21.8	6.5	3.2
NSL-1	20.2	16.8	7.5	8.0
OPH-1	25.6	20.0	6.6	4.7
WSF-1	23.4	19.4	6.1	13.3
WYK-15	17.8	4.7	2.9	29.4
WYK-21	24.0	13.8	4.9	14.8

Show, status and test data Zechstein 2 Carbonate

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*
AKM-2	–	D&A	DST 3	2275-2294	MF	
AKM-13	gas	GAS	PRP		G	(ns)
NSL-1	oil	SUS	PRP 1	2067-2077	O	27
					W	81
					(G)	
			FIT 1	2077	MF	10.5
OPH-1	gas	SUS	PRP	1993-2015	G	225 (pa)
					C	0.3 (pa)
WSF-1	gas	SUS	PRP	1934-1943	G	108 (pa)
					W	0.5 (pa)
			RFT	1937	G	900
					FW + C	1
WYK-15	–	D&A	RFT	2827-2833	tight	
WYK-21	–	D&A	RFT	2708-2730	O	0

Reservoir calculations Vlieland Sandstone

Cut-off values applied: clay content Vcl(co)=50%; effective porosity Øe(co)=8%. The cut-off value of the effective porosity is based on core data.

Gross, net in metres
Øem = average effective porosity (in percentages)
Vclm = average clay content (in percentages)

Well	*Gross*	*Reservoir*		
		Net	*Øem*	*Vclm*
AKM-2	19.3	8.7	13.0	35.5
AKM-11	3.7	2.5	13.1	41.3
BOZ-1	42.2	25.2	11.4	35.0
BWD-1	8.0	2.5	13.6	42.9
NSL-1	18.3	12.3	15.3	36.1
TID-105	35.8	29.6	14.3	21.6
WYK-15	3.2	0.0	–	–

Show, status and test data Vlieland Sandstone

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*
AKM-2	–	D&A	DST 1	1975-1979	FW + MF	11400
			DST 2	1978-1983	FW + MF	19200
BOZ-1	gas	GAS	PRP	1880-1889	G	0
NSL-1	gas	SUS	PRP 2	1970-1979	G	2000
					C	29.8

Thin sections

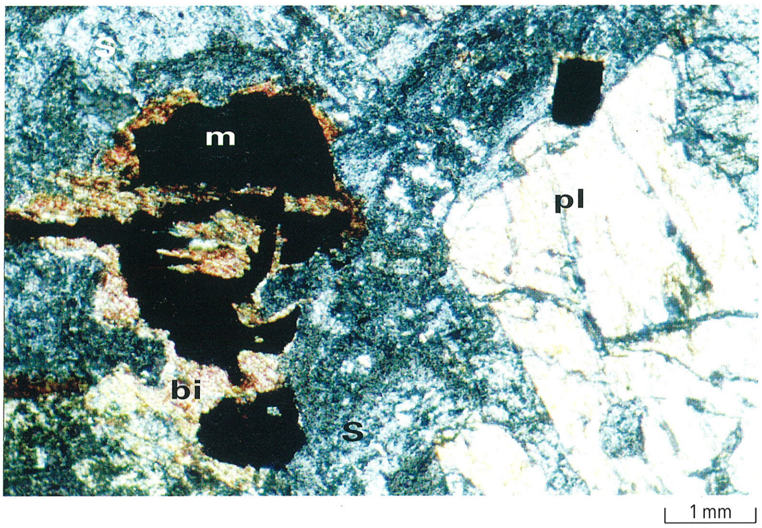


Photo 1 Microscopic view of serpentinitised gabbro from the Wanneperveen-1 well (2064 – 2069.50 m; pl = plagioclase, bi = biotite, s = serpentinite, m = magnetite; crossed nichols). Serpentinite is an alteration olivine. Olivine was the former essential constituent mineral of the gabbro.

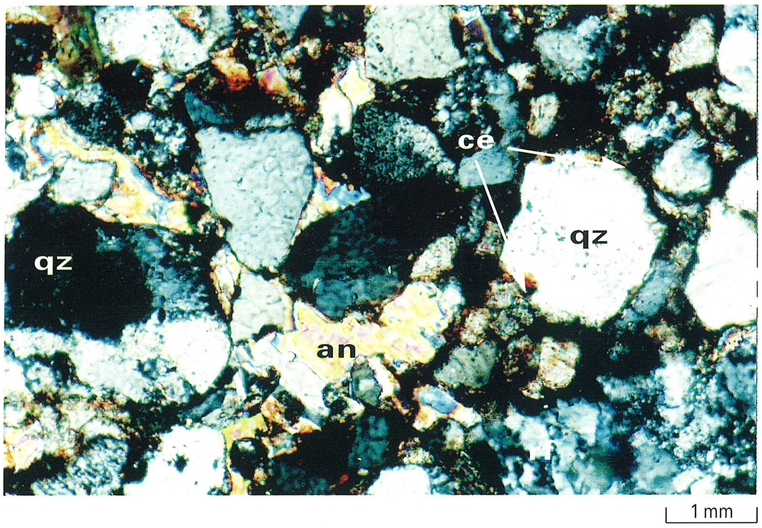


Photo 2 Microscopic view of Slochteren Sandstone: lithified fluvial sands from the Oudega-Akkrum-2 well at a depth of 2381.50 m (qz = quartz, rf = rock fragment, an = anhydrite ce = red-brown ferruginous cement; crossed nichols).

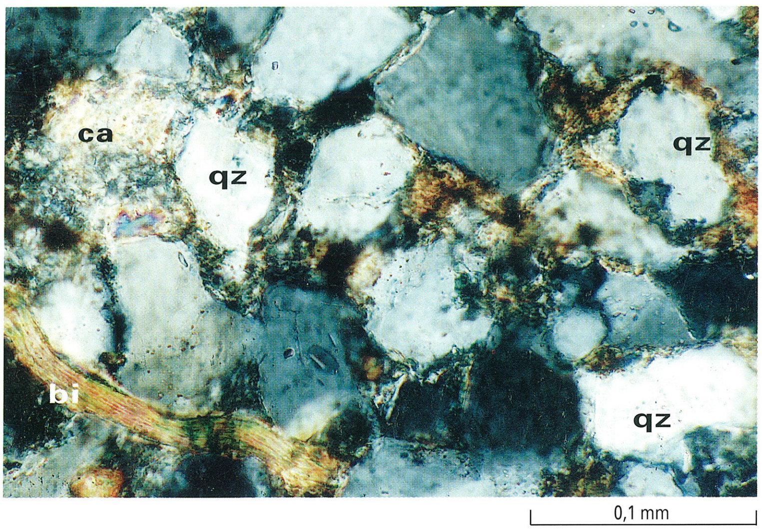
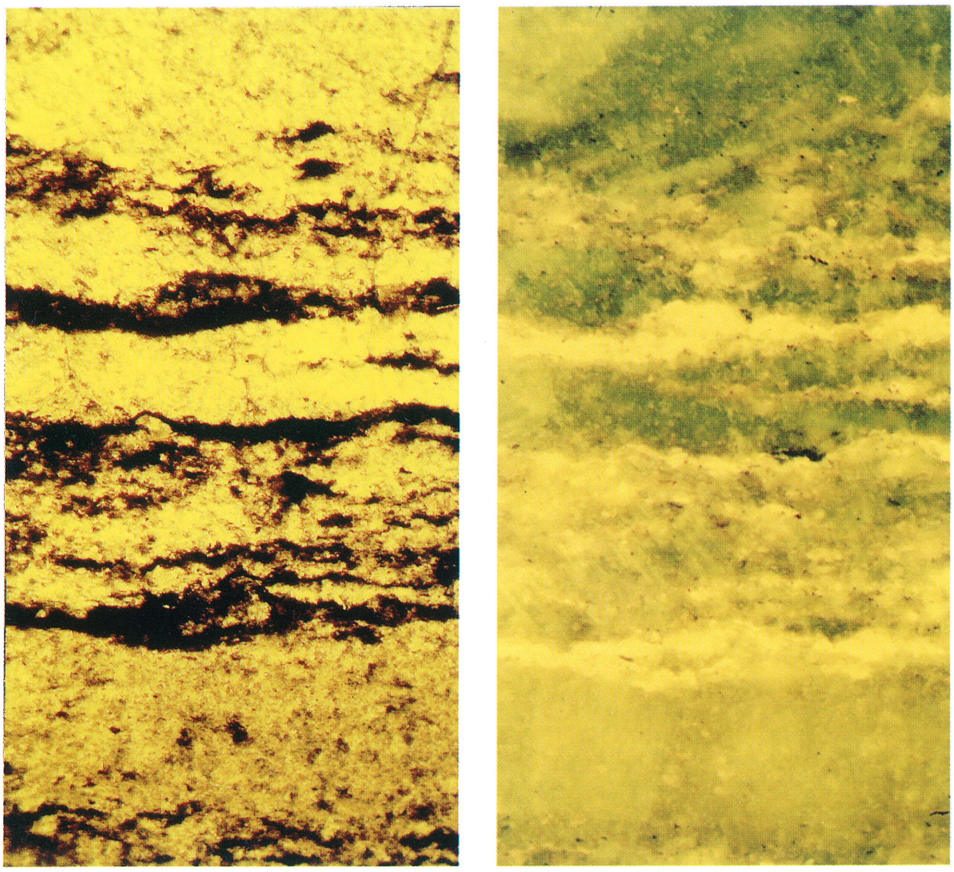


Photo 3 Microscopic view of thin section of the Vlieland Sandstone from the Oudega-Akkrum-2 well at 1984.1 m (qz = quartz, ca = calcite, bi = biotiet; crossed nichols).



a 0,2 mm b 0,2 mm

Photo 4 Microscopic view of Zechstein 2 Carbonate from the Oudega-Akkrum-2 well at 2273.5 m.

a Normal transmitted light with blue filter (yellow = calcite/dolomite, black = clay or oil).

b Fluorescence image (green = calcite/dolomite, brown = clay, fluorescent yellow/white = oil).

References

Literature references

Arthaud, F. & Matte, P. (1975) *Les déchrochements tardi-Hercyniens du sud-ouest de l'Europe; géometrie et essais de réconstruction des conditions de la déformation.* Tectonophysics 25, p. 139–170.

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

Baldschuhn, R., Best, G. & Kockel, F. (1991) *Inversion tectonics in the Northwest German Basin.* In: Generation, Accumulation and Production of Europe's Hydrocarbons (Spencer, A.M., ed.), Special publication EAPG no.1.

Bertelsen, F. (1980) *Lithostratigraphy and depositional history of the Danish Triassic.* Geol. Surv. Denmark, Ser.B, no.4, 59 pp.

Best, G. (1989) *Die Grenze Zechstein/Buntsandstein in Nordwestdeutschland und in der südlichen deutschen Nordsee nach Bohrlochmessungen.* Zeit. deut. 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.

Beutler, G. & Schüler, F. (1979) *Über altkimmerischen Bewegungen im Norden der DDR und ihre regionale Bedeutung (Fortschrittsbericht).* Zeit. geol. Wiss., Berlin 6 (4), p. 403–420.

Bischoff, G. & Wolburg, J. (1963) *Zur Entwicklung des Obermalm im Emsland.* Erdöl-Zeitschrift, vol.79, p. 1–55.

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 Sci., vol.82, p. B85–B89.

Bless, M.J.M., Bouckaert, J., Claver, M.A., Graulich, J.M. & Paproth, E. (1977) *Paleogeography of Upper Westphalian deposits in NW Europe with reference to the Westphalian C North of the mobile Variscan Belt.* Med. Rijks Geol. Dienst, Volume 28-5, p. 101–147.

Bless, M.J.M., Bouckart, J. & Paproth, F. (1983) *Recent exploration on Pre-Permian rocks arond the Brabant Massif in Belgium, The Netherlands and the Federal Republic of Germany.* Geologie en Mijnbouw, vol.62(1), p. 51–62.

Brennand, T.P. (1975) *The Triassic of the North Sea.* In: Petroleum Geology and the Continental Shelf of North-West Europe (Woodland, A.W., ed.), Inst. Petroleum Appl. Sci. Publ., Barking, England, p. 295–311.

Brüning, U. (1986) *Stratigraphie und Lithofazies des Unteren Buntsandsteins in Südniedersachsen und Nordhessen.* Geologisches Jahrbuch, A90, p. 3–125.

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

Christensen, T. (1962) *Alger.* Botanik, 2 (2), 178 pp.

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

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.

Dorsman, L. (1954) *Geological occurences of natural gas in the Netherlands.* Geologie en Mijnbouw, vol.16, p. 443–448.

Eckhardt, H.J. (1979) *Der Permische Vulkanismus Mitteleuropas.* Geologisches Jahrbuch, Ser. D35, 84 pp.

Eigenfeld, R.W.F., Eigenfeld-Mende, I. (1986) *Niederländische Permo-Karbone basische Magmatite als Fortzetsung der spilitisierten effusiva in NW-Deutschland.* In: Mededelingen Rijks Geol. Dienst (Haarlem), volume 40-1, p. 11–21.

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

Francis, E.H. (1988) *Mid-Devonian to early Permian volcanism in the Old World.* In: The Caledonian-Appalachian orogene (A.L. Harris & D.J. fettes, eds.), Geol. Soc., London, Spec. Publ. 38, p. 573–584.

Fuchs, K., von Gehlen, K., Mälzer, H., Murawski, H. & Semmel, A., eds. (1983) *Plateau Uplift. The Rhenish Shield – a case history.* Springer Verlag, Berlin, Heidelberg, New York, Tokyo, 411 pp.

GAPS (1991) *Bury, version 5.42E.* Burial analysis software (GAPS Geological Consultants).

Gdula, J.E., (1983) *Reservoir geology, structural framework and petrophysical aspects of the De Wijk gasfield.* In: Petroleum Geology of the southeastern North Sea and adjacent onshore areas (Kaasschieter, J.P. H. & Reijers, T.J.A., eds.), Geologie en Mijnbouw 62, p. 191–202.

Glennie, K.W. (1972) *Permian Rotliegend of North-West Europe, interpreted in the light of modern desert sedimentation.* AAPG Bull. 56, p. 1048–1071.

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

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

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

Haanstra, U. (1963a) *Het pré-Tertiair van Twente.* In: Geologie van Twente (Anderson, W.H., Krul, P. C. & Römer, J.H., eds.). Uitg: Ned. Geol. Veren., p. 115–123.

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

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

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

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

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

Herngreen, G.F.W. & Wong, Th.E. (1989) *Revision of the 'Late Jurassic' stratigraphy of the Dutch Central North Sea Graben.* Geologie en Mijnbouw, vol.68, p. 73–105.

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.

Jeans, C.V., Long, D., Hall, M.A., Bland, D.J. & Cornford, C. (1991) *The geochemie of the Plenus Marls at Dover, England: evidence of fluctuating oceanographic conditions and of glacial control during development of the Cenomanian-Turonian $\delta 13C$ anomaly.* Geological Magazine, vol.128(6), p. 603–632.

Kimpe W.F.M. (1953) *Doleritic and gabbroic intrusives in the Autunian (Lower Permian) of the boring Wanneperveen-1, Eastern Netherlands.* Geologie en Mijnbouw, vol.15(3), p. 57–65.

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

Lorentz, V. & Nicholls, I.A. (1984) *Plate and intraplate processes of Hercynian Europe during the late Paleozoic.* Tectonopyhics, 107, p. 25–56.

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

NAM & RGD (1980), (Nederlandse Aardolie Maatschappij BV & Rijks Geologische Dienst) *Stratigraphic nomenclature of The Netherlands.* Verhandelingen Kon. Ned. Geol. Mijnb. Gen., vol.32, 77 pp.

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.

Pitman III, W.C. (1978) *Relationship between eustasy 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.

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

Richards, P. (1991) *Experiments on faulting in a two-layer cover sequence overlying a reactivated basement fault with oblique slip.* Journal of Structural Geology, vol.13, No.4, p. 459–469.

Richter-Bernburg, G. (1986) *Zechstein 1 and 2 Anhydrites: facts and problems of sedimentation.* In: The English Zechstein and related topics (G.M. Harwood & D.B. Smith, eds.), Geological Society, London, Special publication 22, p. 33–70.

RGD & NOGEPA (1993) *Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA.* Mededelingen Rijks Geol. Dienst (Haarlem), volume 50.

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

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

Rijks Geologische Dienst (1988) *Geologische inventarisatie en ontstaansgeschiedenis van zoutvoorkomens in Noord-Oost Nederland.* Rapport nr. 10568.

Rijks Geologische Dienst (1991a) *Geological Atlas of the Subsurface of The Netherlands, Explanation to map I: Vlieland –Terschelling.* Geological Survey of The Netherlands RGD, Haarlem, 77 pp.

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

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

Schlanger, S.O., Arthur, M.A., Jenkyns, H.C. & Scholle, P. A. (1987) *The Cenomanian-Turonian oceanic anoxic event. Stratigraphy and distrubution of organic carbon-rich beds and the marine ^{18}C incursion.* In: Marine Petroleum Source Rocks (Brooks, J., & Fleet, A.J., eds), Geological Society Special Publications no.16, p. 371–399.

Scholle, P. A. (1979) *A color illustrated guide to constituents, textures, cements and porosities of sandstones and associated rocks,* AAPG Mem. 28, 201 pp.

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

Stach, E., Chandra, D., Makowsky, M.T.H., Taylor, G.H., Teichmuller, M. & Teichmuller, R. (1982) *Textbook of Coal Petrology* (Bornträger, ed.), Stuttgart), 3rd edition, 535 pp.

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

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

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

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

Thiadens, A.A. (1963) *The Palaeozoic of The Netherlands.* Reprint from Verhandelingen Kon. Ned. Geol. Mijnb. Gen., vol.21-1, 28 pp.

Turner, P. (1980) *Continental Redbeds.* In: Developments in Sedimentology, 29. Elsevier, Amsterdam, 562 pp.

Van Adrichem Boogaert, H.A. & Burgers, W.F.J. (1983) *The development of the Zechstein in The Netherlands.* Geologie en Mijnbouw, vol.62, p. 83–92.

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 der Baan, D. (1990) *Zechstein reservoirs in The Netherlands.* In: Classic Petroleum Provinces (Brooks, J., ed.), Geol. Soc. Spec. Publ. No. 50, p. 379–398.

Van der Poel, A.B. (1987) *Porosity development in some uplifted carbonates of the Southern Permian Basin (Texel-IJsselmeer High, The Netherlands and The Harz, Germany),* Mededelingen Rijks Geol. Dienst, vol. 41-1, p. 1–16.

Van Wijhe, D.H. & Bless, M.J.M. (1974) *The Westphalian of The Netherlands with special reference to miospore assemblages.* Geologie en Mijnbouw, vol.53(6), p. 295–328.

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

Van Wijhe, D.H. (1987b) *The structural evolution of the Broad Fourteens Basin.* In: Petroleum Geology of Northwest Europe (Brooks, J., & Glennie, K.W., eds.) Graham & Trotman, London, p. 315–323.

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.

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

Walker, T.R. (1967) *Formation of redbeds in ancient and modern deserts.* Geol. Soc. Am. 78, p. 353–368.

Warrington, G. (1974) *Les évaporites du Trias brittanique.* Bulletin Soc. géologique France, (7) XVI(6), p. 708–723.

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

Wolburg, J. (1962) *Über Schwellungen im Mittleren Buntsandstein des Weser-Ems-Gebietes.* Erdöl-Zeitschrift, 78, p. 183–190.

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

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

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

Ziegler, P.A. (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, 198 pp.

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

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

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

RGD, 1974, Herngreen, G.F.W. *Resultaten van het palynologisch onderzoek van boring KA-27 (IJsselmeer-1).* Rapport Micropal. Mesozoïcum no. 2088a.

RGD, 1986, Plomp, A.N. *Zechstein Randfacies Studie.* Rapport no. 86ADV16.

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

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

RGD 1990, Herngreen, G.F.W. *Samenvatting van de micropaleontologische en palynologische onderzoeksresultaten van boring Dronten-1.* Rapport no. 2233.

RGD, 1991a, Witte, L.J. & Lissenberg, Th. *Revisie van het Onder-Krijt van een vijftal boringen, t.w. Leeuwarden-5, Warga-1, Eernewoude-1, Oudega-Akkrum-1 en Oudega-Akkrum-2.* Rapport no. 486.

RGD, 1991b, Witte, L.J. & Schuurman H. *Biostratigrafisch onderzoek aan kernen in het Boven-Krijt van Nederland.* Rapport no. 525.

RGD, 1991c, Witte, L.J. & Lissenberg, Th. *Biostratigrafisch interpretatie aan interval 1392 –1499 m van boring Wanneperveen-1.* Rapport no. 535.

RGD, 1991d, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van interval 2150 m – 2186 van boring Oudega-Akkrum-11.* Rapport no. 536.

RGD, 1992a, Van Amerom, H.W.J. *Rapport betreffende drie kerntrajecten van diepboring Nagele-1* (Elf Petroland). Rapport GB 2362.

RGD, 1992b, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van interval 1590 – 1680 m van boring Emmeloord-1.* Rapport no. 533.

RGD, 1992c, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van interval 1520 – 1620 m van boring Nagele-1.* Rapport no. 534.

RGD, 1992d, Witte, L.J. & Lissenberg, Th. *Biostratigrafische interpretatie van interval 1950–2005 m van boring Nijensleek-1.* Rapport no. 540.

RGD, 1993a, Ramaekers, J.J.F. & Neele, N.N. *Resultaten petrofysische evaluatie van een drietal reservoirs op kaartblad V.* Rapport no. 93KAR07.

RGD, 1993b, Fermont, W., David, P. & Jegers, L. *Geochemische en koolpetrografische prospectiviteitsonderzoek van de diepe ondergrond van Noord-Nederland, Kaartblad V.* Rapport no. GB2424.

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

Geological maps

The maps were compiled by
W. Apon
J. Klijn
R.H.B. Rijkers

Design
R.M. Metten

Cartography
European Institute of Cartography, Zoetermeer

Printing
Haagse Drukkerij, The Hague

Explanation

The explanation accompanying the maps was written by
R.H.B. Rijkers

Figures
R.R. van der Kraan

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

Design
J.A.M. Bruinenberg

Printing
Sdu Grafische Projecten, The Hague

Project management

Th.H.M. van Doorn

ISBN 90-72869-19-21-4

This publication should be referred to as
Rijks Geologische Dienst, 1993 – Geological Atlas of the Subsurface of The Netherlands, Explanation to map sheet V: Sneek–Zwolle, Geological Survey of The Netherlands RGD, Haarlem.

This publication is a translation of the Dutch version (ISBN 90-72869-20-6).