Netherlands Institute of Applied Geoscience TNO
– National Geological Survey

Explanation to map sheet IX Harderwijk-Nijmegen

Geological Atlas of the Subsurface of the Netherlands

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Harderwijk-Nijmegen

Netherlands Institute of Applied Geoscience TNO – *National Geological Survey*, Utrecht 2004

Geological Atlas of the Subsurface of the Netherlands

Lacquer peel of an ice wedge from the Weichselien, Late Pleistocene
Photo by courtesy of TNO-NITG.

Contents

The publication of map sheet IX by the Netherlands Institute of Applied Geoscience TNO – *National Geological Survey* completes the Geological Atlas of the Subsurface of the Netherlands. This atlas provides a unique series of maps of the subsurface of the Netherlands, summarising potential exploitation opportunities. TNO-NITG's extensive regional-geological knowledge of the subsurface of the Netherlands and surrounding countries clearly enhances the quality of these publications, which far exceeds that of routine mapping.

Open publication of information on the geology of the subsurface, deeper than 500 m; used to be very limited because of the confidential status of the data concerned. The old Mining Act, which applied to the Dutch Territory up to 2003, did not permit the general release of this confidential information.

As from 1 January 2003, the new mining legislation applies, which allows release after five years. Data on the Netherlands Territory that are over 10 years old are now immediately available upon request, and transitional arrangements apply for the period in between.

The Harderwijk-Nijmegen map sheet of the Geological Atlas of the Subsurface of the Netherlands is the fifteenth and final sheet to be published as part of the project for the systematic mapping of the subsurface of the Netherlands. For this project, the Netherlands has been divided into 15 map sheets, which have been published on a scale of 1:250 000 (see fig. 1.1 for an overview of the area of the map sheets). Each map sheet has its own characteristic features. The map sheet presented here outlines the geology of most of the province of Gelderland and parts of the provinces of Overijssel, Noord-Brabant, Utrecht and Flevoland. Maps and explanation show that the geological history of this area has been marked by turbulent events. During most of the geological history, the area was characterised by continuous subsidence, and thick marine and continental sequences were deposited. At the end of the Cretaceous, inversion of the prevailing direction of movement caused significant uplift and erosion of the sediments laid down in the originally subsiding areas; while the originally stable highs changed into subsiding areas in which thick chalk sequences were deposited.

The text comprises three main parts. The first part describes the research set-up in Chapter 1. This is followed by the history of hydrocarbon exploration in Chapter 2, and the structural framework in Chapter 3. The second part contains lithostratigraphic descriptions of the strata in Chapters 4 to 12, followed by the geological history of the map sheet area in Chapter 13. The lithostratigraphic descriptions emphasise the variability and areal distributions of the different groups, formations and members, and the links between these and the major structural elements of the map sheet area. Each chapter ends with a section devoted to sedimentary development and palaeogeography. In the third part, Chapter 14, special attention is given to various aspects of economic and applied geology, such as coal petrography, hydrogeology, thermal water, and the processing of liquid sludge by the Vartech process.

TNO-NITG is confident that this map sheet, together with the sheets already issued and the simultaneous publication of the compilation of all 15 map sheets, in the 'Geological Atlas of the Subsurface of the Netherlands – *onshore*' will contribute to a better understanding of the structure and configuration of the subsurface of the Netherlands. This is important, not only to companies which are active in the exploration for and production of mineral and natural resources, but also to various government and local authorities and other interested parties. Digital versions of the maps are also available. TNO-NITG has developed a 3D viewer enabling the maps to be viewed in three dimensions (see: http://dinoloket.nitg.tno.nl).

As well as those people acknowledged for their contributions in the credits, many other TNO-NITG employees have been involved in the compilation this map sheet. Their efforts are greatly appreciated.

Regular consultations have been held with Dr. K.H. Ribbert of the Geologischer Dienst Nordrhein-Westfalen on the tectonic evolution of the adjoining parts of Germany. Special thanks are due to the companies which provided the exploration data used in these map sheets.

Utrecht, November 2004

1 Research set-up

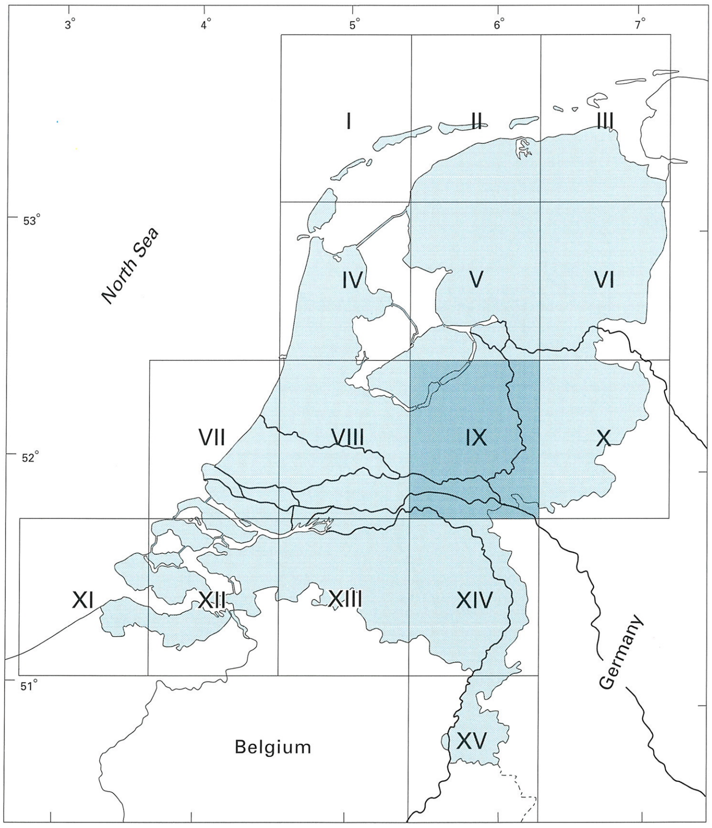
1.1 Extent of area studied

The area covered by map sheet IX (Harderwijk-Nijmegen) of the Geological Atlas of the Subsurface of the Netherlands comprises most of the province of Gelderland and parts of the provinces of Overijssel, Noord-Brabant, Utrecht and Flevoland. The south-eastern corner of the map sheet area just touches the border with Germany (fig. 1.1).

1.2 Data base

The mapping of the map sheet area has made use of seismic and well data acquired by industry. Mapping of this sheet relied mainly on 2D seismic. For the eastern part of the map sheet area, 3D seismic has also been used (fig. 1.2; Appendix B). A total of 23 wells have been drilled in the map sheet area and all of these have been used for the mapping, as well as 14 other wells drilled in areas adjoining this map sheet (fig. 1.3).

Figure 1.1 Map sheet areas used for the regional mapping of the subsurface of the Netherlands showing the location of map sheet IX.



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

1.3 Geological research

The geological research focused on the lithostratigraphic configuration of the sediments that are present in the map sheet area (fig. 1.4) and their geological history with regard to the regional-geological framework. Use was made of the seismic sections and well-log data referred to above. Each lithostratigraphic unit that has been identified in the map sheet area and listed in fig. 1.4, is discussed in detail in a dedicated chapter. The present explanation uses Harland's geological timescale (Harland et al., 1990).

1.4 Seismic mapping

The mapping made use of all available seismic data. The seismic data used were shot between 1965 and 1996. Most of the map sheet area is covered by a wide-mesh grid of 2D seismic. A 3D survey was only available for the eastern part of the map sheet area (fig. 1.2, Appendix A). The 2D seismic surveys vary in quality: for the central part of the map sheet area, the Veluwe, and for the southern part, only poor-quality seismic surveys, dating from the 1960s, were available. However, for other parts of the map sheet area, high-quality seismic surveys shot in the 1970s and 1980s could be used. Most of the available 2D seismic has been interpreted; a few sections were only used to determine the locations of faults and subcrops. The interpretation made use of a total of approximately 350 km² of 3D seismic and almost 2000 km of 2D seismic.

Figure 1.2 Locations of the seismic lines used for the mapping. Appendix A contains additional information on the shooting dates and owners of the various surveys.

The mapped reflectors form the boundaries between the lithostratigraphic units (groups and formations). The seismic data were calibrated against a number of wells, by means of acoustic logs and check-shot surveys. The time-depth conversion of the seismic data was carried out on a layer-by-layer basis (the so-called 'layer-cake' method). This method is based on the assumption that each layer shows a typical linear relationship between its acoustic velocity and its depth (table 1.1).

To ensure consistency between adjacent map sheets, originally, a single velocity-distribution model was derived that was to be applied to all the map sheets of the Geological Atlas of the Subsurface of the Netherlands. The parameters of this countrywide velocity-distribution model were determined from the acoustic data from 61 representative wells drilled all over the Netherlands. Application of this velocity-distribution model, however, gave rise to large discrepancies in the depths of the bases of the Rijnland, Altena and Lower Germanic Trias Groups, particularly in the inversion areas, and consequently the velocity-distribution model was revised. Regional velocity-distribution models (*TNO-NITG, 2001*) were constructed on the basis of acoustic data from over 600 wells located in the Netherlands Territory. For the map sheet area, this produced the velocity-distribution model shown in table 1.1. Because the processing of parts of the adjoining map sheets V and X employed other velocity-distribution models at the time, minor corrections had to be made in the depth and isopach maps near the boundaries with those map sheets.

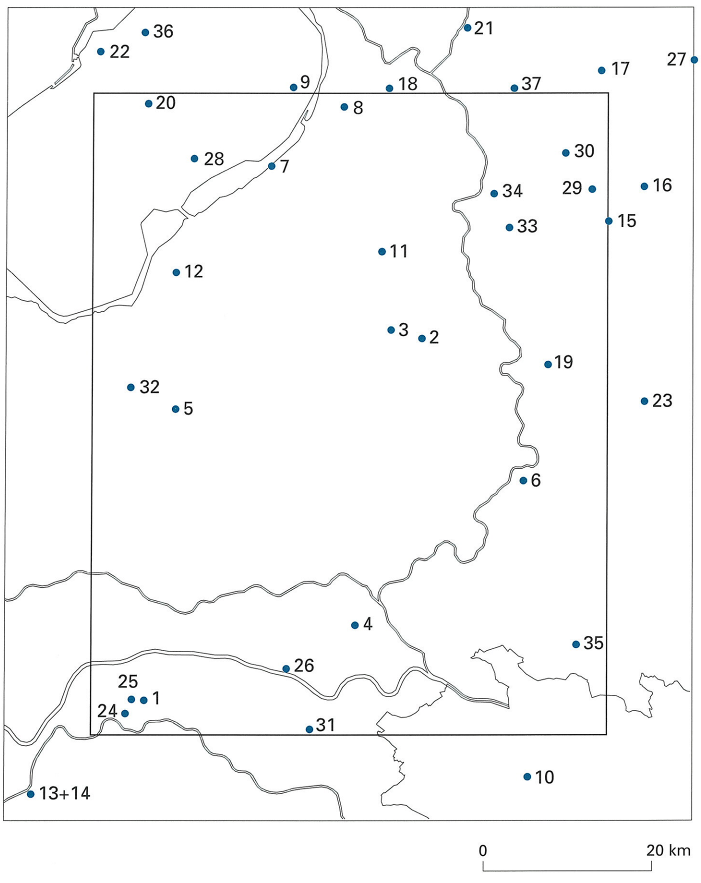


Figure 1.3 Locations of the wells used for the mapping. Please refer to Appendix B for the numbers and the names, owners, total depths and drilling dates of the wells.

The interpreted seismic horizons are the lower boundaries of the following lithostratigraphic groups: the Upper North Sea Group, the North Sea Supergroup, the Chalk, Rijnland, Schieland and Altena Groups, the Lower and Upper Germanic Trias Groups and the Zechstein Group (fig. 1.4).

The Upper North Sea Group is the youngest seismic unit and is characterised, by high-amplitude continuous reflections, just like the Lower and Middle North Sea Groups. Many units within the Middle North Sea Group, in particular, are broken up by numerous small faults. The base of the North Sea Supergroup is readily identified in the entire map sheet area by its high amplitude reflections and good lateral continuity.

The base of the Chalk Group forms a distinct reflector, however, there are hardly any continuous reflections within the Chalk Group itself. In the south-western part of the map sheet area, the Rijnland Group consists virtually solely of the Holland Formation. This formation produces a number of prominent high-amplitude reflections. The Vlieland subgroup is only developed locally and is very thin here. Both in the south-west and in the north-east, the sediments underlying the base of the Rijnland Group show a clear

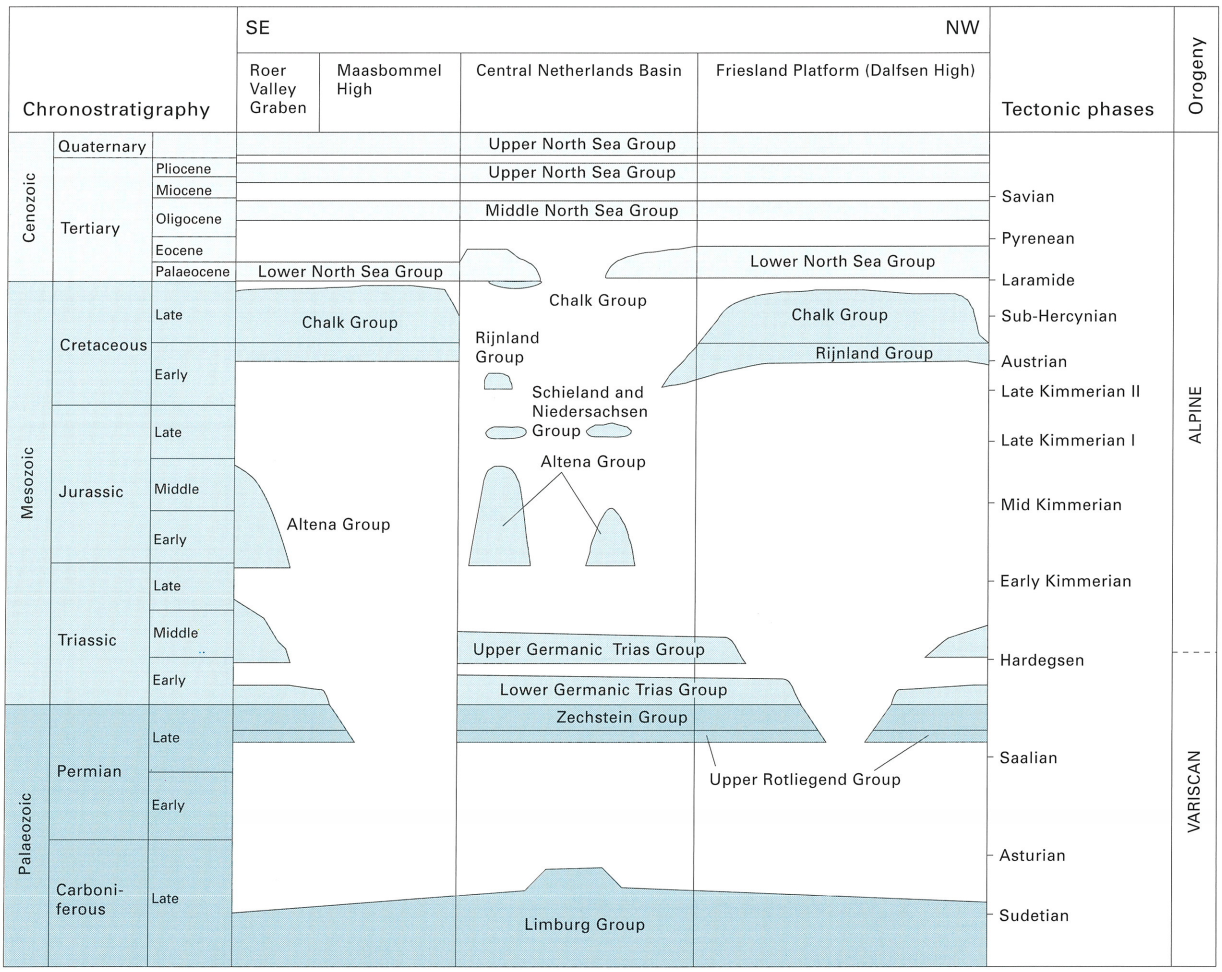


Figure 1.4 Diagram of the lithostratigraphic units and the major tectonic phases that have affected the geological evolution of the map sheet area.

Table 1.1 Velocity-distribution models applied

The velocity-distribution models applied in the map sheets are based on the equation:

$V_z = V_o + k.z$ in which:

V_z: average velocity at depth z (m/s)

V_o: theoretical velocity at depth z = 0 (m/s)

k: specific constant (1/s)

z: depth (m)

Unit	*Vo*	*k*
North Sea Supergroup	1696	0.47
Chalk Group	2156	1.03
Rijnland Group	2026	0.73
Schieland and Niedersachsen Groups	2770	0.53
Altena Group	2451	0.44
Lower and Upper Germanic Trias Groups	3097	0.47
Limburg Group	3443	0.25

angular unconformity. The Rijnland sediments in the central part of the map sheet area are often difficult to trace and conformably overlie the Schieland Group.

The bases of the locally present Schieland and Niedersachsen Groups are difficult to trace, they are locally marked by angular unconformities. Hardly any coherent reflections can be traced within these groups.

Within the Altena Group, coherent reflections can only be recognised on a local scale. The Posidonia Shale Formation, often an easily identifiable reflector on seismic, is, in the map sheet area, only present locally, in grabens (figs 3.2 & 8.4). The base of the Altena Group often forms a strong, continuous reflector. However, in the central part of the map sheet area, this reflector lies very deep and is difficult to trace because it is heavily faulted.

The Lower Germanic Trias Group is acoustically virtually transparent, whereas the Upper Germanic Trias Group contains more continuous reflections and its basis can often be traced -fairly- easily.

In the north of the map sheet area, the base of the Zechstein Group can be interpreted fairly reliably. It may locally contain some salt structures here (fig. 3.2). In the southern part of the map sheet area, the Zechstein is so thin that it cannot be identified on seismic sections. The Upper Rotliegend Group is also so thin in the southern and eastern parts of the map sheet area that it cannot be identified reliably on seismic sections. The isopach maps of the Zechstein and Upper Rotliegend Groups are, therefore, mainly based on well-log data and a general knowledge of the regional geology.

1.5 Biostratigraphic research

To support the geological research, use was made of a large number of biostratigraphic studies (*RGD, 1974; RGD, 1975; RGD, 1981; RGD, 1985; RGD, 1986a; RGD, 1987a,b; RGD, 1990; RGD, 1995; NITG-TNO, 1999; TNO-NITG, 2002a, b*).

1.6 Maps and cross-sections

The results of the mapping are presented on a scale of 1:250 000 in a series of depth and isopach maps of the lithostratigraphic groups, on subcrop maps and in three cross-sections (Maps 1 t/m 19). An overview of the stratigraphy is given in fig. 1.4.

Depth maps have been prepared for the bases of the Upper Rotliegend, the Zechstein, the Lower Germanic Trias, the Altena, the Schieland and Niedersachsen, the Rijnland and the Chalk Groups, the North Sea Supergroup and the Upper North Sea Group. The map of the Zechstein Group was made by adding the thickness of the Zechstein Group to the maps of the Lower and Upper Germanic Trias Groups, The thickness values are based on well data and on seismic interpretation. The map of the Upper Rotliegend Group was compiled in a similar fashion. The depth map of this group is based on the base of the Zechstein Group, to which the thickness of the Upper Rotliegend Group has been added.

Isopach maps have been prepared for the Zechstein, the Lower and Upper Germanic Trias, the Altena, the Schieland and Niedersachsen, the Rijnland and the Chalk Groups. The depth and isopach maps only show those wells in which the interval in question was fully penetrated.

Subcrop maps have been made for the major unconformities: at the bases of the Schieland Group, the Rijnland Group and the North Sea Supergroup. These give an impression of the degree of erosion that preceded deposition of these groups. Finally, three structural cross-sections are included (Map 19).

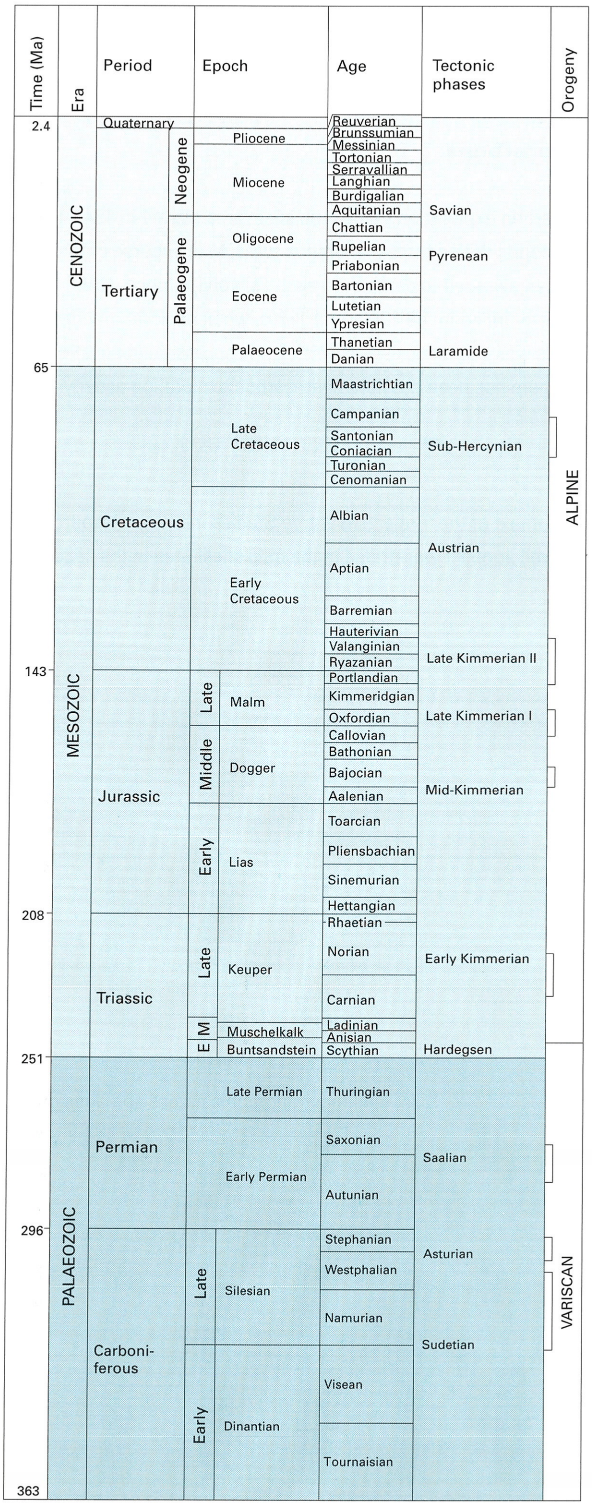
1.7 Explanation

This explanation supplements the information provided by the geological maps and sections in order to provide as complete a picture as possible of the geological configuration and history of the map sheet area. In Chapters 4 to 12, the lithological successions are described, including an account of the lithostratigraphy and sedimentary development. Chapter 13 outlines the geological history of the area, explaining the connection between basin development and tectonic events and the large-scale regional tectonic framework. In the last part, Chapter 14, special attention is given to various aspects of economic and applied geology, such as coal petrography, hydrogeology, thermal water, and the processing of liquid sludge by the Vartech process.

Unless stated otherwise, the lithostratigraphic names and ages of the units are in accordance with the 'Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA' (Van Adrichem Boogaert & Kouwe, 1993-1997). The lithostratigraphic descriptions emphasise the variations and areal distributions of the different groups, formations and members. The areal distribution is generally related to the major structural elements of the map sheet area, which are outlined in Chapter 3. Figure 1.5 shows the geological timescale and the main tectonic phases as used in this explanation. References to internal reports within the body of the text are printed in italics.

The Quaternary deposits are only briefly referred to in this explanation. A detailed description has been published in 'Explanation to the Geological map of the Netherlands 1:50 000, map sheets Arnhem 40 east and Tiel 39 East and West' (Rijks Geologische Dienst, 1977 and 1984). In addition, section 13.2.6.1 takes a closer look at the relationships between old fault systems, neotectonics and glacial landforms.

Figure 1.5 Geological timescale used in this explanation, after Harland et al., 1990. All chronostratigraphic references in this explanation are based on this timescale. The tectonic phases mentioned in the text are also listed in this figure.



2 Exploration history

2.1 Introduction

The main targets of exploration in the map sheet area have been hydrocarbons, coal and thermal water. Near Apeldoorn, a large-diameter well was drilled for the purpose of processing liquid sludge.

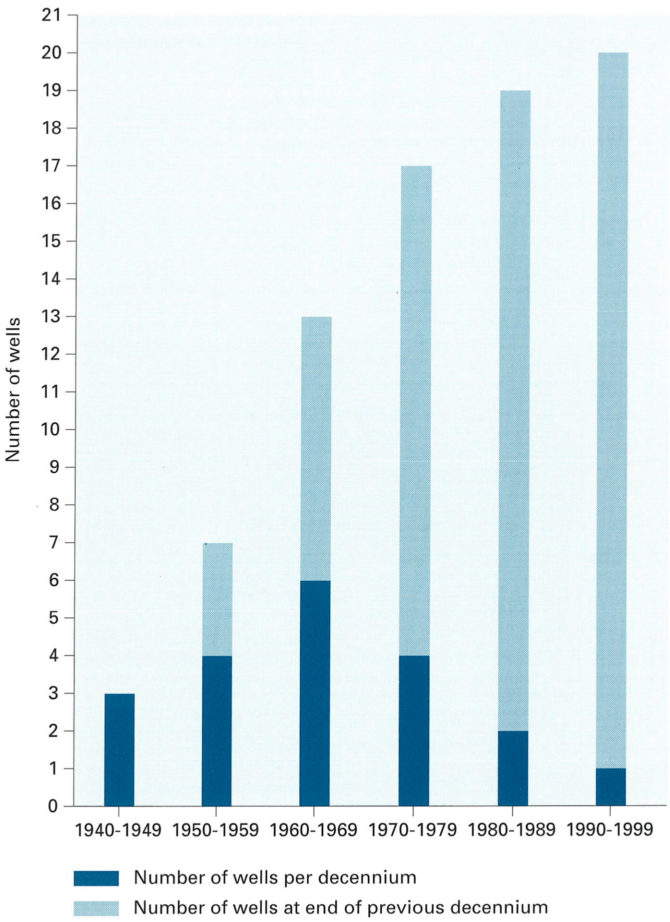
2.2 Hydrocarbons

Hydrocarbon exploration in the map sheet area started in 1943-1944, when the Bataafse Petroleum Maatschappij drilled three exploration wells. In the course of the following decades, ten drilling licences have been awarded to companies such as Mobil, Amoco, NAM, Petroland, BP, and Conoco. A further ten wells were drilled in the 1960s and 1970s, when exploration efforts peaked (fig. 2.1). Because none of the wells was economically successful, no concession applications have ever been filed. In the past few years, there has been no more hydrocarbon exploration activity in the map sheet area.

2.3 Coal

In the context of the 'Project Inventory Studies into Coal Resources in the Netherlands, phase 1, 1981 – 1985', well Joppe-1 was drilled in the map sheet area in the 1980s. Carboniferous strata were penetrated

Figure 2.1 Overview map of the hydrocarbon exploration wells drilled within the map sheet area.



from 819 to 1494 metres. The results of this well are discussed in section 14.2, dealing with Applied Geology.

2.4 Thermal water

In 1994, a well was drilled near Nijmegen with the objective of producing mineral water for the Sanadome Thermae. The well aimed at the Chalk Group and reached a total depth of 759 m. The bottom 50 metres of this well transsected very marly chalk deposits with poor porosities and permeabilities. Therefore, the water filters were placed at 695 m, in the sands of the Heers Member, which is part of the Lower North Sea Group.

3 Structural framework

This chapter describes, in chronological order, the various structural units (fig. 3.1) that are distinguished within the map sheet area. Structural evolution was predominantly controlled by the Variscan and Alpine Orogenies; most of the structural elements had, however, presumably already formed during the Caledonian Orogeny.

During the Late Carboniferous, the northern part of the map sheet area was occupied by the **Netherlands High** (fig 3.1a), a significantly uplifted area covering a large part of the central and northern Netherlands, where only Westphalian A and B strata still remain. The **Achterhoek High** occupied the southern part of the map sheet area. In this wide anticlinal structure, sediments deposited during the Westphalian A, B and Early Westphalian C unconformably underlie Permian deposits.

In the Late Permian, a new NW-SE-oriented basin formed: the **Central Netherlands Basin** (fig. 3.1b). To the south, this basin is bordered by the **South Netherlands Platform** and to the north by the **Texel-IJsselmeer High**.

During the Triassic the **Netherlands Swell** developed in the northern part of the map sheet area; where only the lowermost Triassic deposits are preserved.

The Central Netherlands Basin experienced a period of rapid differential subsidence during the Kimmerian tectonic phases, resulting in a pattern of local grabens and highs with a WNW-ESE trend. In the grabens, a fairly complete sequence of Jurassic and older sediments has been preserved. Upper Jurassic and Lower Cretaceous sediments have only been preserved in smaller, local grabens, such as the **Gouwzee Trough** and the **Voorthuizen Trough**. In the north, the Central Netherlands Basin is separated from the **Texel-IJsselmeer High** and its south-eastward extension, the **Friesland Platform** by a large boundary fault: the **Raalte Boundary Fault** (fig. 3.1c). The **Dalfsen High** (fig. 3.1c), in the far north-eastern corner of the map sheet area, suffered deep erosion during the Late Kimmerian phases. On the Dalfsen High, the Rijnland Group unconformably overlies Carboniferous strata (Map 17).
The southern boundary of the Central Netherlands Basin is formed by the **Maasbommel High**, which experienced significant uplift during the Mesozoic (TNO-NITG, 2001a). The **Mid-Netherlands Fault Zone**, is a major lineament that encompasses, in addition to faults, associated structures such as the Zandvoort Ridge and IJmuiden High to the west of the map sheet area; the Maasbommel High in the map sheet area; and the **Peel** and **Venlo Blocks** to the south of the map sheet area. This fault zone also forms the north-eastern boundary of the West Netherlands Basin and the **Roer Valley Graben** (fig. 3.1c). During the Late Kimmerian phase, the individual highs between Zandvoort and Venlo suffered severe erosion as a result of tilting and uplift, followed by a marked subsidence during the Late Cretaceous.

During the Late Cretaceous, inversion caused uplift of the Central Netherlands Basin and thus, all sediments above the Jurassic and Triassic were removed by deep erosion. Thrusting occurred along the basin fringes while the centre of the basin experienced the greatest uplift. During and towards the end of the Late Cretaceous, the local highs within the basin were also uplifted. The Tertiary sediments on these highs, e.g. the **Knardijk High**, the **Apeldoorn High** and the **Joppe High** (fig 3.1c), therefore immediately overlie Carboniferous strata. The Chalk Group is missing in the Central Netherlands Basin, with the exception of a small area of sediments of a Danian age, deposited after the inversion period, which have been preserved in the north-western part of the map sheet area and in the adjoining part of Germany (fig. 11.4). During the inversion period, the former basin fringes underwent subsidence. Thick Chalk sequences are encountered on the Maasbommel High as well as in the north-eastern part of the map sheet area, on the Friesland Platform.

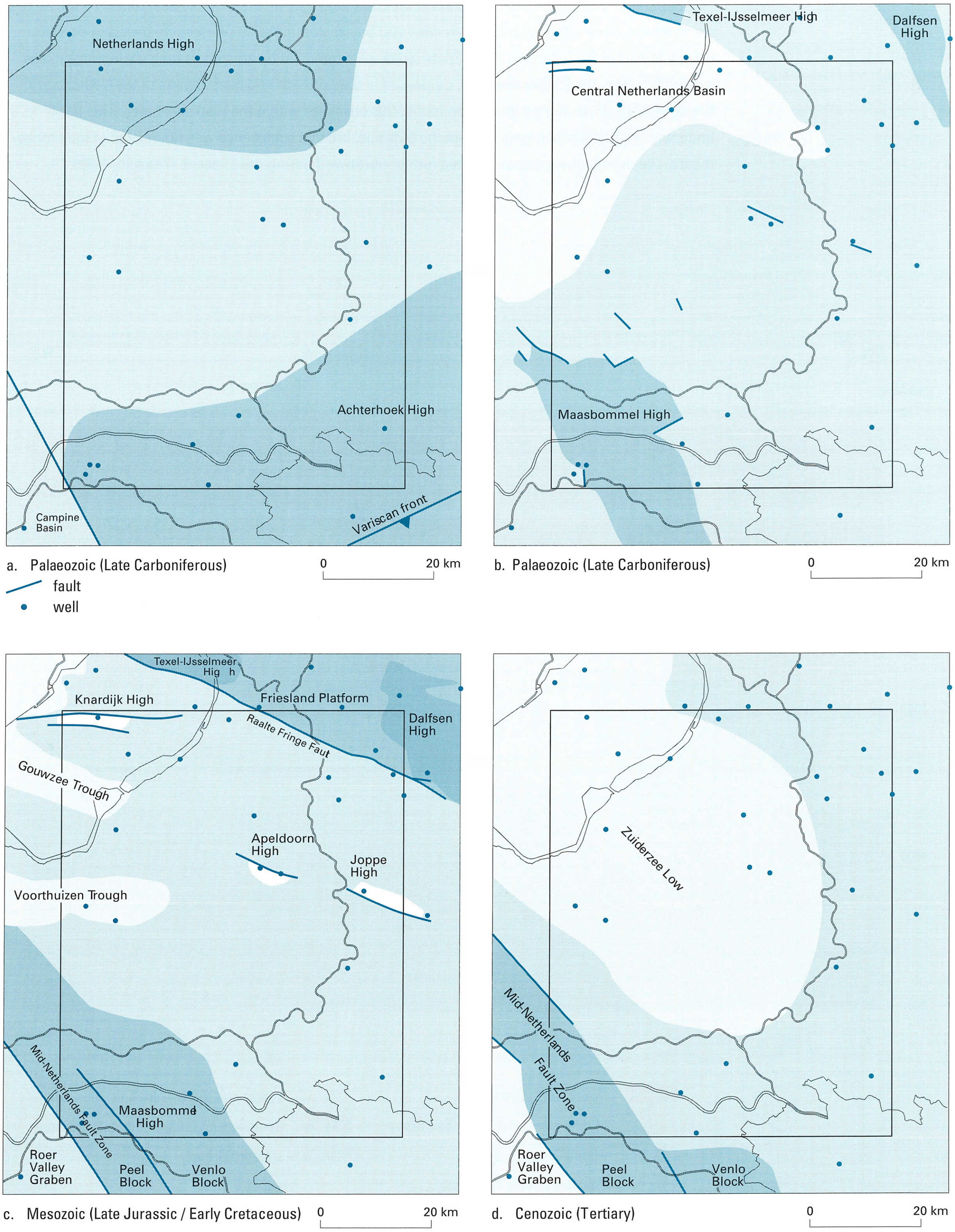


Figure 3.1 Overview of the evolution of the structural elements present in the map sheet area.
a. Palaeozoic (Late Carboniferous); b. Palaeozoic (Late Permian); c. Mesozoic (Late Jurassic/Early Cretaceous); d. Cenozoic (Tertiary).

Right up to the Late Oligocene, the Cenozoic was dominated by inversion tectonics caused by the Alpine compression. During the Laramide, Pyrenean and Savian compression phases, the basins underwent uplift and part of the Mesozoic and Tertiary strata were removed by erosion. During the Tertiary, a new subsidence area, the **Zuiderzee Low**, developed in the northern and central parts of the Netherlands (fig. 3.1d & fig. 13.4). The south-eastern part of this basin lies within the map sheet area. This basin underwent regional subsidence as from the Miocene, but this subsidence was not related to fault movements. The depocentre gradually shifted further northward during the Pliocene (Zagwijn, 1989).

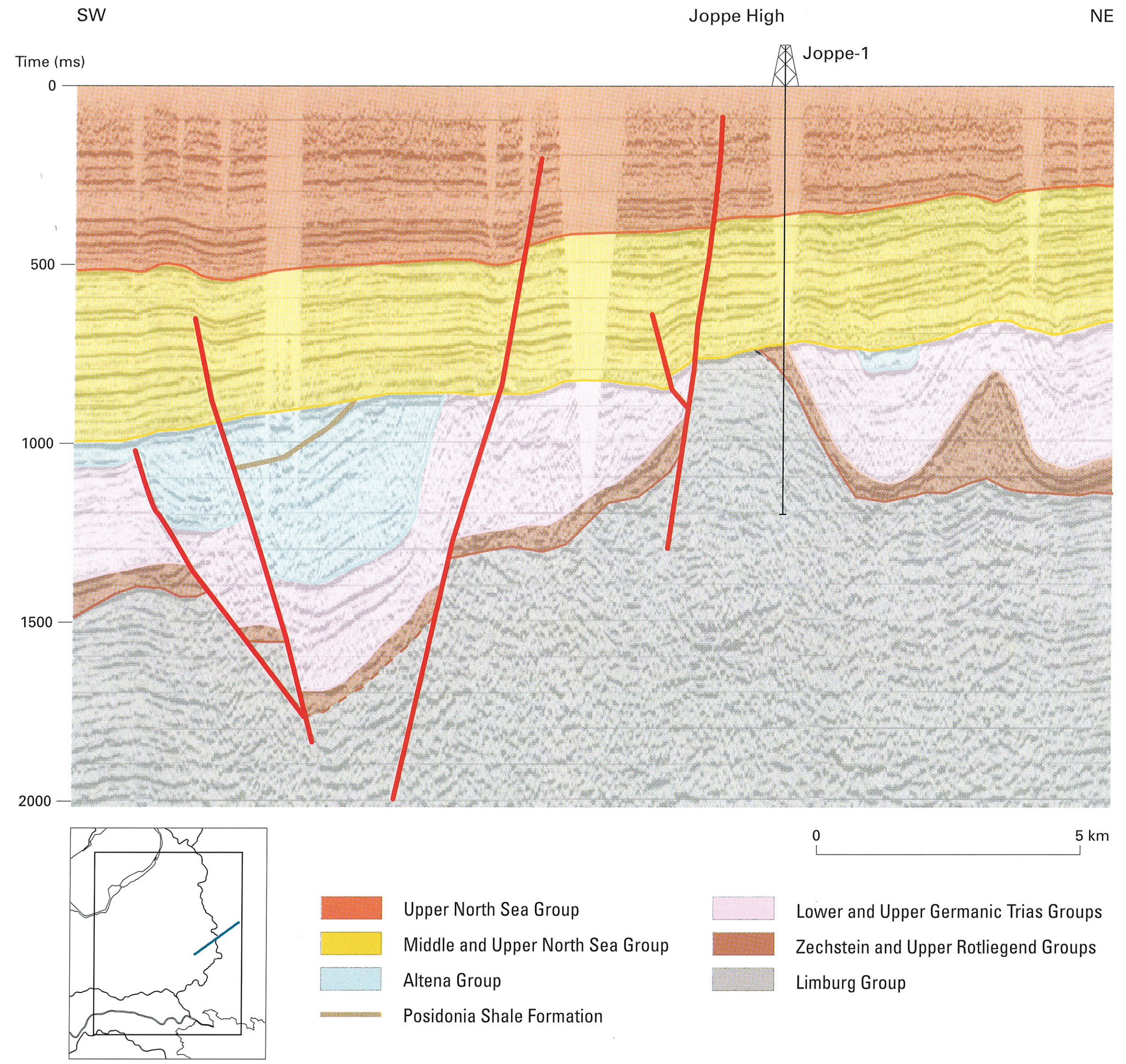


Figure 3.2 Seismic section through the eastern part of the map sheet showing the Joppe High and a salt pillow to the north-east of it.

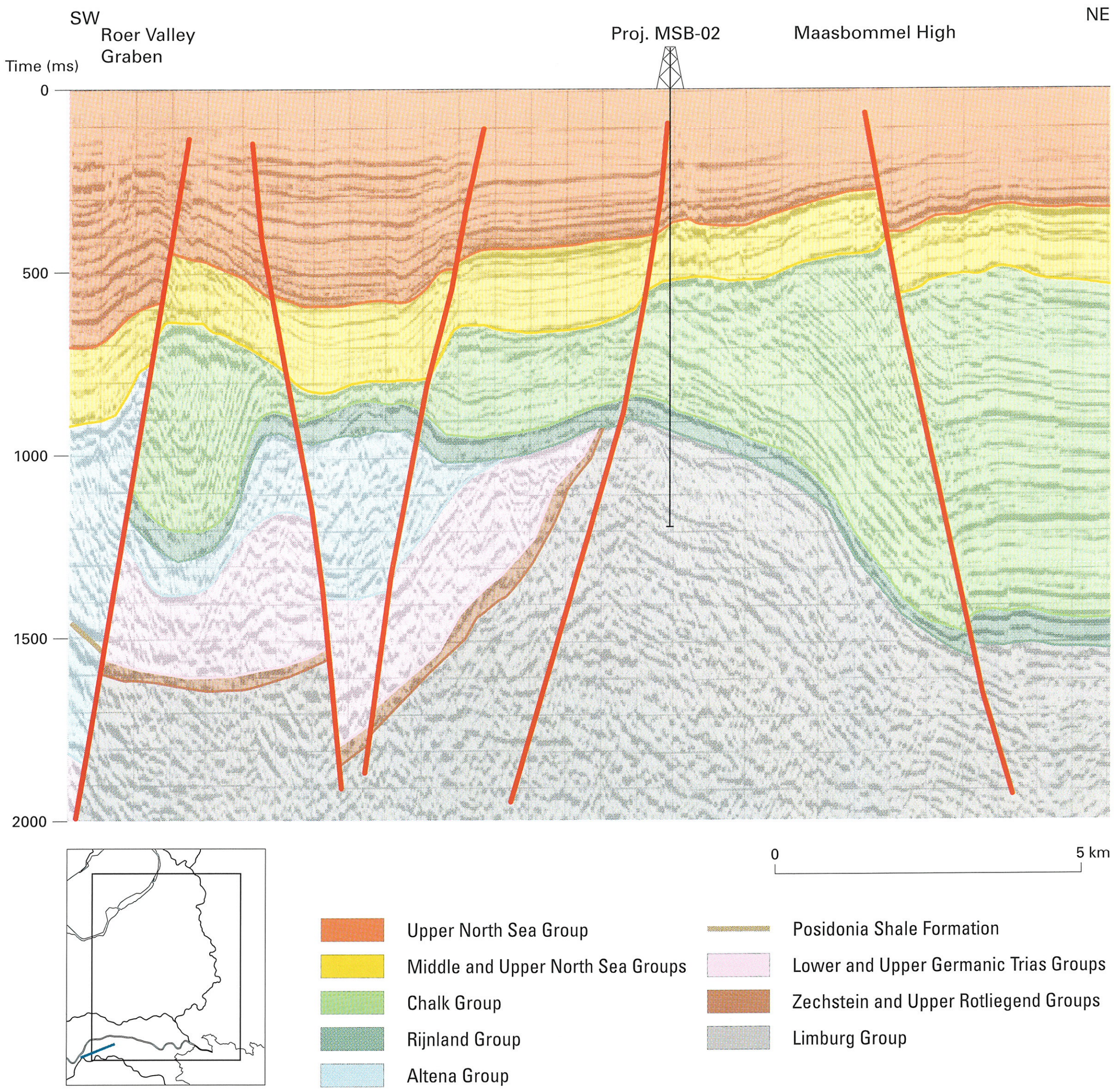


Figure 3.3 Seismic section through the Maasbommel High showing considerable thickening of the Chalk deposits on this high.

4 Limburg Group

4.1 Stratigraphy

The Limburg Group, of Silesian (Late Carboniferous) age, is the oldest unit penetrated in wells in the map sheet area. The group consists of an intercalation of mainly grey to black claystones; siltstones and sandstones containing, especially in the Westphalian B and C, many intercalated coal seams. The group is subdivided into four subgroups (fig. 4.1), each representing a particular phase of the Late Carboniferous regressive megasequence. The basal part, the Geul Subgroup, has not been penetrated in any wells in this map sheet area. The characteristic lithologies of the Caumer Subgroup are claystones and coal seams. The Dinkel Subgroup consists predominantly of sandstone. The last subgroup, the Hunze Subgroup, which consists mainly of red claystones, only occurs in the south-western part of the map sheet area.

The Limburg Group is, in the major part of the map sheet area, unconformably overlain by the Upper Rotliegend Group (Map 1), with the exception of a number of highs in the northern part, where the group is unconformably overlain by the sediments of the Schieland Group or the Rijnland Group, and the central part of the map sheet area, where the subgroup is unconformably overlain by the North Sea Supergroup. On the Maasbommel High, the Limburg Group is unconformably overlain by the Rijnland Group (Map 10).

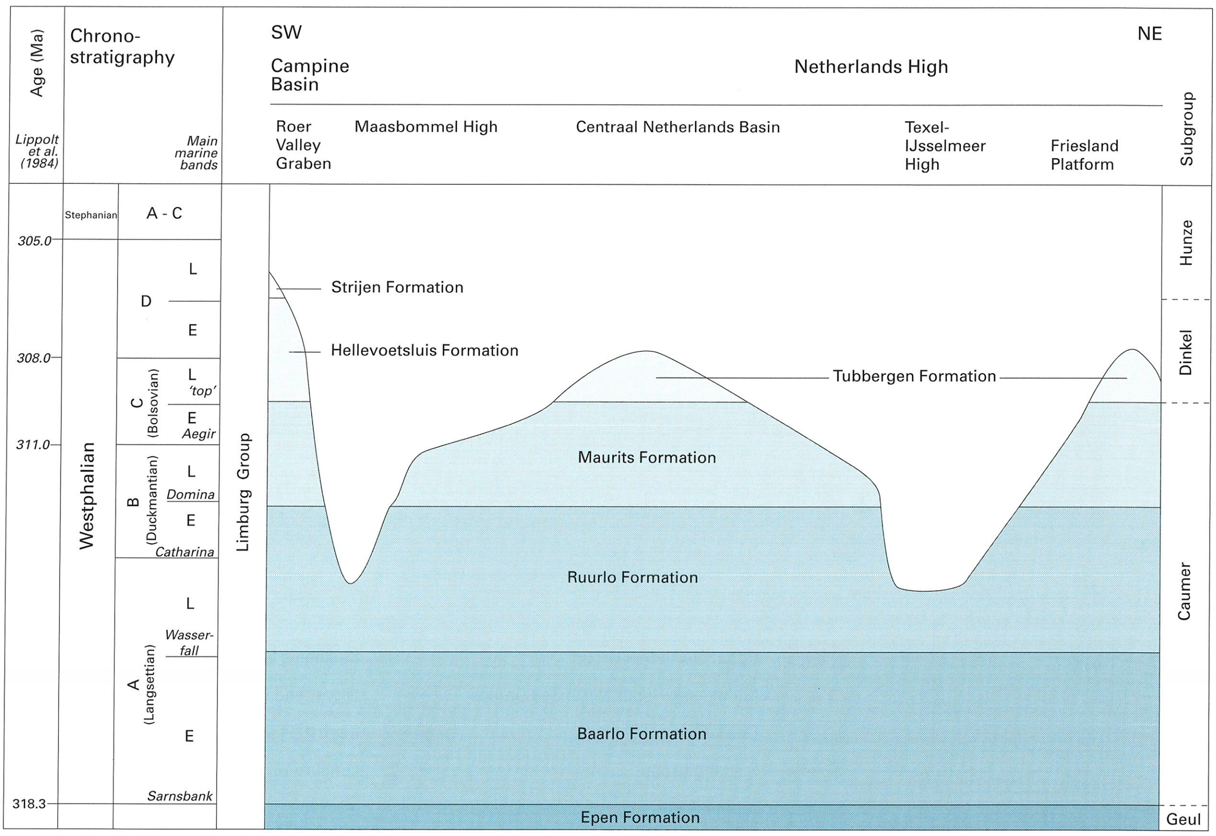
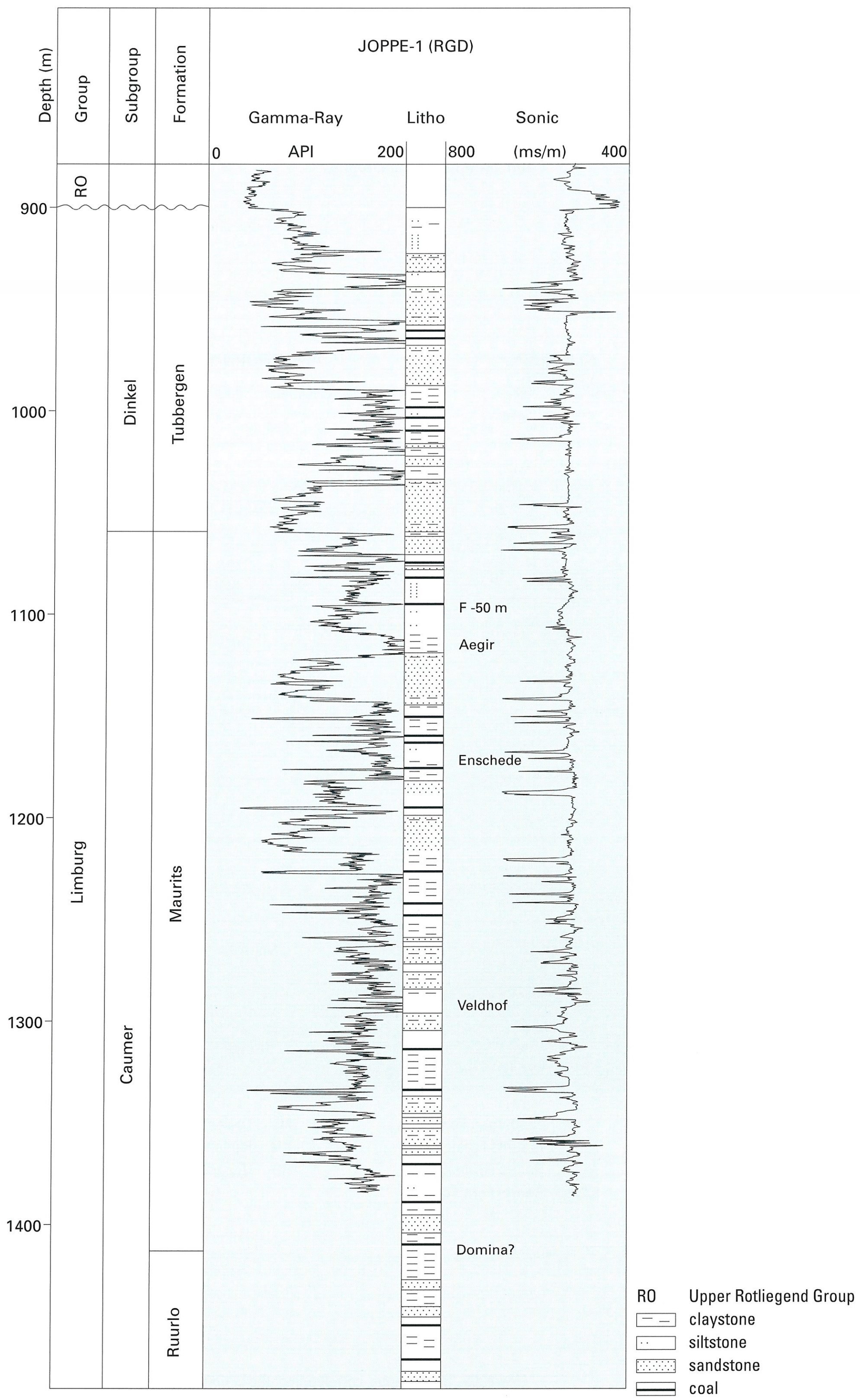


Figure 4.1 Lithostratigraphy of the Limburg Group.

Figure 4.2 Stratigraphic distribution and log characteristics of the Limburg Group in well Joppe-1. The main marine horizons are indicated.



Deposits of the Limburg Group are present throughout the map sheet area. The total thickness of this group is not known but in view of the position of the map sheet area in the basin, the total thickness probably exceeds 5 km in the central part of the map sheet area. In the northern and southern parts, the younger sediments are missing owing to erosion (fig. 4.4).

The depth of the top of the Limburg Group exceeds 4400 m in the grabens, whereas it is encountered at 700 m depth on local highs.

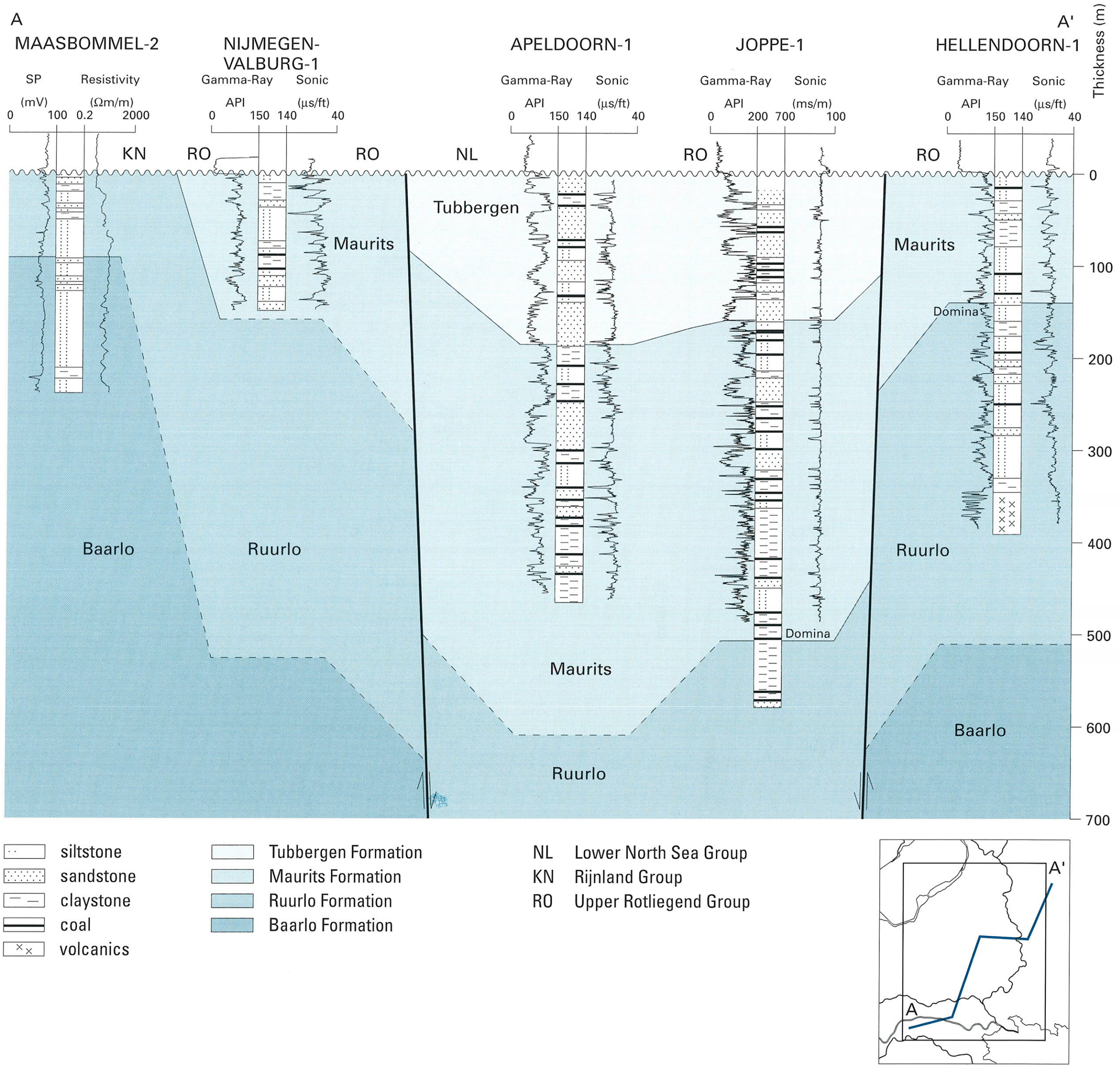


Figure 4.3 Stratigraphic correlation of the Limburg Group along line A-A' between wells Maasbommel-2, Nijmegen-Valburg-1, Apeldoorn-1, Joppe-1 and Hellendoorn-1. Owing to intense tectonic activity, the Limburg Group is unconformably overlain by the Upper Rotliegend, the Rijnland and the Lower North Sea Groups.

4.1.1 Geul Subgroup

The Geul Subgroup consists of dark claystones. Coal seams do not occur in this subgroup. The subgroup comprises the Epen Formation; of Namurian to Early Westphalian A age. The subgroup has only been encountered in wells to the east of the map sheet area. The description of the unit is based on data from these wells.

4.1.1.1 Epen Formation

The formation rests disconformably on the Carboniferous Limestone Group, and is conformably overlain by the Baarlo Formation. The unit comprises predominantly dark-coloured claystones and siltstones with a minor percentage of sandstones. The formation is characterised by stacked, coarsening-upward sequences with a thickness of 50 to 100 m each. The total thickness of the Epen Formation is approximately 1800 m. The formation is subdivided into two members: the Geverik, and the Ubachsberg Members.

The *Geverik Member*, of Early Namurian A age, forms the base of the Epen Formation and consists of a black, bituminous shale. East of the map sheet area, the member is 50 to 80 m thick.

The *Ubachsberg Member*, of Early Namurian C age, comprises two thick sandstone bodies, with a combined thickness of 25 to 35 m.

4.1.2 Caumer Subgroup

The Caumer Subgroup, of Late Namurian C to Early Westphalian C age, is a succession of dark-coloured claystones with intercalated sandstones and coal seams. The Caumer Subgroup comprises three formations, the Baarlo, Ruurlo and Maurits Formations. The Caumer Subgroup is present throughout the map sheet area. In the central part of the map sheet area, the Dinkel Subgroup conformably overlies the Caumer Subgroup. In the north and south the Upper Rotliegend Group conformably overlies Caumer Subgroup, while on the Maasbommel High, the Rijnland Group is the overlying unit. On the Knardijk High, the North Sea Supergroup unconformably overlies the Caumer Subgroup. The Caumer Subgroup has not been completely penetrated in any well in the map sheet area. Data from wells further to the east, and from Dutch reports and German literature sources, however, imply that the thickness of the Caumer Subgroup may be as much as 2000 m (*RGD, 1986b*; Drozdzewski, 1992, 1993).

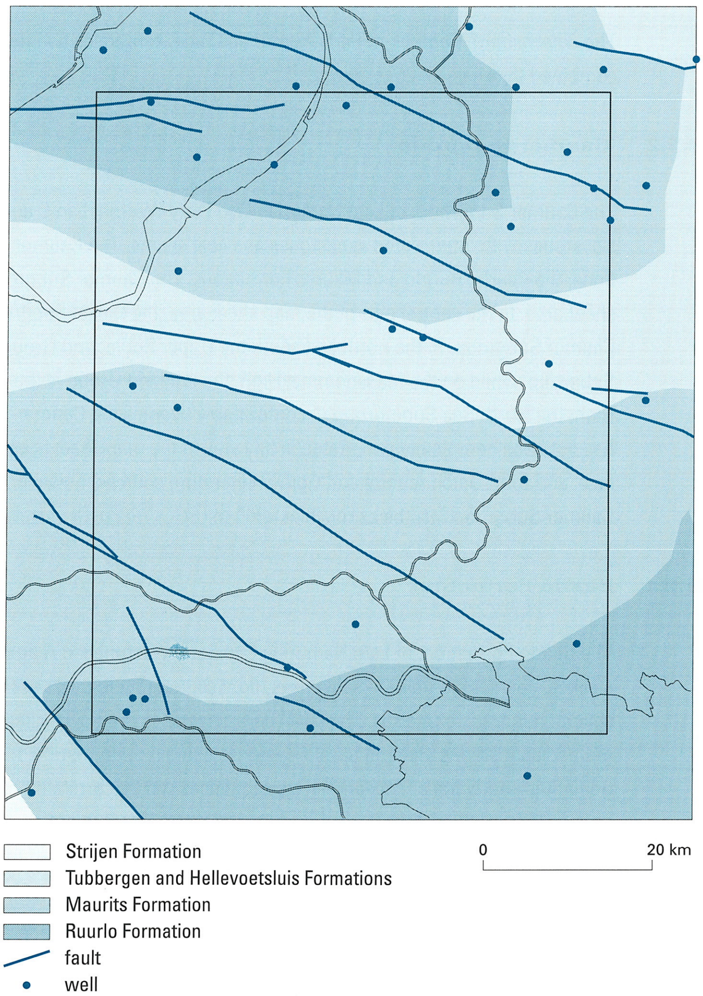
4.1.2.1 Baarlo Formation

The Baarlo Formation, of Late Namurian C to Early Westphalian A age, consists of a large number of stacked, coarsening-upward sequences (fig. 4.3), ranging in thickness from a few tens of metres to several hundreds of metres. The basal dark claystones grade via siltstones into fine-grained to medium-grained sandstones. Several basal claystones contain open-marine or brackish-water fossils, such as goniatites and *Lingula*. The large-scale sequences can be correlated regionally, the lateral continuity of each individual sandstone body, however, is limited. The Baarlo Formation generally contains fewer than four coal seams per hundred metres. Most coals seams are a few decimetres thick, but some can be up to 2 m thick. They are restricted to the upper parts of the sequences. The formation is present throughout the map sheet area, but has only been encountered in wells Maasbommel-2 (fig. 4.3) and Zeddam-1. The sandstones of the Baarlo Formation can be up to 30 m thick and are present at the tops of coarsening-upward sequences. East of the map sheet area, the thickness of the formation is approximately 600 m.

4.1.2.2 Ruurlo Formation

The Ruurlo Formation, of Late Westphalian A to Early Westphalian B age, consists of alternating dark-grey or black, silty claystones, with a varying number of intercalated coal seams (figs 4.2 & 4.3), and grey or pale yellow, fine-grained, clayey or silty sandstones. The sandstones are stacked fluviatile deposits. The units, which are on average 50 metres thick, show coarsening-upwards as well as fining-upwards trends. The sandstones were deposited in small channels, but thin sand layers with good lateral continuity are also present. Coal seams of up to two metres thick are common, but laterally, their numbers vary greatly. The formation is present in the entire map sheet area and conformably overlies the Baarlo Formation. Within the formation, two major marine horizons can be distinguished. The base is formed by the marine Wasserfall horizon; the Catharina horizon forms the Westphalian A/B boundary, while the equivalent of the Domina horizon at the top of the formation, forms the boundary between the Early and Late Westphalian B. No marine fauna has been encountered in this horizon. (H. Pagnier, pers. comm.).

Figure 4.4 Subcrop map of the top of the Limburg Group. The map is based on Van Adrichem Boogaert & Kouwe (1993-1997), supplemented by new data resulting from the present mapping.



No well has penetrated or encountered the complete Ruurlo Formation in this map sheet area. The maximum penetrated thickness in the map sheet area is approximately 350 m, but east of the map sheet area, thicknesses of 600 to 700 m have been encountered (NITG-TNO, 1998).

The formation is conformably overlain by the Maurits Formation or unconformably by the Upper Rotliegend, Zechstein or the Rijnland Group.

4.1.2.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Early Westphalian C age, mainly comprises light-grey claystones with abundant intercalated coal seams. A few rare, fine-to coarse-grained, sandstone layers are up to 10-15 m thick. This formation differs from the underlying formation in being finer grained and containing a larger number of coal seams. The formation conformably overlies the Ruurlo Formation and is, in the central part of the map sheet area, unconformably overlain by the Dinkel Subgroup, or elsewhere, by the Upper Rotliegend Group. The Maurits Formation is present in most of the map sheet area, but is missing owing to erosion in the north-west and south (fig. 4.4). The maximum thickness penetrated is approximately 380 m in well Joppe-1 (fig. 4.2). The complete section of the Maurits Formation was penetrated in a well east of the map sheet area, where its maximum thickness is also 380 m (NITG-TNO, 1998).

The Maurits Formation contains an important marine horizon, the Aegir horizon, which forms the boundary between Westphalian B and C deposits. The top of the formation is marked by the first occurrence of the thick fluviatile sands of the Dinkel Subgroup.

4.1.3 Dinkel Subgroup

The Dinkel Subgroup, of Early Westphalian C up to and including Early Westphalian D age, is represented in the map sheet area by the Tubbergen and the Hellevoetsluis Formations.

4.1.3.1 Tubbergen Formation

The Tubbergen Formation, of Early Westphalian C to Early Westphalian D age in this area, consists predominantly of sandstone bodies, ranging in thickness from 10 m to over 30 m. The sandstone bodies are separated by 5 to 40 m thick claystone and siltstone intervals (figs 4.2 & 4.3). The sandstone bodies make up 50 to 80% of the formation. Sand percentages decrease northward. The sandstone bodies consist of medium-grained, very coarse-grained to conglomeratic sandstones, with poorly rounded grains and the predominant colour is light grey. Regional mapping of the eastern part of the Netherlands has shown that the sandstone bodies display good lateral continuity (NITG-TNO, 1998). In the map sheet area, the Tubbergen Formation was penetrated in only two wells, Apeldoorn-1 and Joppe-1. The maximum thickness in both wells was only 180 metres owing to erosion. East of the map sheet area, thicknesses of up to 500 m have been encountered. The formation is present in the central part of the map sheet area, and disconformably or slightly unconformably overlies the Maurits Formation. It is unconformably overlain by the Upper Rotliegend Group or the North Sea Supergroup (figs 4.3 & 4.4).

4.1.3.2 Hellevoetsluis Formation

The Hellevoetsluis Formation, of Early Westphalian C to Early Westphalian D age, consists predominantly of sandstone. It disconformably or slightly unconformably overlies the Maurits Formation. Within the map sheet area, the formation is only present in the Roer Valley Graben. To the south-west of the map sheet area, the Strijen Formation overlies the Hellevoetsluis Formation; in the rest of the map sheet area the formation is unconformably overlain by the Upper Rotliegend Group. The formation has not been penetrated in this map sheet area, but elsewhere in the Roer Valley Graben, thicknesses exceeding 200 m have been encountered.

4.1.4 Hunze Subgroup

The Hunze Subgroup, of Late Westphalian C to Westphalian D age, is represented by the Strijen Formation.

4.1.4.1 Strijen Formation

The Strijen Formation, of Late Westphalian C to Westphalian D age, is present to the south-west of the map sheet area in the Roer Valley Graben (fig. 4.4). The formation consists of stacked red-brown, sometimes also green-grey, silty to fine-grained sandy claystones. The Strijen Formation conformably overlies the Hellevoetsluis Formation, and is unconformably overlain by the Upper Rotliegend Group. West of the map sheet area, in the Roer Valley Graben, the formation is up to approximately 200 m thick.

4.2 Volcanics

In several wells, intrusive rocks were encountered in the Limburg Group. In well Haarle-1, a 17-m-thick intrusive body was encountered in the Maurits Formation at a depth of approximately 1480 m. No geochemical or petrological analyses have been carried out, so neither the mineralogical composition of this rock or its age is known. In well Hellendoorn-1, at a depth of 1455 m, some claystones, penetrated in the Ruurlo Formation show (contact?)metamorphic features that may be attributable to nearby intrusive rocks. Earlier studies (RGD, 1993 & NITG-TNO, 1998) indicated that intrusive rocks were encountered in wells east of the map sheet area; the age of which was established as Late Triassic (Early Kimmerian phase). North of the map sheet area, intrusive rocks have also been encountered; the age of several of these coincides with the Saalian phase (289 ± 7 Ma), and the age of others with the Mid-Kimmerian phase (155 ±4 Ma).

4.3 Sedimentary development and palaeogeography

The deposits of the Limburg Group represent the basin-fill of an east-west oriented foreland basin. The thick, regressive succession displays only gradual transitions between the different facies, which indicates that sedimentation kept pace with subsidence. For a long period, the land surface lay around palaeo-sea level; even a minor sea-level rise would cause flooding over extensive areas, resulting in the deposition of marine or brackish-water sediments. Moreover, the high water table gave rise to extensive marshes, where peat formation took place. When sea level fell, the fluviatile systems prograded across the area once again.

The basal part of the succession, the Geul Subgroup, comprises marine, lacustrine and deltaic sediments. The middle part of the succession, the Caumer Subgroup, is characterised by fluviatile and lacustrine deposits, with large-scale peat formation in marshes. When the Dinkel Subgroup was deposited, rivers spread from the south-east across the map sheet area, leaving coarse-grained sediments. Later, these rivers were replaced by lakes and flood plains, reflected in the fine-grained deposits of the Hunze Subgroup. These fluviatile sediments represent the detritus of the Rhenish Massif to the south-east of the map sheet area.

5 Upper Rotliegend Group

5.1 Stratigraphy

The Upper Rotliegend Group, of Late Permian age, is represented in the map sheet area by the Slochteren Formation (fig. 5.1).

The sediments of the Upper Rotliegend Group rest unconformably on several formations of the Limburg Group; separated by the Saalian unconformity (fig. 5.3). The group is present in a large part of the map sheet area, but is absent on the Maasbommel High and the Dalfsen High, which lies just east of the map sheet area (fig. 5.4). The group is also absent on several smaller highs in the younger Central Netherlands Basin (fig. 5.4; Map 1). In most of the area, the deposits of the group are conformably overlain by deposits of the Zechstein Group (Map 2). Only in a small area, around the Dalfsen High, the Rijnland Group unconformably overlies the Upper Rotliegend Group (Maps 10, 17). The depth of the base of the group ranges from less than 800 m in the east to over 4400 m in the north-west of the map sheet area (Map 1).

The thickness of the Upper Rotliegend Group ranges from a few metres in the eastern part of the map sheet area to over 150 metres in the northern part.

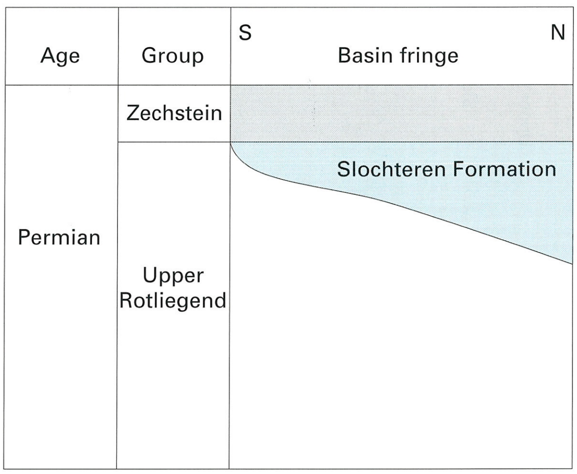
5.1.1 Slochteren Formation

The Slochteren Formation (figs 5.2 & 5.3) comprises two lithologies in the map sheet area.

Conglomeratic deposits are typical of the formation in the east and south-east of the map sheet area. In the south-eastern part of the map sheet area, they consist of grey, sandy conglomerate, cemented by anhydrite or dolomite. The fragments include rounded quartz pebbles and, locally, coal fragments. In the northern part of the map sheet area, a basal conglomerate of several tens of metres thick was encountered in several wells, e.g. Doornspijk-2 (fig. 5.2).

The sandstone has a typical red-brown colour, is well sorted and medium to coarse-grained and exhibits a typical blocky pattern on gamma ray logs. Dipmeter logs show that, in the northern part of the map sheet area and to the north-west of it (TNO-NITG, 2002), the sandstones are characterised by ubiquitous cross-bedded dune deposits.

Figure 5.1 Stratigraphy of the Upper Rotliegend Group.



5.2 Sedimentary development and palaeogeography

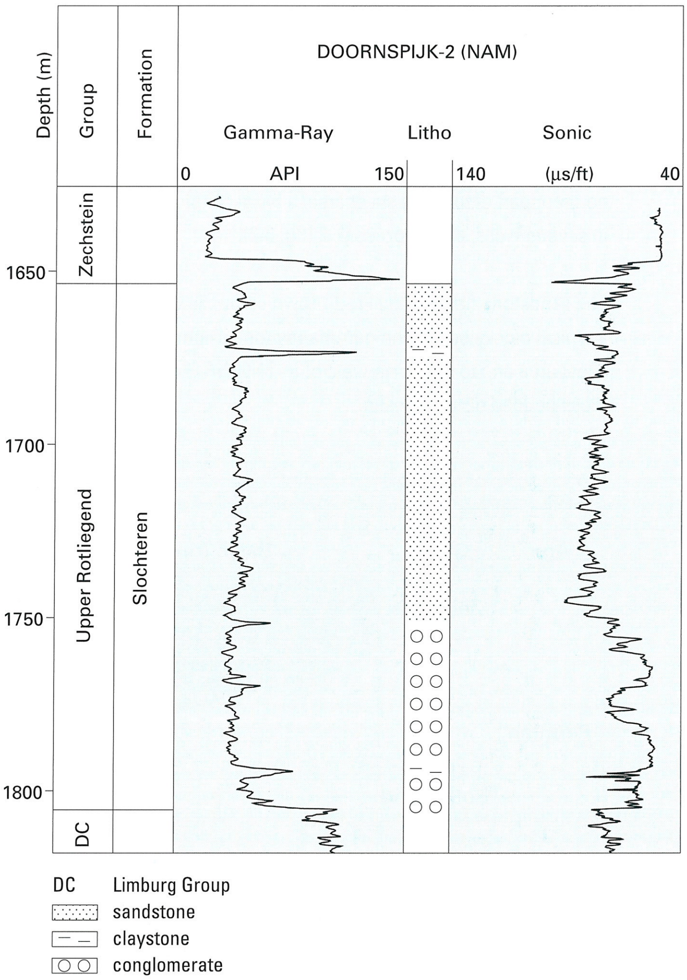
The Upper Rotliegend Group was deposited under continental conditions on the south-eastern fringe of the intra-cratonic Southern Permian Basin. The sediments deposited in the map sheet area are the erosion products of the Variscan Mountains situated to the south-east.

The conglomerates and conglomeratic sandstones of the Slochteren Formation were deposited by braided rivers in alluvial fans. The characteristic log data indicate an aeolian origin for the clean sandstones of the Upper Rotliegend Group. In this area, they mainly filled local depressions.

The red staining of the sediments is probably due to fluctuations in the water table shortly after deposition. During periods when the groundwater was at lowstand, iron-bearing minerals oxidised and hematite formed.

The basin structure was determined by reactivation of old NW-SE lineaments (Ziegler, 1990). The thickness distribution within the map sheet area is apparently related to a NW-SE-oriented fault system, which largely coincides with the Mesozoic Central Nederlands Basin. As part of the South Netherlands

Figure 5.2 Stratigraphic subdivision and log characteristics of the Upper Rotliegend Group in well Doornspijk-2.



Platform, the Maasbommel High must have been active as early as the Rotliegend, for only a few metres of Rotliegend sandstone are present on this high (Geluk et al., 1996), conformably overlain by Zechstein sediments. This may be due to synsedimentary tectonics, resulting in thinning owing to faulting (Geluk et al., 1996). The thickness of the formation significantly increases northward (figs 5.3 & 5.4), where the deposits are mainly aeolian. The sediment south of the Central Netherlands Basin was transported by rivers.

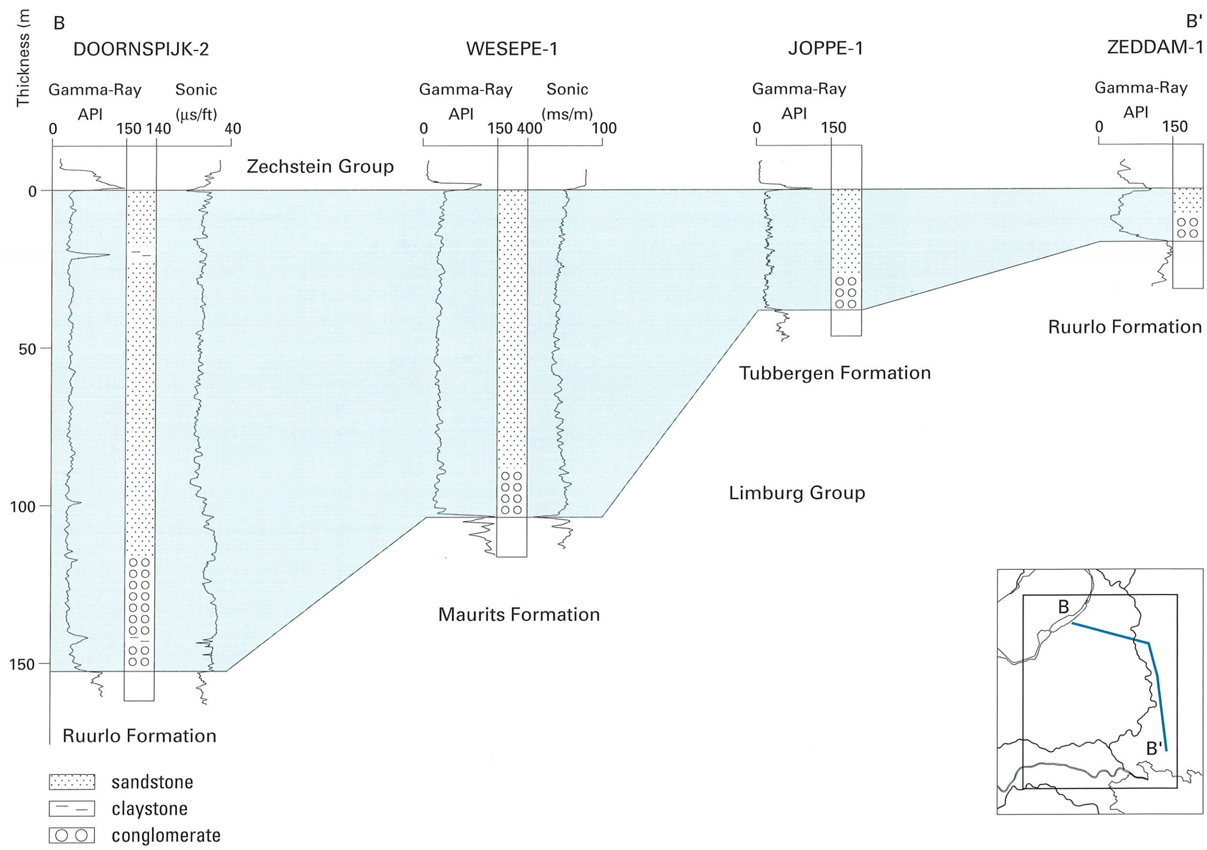
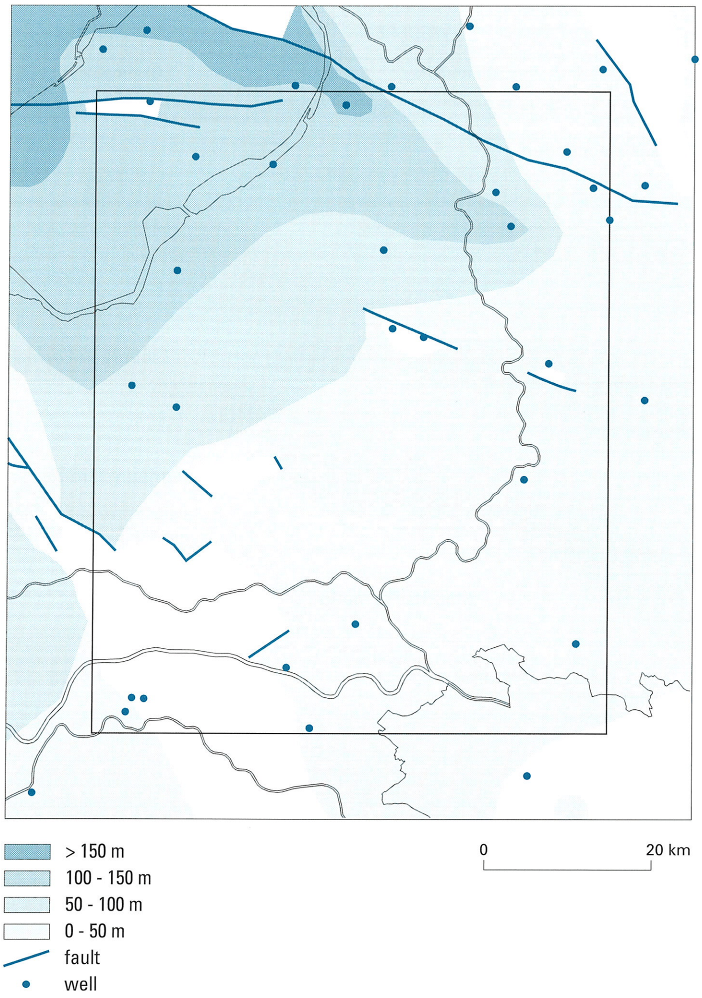


Figure 5.3 Stratigraphic correlation of the Upper Rotliegend Group along line B-B′ between wells Doornspijk-2, Wesepe-1, Joppe-1 and Zeddam-1. Reference level is the base of the Zechstein Group.

Figure 5.4 Isopach map of the Upper Rotliegend Group in the map sheet area.



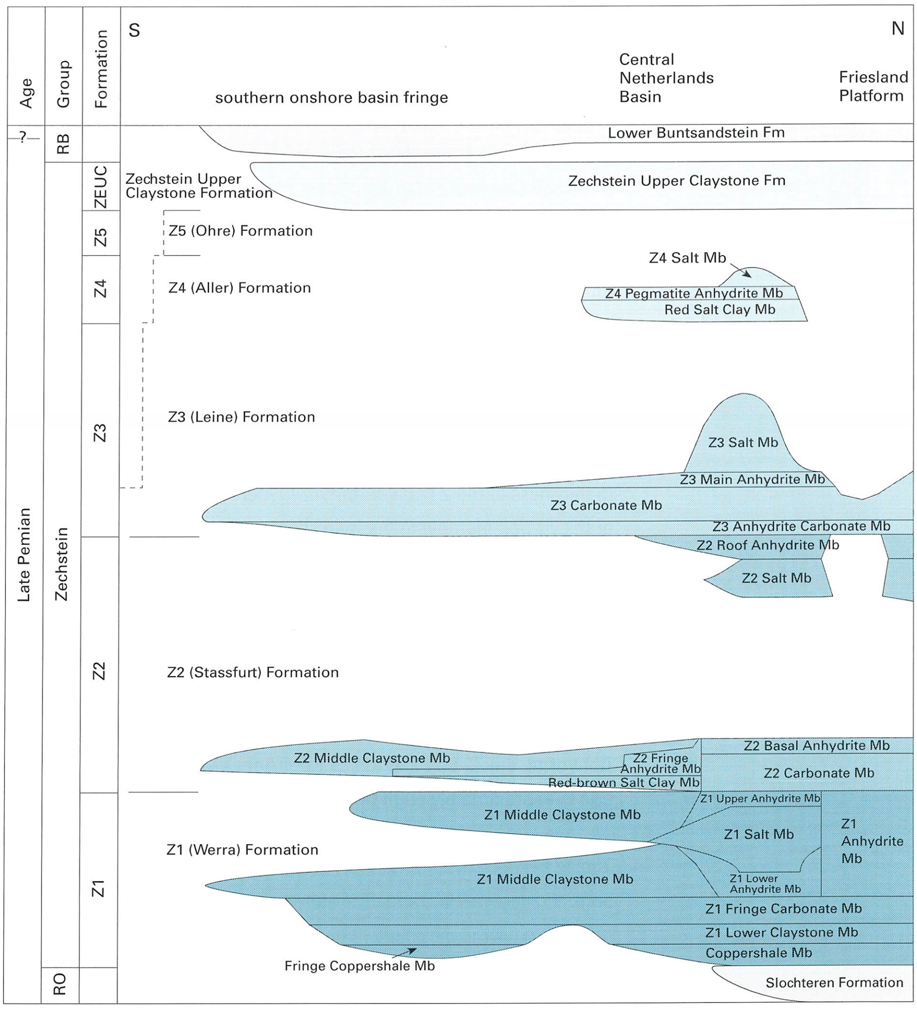
6 Zechstein Group

6.1 Stratigraphy

The Zechstein Group, of Late Permian age, is subdivided into five formations in the map sheet area: the Z1 (Werra), Z2 (Stassfurt), Z3 (Leine), Z4 (Aller) and the Zechstein Upper Claystone Formations. The four evaporite cycles are mainly present in the Central Netherlands Basin and consist of clastic sediments, carbonates and evaporites (fig. 6.1 & fig. 6.4a to d). In the southern part of the map sheet area and near the Raalte Boundary Fault, clastic equivalents of the Z1 and Z2 Formations are encountered. The lithological subdivision of the group is depicted in figures 6.2 & 6.3.

In the map sheet area, the Zechstein Group conformably overlies the Upper Rotliegend Group. The Zechstein Group wedges out southward and the increased fine-clastics content lends the group its fringe-facies appearance. In the Central Netherlands Basin, the thickness of the group exceeds 300 metres. The thin Zechstein Upper Claystone Formation rests unconformably on older Zechstein deposits (Geluk, 1999a; TNO-NITG, 2001). The Zechstein Group is conformably overlain by the Lower Germanic Trias Group.

Figure 6.1 Stratigraphy of the Zechstein Group.



RB Lower Germanic Trias Group
RO Upper Rotliegend Group

6.1.1 Z1 (Werra) Formation

The Z1 (Werra) Formation comprises ten members, which are, to some extent, each other's lateral equivalents (fig. 6.1). The clastic equivalents are the Fringe Coppershale, the Z1 Lower Claystone, the Z1 Fringe Carbonate, and the Z1 Middle Claystone Members. The maximum thickness of the Z1 sequence is 200 m and is encountered in the north-western part of the map sheet area and to the north-east and south-east of it (fig. 6.4a).

The *Coppershale Member* is a finely laminated, brown to grey, bituminous claystone of up to 1 m thick. It conformably overlies the Slochteren Formation and is present virtually throughout the map sheet area. In the south, the *Fringe Coppershale Member* has been penetrated in a number of wells. This deposit is characterised by a lower content of organic matter.

The *Z1 Lower Claystone Member* is a grey to brown claystone sequence, which, towards the top, gradually grades into marl. The unit is locally developed in an anhydritic or dolomitic facies. The member conformably overlies the Coppershale Member. It is present in the southern part of the map sheet area and locally in the northern part in the Central Netherlands Basin. The maximum thickness of this unit is 12 m.

The *Z1 Carbonate Member* is a grey to brown limestone or dolomite. A few intercalated claystone layers are locally present. The unit is present in the northern and eastern parts of the map sheet area and ranges in thickness from a few metres to almost 30 m in the east. The member grades southward into the *Z1 Fringe Carbonate Member*, this is 34 to 45 m thick.

The *Z1 Middle Claystone Member* consists of a red to greyish, laminated claystone containing numerous anhydrite concretions, desiccation cracks and thin sand layers and sand lenses. The member is up to 37 m thick. The unit was mainly deposited in the southern part of the map sheet area and near the Raalte Boundary Fault. Its evaporitic equivalent, the *Z1 Anhydrite Member* is present wherever Z1 salt did not precipitate and it thickness may exceed 200 m in the north-eastern part of the map sheet area.

The Z1 evaporite sequence is mainly encountered in the Central Netherlands Basin (fig. 6.4a). A full 100 m thickness of the *Z1 Lower Anhydrite Member* was penetrated in well Joppe-1. The areal distribution of the *Z1 Salt Member* in the map sheet area is identical to that of the underlying anhydrite. The member is up to 170 m thick in the Central Netherlands Basin. The Z1 halite sequence is conformably overlain by the *Z1 Upper Anhydrite Member*, of up to 70 m thick.

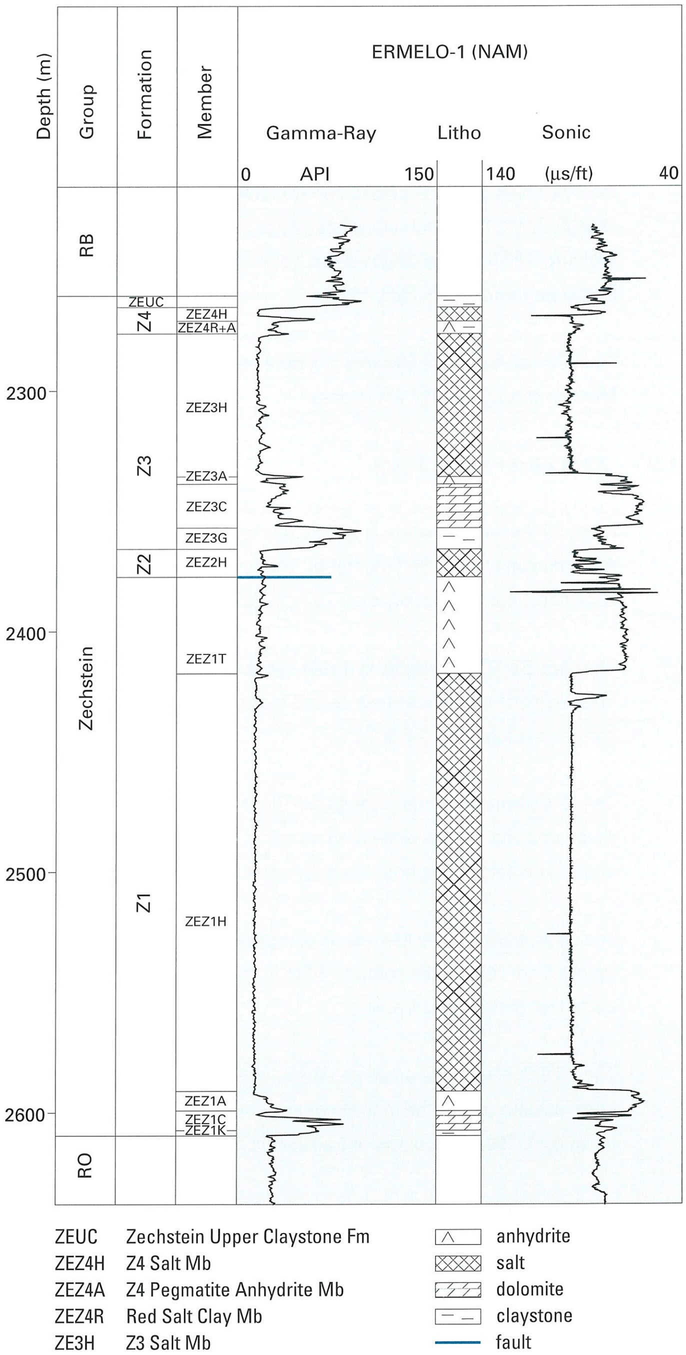
6.1.2 Z2 (Stassfurt) Formation

The Z2 (Stassfurt) Formation comprises the Z2 Middle Claystone, the Z2 Carbonate, the Z2 Basal Anhydrite, the Z2 Salt and the Z2 Roof Anhydrite Members. In the Central Netherlands Basin, the formation is approximately 50 m thick.

The *Z2 Middle Claystone Member* consists of a red to grey, laminated claystone containing anhydrite concretions and dessication cracks. The anhydrite occurs predominantly at the base of the member. The unit may be up to 30 m thick in the southern part of the map sheet area and grades northward into the Z2 Carbonate Member. In the vicinity of the Raalte Boundary Faults, thicknesses of up to 50 m have been encountered.

The *Z2 Carbonate Member* is present in the Central Netherlands Basin and also further to the north. The unit consists of a dolomitic limestone, with an intercalated 10-to-15-m-thick anhydrite horizon. The unit's total thickness ranges from just over 10 m to more than 50 m.

Figure 6.2 Stratigraphic subdivision and log characteristics of the Zechstein Group in well Ermelo-1.



ZEUC	Zechstein Upper Claystone Fm
ZEZ4H	Z4 Salt Mb
ZEZ4A	Z4 Pegmatite Anhydrite Mb
ZEZ4R	Red Salt Clay Mb
ZE3H	Z3 Salt Mb
ZEZ3A	Z3 Main Anhydrite Mb
ZEZ3C	Z3 Carbonate Mb
ZEZ3G	Grey Salt Clay Mb
ZEZ2H	Z2 Salt Mb
ZEZ1T	Z1 Upper Anhydrite Mb
ZEZ1H	Z1 Salt Mb
ZEZ1A	Z1 Lower Anhydrite Mb
ZEZ1C	Z1 Carbonate Mb
ZEZ1K	Coppershale Mb
RB	Lower Germanic Trias Group
RO	Upper Rotliegend Group

The areal distribution of the *Z2 Basal Anhydrite Member* is identical to that of the Z2 Carbonate. The unit can be up to approximately 35 m thick.

The *Z2 Salt Member* is encountered in the central part of the Central Netherlands Basin, and in the south-eastern and north-eastern parts of the map sheet area (fig. 6.4b). The unit consists of white to pale grey halite, occasionally of a coarse-crystalline texture. What is remarkable is, that to the south-east of the map sheet area, the Z2 Salt conformably overlies the Z1 Salt with a normal stratigraphic contact (well Zeddam-1); the same has been observed in neighbouring Germany (wells Isselburg-1 and -2; Wolburg, 1957). These observations have up to now only been recorded from this location in the Zechstein basin (NITG-TNO, 1998).

The *Z2 Roof Anhydrite Member* is a pure anhydrite of several metres thick, which overlies the Z2 Salt Member throughout the entire area.

6.1.3 Z3 (Leine) Formation

In the Z3 (Leine) Formation is subdivided into the Grey Salt Clay, the Z3 Carbonate, the Z3 Main Anhydrite and the Z3 Salt Members. The formation thickness varies within the map sheet area from 20 m in the south to locally over 75 m in the Central Netherlands Basin (fig. 6.4c).

The *Grey Salt Clay Member* is a well-bedded, dark-grey to black claystone of only a few metres thick. The claystone contains anhydrite and rock-salt crystals. This unit shows a characteristic peak on the gamma-ray logs (figs 6.2 & 6.3).

The *Z3 Carbonate Member* consists of light-coloured limestone and dolomite in the south of the map sheet area and of a dark-coloured, massive dolomite in the north. The unit's maximum thickness is 40 m, and it is present throughout the map sheet area, with the exception of the highs.

The *Z3 Main Anhydrite Member* is composed of a massive, light-coloured anhydrite. The unit's thickness ranges from 10 m in the south to 40 m in the north of the map sheet area. Its areal distribution is identical to that of the Z3 Carbonate.

The *Z3 Salt Member* is present in the centre of the Central Netherlands Basin, and in a small area in the north-eastern part of the map sheet area. In the centre, the thickness is 30 m, increasing to 70 m in the north-east. The salt consists of translucent halite, with local orange, pink and brown zones.

6.1.4 Z4 (Aller) Formation

The Z4 (Aller) Formation is subdivided into the Red Salt Clay, the Z4 Pegmatite Anhydrite and the Z4 Salt Members. The formation's thickness increases northward, from less than 10 m to over 20 m (fig. 6.4d).

The *Red Salt Clay Member* is a red-brown to greenish, sandy to dolomitic claystone, of approximately 5 m thickness.

The *Z4 Pegmatite Anhydrite Member* is a coarse-crystalline aggregate of anhydrite and rock salt, with a maximum thickness of 2 m.

The *Z4 Salt Member* is composed of translucent to red-brown halite and is only present in the central part of the Central Netherlands Basin, with a maximum thickness of 11 m.

6.1.5 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation disconformably overlies the deposits of the Z4 (Aller) Formation (fig. 6.1). The deposits, ranging in thickness from 10 m in the south to 35 m in the north-east of the map sheet area, consist of anhydritic red and grey claystones. These claystones are characterised by low acoustic velocities.

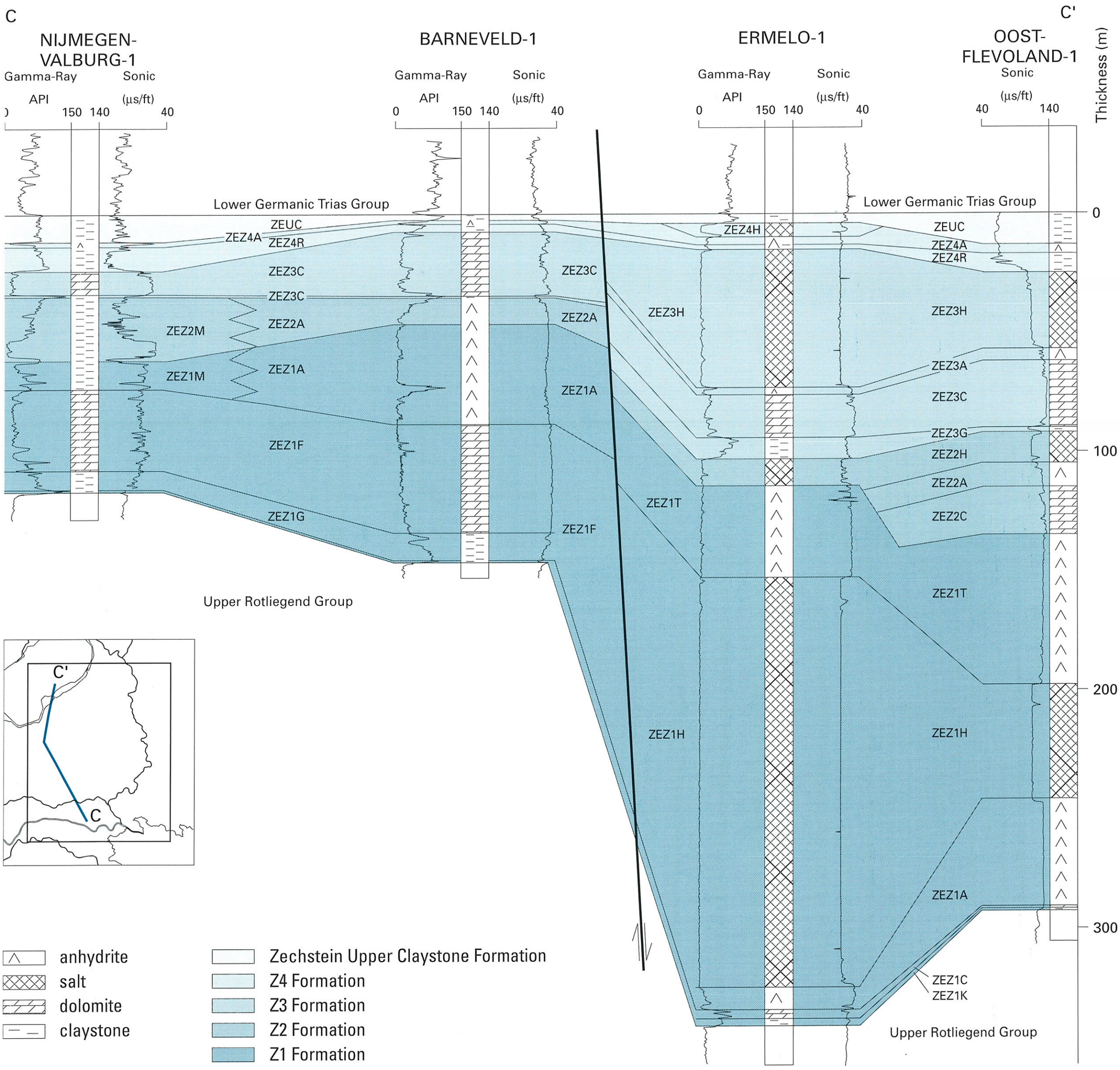


Figure 6.3 Stratigraphic correlation of the Zechstein Group along line C-C' between wells Nijmegen-Valburg-1, Barneveld-1, Ermelo-1 and Oost-Flevoland-1. Reference level is the base of the Lower Germanic Trias Group.

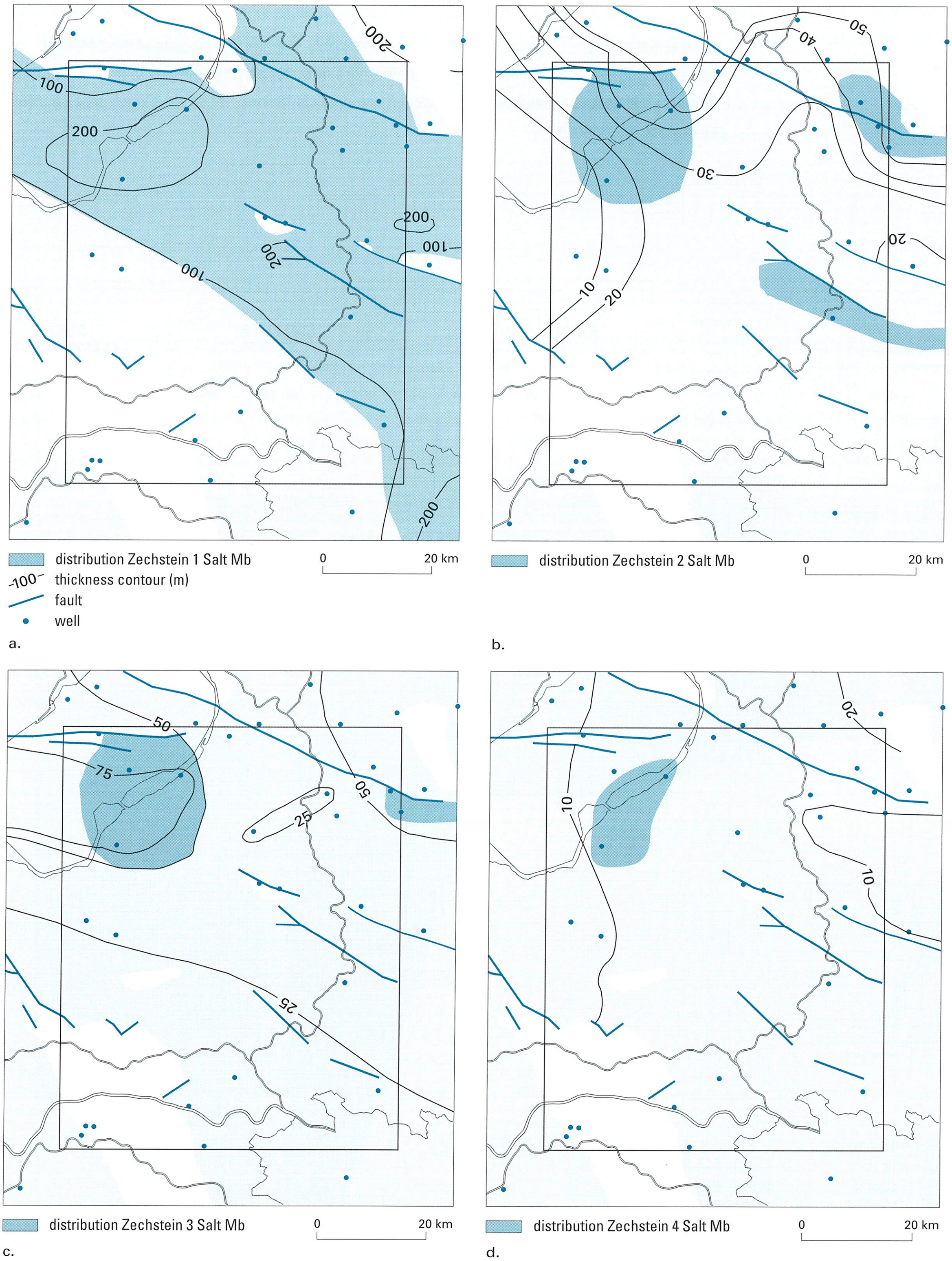


Figure 6.4 Isopach maps of the a: Z1 (Werra), b: Z2 (Stassfurt), c: Z3 (Leine) and d: Z4 (Aller) Formations showing the extent of the salt.

6.2 Sedimentary development and palaeogeography

During deposition of the Zechstein Group, the map sheet area was situated on the southern fringe of the Southern Permian Basin. Thick successive cycles of evaporites precipitated in a prevailing arid climate, facilitated by the shape of the basin and the periodic influx of seawater.

The four evaporite cycles in the Zechstein Group represent transgressive and regressive sequences. During a transgressive phase, clays and carbonates were deposited under fairly normal saline conditions. During the regressive phases of the cycles, the salinity increased, resulting in evaporite deposits. These large-scale sea-level fluctuations were presumably related to alternating Late Permian glacials and interglacials. (Ziegler, 1990).

The deposition of the Z1 (Werra) Formation began with a transgression, during which the Coppershale was deposited in an anoxic environment over a large part of the map sheet area (Taylor, 1986). A thin carbonate sequence was subsequently deposited in an initially deep marine environment (>50 m water depth). During deposition, the environment rapidly became shallower; the intercalation of anhydrite nodules in the topmost part of the carbonates indicates a sabkha-type depositional environment. The north-eastern part of the map sheet area was, during deposition of the Z1 Anhydrite, part of a shallow platform, where anhydrite precipitated rapidly. The load of the thick mass (up to 200 m) of the relatively heavy mineral anhydrite as well as tectonic differentiation of the substrate (Geluk et al., 1997) triggered an intense reactivation of old (Variscan) fault zones. The thickest sequences of Z1 Salt precipitated in the depressions between the fault zones. The areal distribution of the salt in the map sheet area reflects the NW-SE fault trend. In the south-western part of the map sheet area and in the vicinity of the Raalte Boundary fault, clastic deposits are encountered, which indicates reactivation of this fault.

The Z2 (Stassfurt) Formation began with a transgression, while normal saline conditions prevailed in most of the area, with the exception of the southern part where no carbonates were deposited. In the north, oolite banks were deposited in the Z2 Carbonate in a high-energy marine environment, while fine-grained lagoonal deposits, algal mats and anhydrite were deposited under sabkha conditions. In the south-east, at the basin fringe, an alternation of anhydrite and rock salt precipitated in a extensive salt lake. Because the anhydrites of the Z1 cycle are missing in the south-eastern part of the area, the Z2 Salt is found here in direct stratigraphic contact with the Z1 Salt. The rising brine concentration in the basin resulted in precipitation of anhydrite and rock salt. Since the map sheet area is situated on the southern fringe of the Southern Permian Basin, only a thin sequence precipitated here. The decrease in salinity during the period when the Z2 Roof Anhydrite precipitated reflects the onset of the third major Zechstein transgression.

The transgression of the Z3 (Leine) Formation resulted in carbonate deposition in a shallow-marine environment throughout the map sheet area. An increasing concentration of the salts dissolved in the seawater resulted in precipitation of anhydrite and rock salt, in that order. Salt is now encountered only in local depressions in the northern half of the map sheet area, but may originally have had a wider areal distribution and has probably disappeared as a result of dissolution.

The hypersaline character of the brine in the Southern Permian Basin, the alternation of salt and claystone and the limited areal distribution of the Z4 Salt reflect a gradual transition from a marine into a continental evaporite basin. The location on the fringe of the basin is indicated by the limited areal distribution of the Z4 salt in the north-western part of the map sheet area.

The clays of the Upper Zechstein Claystone disconformably overlie the Z4 (Aller) Formation; these clays reflect the transition of the evaporite deposits of the Zechstein Group to the lacustrine deposits of the Lower Germanic Trias Group.

7 Lower and Upper Germanic Trias Groups

7.1 General

The Triassic deposits, of Late Permian/Scythian to Norian age, consist predominately of red and green clastic sediments and grey limestones, marls and evaporites. The Triassic deposits are subdivided into the Lower and Upper Germanic Trias Groups (fig. 7.1).

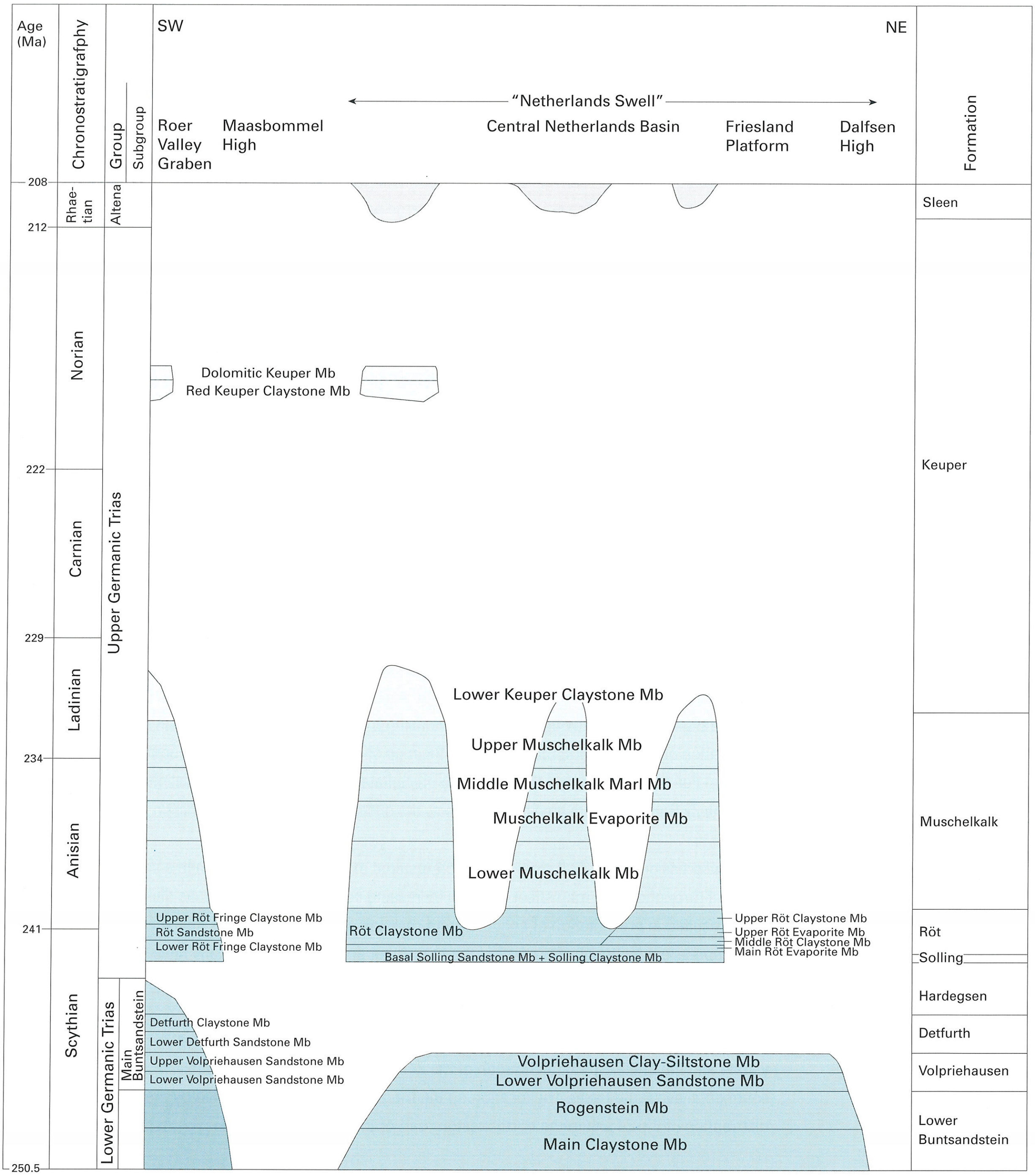


Figure 7.1 Stratigraphy of the Upper and Lower Germanic Trias Groups.

The deposits of the Lower and Upper Germanic Trias Groups are present throughout the map sheet area, except on a few local highs in the Central Netherlands Basin: the Maasbommel High and the Dalfsen High. The greatest thickness of these deposits, over 1200 m, is encountered in the western and central parts of the map sheet area (Map 5). The deposits conformably overlie the Zechstein Group and are unconformably overlain by the Altena, the Niedersachsen, the Rijnland, or the Chalk Group or by the North Sea Supergroup (Maps 16, 17 & 18).

The depth of the base of the Triassic deposits ranges from less than 600 m in the vicinity of Lochem to over 4000 m near East Flevoland (Map 4). The Triassic deposits are heavily fractured owing to differential tectonics and the thickness varies greatly as a result of erosion.

The lithostratigraphic composition of the deposits of the Lower and Upper Germanic Trias Groups is illustrated by two wells and two stratigraphic correlation diagrams (figs 7.2, 7.3, 7.6 & 7.7).

7.2 Lower Germanic Trias Group

7.2.1 Stratigraphy

Within the map sheet area, four formations are distinguished within this group: i.e., the Lower Buntsandstein, Volpriehausen, Detfurth and Hardegsen Formations (fig. 7.1). The first-mentioned formation consists predominantly of claystones and siltstones, and the other formations of an alternation of sandstones and claystones. The last-mentioned formations are described together as the Main Buntsandstein Subgroup (fig. 7.1).). Within the group, minor unconformities exist at the base of the Volpriehausen and Detfurth Formations, which may well represent some tens of metres of local erosion (Geluk & Röhling, 1997).

The Lower Germanic Trias Group, of Late Permian to Scythian age, rests conformably on the Zechstein Group, and is unconformably overlain by the Upper Germanic Trias (fig. 7.1) or Rijnland Group, or by the North Sea Supergroup.

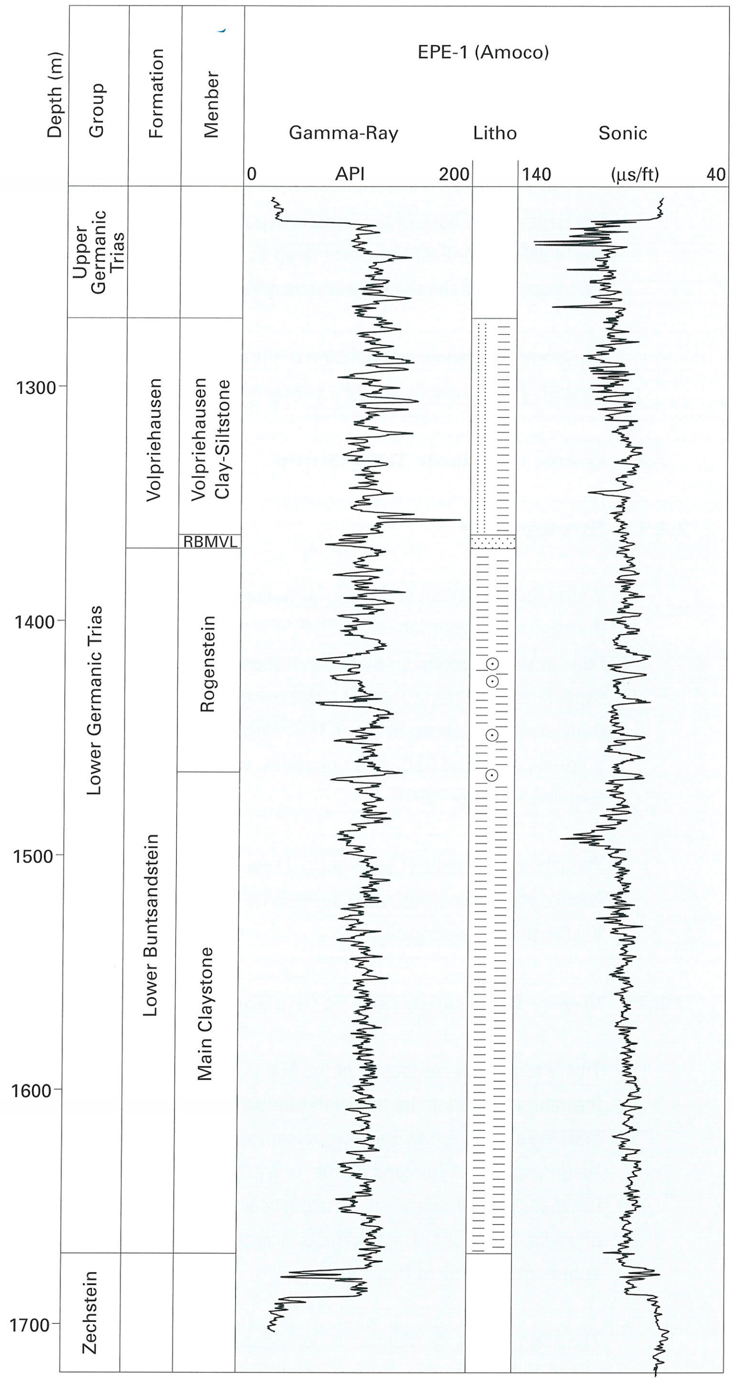
7.2.2 Lower Buntsandstein Formation

This formation is composed of the Main Claystone and the Rogenstein Members (figs 7.1 & 7.2). The formation is overlain by the Main Buntsandstein Subgroup, separated by a sharply defined boundary marking a minor unconformity, or is unconformably overlain by the Upper Germanic Trias, Niedersachsen or Rijnland Group, or by the North Sea Supergroup. The formation has a highly uniform thickness and lithology and its acoustically transparent character on seismic makes it clearly identifiable on seismic sections. The thickness increases north-eastward from 200 m in the extreme south to approximately 350 m (fig. 7.4).

The *Main Claystone Member* is composed of a cyclical succession of 20-to-35 m-thick, fining-upwards claystone/siltstone sequences, with thin, fine-grained, sandstone beds at the base. Towards the south of the map sheet area, these sandstone beds increase in thickness. The total thickness of the complete member is 150 to 200 m.

The *Rogenstein Member* consists of red and green, fine-grained sandy, finely laminated claystones and siltstones containing many mica particles and oolite beds. The member also comprises cyclical stacks of coarser and finer deposits but, in contrast to the Main Claystone Member, frequently contains oolites at the bases of the cycles, which give the member its characteristic appearance. Desiccation cracks are

Figure 7.2 Stratigraphic subdivision and log characteristics of the Lower Germanic Trias Group in well Epe-1.



RBMVL Lower Volpriehausen Sandstone Mb
sandstone
siltstone
claystone
oolite

abundant in the fine-grained deposits. Towards the south, in particular in the Roer Valley Graben, the oolite beds grade into sandstones. The oolite beds give the Rogenstein a characteristic log reading on account of the low gamma-ray values, high density and high acoustic velocity. The member's thickness increases northward from 90 to 180 m. The limited thickness in the south is mainly due to erosion preceding deposition of the Volpriehausen Formation.

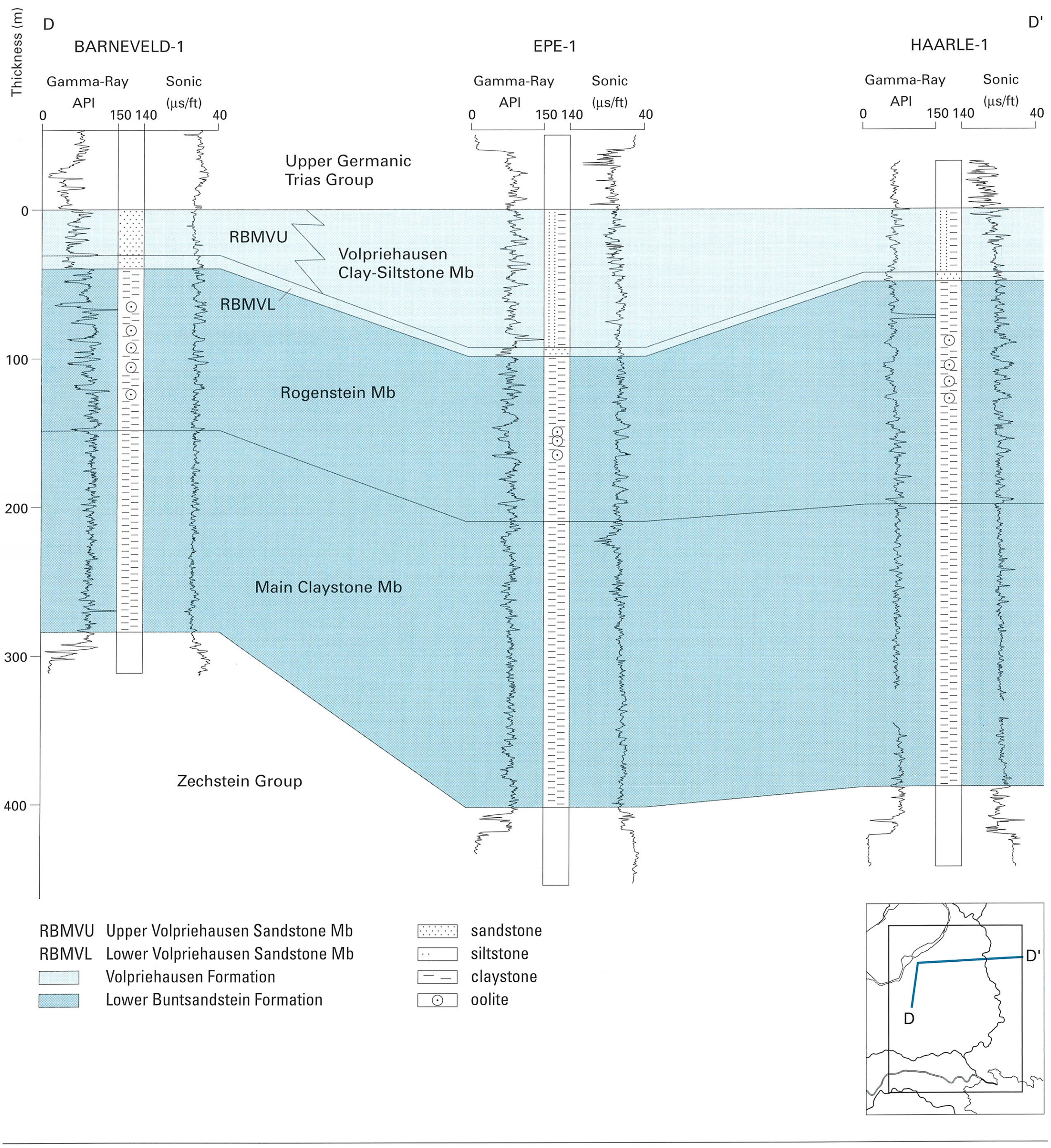


Figure 7.3 Stratigraphic correlation of the Lower Germanic Trias Group along line D-D' between wells Barneveld-1, Epe-1 and Haarle-1. Reference level is the base of the Upper Germanic Trias Group.

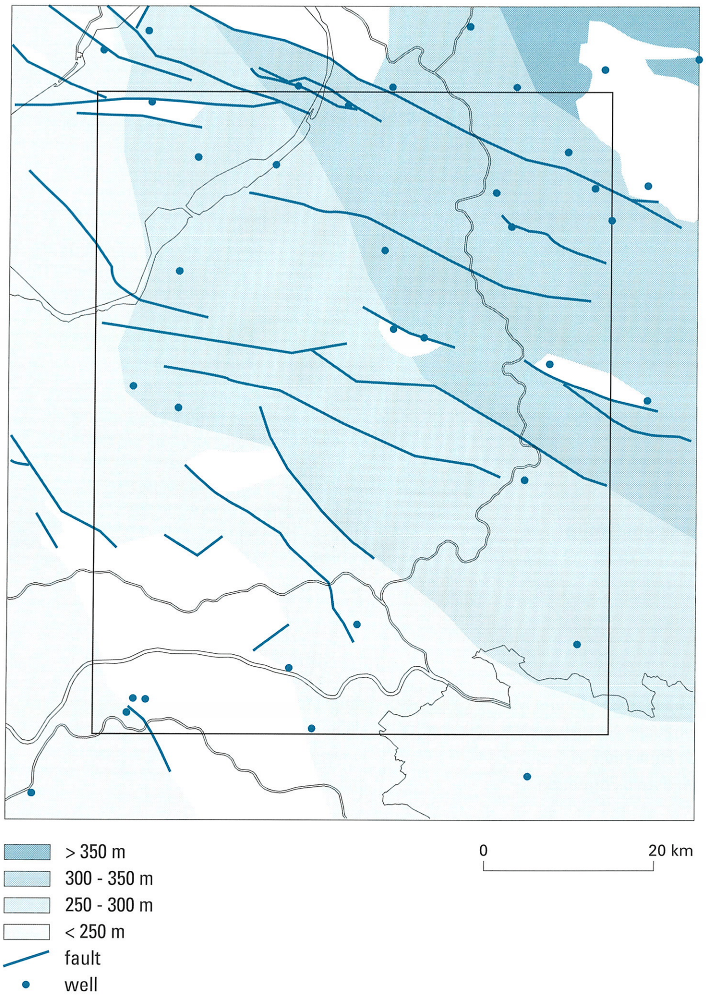
7.2.3 Main Buntsandstein Subgroup

This subgroup consists of an alternation of claystone, siltstone and sandstone. Within the map sheet area, the subgroup's thickness ranges from 20 m in the Central Netherlands Basin to almost 300 m in the Roer Valley Graben, south-west of the Maasbommel High. Within the subgroup, three formations can be distinguished, the Volpriehausen, Detfurth and Hardegsen Formations (figs 7.1 & 7.5).

The variation in thickness within this subgroup is due to erosion prior to deposition of the Solling Formation of the Upper Germanic Trias Group. In most of the map sheet area, only part of the Volpriehausen Formation has been preserved; the full stratigraphic record is only present in the Roer Valley Graben.

The Main Buntsandstein Subgroup overlies the Lower Buntsandstein Formation, separated by a sharply defined boundary marking a minor disconformity, and is unconformably overlain by the Upper Germanic Trias Group.

Figure 7.4 Isopach map of the Lower Buntsandstein Formation.



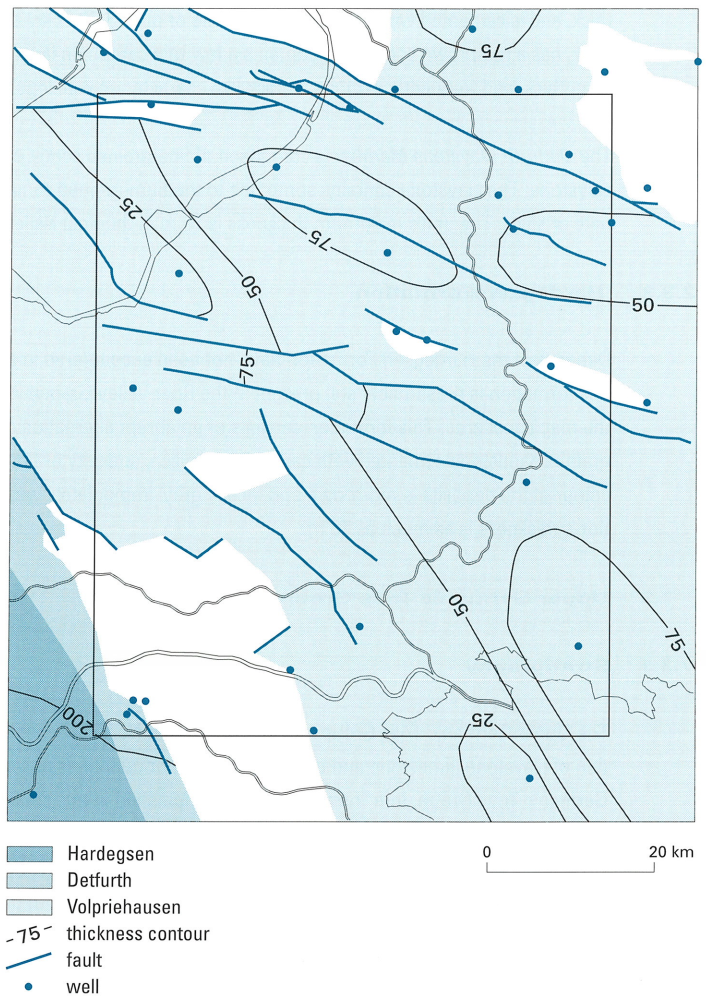
7.2.3.1 Volpriehausen Formation

The Volpriehausen Formation is subdivided into the Lower Volpriehausen Sandstone and Volpriehausen Clay-Siltstone Members. In the Roer Valley Graben and in the western part of the map sheet area, it is subdivided into the Lower and Upper Volpriehausen Sandstone Members. The formation slightly disconformably overlies the Lower Buntsandstein Formation and is unconformably overlain in the southwest by the Detfurth Formation and in other parts of the map sheet area by the Solling Formation. The maximum thickness of the formation, almost 100 m, was encountered in well Epe-1.

The lower boundary of the *Lower Volpriehausen Sandstone Member* is marked by a sharply defined boundary, and the member is overlain by the Volpriehausen Clay-Siltstone Member or the Upper Volpriehausen Sandstone Member. The sandstone is, generally, fine-grained and calcareous. The member's thickness ranges from a few metres to 40 m.

The *Upper Volpriehausen Sandstone Member* consists of stacked light-coloured sandstone and siltstone beds with a finely laminated siltstone at the base, which correlates well regionally. The most complete sequence, of almost 70 m thick, has been encountered in Roer Valley Graben and is overlain by Lower

Figure 7.5 Subcrop map of the unconformity under the Upper Germanic Trias Group, at the base of the Solling Formation, showing the thickness of the Main Buntsandstein Subgroup.



Detfurth Sandstone Member. The proportion of clay and silt layers rapidly increases northward where the unit grades into the Volpriehausen Clay-Siltstone Member (fig. 7.3).

The *Volpriehausen Clay-Siltstone Member* consists of a cyclic sequence of red, fine-grained sandy clay-siltstone beds with intercalated red to green, fine-grained, sandstone beds. The sandstone beds sometimes contain oolites. The unit is overlain by the Solling Formation. The most complete succession, over 90 m, was encountered in well Epe-1.

7.2.3.2 Detfurth Formation

The Detfurth Formation is subdivided into the Lower Detfurth Sandstone and the Detfurth Claystone Members. The formation is only present in the Roer Valley Graben. The Detfurth Formation unconformably overlies the Volpriehausen Formation and is conformably overlain by the Hardegsen Formation or unconformably by the Solling Formation. The maximum thickness of 60 m was encountered in well Maasbommel-1.

The *Lower Detfurth Sandstone Member* consists of a complex of medium-fine to coarse-grained, red-brown sandstone and likewise reddish clay-siltstone layers. The unit is divided into two sandstone intervals by an intercalated clay-siltstone sequence. The lower sandstone interval is approximately 10 m thick, and is cemented with carbonate, anhydrite or quartz. The clay-siltstone sequence is a few metres thick, has a red-brown colour and contains a few thin carbonate layers. The upper sandstone interval is 10 m thick, and frequently exhibits a block-like character on well logs.

The *Detfurth Claystone Member* is composed of fine-grained sandy or silty, predominantly red-brown claystone. The claystone contains some fine to medium-grained sandstone beds cemented with carbonate or silica. The unit's maximum thickness is 35 m in the Roer Valley Graben.

7.2.3.3 Hardegsen Formation

Deposits of the Hardegsen Formation have not been encountered in any wells in the map sheet area, but this formation is presumably still present in the Roer Valley Graben in the far south-western corner of the map sheet area. This formation consists of an abrupt alternation of thin layers of medium-coarse-grained sandstone cemented with carbonate or silica, and silty or fine-grained sandy claystone. The colour of the deposits is red-brown and locally grey. Immediately west of the map sheet area, the formation's thickness is as much as 70 m.

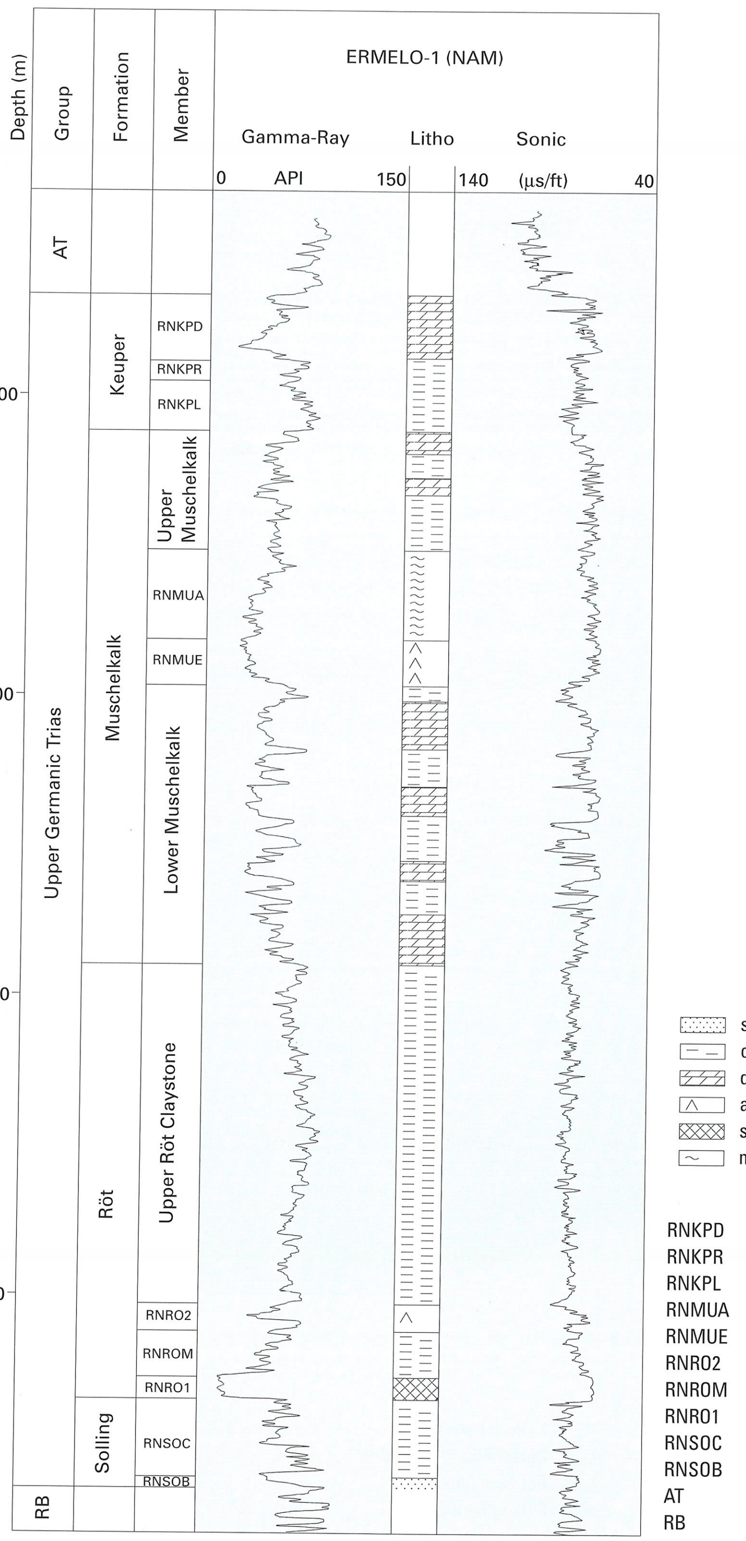
7.3 Upper Germanic Trias Group

7.3.1 Stratigraphy

The Upper Germanic Trias Group, of Late Scythian to Norian age, consists predominantly of an alternation of claystone, limestone and evaporite and minor quantities of sandstone. Within the Upper Germanic Trias Group, four formations are distinguished in this area: the Solling, the Röt, the Muschelkalk and the Keuper Formations (figs 7.1, 7.6 & 7.7).

The group is present in the central part of the map sheet area; with the exception of the local highs, and in the Roer Valley Graben. The group is missing in the north-western part of the map sheet area and on the Maasbommel High (figs 7.8 & 7.9). The group unconformably overlies the Lower Germanic Trias

Figure 7.6 Stratigraphic subdivision and log characteristics of the Upper Germanic Trias Group in well Ermelo-1.



RNKPD	Dolomitic Keuper
RNKPR	Red Keuper Claystone
RNKPL	Lower Keuper Claystone
RNMUA	Middle Muschelkalk Marl
RNMUE	Muschelkalk Evaporite
RNRO2	Upper Röt Evaporite
RNROM	Middle Röt Claystone
RNRO1	Main Röt Evaporite
RNSOC	Solling Claystone
RNSOB	Basal Solling Sandstone
AT	Altena Group
RB	Lower Germanic Trias Group

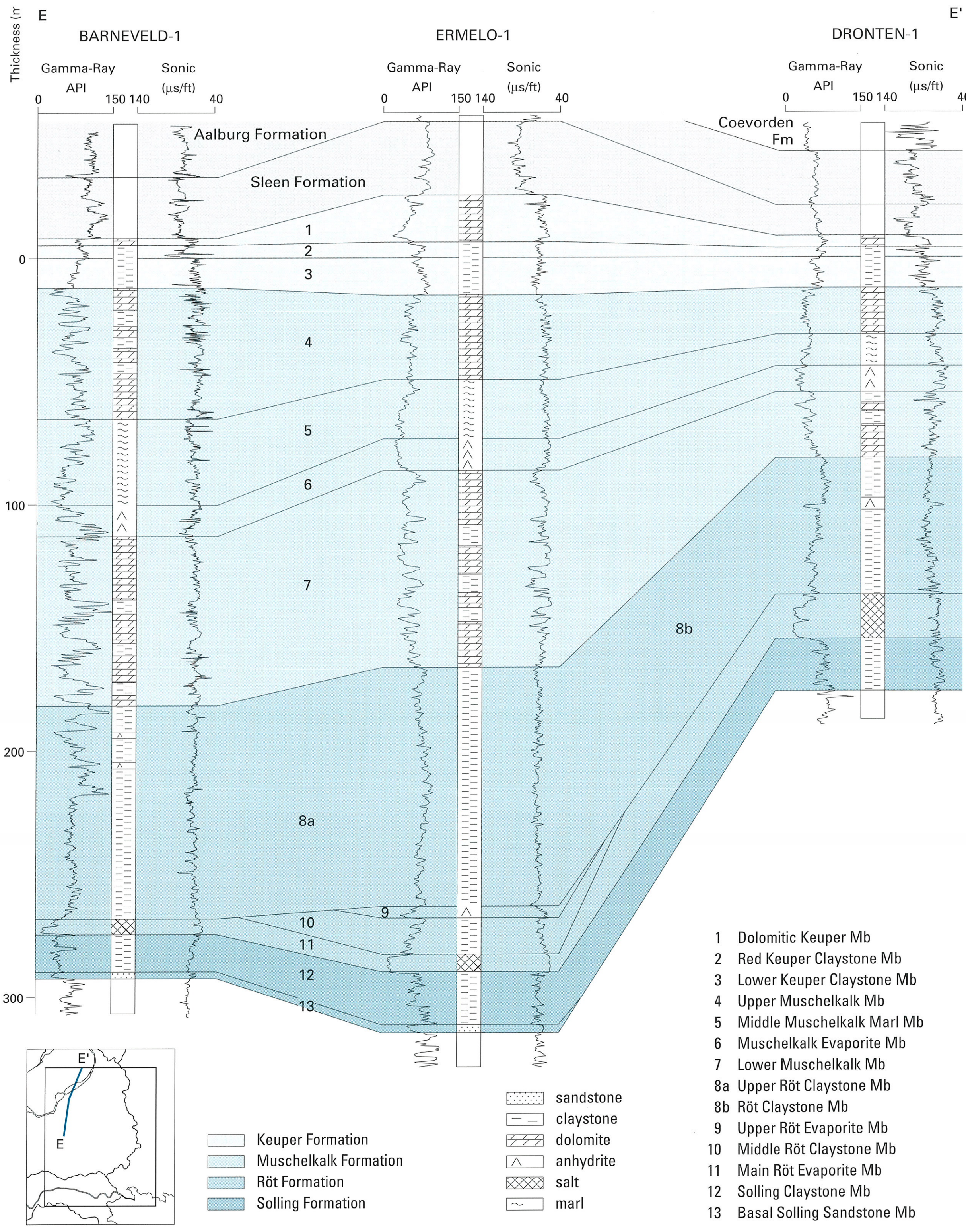


Figure 7.7 Stratigraphic correlation of the Upper Germanic Trias Group along line E-E' between wells Barneveld-1, Ermelo-1, and Dronten-1. Reference level is the base of the Red Keuper Claystone Member (Early Kimmerian unconformity).

Group and is overlain, either disconformably or unconformably, by the Altena, Niedersachsen, Rijnland or Chalk Group or by the North Sea Supergroup.

7.3.2 Solling Formation

The Solling Formation is subdivided into the Basal Solling Sandstone and the Solling Claystone Members. The formation unconformably overlies the Lower Germanic Trias Group and is conformably overlain by the Röt Formation or unconformably by the Rijnland Group or the North Sea Supergroup. The formation's thickness exceeds 90 m in the Central Netherlands Basin.

The *Basal Solling Sandstone Member* is only a few metres thick in the map sheet area. The presence of this sandstone is confined to the Central Netherlands Basin. The sandstone consists of a calcareous, reddish, fine-grained calcareous sandstone.

The *Solling Claystone Member* consists of red or red-brown dolomitic, silty claystone; characteristic of this member are the green mottles. Towards the south, the sand content of the unit increases. The thickness exceeds 90 m in the Central Netherlands Basin.

7.3.3 Röt Formation

The Röt Formation, of Early Anisian age, is subdivided into the Main Röt Evaporite, the Intermediate Röt Claystone, the Upper Röt Evaporite and the Upper Röt Claystone Members. In places where the Upper Röt Evaporite is not present, the formation is subdivided into the Main Röt Evaporite and the Röt Claystone Members. In the Roer Valley Graben, evaporites are virtually absent and here the formation is subdivided into the Lower Röt Fringe Claystone, the Röt Fringe Sandstone, and the Upper Röt Fringe Claystone Members (fig. 7.8). The formation conformably overlies the Solling Formation and is conformably overlain by the Muschelkalk Formation or unconformably by Niedersachsen or the Chalk Group or by the North Sea Supergroup. The thickness of the Röt Formation ranges from 200 m in the Central Netherlands Basin to over 50 m in the eastern part of the map sheet area, while thicknesses of approximately 200 m have been encountered in the Roer Valley Graben.

The *Main Röt Evaporite Member* consists predominantly of halite in the Central Netherlands Basin. The rock-salt deposits are light-grey or bright coloured, sometimes with an intercalated layer of reddish salt owing to admixture of polyhalite and reddish claystone. The maximum thickness of the salt deposits is 50 m. A thin anhydrite layer is present at the base of the Main Röt Evaporite Member, while the top of the evaporites is formed by a 10-to-15-m-thick sequence with intercalated thin claystone bands. At the southern limit of the salt (fig. 7.8), the member consists mainly of anhydrite, and is approximately 20 m thick.

The *Intermediate Röt Claystone Member* consists of a red-brown claystone, with a uniform thickness of 20 to 30 m. Owing to its high gamma-ray readings; this member can easily be distinguished on well logs from the underlying and overlying evaporite members.

The *Upper Röt Evaporite Member* is, in the map sheet area, developed in an anhydrite facies, and consists of an alternation of anhydrite and thin claystone layers. The member's thickness is a few metres.

The *Upper Röt Claystone Member* consists of purple, bright orange-red, dark-red, red-brown or green claystone. The claystone is often silty or sandy; gypsum nodules are also found. In the uppermost part, which is approximately 50 m thick, the claystones alternate with marl and thin limestone layers. The unit is over 100 m thick in the Central Netherlands Basin.

Where the Upper Röt Evaporite Member is absent, the formation is subdivided into the Main Röt Evaporite and the Röt Claystone Members.

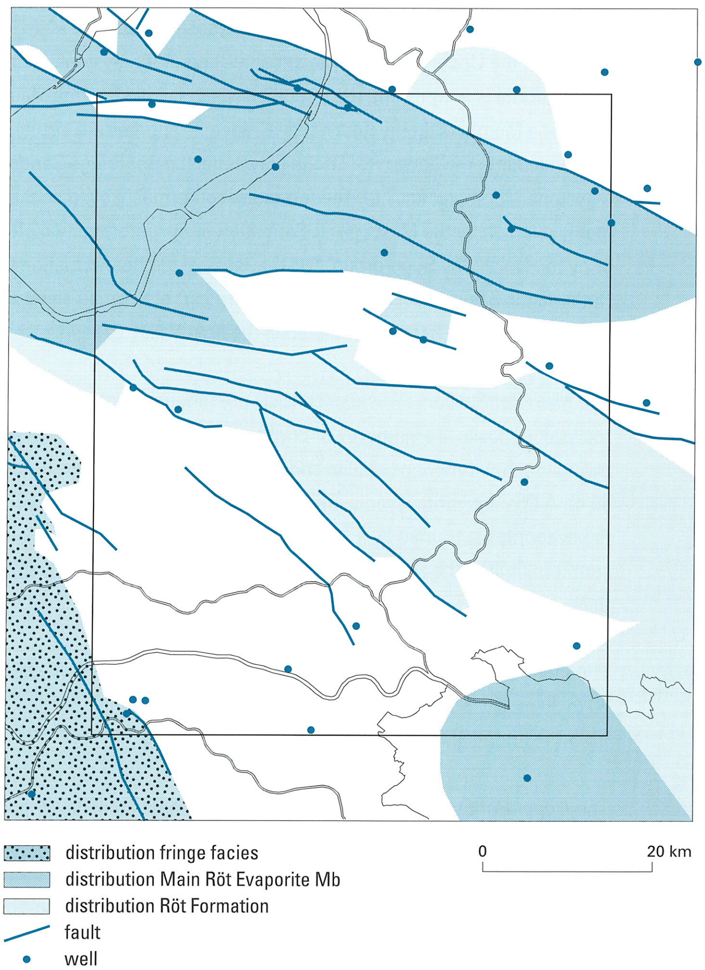
The *Röt Claystone Member* has the same lithological composition as the Upper Röt Claystone Member and has the same maximum thickness of approximately 100 m.

The *Lower Röt Fringe Claystone Member* is present in the Roer Valley Graben. The unit consists of a red-brown, silty claystone and has a thickness of almost 100 m.

The *Röt Fringe Sandstone Member* consists of an alternation of grey, arkosic sandstone and red-brown claystone beds and is up to approximately 50 m thick. The thickness of the sand rapidly decreases northward.

The *Upper Röt Fringe Claystone Member* consists of a silty, sometimes sandy claystone. The member contains a few thin dolomite beds. This unit is also approximately 50 m thick.

Figure 7.8 Areal distribution of the Röt Formation, showing the fringe facies and the extent of the salt.



7.3.4 Muschelkalk Formation

The Muschelkalk Formation, of Anisian to Ladinian age, is, in the map sheet area, subdivided into the Lower Muschelkalk, the Muschelkalk Evaporite, the Middle Muschelkalk Marl and the Upper Muschelkalk Members. The present areal distribution and the thickness of this formation are mainly the result of uplift and erosion during the Early Kimmerian and subsequent tectonic phases; the most complete succession is found in the grabens in the Central Netherlands Basin and in the Roer Valley Graben (fig. 7.9). In the south-west and the north-east of the map sheet area and on the highs in the Central Netherlands Basin the formation is completely absent. The formation is unconformably overlain by the Keuper Formation, the Altena, or the Chalk Group or by the North Sea Supergroup (Maps 16, 17, and 18). The formation is up to 200 m thick.

The *Lower Muschelkalk Member* consists of a grey, marly to argillaceous limestone, with intercalations of dolomite, marl and claystone. The unit is also found in the grabens in the Central Netherlands Basin and in the Roer Valley Graben. It is unconformably overlain by the Keuper Formation, by the Altena Group or by the North Sea Supergroup. Where the member is conformably overlain by the Muschelkalk Evaporite Member, its thickness can exceed 100 m.

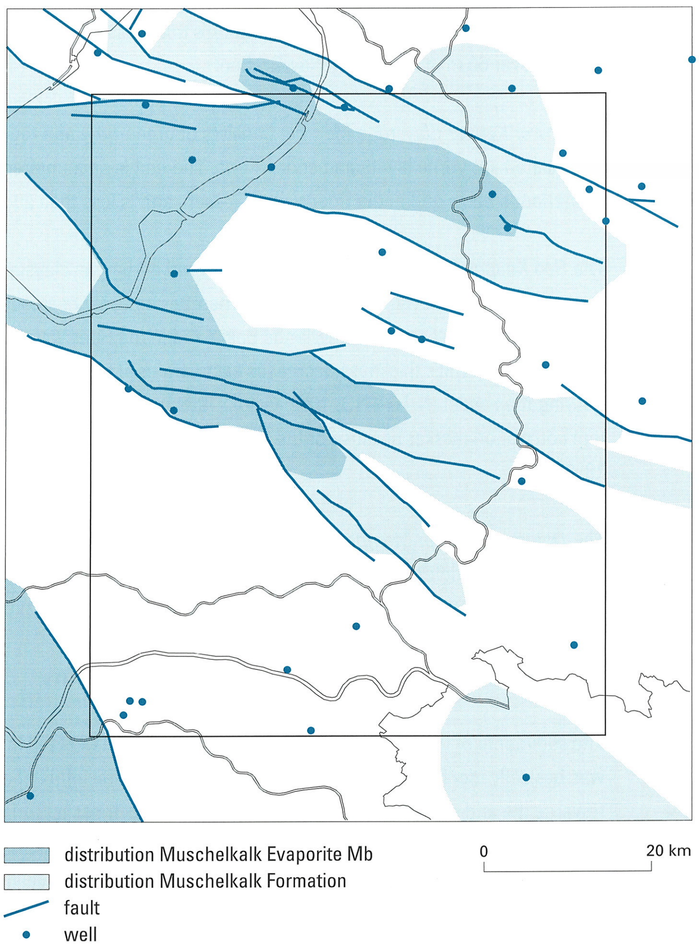


Figure 7.9 Areal distribution of Muschelkalk Formation, showing the extent of the salt.

The *Muschelkalk Evaporite Member* consists of rock salt and anhydrite and is only present in a small area in the north of the Central Netherlands Basin and in the Roer Valley Graben (fig. 7.9). Mainly anhydrites are present in the Central Netherlands Basin, while in the Roer Valley Graben an approximately 30-m-thick layer of rock salt was precipitated.

The *Middle Muschelkalk Marl Member* consists of a grey dolomitic marl, the clay content of which increases towards the top. The unit has roughly the same areal distribution as the Muschelkalk Evaporite Member. The thickness is 15 to 40 m.

The *Upper Muschelkalk Member* consists of a succession of pale brown to grey dolomite and marl. As the member's thickness has been reduced by erosion, it is only present locally in the Central Netherlands Basin. The thickness is 15 to 60 m.

7.3.5 Keuper Formation

The Keuper Formation consists predominantly of claystones with intercalated dolomite layers. The formation is present in the western and northern parts of the map sheet area and is far from complete. Only three of the seven members, in which the Keuper Formation is normally subdivided, are present; i.e.: the Lower Keuper Claystone, the Red Keuper Claystone, and the Dolomitic Keuper Members, representing a Late Ladinian to Norian age. The base of the Red Keuper Claystone Member is formed by the Early Kimmerian unconformity. The formation's thickness is up to 40 m in the Central Netherlands Basin and just over 60 m in the Roer Valley Graben.

The *Lower Keuper Claystone Member* consists of green-grey and red-brown, dolomitic claystone with intercalated anhydrite layers and concretions. The unit is encountered only locally in the Central Netherlands Basin and in the Roer Valley Graben, and is less than 20 m thick.

The *Red Keuper Claystone Member* consists of red and green claystones and unconformably overlies the Lower Keuper Claystone Member. The member has only been encountered in three wells in the western part of the Central Netherlands Basin and in the Roer Valley Graben, where its thickness is less than 10 m. The unit's thickness decreases eastward until the member is completely absent in the neighbouring map sheet (NITG-TNO, 1998; Geluk, 1999b). The Red Keuper Claystone Member is a very important correlation marker because of the Early Kimmerian unconformity at its base (Wolburg, 1969; Geluk, 1999b).

The *Dolomitic Keuper Member* consists of an alternation of claystone and several anhydrite and dolomite layers. The dolomite is characterised by a conspicuous pale colour. The member's areal distribution is identical to that of the Red Keuper Claystone Member and its maximum thickness is 18 m.

7.4 Sedimentary development and palaeogeography

The sediments of the Lower Germanic Trias Group were deposited in a large continental basin, which was basically identical in shape to the Zechstein basin. The influx of clastic material, which had started towards the end of the Zechstein, continued during the Triassic. During the Triassic, a continental depositional environment prevailed initially, but a gradual sea-level rise brought increasingly marine conditions. The Muschelkalk Formation was deposited during a sea-level highstand. Tectonic activity occurred in two phases: the Hardegsen phase, which gave rise to a disconformity between the Lower and the Upper Germanic Trias Groups (fig 7.1) and the Early Kimmerian phase. The first pulse occurred during deposition of the Keuper Formation while the second pulse marks the end of the Keuper, and is expressed as a disconformity between the Upper Germanic Trias Group and the Altena Group (fig. 7.1).

The Lower Buntsandstein Formation consists predominantly of brackish to fresh-water lacustrine deposits. The cyclical character of these deposits is ascribed to the so-called Milankovitch cyclicity, with a periodicity of 100,000 years (Geluk & Röhling, 1997). The oolites in the upper part of the Lower Buntsandstein Formation formed in brackish water, in a high-energetic environment, during periods when the influx of clastics was limited (Peryt, 1975). The red colour of the sediments and the presence of desiccation cracks reflects the regular drying up of the lake.

During deposition of the Main Buntsandstein Subgroup, river systems prograded episodically from the south across the entire map sheet area. As a result, deposition of sands (Lower Volpriehausen Sandstone, Upper Volpriehausen Sandstone and Lower Detfurth Sandstone Members) alternated with that of fine-grained lacustrine deposits (Volpriehausen Clay-Siltstone and Detfurth Claystone Members). At the bases of the Lower Volpriehausen Sandstone and the Lower Detfurth Sandstone Members, disconformities are present. Comparatively severe erosion, preceded deposition of in particular the Detfurth Formation; this is reflected in the absence of the top part of the Volpriehausen Clay-Siltstone Member (Geluk et al., 1996; Geluk & Röhling, 1997).

The unconformity at the base of the Upper Germanic Trias Group is prominently developed in the map sheet area. In most of the map sheet area, the group overlies the oldest sediments of the Main Buntsandstein Subgroup and the Volpriehausen Formation, while in the Roer Valley Graben it overlies the youngest sediments: the Detfurth and Hardegsen Formations (fig. 7.5). The Upper Germanic Trias Group exhibits an alternation of continental and more marine depositional environments.

The Solling Formation reflects, in the main basin, a transgression by the sea from an easterly direction into the basin. The sea did not actually reach the map sheet area and therefore, mainly lacustrine sediments were deposited here. At the onset of deposition of the Röt Formation, the map sheet area was finally also flooded by the sea. When the connection with the sea was blocked, the water that was present in the basin evaporated, resulting in the salt and anhydrite deposits of the Main and Upper Röt Evaporite Members, followed by a sequence of claystones. The top part of the Röt Formation reflects the continuing transgression, with a gradual return to more open marine conditions in the basin. The provenance areas of the sediments were also increasingly flooded by the advancing transgression, and clastic sedimentation was replaced by the limestone-dominated strata of the Muschelkalk Formation. The Lower Muschelkalk Member was deposited under shallow-marine to storm-surge conditions, a subsequent closing of the seaway between the North-west European Basin and the Tethys Ocean, resulted in deposition of the Muschelkalk Evaporite Member. Subsequently, the Middle Muschelkalk Marl and the Upper Muschelkalk Members were deposited in more open-marine conditions again.

The Keuper Formation was deposited in shallow-marine, marginal-marine, and evaporitic depositional conditions. During deposition of this formation, major tectonic activity, representing the first pulse of the Early Kimmerian Phase, caused deep erosion of the underlying sediments, resulting in a major hiatus in the stratigraphic record.

8 Altena Group

8.1 Stratigraphy

The Altena Group, of Rhaetian to Aalenian/ Bajocian age, consists predominantly of dark-coloured claystones with intercalated sandstone, limestone and marl layers in the top part. The Altena Group is subdivided into five formations (fig. 8.1), four of which are present within the map sheet area: the Sleen, the Aalburg, the Posidonia Shale, and the Werkendam Formations. The Brabant Formation is not present in this map sheet area.

Within the map sheet area, the Altena Group rests disconformably on the Upper Germanic Trias Group. The sediments of the Altena Group are present in the Central Netherlands Basin and in the Roer Valley Graben (Map 6; fig. 8.4). Differential movements have resulted in large variations in thickness, from a few metres to over 1000 m in the Central Netherlands Basin (Map 7). The depth of the base of the group ranges from 600 to 3000 m (Map 6). The deposits are unconformably overlain by the Schieland, the Niedersachsen, the Rijnland, or the Chalk Group, or by the North Sea Supergroup.

8.1.1 Sleen Formation

The Sleen Formation, of Rhaetian age, consists of dark-grey to black, occasionally bituminous, claystone and shale, locally containing abundant pyrite. The formation is divided into two parts by a thin sandstone unit, and is present throughout the distribution area of the Altena Group. The colour of the top part can be red-brown. The formation rests disconformably, or in the eastern part of the map sheet area unconformably, on the Upper Germanic Trias Group and are conformably overlain by the Aalburg Formation. The formation's thickness is nearly 30 m.

8.1.2 Aalburg Formation

The Aalburg Formation, of Hettangian to Pliensbachian age, has a monotonous lithology and consists of green-grey to black, sometimes calcareous claystone with thin limestone beds (fig. 8.3). In addition, a few dark-coloured, organic-rich claystone beds are found in the lower part of the formation (Herngreen & De Boer, 1974). The formation contains numerous ammonites, belemnites and molluscs. Pyrite, iron ooids and siderite nodules are also common. The thickness of the Aalburg Formation varies greatly as a result of differential faulting and erosion. The maximum thickness exceeds 1000 m, and is reached in the Central Netherlands Basin. In the Roer Valley Graben, thicknesses of over 900 m have been encountered. The formation rests conformably on the Sleen Formation and is conformably overlain by the Posidonia Shale Formation or unconformably by the Schieland, the Rijnland or the Chalk Group, or by the North Sea Supergroup.

8.1.3 Posidonia Shale Formation

The Posidonia Shale Formation, of Toarcian age, consists of dark, bituminous shales containing a few limestone beds. The formation has not been encountered in any well within the map sheet area, but is present further to the west of it. The formation has been identified within the map sheet area on seismic in a number of grabens in the Central Netherlands Basin. Our knowledge of the regional geology, resulting from the mapping of the deep subsurface, gives rise to the assumption that the Posidonia Shale Formation is also present locally in the Central Netherlands Basin and in the Roer Valley Graben (fig. 8.4). The high organic content makes this shale an important oil source rock in the Netherlands. The formation rest conformably on the Aalburg Formation and is, in the map sheet area, overlain by the by the Schieland, the Rijnland or the Chalk Group, or by the North Sea Supergroup.

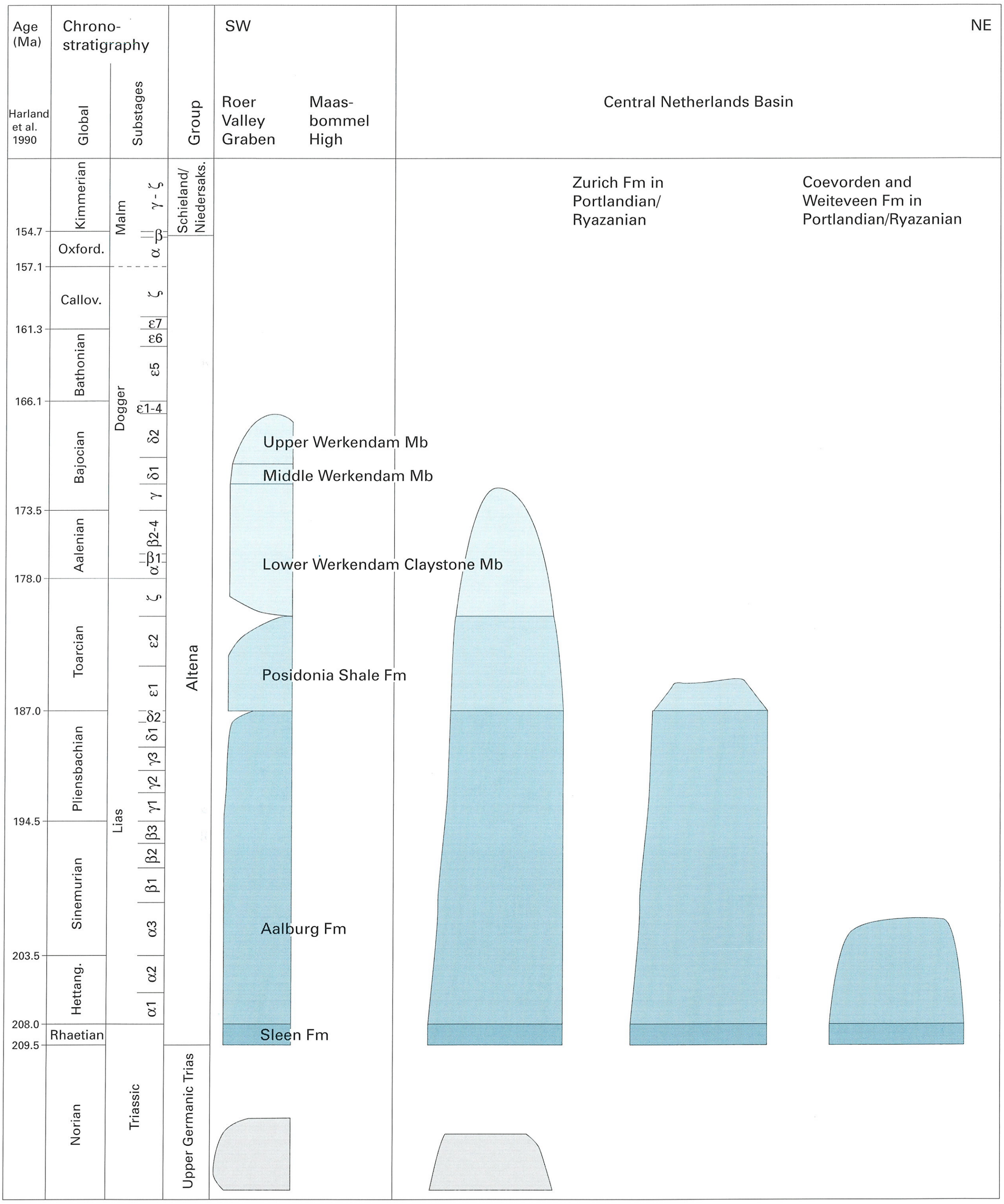
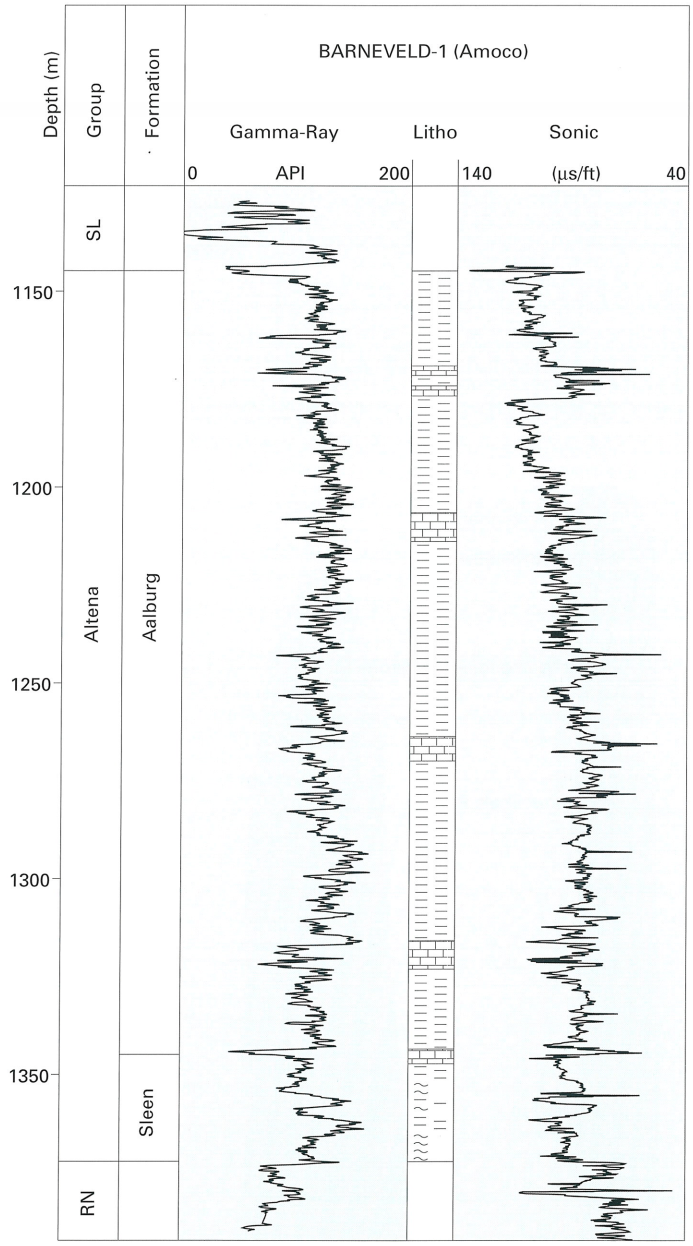


Figure 8.1 Stratigraphy of the Altena Group.

Figure 8.2 Stratigraphic subdivision and log characteristics of the Altena Group in well Barneveld-1.



SL Schieland Group
RN Upper Germanic Trias Group
claystone
limestone
marl

8.1.4 Werkendam Formation

The Werkendam Formation, of Late Toarcian - Bajocian age, consists of grey, marly claystone with an interval of more calcareous, silty to sandy beds and siltstone in the middle of the formation. The formation is subdivided into three members: the Lower Werkendam, the Middle Werkendam and the Upper Werkendam Members. The formation has not been encountered in any wells in the Central Netherlands Basin, but considering the thickness of the Altena Group, it must be present. In the Roer Valley Graben, the formation has been encountered in wells to the south-west of the map sheet area. In the Central

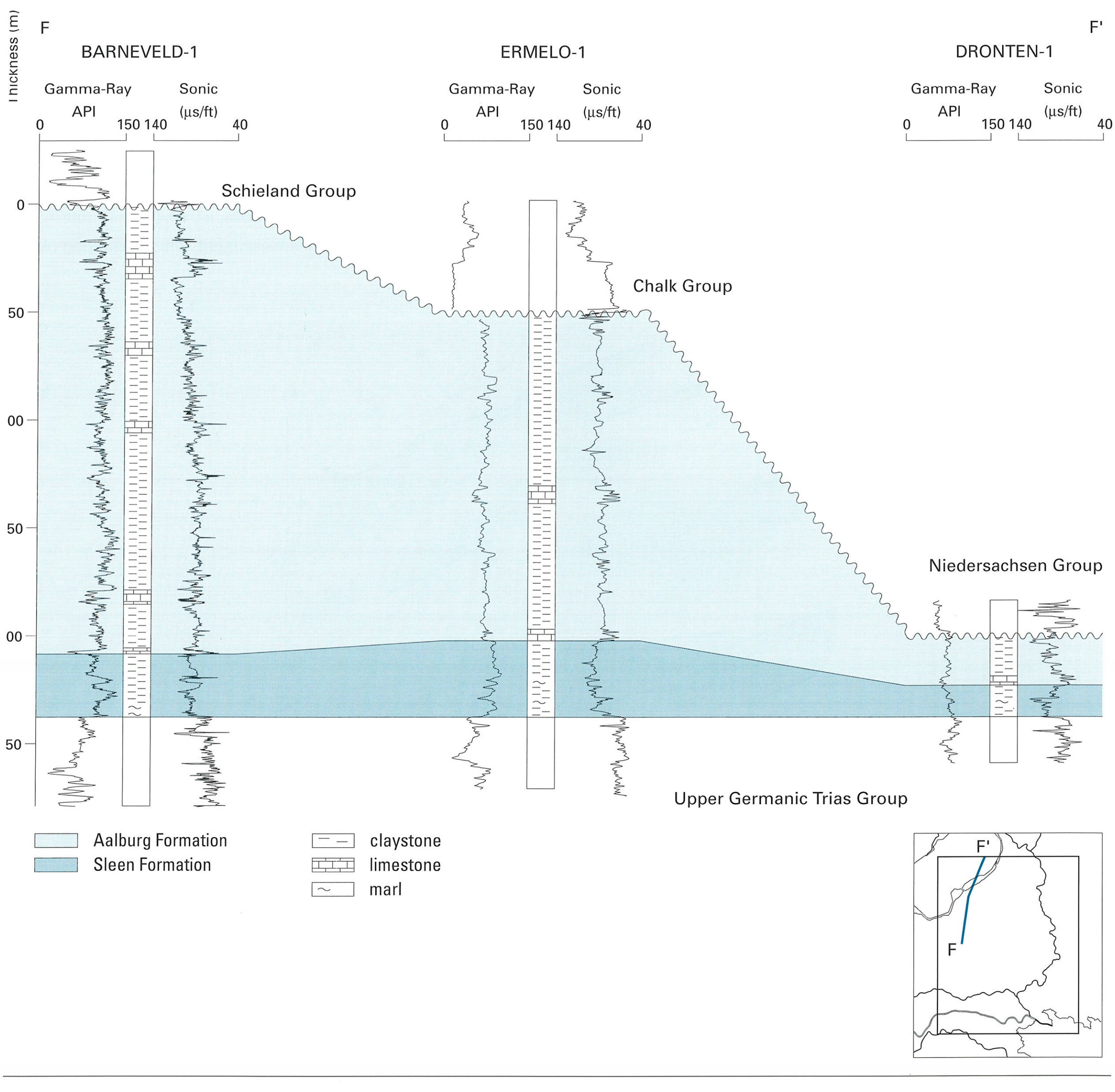


Figure 8.3 Stratigraphic correlation of the Altena Group along line F-F' between wells Barneveld-1, Ermelo-1 and Dronten-1. Reference level is the base Altena Group.

Netherlands Basin, the thickness ranges from 300 to 400 m, while in the Roer Valley Graben it is 200 m thick.

The *Lower Werkendam Member* consists predominantly of dark-coloured, sometimes silty claystone with intercalated light-coloured marls and a few iron-oolite horizons. The member is clearly less calcareous than the overlying Middle Werkendam Member is.

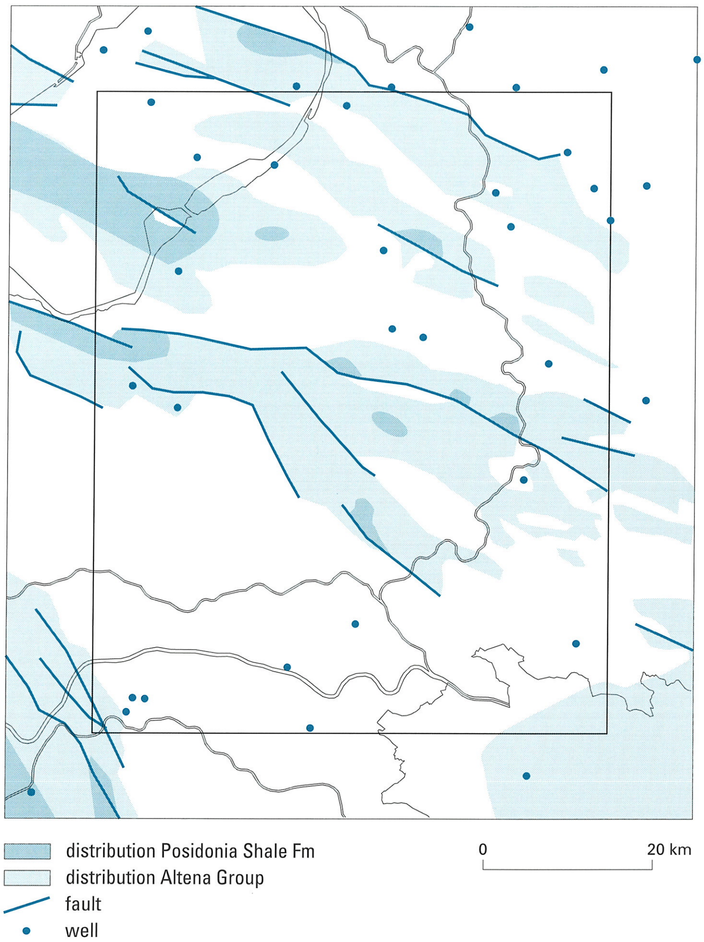
The *Middle Werkendam Member* comprises an alternation of calcareous sandstones, calcareous siltstones, and sandstones and shows distinctly lower sonic- and resistivity-log readings than the underlying and overlying members.

The Upper Werkendam Member consists of a homogenous sequence of grey, slightly marly claystones and conformably overlies the calcareous sediments of the Middle Werkendam Member.

8.2 Sedimentary development and palaeogeography

After a long period of continental and shallow-marine depositional conditions, a transgression during the Late Triassic (Rhaetian) resulted in an open-marine depositional environment, which extended over

Figure 8.4 Areal distribution of the Altena Group showing the locations where the Posidonia Shale Formation is present.



large parts of North-western Europe. This transgression marks the beginning of the deposition of the Altena Group.

The earliest sediments of the Altena Group in the map sheet area are the transgressive deposits of the Sleen Formation. A brief regressive period followed deposition of this formation, which lent its top part a lagoonal character. Subsequently, sea level rose again and the open-marine sediments of the Aalburg Formation were deposited, predominately below wave base. The presence of organic-rich layers indicates that anoxic conditions periodically prevailed in the basin. The thickness variation within the formation reflects differential subsidence in this area.

The Posidonia Shale Formation is a pelagic deposit with a bituminous character, deposited under anoxic conditions. These may have been due to stagnation of the deep-water circulation, probably caused by a combination of a deep basin and an intensely faulted basin floor and a restriction of the seaway to the open ocean. This could account for the reducing conditions.

Open-marine conditions returned during deposition of the Werkendam Formation and the Brabant Formation. The latter formation is missing in the map sheet area owing to Late-Kimmerian erosion.

9 Schieland and Niedersachsen Groups

9.1 General

The Late Jurassic deposits of the Schieland Group and the Niedersachsen Group are of Late Portlandian to Ryazanian age. The Schieland Group is represented by the Zurich Formation of the Delfland Subgroup, which consists here predominantly of alternating dark-coloured to variegated claystones, sandstones and calcareous sandstones. The Zurich formation is present in the Central Netherlands Basin (fig. 9.1). The Niedersachsen Group is only present in the far north of the map sheet area and comprises the Weiteveen and Coevorden Formations, composed of dark- to pale-grey calcareous shales, dolomite layers and marly claystones. In the map sheet area, the depth of the base of the Schieland and the Niedersachsen Groups ranges from 900 to 2100 m (Map 8). The maximum thickness is 700 m (Map 9), but it has been reduced by synsedimentary faulting and later erosion. The Schieland Group unconformably overlies the Limburg, Upper Germanic Trias, or Altena Group and is conformably, or slightly disconformably, overlain by the Rijnland Group in the Voorthuizen Trough, or, elsewhere, unconformably by the North Sea Supergroup.

The original distribution area of the Late Jurassic sediments included both the Central Netherlands Basin and the Lower Saxony Basin east of it. Owing to basin inversion and the associated erosion at the end of the Cretaceous, it is difficult to identify the original areal distribution of these sediments. The Late Jurassic deposits in this map sheet area are therefore included in the Schieland Group, with the exception of the sediments in the far north of the map sheet area, where the Niedersachsen Group is present in a marine to lacustrine facies. In well Dronten-1, the lithology is mixed (fig. 9.3; RGD 1990 and Rijks Geologische Dienst, 1993b).

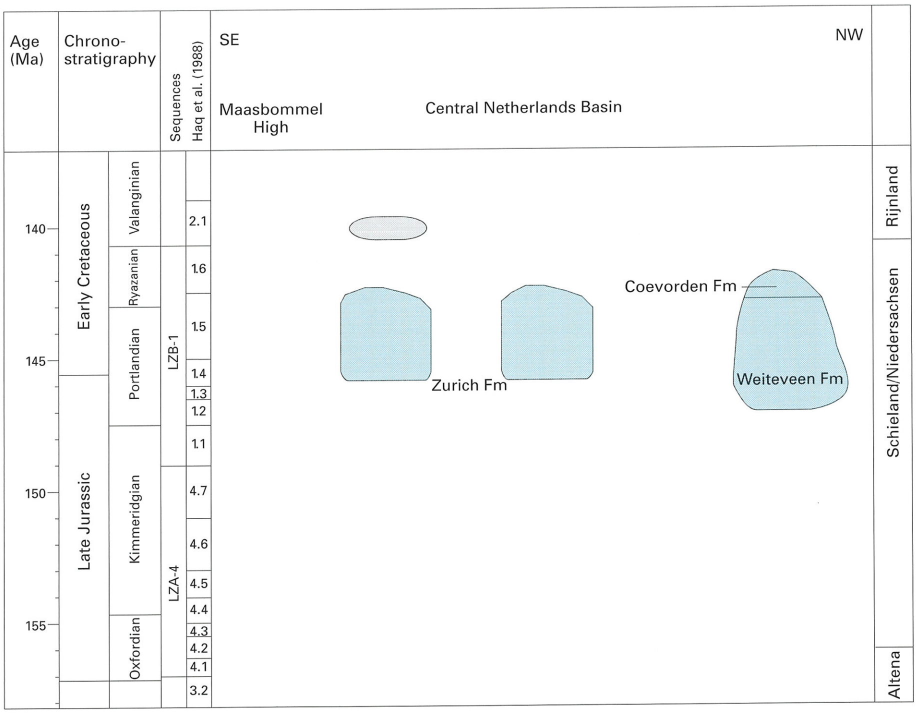


Figure 9.1 Stratigraphy of the Schieland and Niedersachsen Groups.

9.2 Schieland Group

9.2.1 Stratigraphy

The Schieland Group, of Late Portlandian to Ryazanian age (*NITG-TNO, 1999; TNO-NITG 2002a*), is represented by the Zurich Formation of the Delfland Subgroup in the map sheet area, and is encountered in a few grabens of the Central Netherlands Basin. The maximum thickness is 700 m and the depth of the base of the group ranges from 1100 to 2100 m. The group unconformably overlies the Limburg, the Upper Germanic Trias or the Altena Group, and is conformably, or slightly disconformably, overlain by the Rijnland Group in the Voorthuizen Trough, or by the North Sea Supergroup elsewhere.

9.2.1.1 Zurich Formation

The Zurich Formation, of Late Portlandian to Ryazanian age (*NITG-TNO, 1999 & 2002a*), consists of varicoloured or grey, sandy to silty claystone with thin intercalated sandstone, limestone and coal seams. The claystone sequence also contains pyrite, siderite, sandstone, and limestone and coal seams. On the basis of the sparse data, the formation can be subdivided into a calcareous sequence at the base, overlain by a sandy and clayey sequence (Van Adrichem Boogaert & Kouwe, 1993-1997). The most complete sequence was penetrated by a well in the Voorthuizen Trough (fig. 9.2), where, however, no coal beds are present in the top part of the sequence.

9.3 Niedersachsen Group

9.3.1 Stratigraphy

The Niedersachsen Group, of Late Portlandian to Ryazanian (*RGD, 1990*) age, comprises the Weiteveen and Coevorden Formations, and is only present in the far north of the map sheet area. The group is found at a depth from 900 to 1400 m. and its thickness is 400 m. It unconformably overlies the Upper Germanic Trias or the Altena Group and it is overlain by the North Sea Supergroup.

9.3.1.1 Weiteveen Formation

The Weiteveen Formation of the Niedersachsen Group, possibly of Late Portlandian age, consists of calcareous claystones and interfingers in the far north of the map sheet area with the calcareous strata of the Zurich Formation. The sediments contain some equally marine and lacustrine elements, such as ostracods. Some horizons have been encountered that are rich in organic matter. The thickness of the formation in well Dronten-1 is 285 m, but this may be double the true thickness as a result of reverse faulting at 1325 m depth (fig. 9.3; *RGD, 1990*). The Weiteveen Formation unconformably overlies the Altena Group and is conformably overlain by the Coevorden Formation.

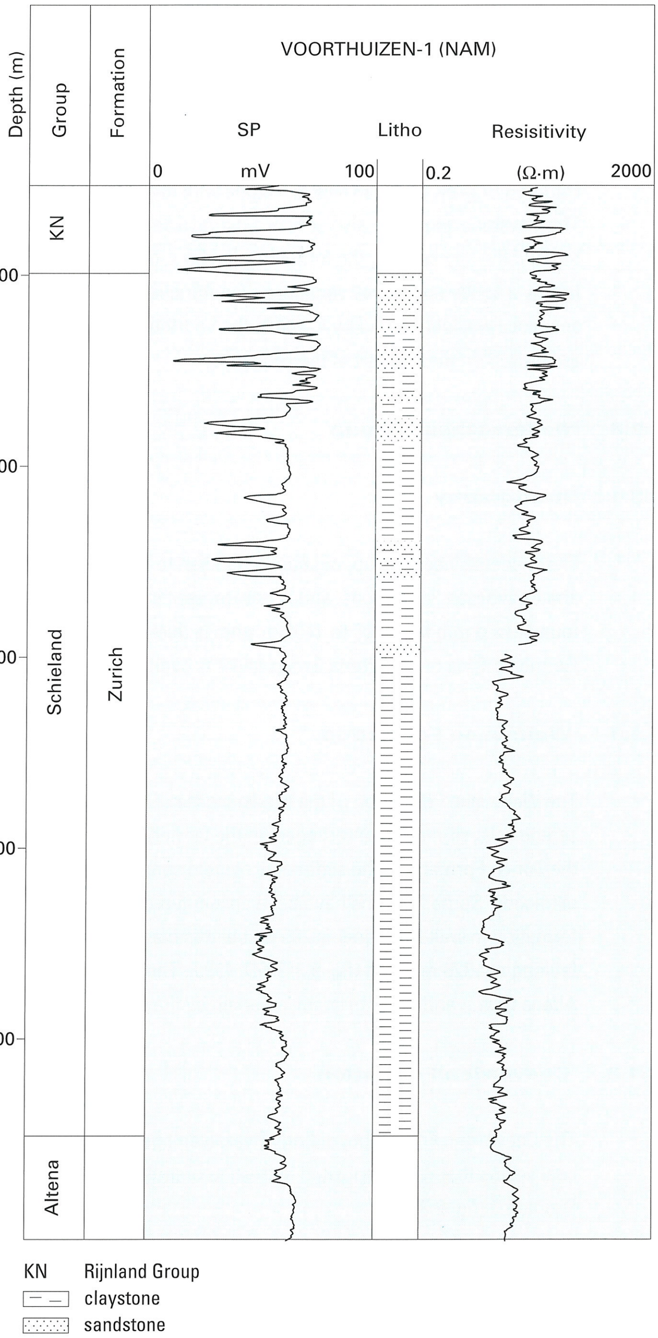
9.3.1.2 Coevorden Formation

The Coevorden Formation, of Early Ryazanian age, consists of marly claystones, limestone beds and coal seams that were deposited in fresh to brackish water. The formation's thickness is 140 m in well Dronten-1 (fig. 9.3).

9.4 Sedimentary development and palaeogeography

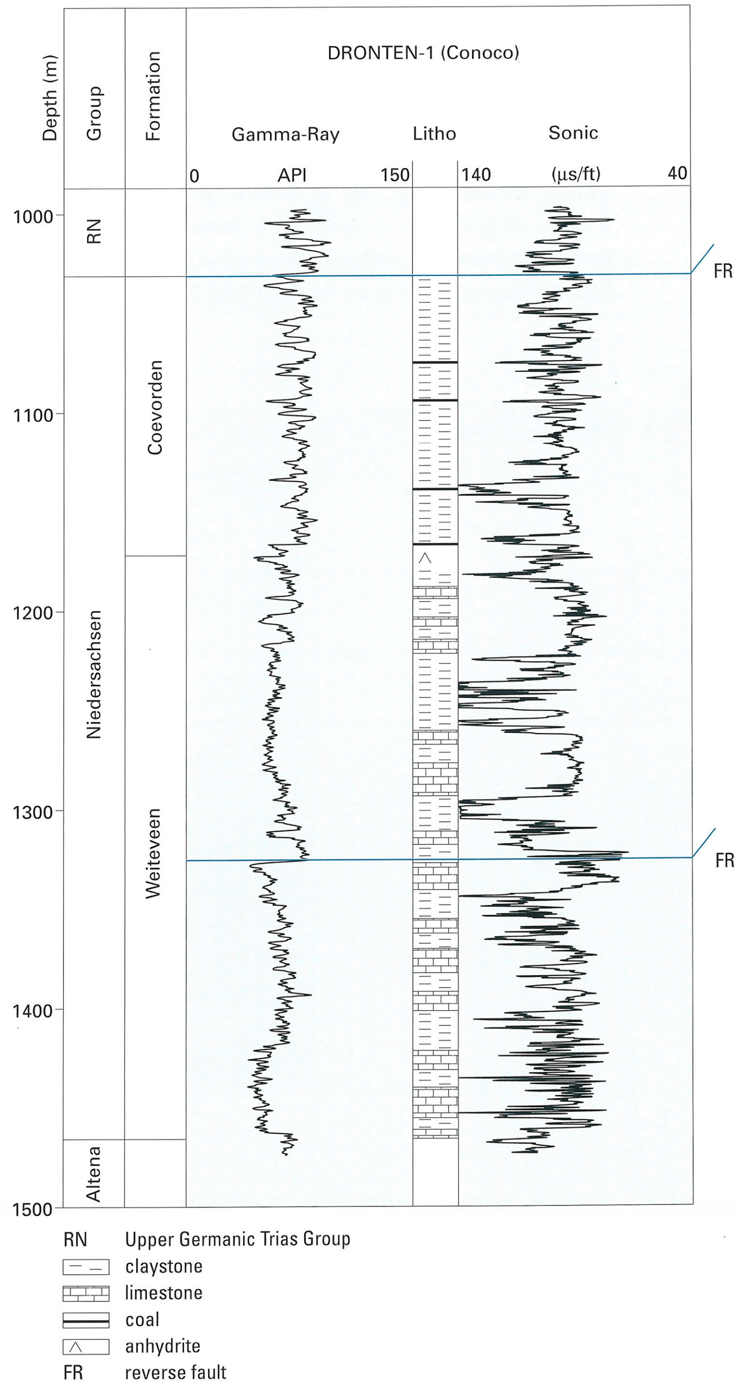
The sediments of the Zurich Formation were deposited during the Late Jurassic in the rapidly, but very unevenly, subsiding, Central Netherlands Basin. The climate was initially semi-arid and gradually became more humid (TNO-NITG, 2002a; Herngreen et al., 2000). The claystone sequence of the Zurich Formation is a brackish-water deposit, whereas the overlying sandy sequence was deposited in fresh water (*RGD, 1990; NITG-TNO 1999*). The latter sediments were transported by rivers flowing along the long axis of the subsiding grabens. Consequently, sand was deposited in channels, but also in the flood-

Figure 9.2 Stratigraphic subdivision and log characteristics of the Schieland Group in well Voorthuizen-1.



plain areas, in the form of crevasse splays, in between clays and peat layers. The Weiteveen Formation, in the far north of the map sheet area, was deposited in shallow-marine or lacustrine conditions in a lagoon or inland lake, which was in communication with the Lower Saxony Basin, north-east of the map sheet area. The Coevorden Formation, again, comprises both lacustrine and fluviatile elements. The provenance area of the sands in the Central Netherlands Basin is probably the Texel-IJsselmeer High (Rijkers & Geluk, 1996), but some sands may have been derived from the Maasbommel High.

Figure 9.3 Stratigraphic subdivision and log characteristics of the Niedersachsen Group in well Dronten-1.



10 Rijnland Group

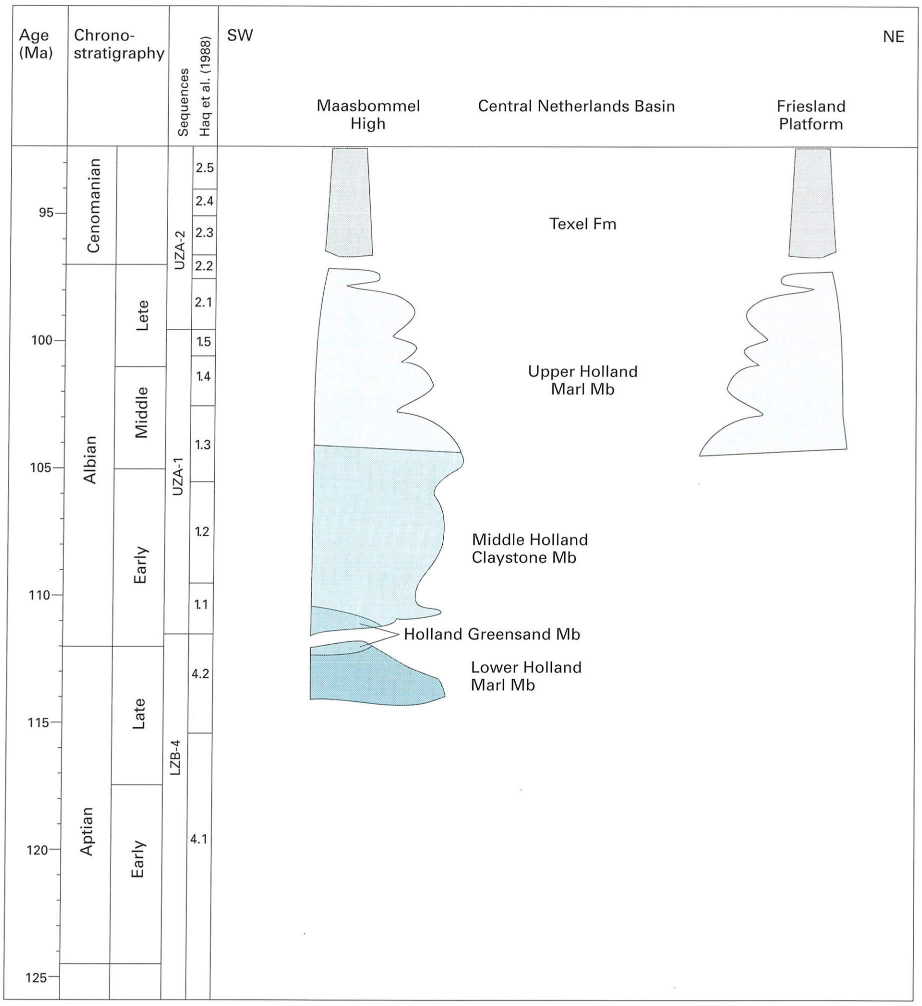
10.1 Stratigraphy

The Rijnland Group, of Valanginian to Albian age, consists of glauconitic sandstones, siltstones, claystones and marls. The group is subdivided into the Vlieland Sandstone, Vlieland Claystone and Holland Formations. The first two formations together form the informal Vlieland subgroup.

The Rijnland Group is present in the north-eastern and south-western parts of the map sheet area, and also in the Voorthuizen Trough in the Central Netherlands Basin. The depth of the group ranges from 700 to 2800 m (Map 10). The group's maximum thickness is 400 m in the south-western corner of the map sheet area (Map 11).

During deposition of this group, the depositional area expanded from the basins west and north-east of the map sheet area, across the neighbouring highs. As a result, the sediments at the base of the group are progressively younger towards the south-west. The group is conformably overlain by the Chalk Group or unconformably by the North Sea Super Group (Map 18). It slightly disconformably overlies the Schieland Group, or unconformably overlies either the Limburg, Upper Rotliegend, or Zechstein Group, or the Lower and Upper Germanic Trias Groups or the Altena Group.

Figure 10.1 Stratigraphy of the Rijnland Group.



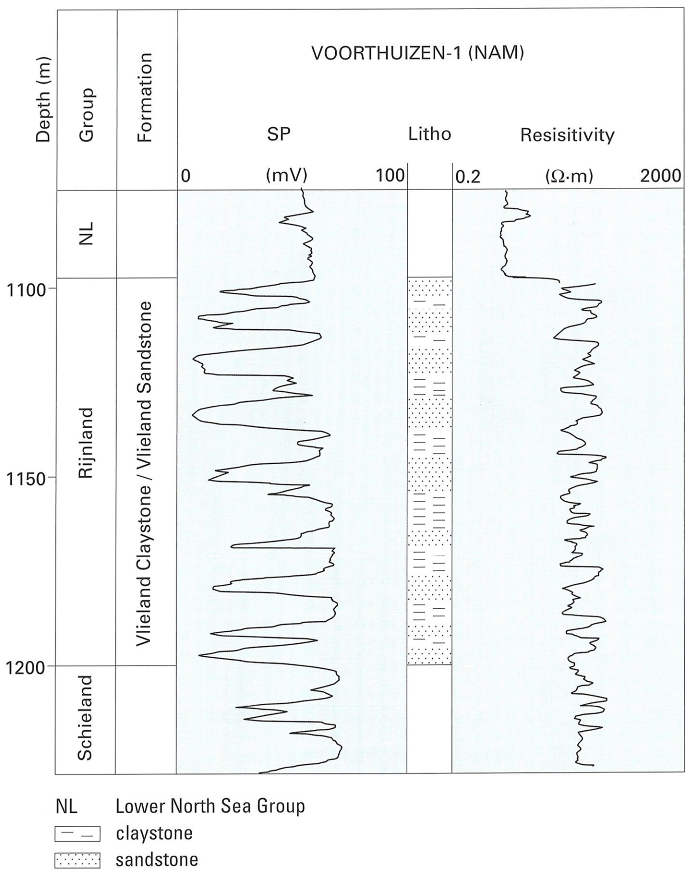
10.1.1 Vlieland subgroup

The Vlieland subgroup is only present in a small part of the map sheet area: in the Voorthuizen Trough and along the north-eastern margin of Maasbommel High (fig. 10.4). The subgroup is overlain, either conformably or slightly disconformably, by the Holland Formation or unconformably by the North Sea Supergroup in the Voorthuizen Trough. Within the map sheet area, the subgroup was only encountered in well Voorthuizen-1 (fig. 10.2), where a thickness of 100 m was penetrated. The absence of the subgroup in the Central Netherlands Basin is due to basin inversion and erosion during the Late Cretaceous and the Early Tertiary. West of the map sheet area, the subgroup is subdivided into the Vlieland Sandstone and the Vlieland Claystone Formations. In well Voorthuizen-1, the Early-Cretaceous strata consist of an alternation of sandstone and claystone and further subdivision is not possible. The sandstones consist of pale grey, predominantly very fine-grained, moderately well sorted sands. Palynological analysis has not clarified the exact age of the sediments because the palynoflora in the cores was very sparse and analysed cuttings contained a lot of Tertiary cavings (*NITG-TNO, 1999*). Just west of the map sheet area in the West Netherlands Basin, analysis of samples from the Vlieland subgroup yielded a Valanginian to Barremian age (Rijks Geologische Dienst, 1993).

10.1.2 Holland Formation

The Holland Formation, of Aptian to possibly Early Cenomanian age, consists predominantly of grey and red-brown marls and claystones. The formation is subdivided into the Lower Holland Marl, the

Figure 10.2 Stratigraphic subdivision and log characteristics of the Vlieland subgroup in well Voorthuizen-1.

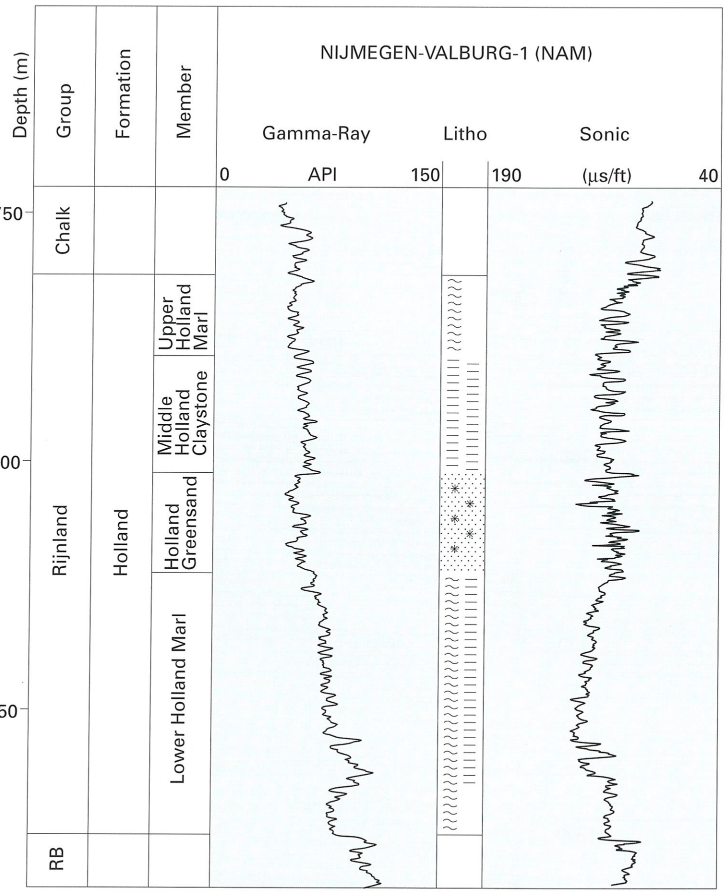


Holland Greensand, the Middle Holland Claystone and the Upper Holland Claystone Members (fig. 10.3). The Holland Formation conformably overlies the Vlieland subgroup or unconformably overlies either the Limburg, Upper Rotliegend, or Zechstein Group, or the Lower and Upper Germanic Trias Groups or the Altena Group and is conformably overlain by the Chalk Group or unconformably by the North Sea Supergroup (Map 18). The formation is present in the north-eastern and south-western parts of the map sheet area (fig. 10.4). Its thickness exceeds 300 m in the north-east, whereas it is approximately 400 m in the south-west.

The *Lower Holland Marl Member,* of Aptian age, consists of grey, sometimes, red, brown or yellowish marly claystone. The member's thickness exceeds 60 m in south-western part of the map sheet area.

The *Holland Greensand Member,* of Late Aptian to Early Albian age, consists of an alternation of dark, silty and sandy clayey and glauconitic sands (greensands) with intercalated limestone beds. The unit overlies the Lower Holland Marl Member and is overlain by the Middle Holland Claystone Member. The

Figure 10.3 Stratigraphic subdivision and log characteristics of the Holland Formation in well Nijmegen-Valburg-1.



RB Lower Germanic Trias Group
sandstone
marl
claystone
glauconite

member is only present in the south-western part of the map sheet area, where its thickness is approximately 20 m.

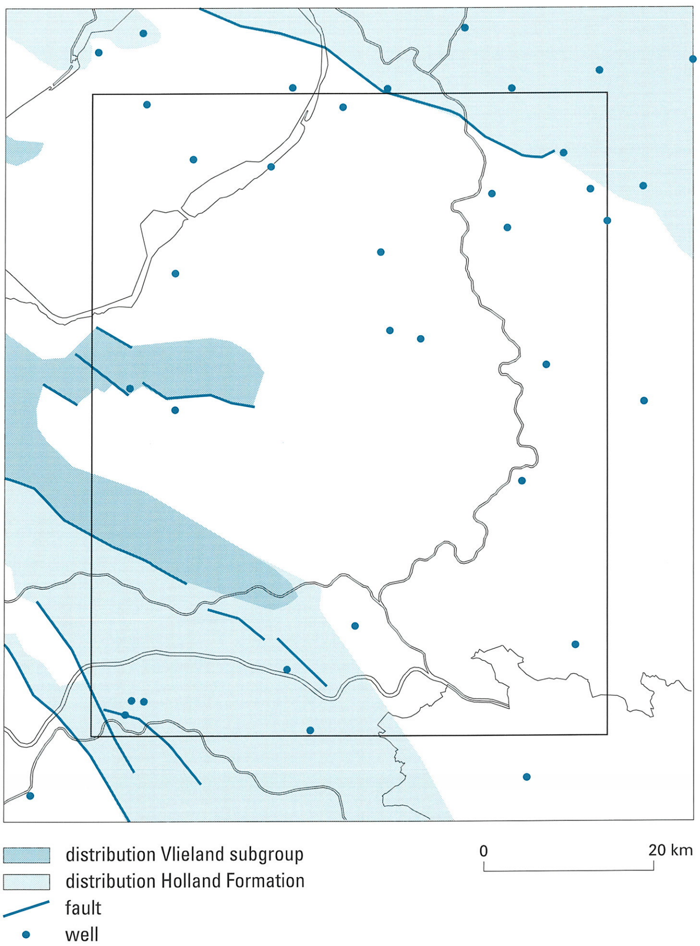
The *Middle Holland Claystone Member*, of Early to Middle Albian age, consists of grey, marly, clays. The clay content is higher than that of the underlying and overlying members. Both in the north-eastern and in the south-western parts of the map sheet area, the member can be several tens of metres thick.

The *Upper Holland Marl Member*, of Middle Albian to probably earliest Cenomanian age, consists of pale grey, and locally variegated, marly and silty claystones. The top part is frequently paler in colour. The member is characterised by a reduction in clay content from the base upwards towards the top. The member overlies the Middle Holland Claystone Member and is unconformably overlain by either the Chalk Group or the North Sea Supergroup. The maximum thickness is 100 m in the north-eastern part of the map sheet area and on the former Maasbommel High.

10.2 Sedimentary development and palaeogeography

A large-scale transgression heralded the onset of a long period of marine deposition. The deposits of the Vlieland subgroup are represented in the map sheet area by shallow marine sediments, in particular

Figure 10.4 Map showing the areal distribution of the Vlieland subgroup and the Holland Formation.



transgressive and near-coastal deposits. The Texel-IJsselmeer High, the Maasbommel High and the Dalfsen High supplied sediment for the deposits of the Vlieland subgroup.

During deposition of the Holland Formation, these highs were increasingly flooded by the sea and clayey marls and clays were deposited in the basins (Lower Holland Marl Member and Middle Holland Claystone Member). Along the edge of and on top of the former Maasbommel High, glauconitic sand, the Holland Greensand, was deposited at the same time in a shallow marine environment. Deposition of the Upper Holland Marl Member started when the Albian transgression flooded large parts of Western Europe (Crittenden, 1987). The highs in and around the map sheet area were completely covered by the sea, putting an end to the supply of clastic material.

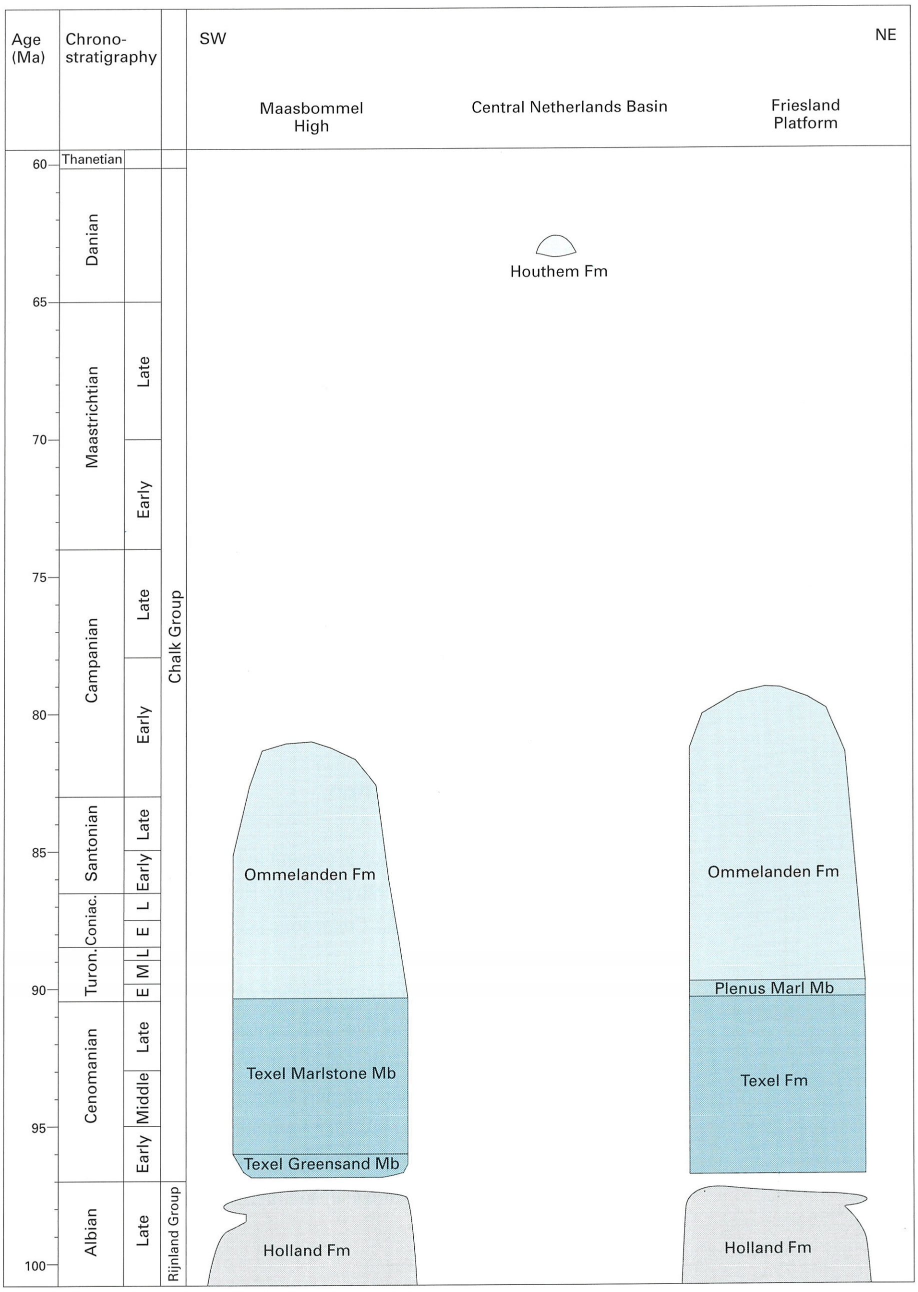
11 Chalk Group

11.1 Stratigraphy

The Chalk Group (fig. 11.1), of Cenomanian to Danian age, consists of stacked, well-cemented, light-coloured, fine-grained chalks and marly limestones. A characteristic feature of these sediments is, that the main constituents are calcareous skeletons of planktonic and benthonic organisms with very little terrigenous material (Van Adrichem Boogaert & Kouwe, 1993-1997).

Chalk sediments are present in the north-eastern and south-western parts of the map sheet area. In the north-east, the depth of the base of group ranges from 700 to 1600 m. In the south-west, the maximum

Figure 11.1 Stratigraphy of the Chalk Group.



depth of the base is 2500 m. Owing to inversion and erosion of the Central Netherlands Basin, the Chalk Group is missing in most of the map sheet area. The group's thickness within this map sheet area exceeds 2000 m on the Maasbommel High and over 800 m in the north-east (Map 13).

The Chalk Group is subdivided into the Texel and the Ommelanden Formations (fig. 11.2). The Houthem Formation is found locally in the Central Netherlands Basin (fig. 11.3 & 11.4) and to the south-east of the map sheet area in Germany (fig. 11.4), where the formation unconformably overlies the Altena Group (well Emmerich-1; Elberskirch & Wolburg, 1962).

The group conformably or disconformably overlies the Holland Formation or unconformably overlies either the Upper Germanic Trias or Altena Group. The Chalk Group is unconformably overlain by the clastic sediments of the North Sea Supergroup. Where the Houthem Formation is present, the North Sea Supergroup disconformably overlies the Chalk Group. The group's sedimentary succession is illustrated by wells Maasbommel-1 and Hessum-1 (fig. 11.2). The age of the group within the map sheet area is Cenomanian up to and including Campanian; in the centre of the map sheet area and in the south-east, chalk sediments of a Danian age have been encountered.

11.1.1 Texel Formation

The Texel Formation, of Cenomanian to possibly earliest Turonian age, is present in the north-east and the south-west of the map sheet area. The formation is subdivided into the Texel Greensand, the Texel Marlstone and the Plenus Marl Members. The formation's thickness is approximately 80 m.

The *Texel Greensand Member*, of Cenomanian age, consists of glauconitic sands and is only present on the Maasbommel High. Its thickness is approximately 12 m.

The lower 10-20 metres of the *Texel Marlstone Member*, of Cenomanian age, consist of a alternating white marls and limestone beds, while above that, it consists solely of limestone beds.

The *Plenus Marl Member*, of latest Cenomanian to possibly earliest Turonian age, consists of a calcareous, dark-coloured, laminated claystone, producing a very characteristic peak on gamma-ray and sonic logs. The member is generally 1 to 2 m thick.

11.1.2 Ommelanden Formation

The Ommelanden Formation is present in the north-east and south-west of the map sheet area. The formation is not subdivided into members. However, log correlation, supported by age dating, enables identification of the various Cretaceous stages (fig. 11.2).

The lower part of the formation consists of massive limestones of a Turonian age, succeeded by more marly sequences of a Coniacian and Santonian age. This is overlain by a more calcareous sequence of Campanian age, of which the lower part consists of calcareous sandstones, which grade upward into massive limestones containing numerous chert nodules. On seismic, more unconformities have been identified within the Ommelanden Formation in the north-east on the former Dalfsen High in the vicinity of the Central Netherlands Basin. On the basis of well calibration these unconformities have been placed in Santonian to Early Campanian sediments (NITG-TNO, 1998).

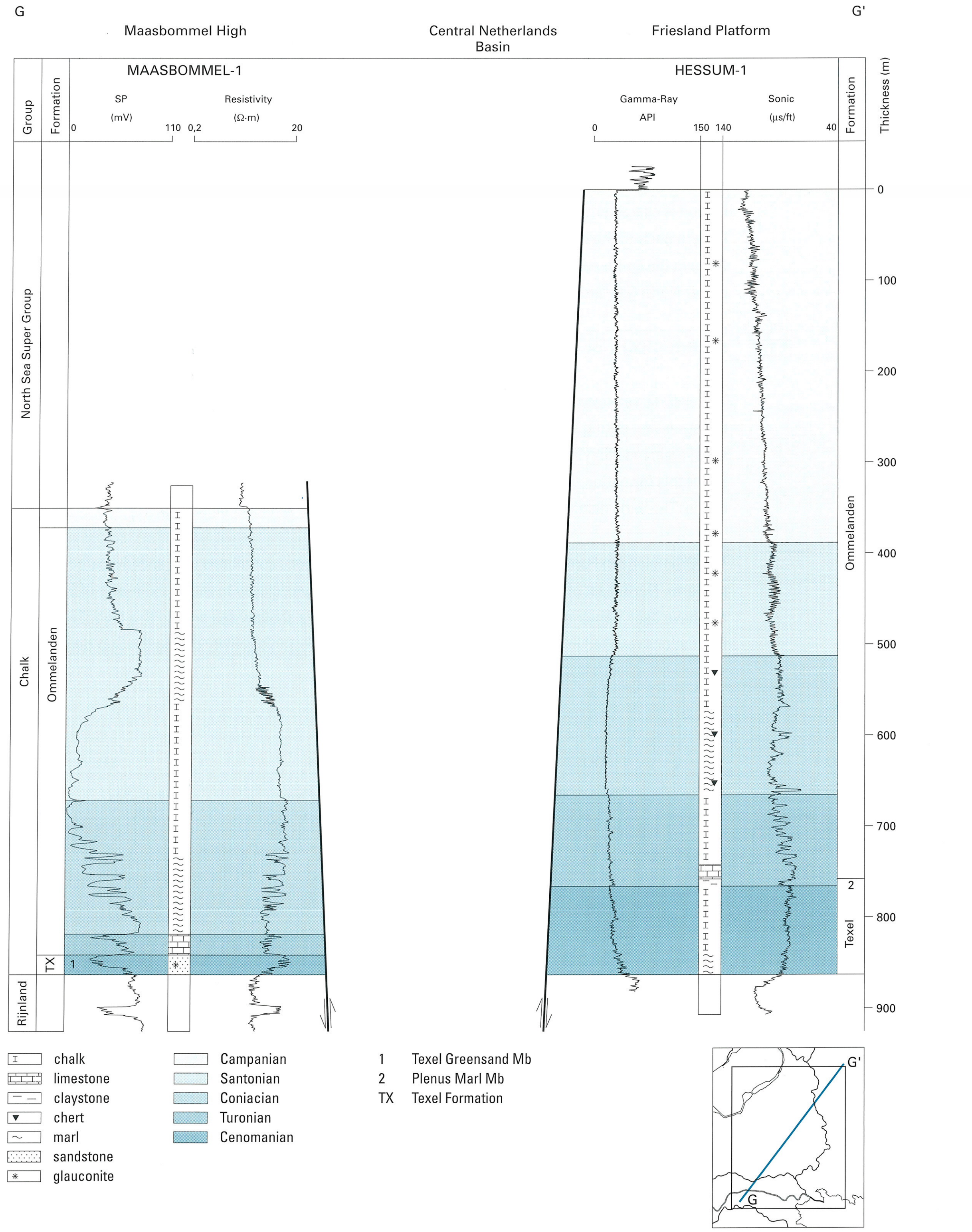


Figure 11.2 Stratigraphic correlation of the Chalk Group along line G-G′ between wells Maasbommel-1 and Hessum-1. Reference level is base Chalk Group.

11.1.3 Houthem Formation

The Houthem Formation, of Danian age, has not been mapped on seismic because of the formation's limited thickness. Depths and thickness data at the well locations are shown on Maps 12 and 13. The sediments' areal distribution shown in figure 11.4 is also based on well data (fig. 11.3; *TNO-NITG, 2002b).*

The formation consists of soft, pale-grey to pale-yellow, fine- to coarse-grained limestones. The formation contains limestone concretions, hardgrounds and fossil debris horizons. The lower part of the formation is characterised by the presence of glauconite. The formation is present in the central and south-eastern parts of the map sheet area, where it unconformably overlies the Upper Germanic Trias Group, while in the south-east it overlies the Altena Group. The formation is disconformably overlain by the Lower North Sea Group. The maximum thickness is 25 m.

11.2 Sedimentary development and palaeogeography

The eustatic sea-level rise, which started during deposition of Rijnland Group, developed into a global transgression during deposition of the Chalk Group. The coastline shifted ever more south of the map sheet area, resulting in an increased carbonate content in the Texel Formation. The Plenus Marl, at the top of this formation, reflects a period during which anoxic conditions in the basins prevailed worldwide. The wide distribution of this unit indicates a maximum sea-level highstand.

The Ommelanden Formation was deposited under low-energetic conditions on a shallow carbonate platform. North-east of the former Maasbommel High, however, clayey to marly sediments of Santonian age have been penetrated in wells, implying the presence of a shallow sea around this high. Sea-level fluctuations resulted in variations in marl and clay content. Tectonic activity during the Sub-Hercynian

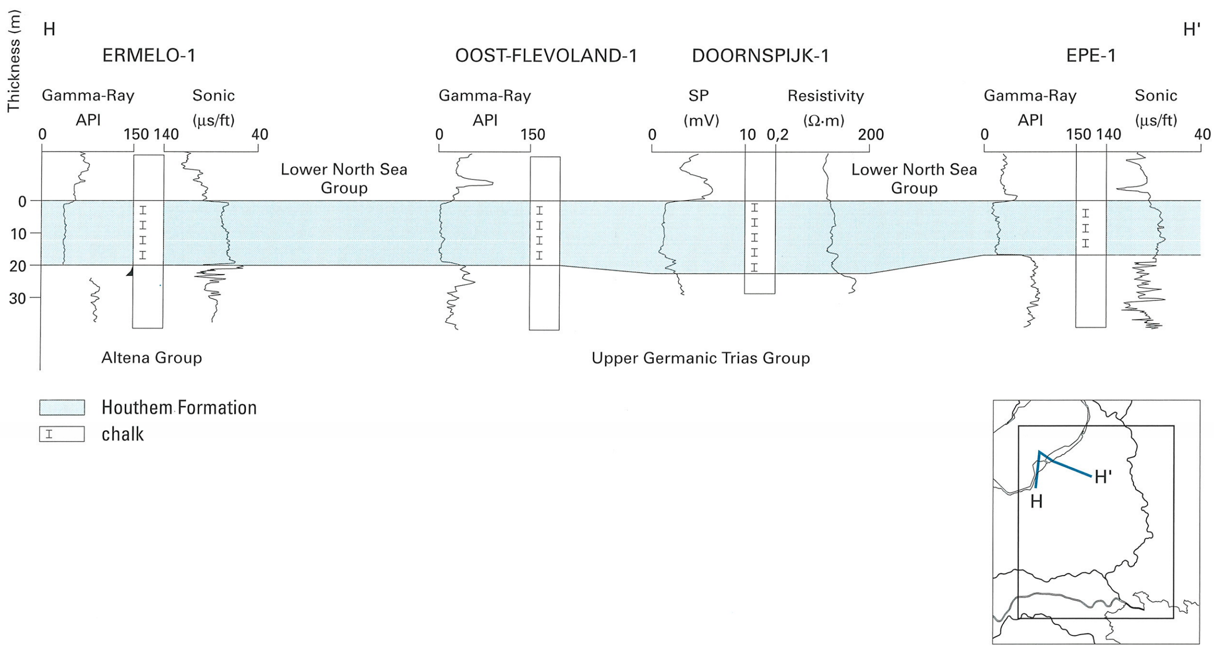


Figure 11.3 Stratigraphic correlation of the Houthem Formation along line H-H' between wells Ermelo-1, Oost-Flevoland-1, Doornspijk-1 and Epe-1-1. Reference level is base Lower North Sea Group.

phase is largely responsible for the present-day areal distribution and has caused pronounced subsidence of the former Lower Cretaceous highs.

During the Late Campanian to Danian, the sea gradually invaded the inverted basins again, resulting in post-inversion deposition of the Ommelanden and Houthem Formations. No deposits of Late Campanian to Maastrichtian age have been encountered in the former Central Nederlands Basin in the map sheet area, not even underneath the Houthem Formation, which implies non-deposition rather than erosion. Elsewhere in the map sheet area, the post-inversion sediments are missing owing to erosion during the Laramide phase.

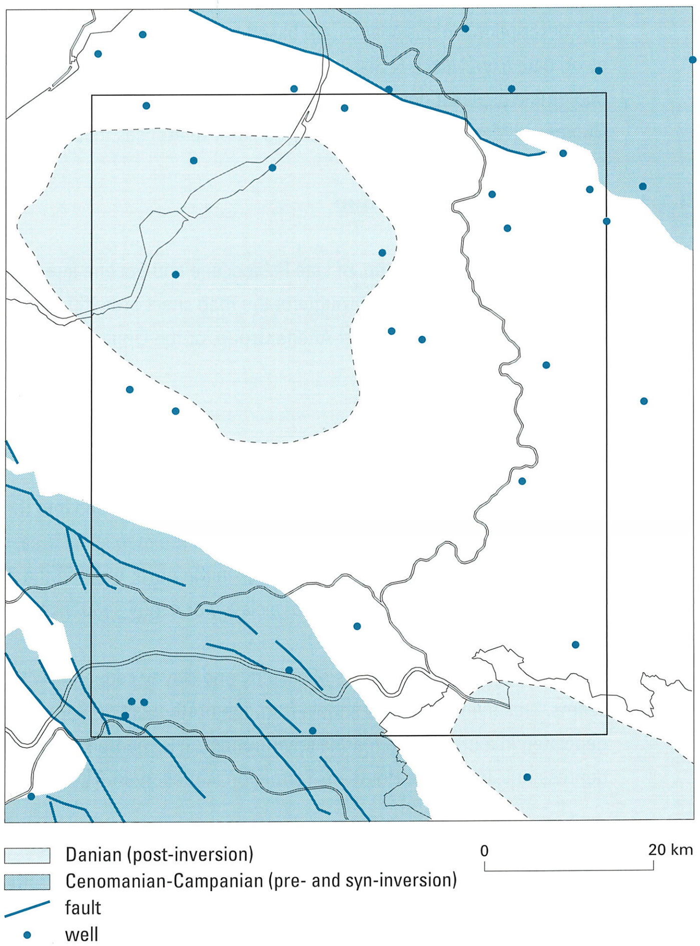


Figure 11.4 Map showing the areal distribution of the Chalk Group and the areal distribution of the Houthem Formation.

12 North Sea Supergroup

12.1 Stratigraphy

The North Sea Supergroup, of Late Palaeocene to Holocene age, is subdivided into the Lower, Middle and Upper North Sea Groups (fig. 12.1). The sediments consist virtually entirely of marine sands and clays. The boundaries between the three groups are marked by unconformities, but additional unconformities also occur within the groups. The North Sea Supergroup disconformably or unconformably overlies the Chalk Group, or unconformably overlies older lithostratigraphic units such as the Rijnland, Schieland and Niedersachsen Groups, the Altena and Lower and Upper Germanic Trias Groups, and the Zechstein, Upper Rotliegend and Limburg Groups.

The three groups of the North Sea Supergroup are present throughout the area, and their depths range from 400 m in the south to over 1500 m in the Zuiderzee Low (Map 14).

The descriptions in this chapter are based on log interpretation (figs 12.2 & 12.3) and on seismic, as well as on data from Letsch & Sissingh (1983), Zagwijn (1989), Van Adrichem Boogaert & Kouwe (1993-1997), and on the explanations to the map sheet areas (Rijks Geologische Dienst, 1977 & 1984) of the Geological Map of the Netherlands. The latter references focus on the youngest sediments.

12.1.1 Lower North Sea Group

The Lower North Sea Group, of Late Palaeocene and Eocene age, consists of the Landen and Dongen Formations, and is present throughout the map sheet area (fig. 12.4). The deposits unconformably overlie either the Chalk, Rijnland, or Altena Group, or the Upper and Lower Germanic Trias Groups, or the Zechstein or Limburg Group.

12.1.1.1 Landen Formation

The Landen Formation, of Late Palaeocene age, is subdivided into the Swalmen, Heers, Gelinden, and Landen Clay Members and is present in most of the map sheet area, with the exception of the Friesland Platform. The formation is up to 70 m thick in the north-west. In the Zuiderzee Low, where the formation is most complete, its base consists of a clayey or sandy sequence, overlain by marl and clay.

The *Swalmen Member* consists of a sandy and clayey sequence with a few intercalated brown-coal seams. This member is only known from the north-west of the map sheet area. The sediments were deposited in a brackish to marine environment. The member is encountered only locally in the same depressions, where the Houthem Formation is preserved. The maximum thickness is 10 m.

The *Heers Member* consists of a fine-grained, glauconitic sand, which can be considered as the transgressive base of the formation. The member's thickness ranges from 10 tot 25 m and the unit is only present in the western part of the map sheet area.

The *Gelinden Member* consists of grey-white to yellow-brown, clayey marl containing yellow concretions. Its base is usually formed by a dark-green, marly clay. The member's areal distribution is limited to the south-western part of the map sheet area and the Zuiderzee Low. The thickness ranges from 5 to 25 m.

The *Landen Clay Member* consists of a green, silty clay. It is present throughout the map sheet area, with the exception of the Friesland Platform, and ranges in thickness from 15 to 95 m.

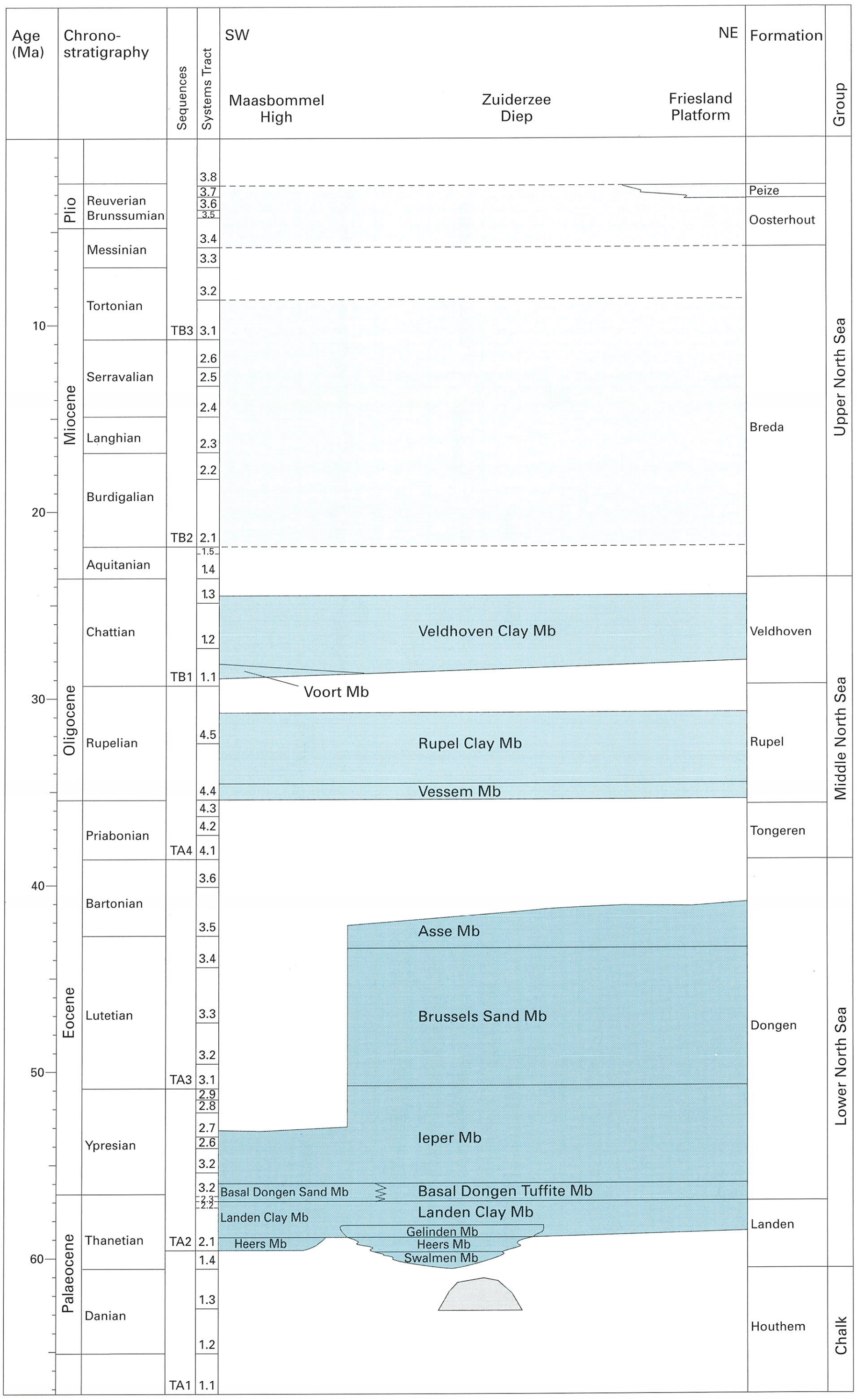
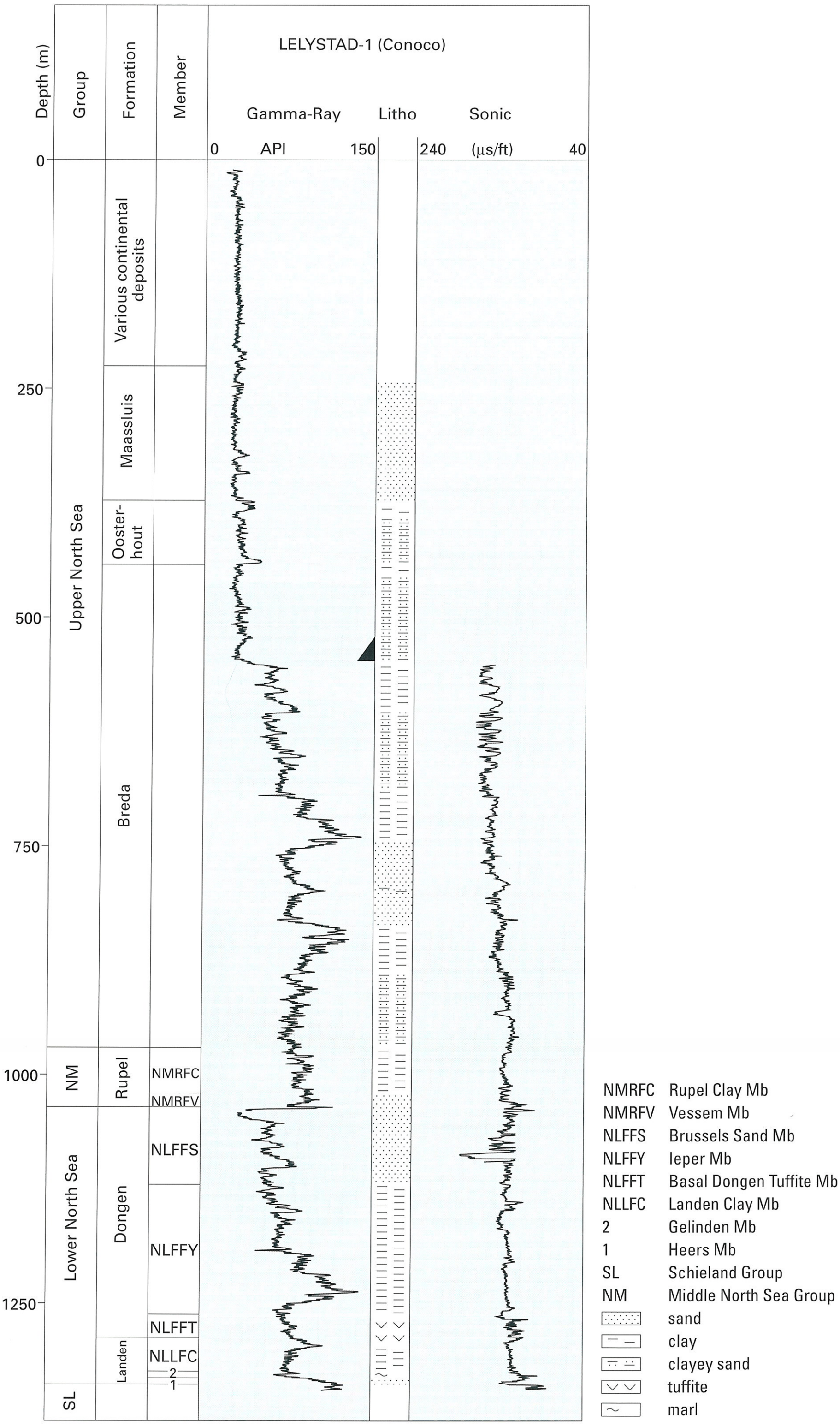


Figure 12.1 Stratigraphy of the North Sea Supergroup. The subdivision into sequences is based on Haq et al., 1988.

Figure 12.2 Stratigraphic subdivision and log characteristics of the North Sea Supergroup in well Lelystad-1.



12.1.1.2 Dongen Formation

The Dongen Formation, of Eocene age, is subdivided into the Basal Dongen Sand or Basal Dongen Tuffite, the Ieper, the Brussels Sand and the Asse Members. The formation is present throughout the map sheet area, except on the north-eastern edge of the Maasbommel High. The Dongen Formation conformably overlies the Landen Formation and is unconformably overlain by the Middle North Sea Group. The formation's thickness is largely controlled by tectonic movements and erosion, which took place during the Pyrenean and Savian phases. The thickness exceeds 250 m in the Zuiderzee Low.

The *Basal Dongen Sand Member*, of Early Eocene age, consists of fine-grained, sometimes glauconitic sand. The member is only present in the Roer Valley Graben. The maximum thickness is 13 m.

The *Basal Dongen Tuffite Member*, of Early Eocene age, consists of thin, alternating layers of brown clay and volcanic ash. The member is present in the northern half of the map sheet area, and its thickness ranges from 5 to 40 m.

The *Ieper Member*, of Early Eocene age, consists of brown-grey and red-brown clay at the base, and sandy clay at the top, and may locally contain pyrite, shells, coalified plant remains, and benthonic foraminifers. The mostly stiff clays contain sandy and silty horizons. The upper part of the unit contains green-grey, glauconitic and marly sand intercalations. The member is present in most of the map sheet area and its thickness can exceed 100 m. In the southern part of the map sheet area, the member is reduced in thickness or completely missing, owing to erosion.

The *Brussels Sand Member*, of Middle Eocene age, consists of fine-grained, glauconitic and calcareous sands. The unit's thickness is up to 80 m in the Zuiderzee Low.

The *Asse Member*, of Late Eocene age, is a highly plastic, green-grey to blue-grey, calcareous clay. The member is up to 50 m thick, and is only present in the northern half of the map sheet area.

12.1.2 Middle North Sea Group

The Middle North Sea Group, of Oligocene age, is subdivided into the Rupel and Veldhoven Formations. The two formations consist of fine-grained sands and clays. The group unconformably overlies the Lower North Sea Group and is, also unconformably, overlain by the Upper North Sea Group. The maximum thickness was penetrated in a well near Apeldoorn, and is approximately 300 m (fig. 12.5).

12.1.2.1 Rupel Formation

The Rupel Formation, of Early Oligocene age, is subdivided into the Vessem and Rupel Clay Members. It is present throughout the map sheet area and can be up to approximately 190 m thick.

The *Vessem Member* consists of a number of fine-grained, glauconitic sands, which can be considered as the transgressive base of the formation. The sands exhibit several coarsening-upward sequences. The member's maximum thickness ranges from a few metres to 30 m.

The overlying *Rupel Clay Member* consists of alternating silty and sandy beds. The member is locally rich in pyrite. The member's maximum thickness is 180 m.

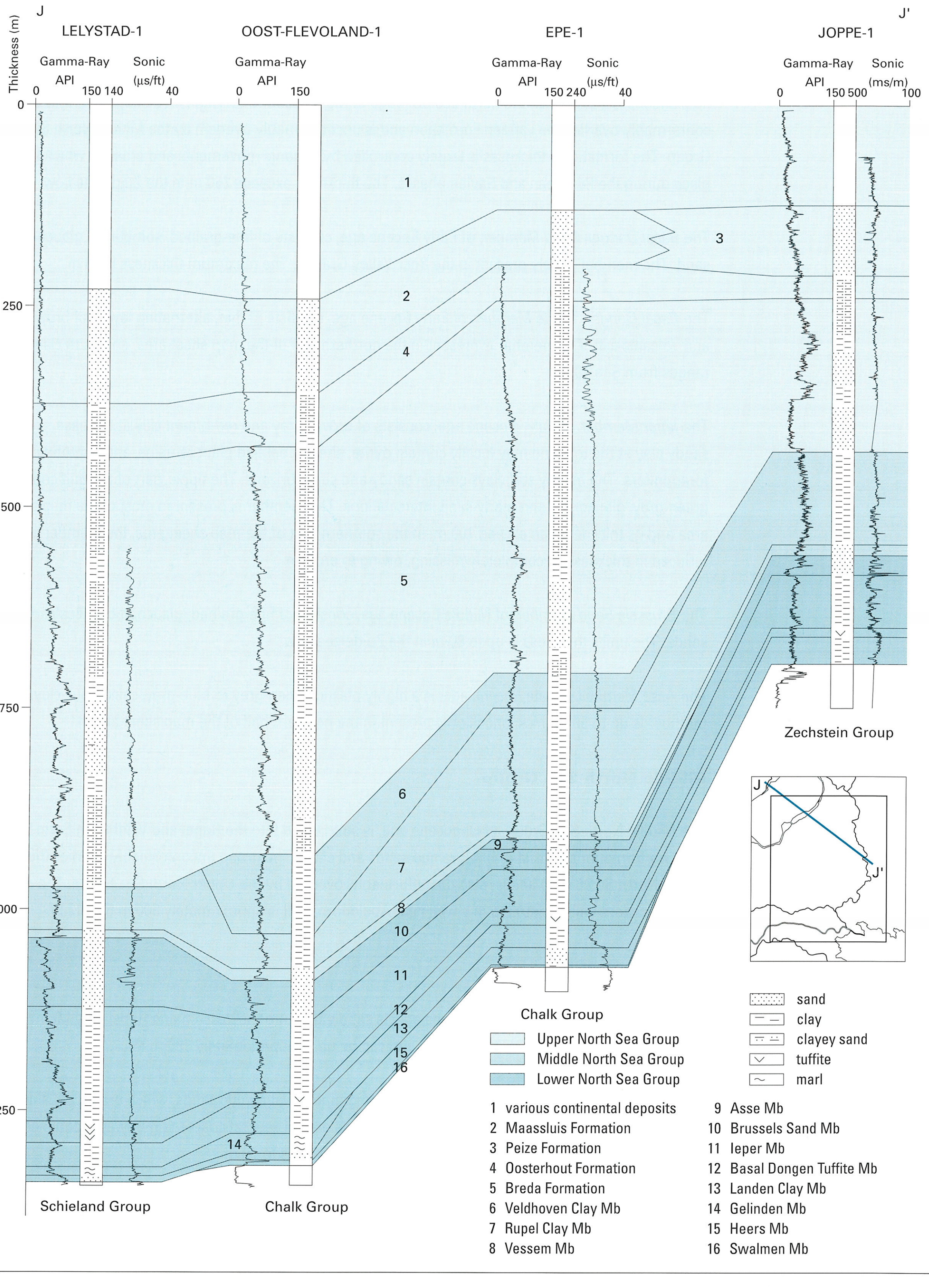


Figure 12.3 Stratigraphic correlation of the North Sea Supergroup along line I-I' between wells Lelystad-1, Oost-Flevoland-1, Epe-1 and Joppe-1.

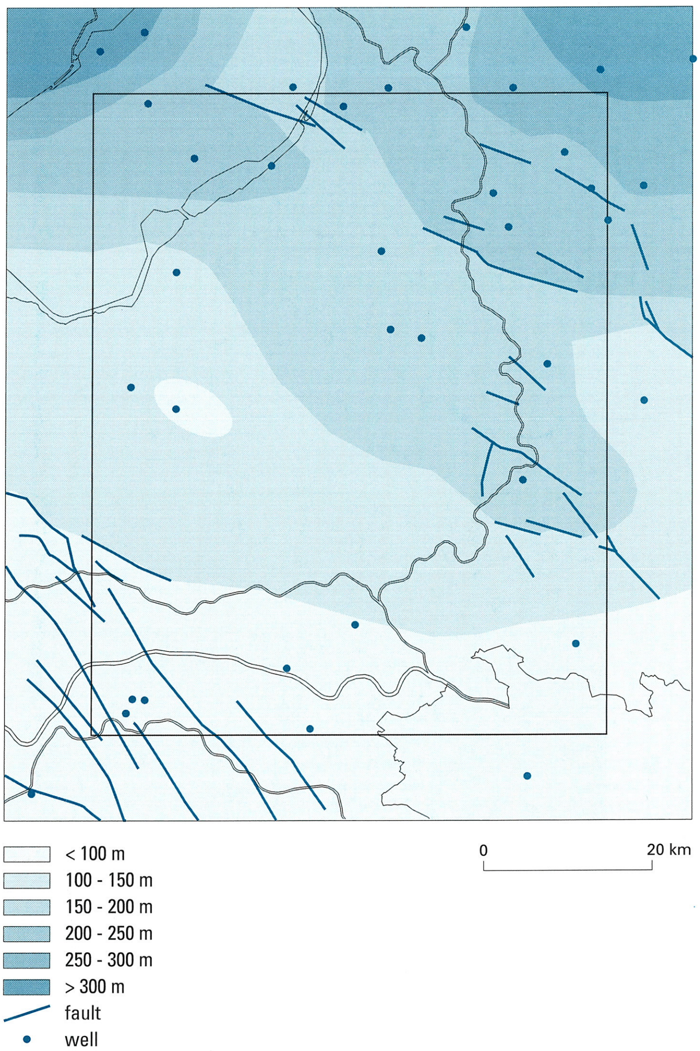
12.1.2.2 Veldhoven Formation

The Veldhoven Formation, of Late Oligocene age, is subdivided into the Voort and Veldhoven Members. The formation is present throughout the map sheet area, with the exception of the north-eastern part. The formation is thickest in the southern part of the map sheet area, where it can be up to 150 m thick, while in the Zuiderzee Low, the formation's thickness is 120 m.

The *Voort Member* comprises a sequence of coarsening-upwards sandy units. It is only present locally, in particular in the southern part of the map sheet area, where it can be up to more than 70 m thick. The unit wedges out towards the north, where it is locally absent.

The *Veldhoven Clay Member* consists predominantly of green-grey silty clays. Its maximum thickness is over 140 m in the south of the map sheet area. In the Zuiderzee Low, thicknesses of 120 m have been encountered in wells.

Figure 12.4 Isopach map of the Lower North Sea Group, based on well data.



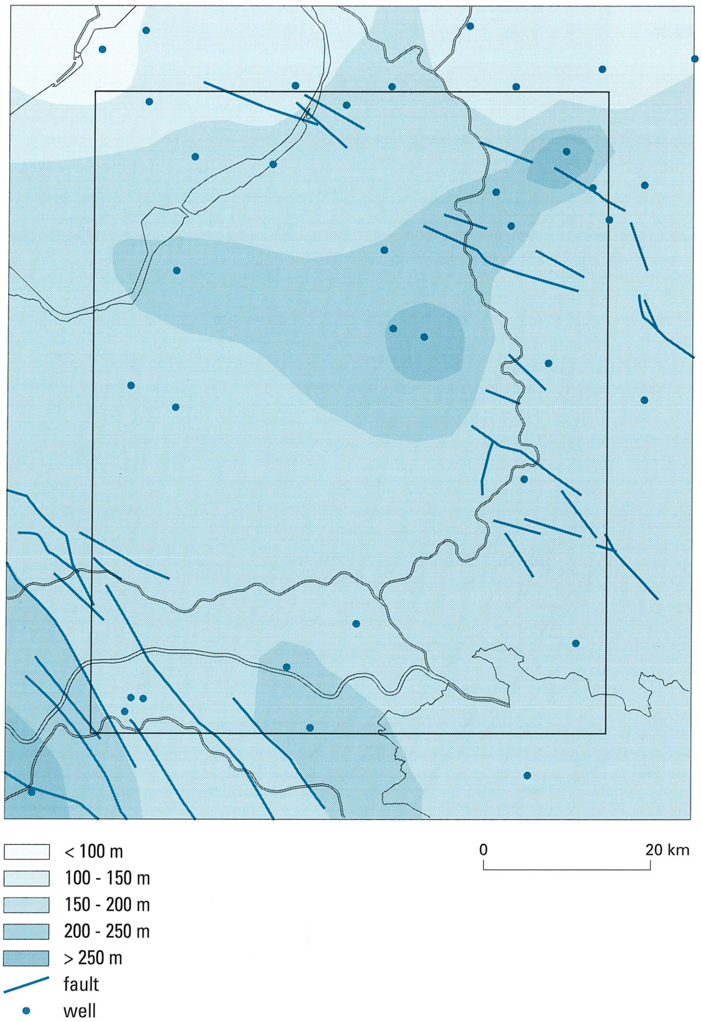
12.1.3 Upper North Sea Group

The Upper North Sea Group, of Miocene to Quaternary age, is, in the map sheet area, subdivided into the Breda, Oosterhout, Peize, Kieseloolite, and Maassluis Formations and other Quaternary deposits. The group unconformably overlies either the Middle North Sea Group, the Lower North Sea Group or older deposits. The depth of the base of the group, and the group's thickness, vary greatly. In the Zuiderzee Low, the thickness exceeds 1000 m; in the east and the south of the map sheet area, the thickness can be 300 m (Map 15).

12.1.3.1 Breda Formation

The Breda Formation, of Miocene age, was deposited throughout the map sheet area, and consists of glauconitic sandy clays, clays and sands. The sandy clays at the base of the formation produce a relatively high gamma-ray log response (figs 12.02 & 12.03). Towards the top, the glauconite content decreases while the sand content increases. In the Zuiderzee Low, the formation is 600 m thick, whereas in the north-eastern part of the map sheet area, its thickness is less than 100 m. These differences in thickness are due to differential subsidence of the basin in the Zuiderzee Low area.

Figure 12.5 Isopach map of the Middle North Sea Group, based on well data.



12.1.3.2 Oosterhout Formation

The Oosterhout Formation, of Late Miocene to Pliocene age, is a predominantly sandy, glauconitic formation. It has not been deposited in the south-eastern part of the map sheet area. In the north-eastern part of the map sheet area, the formation grades laterally into the continental deposit of the Peize Formation. In the Zuiderzee Low, thicknesses of 300 m have been encountered.

12.1.3.3 Peize Formation

The Peize Formation, of Pliocene to Early Pleistocene age, is present in the north and centre of the map sheet area. The formation consists predominantly of sands. Its lower part consists of well-sorted, fine-grained sands, but upwards, the sorting decreases and the grain size increases. The formation was deposited in the eastern part of the map sheet area as lateral equivalents of the Oosterhout Formation and younger marine deposits. The thickness can exceed 100 m.

12.1.3.4. Kieseloolite Formation

The Kieseloolite Formation, of Late Miocene and Pliocene age, is present in the south-east of the map sheet area, and consists of sands and gravels with intercalated clay and brown-coal beds. The thickness is approximately 20 m.

12.1.3.5 Maassluis Formation

The Maassluis Formation, of Pleistocene age, consists of glauconite-poor, fine-grained to coarse-grained sands with shell fragments and locally intercalations of sandy clays and clay lenses. It is only present in the western and northern parts of the map sheet area and its maximum thickness exceeds 300 m in the Zuiderzee Low.

The other Quaternary deposits include clays, sands and gravels that were deposited under predominantly continental, sometimes glacial conditions. They are identified by their mineral content and grain size (Rijks Geologische Dienst, 1977 & 1984). Their thickness increases north-westward and the maximum thickness of approximately 250 m is encountered in the Zuiderzee Low.

12.2 Sedimentary development and palaeogeography

During deposition of the North Sea Supergroup, the maps sheet area was situated in the southern sector of the North Sea Basin. As a result of this location, the sedimentation pattern was largely controlled by tectonic movements and eustatic sea-level fluctuations. Deposition in the map sheet area was in particular influenced by the rapid subsidence of the Roer Valley Graben and the Zuiderzee Low.

After the Laramide phase, a period of predominantly clastic deposition in a marine environment started. The transgression following the Laramide phase resulted in deposition of the marine sediments of the Landen Formation during the Late Palaeocene. The continuing transgression resulted in the subsequent deposition of the similarly marine sands, clays and marls of the Dongen Formation. Erosion during the Pyrenean tectonic phase at the end of the Eocene, resulted, in the map sheet area, in the removal of the Eocene deposits around and on the Maasbommel High. The Pyrenean phase did not cause any erosion of Eocene deposits elsewhere in the map sheet area.

The deposits of the Rupel Formation reflect resumption of sedimentation in the map sheet area, during the Early Oligocene. Conditions were initially shallow-marine, and later on, fully marine. There are no indications of differential subsidence of the area, and the homogenous character of the Rupel Clay indicates deposition in an extensive marine basin. During the Late Oligocene, the Veldhoven Formation was deposited in a shallow-marine environment.

At the time of the transition from the Oligocene to the Miocene, regional uplift resumed with the Savian phase. Combined with a sea-level lowstand, this resulted in regional erosion during the Early Miocene, truncating the Late Oligocene sediments in the central and eastern parts of the map sheet area. In the Zuiderzee Low, sediments of the Breda Formation were encountered that are obviously part of a very large sediment body, which, being fed by rivers, prograded westward. To the north of the map sheet area, progradation continued into the Pliocene, and in the northern offshore into the Pleistocene (Bijlsma, 1981; Zagwijn, 1989).

The continuing progradation during the Pliocene resulted in a westward shift of the coastline. In the eastern part of the map sheet area, the continental, fluviatile sediments of the Peize Formation were deposited, which interfinger here with the marine deposits of the Oosterhout Formation and with younger marine deposits. In the south-east, the Peize Formation interfingers with the Kieseloolite Formation. The Rhenish Massive was the provenance area of the sediments of the Kieseloolite Formation, which were transported by the rivers Rhine and Meuse. During the Quaternary, when the Maassluis Formation was deposited, marine conditions still prevailed in the western part of the map sheet area; the later Quaternary deposits are, however, predominantly of a continental origin.

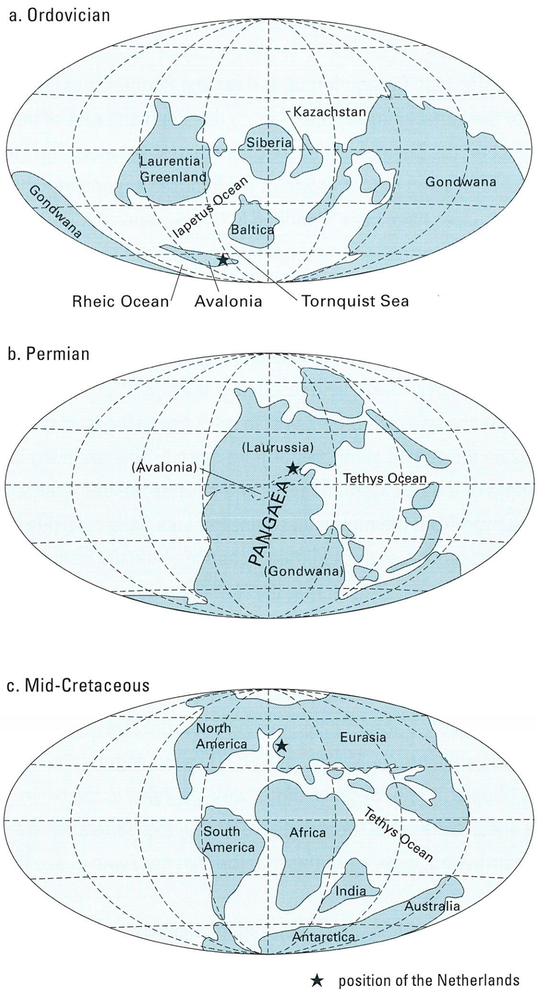
13 Geological history

13.1 Introduction

This chapter describes the geological history of the map sheet area, covering the period from the Carboniferous to the Quaternary. For details of the Quaternary in the map sheet area, please refer to the publications by Zagwijn (1989), and the "Toelichtingen bij de Geologische Kaart van Nederland 1:50.000 [Explanation to the Geological Map of the Netherlands scale 1:50 000], sheets Arnhem 40 East and Tiel 39 East and West (Rijks Geologische Dienst, 1977 and 1984). In the present chapter, however, the relationships between the earlier fault systems, the neotectonics and the Pleistocene glacial landforms, are examined in detail.

The geological history is described chronologically; period-by-period, using the different tectonic phases that affected the map sheet area and the surrounding areas as a framework (fig. 1.4). The Variscan Orogeny, in the Late Carboniferous, shaped the Variscan Mountain to the south-east of the map sheet area (Lorenz & Nicholls, 1976; Ziegler, 1990). During this tectonic phase, the broad outlines of the regional structural framework were put in place. The Late Triassic to earliest Cretaceous period was dominated by the Kimmerian extensional tectonic phases, which were related to the break-up of Pangaea (fig. 13.1) and shaped the major Mesozoic structural units, such as the Central Netherlands Basin. The Sub-Hercynian phase during the Late Cretaceous was characterised by a compressive stress field,

Figure 13.1 Locations of continents and oceans during the Ordovician, Permian and Middle Cretaceous (after Scotese, 1991; Scotese & McKerrow, 1990). The middle picture shows (between brackets) the names of the elements that made up Pangaea.



causing a brief inversion of the direction of movement of the major fault systems and structural elements. The Tertiary tectonic phases (Laramide, Pyrenean and Savian phases) were associated with different phases of the opening of the Atlantic Ocean and the Alpine Orogeny. The geology of the map sheet area was not only shaped by tectonics, but also by climate changes and the associated sea-level fluctuations (Haq et al., 1987).

Figure 13.2 shows the geographical position of the map sheet area in a regional context. The principal structural elements discussed in this chapter are indicated in fig. 3.1. The structural configuration of the map sheet area is illustrated by a SSW-NNE seismic section (fig. 13.5).

13.2 Basin development, sedimentation and tectonics

13.2.1 Carboniferous

During the Early Carboniferous, basin subsidence, which had started during the Devonian, continued. The rising sea level drastically reduced the influx of clastic material. To the north of the basin, an extensive carbonate platform formed, which presumably occupied the greater part of the map sheet area. A brief phase of extensional tectonics, the Bretonian phase, caused differential subsidence during the Early Carboniferous. This resulted in a number of places in more rapidly subsiding zones within the extensive carbonate platform (Ziegler, 1990).

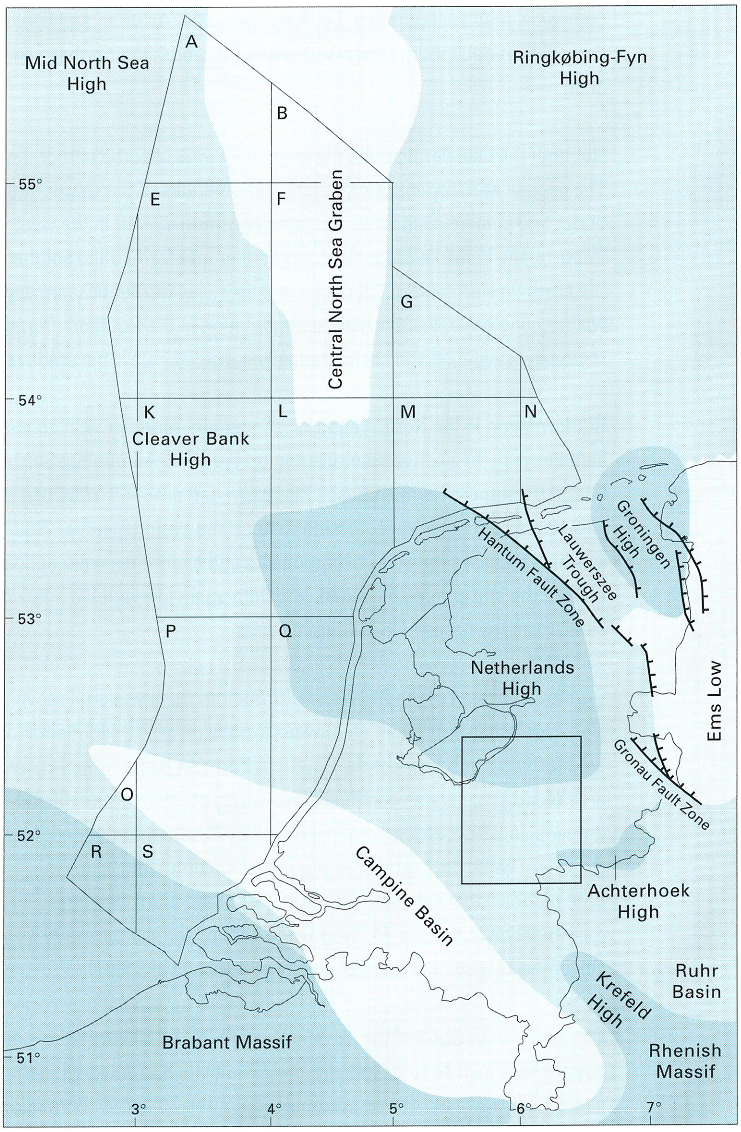
The history of the Late Carboniferous and earliest Permian was controlled by the Variscan Orogeny. The evolution of the Variscan mountain chain to the south and east of the present-day Netherlands had a significant effect on the geological history of the map sheet area. The Variscan Orogeny marks the closure of the Proto-Tethys and the formation of the Pangaea supercontinent (fig. 13.1; Ziegler, 1990). Three deformation-phases have been identified in this orogeny: the Sudetic, Asturian and Saalian tectonic phases, with the deformation front moving progressively further northward.

The Sudetic phase, at the beginning of the Late Carboniferous, reflects the collision between Gondwana (Africa and South America) and Laurasia (Europe, North America and Asia, see fig. 13.1b. The N-S-oriented, compressive, stress field resulted in the formation of a mountain chain running east-west across Europe: the Variscan Mountains. In response to the isostatic loading by this mountain chain, a foreland basin developed along its northern margin. This basin experienced rapid subsidence as from the beginning of the Late Carboniferous and became the depocentre for the huge quantities of erosion products derived from the mountain chain. The Late Carboniferous depositional environment displays a clear regressive tendency; the sediments change gradually from predominantly marine-influenced deltaic and pro-delta deposits during the Namurian, to paralic and finally fluvial deposits during the Westphalian. During the latest Westphalian A and the Westphalian B, river systems increasingly dominated deposition, and extensive peat deposits formed in the marshes in between the rivers. Subsidence in the southern part of the map sheet area was more pronounced than in the north and east, consequently, thicker peat sequences accumulated in the south (Drozdzewski, 1992, 1993). Episodic, ephemeral transgressions persisted into the Westphalian C. These transgressions are attributed to glacio-eustatic sea-level rises (Ziegler, 1990). Because of the very low relief in the basin, the transgressions rapidly flooded extensive areas. During the Westphalian C and D, the climate became drier because the area drifted gradually northward, away from the equator (Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996).

During the Asturian and Saalian deformation phases, the Variscan orogenic front shifted further northward (Lorentz & Nicholls, 1976). The deposits in the foreland basin were folded intensely and pushed northward over gently dipping thrust planes. The northern boundary of this zone of intense deformation is situated immediately to the south-east of the map sheet area (Geluk, 1997; NITG-TNO, 1998). During the Westphalian C, deformation began to affect the map sheet area, resulting in uplift of the southern and northern parts of the map sheet area (Bless et al., 1977; Van Tongeren, 1996). From the Early Westphalian C onwards, sedimentation was increasingly restricted to the central part of the map sheet area. During the Westphalian D, sediments must have been deposited elsewhere in this map sheet area as well, not just in the central part of it, but these sediments were probably removed again by erosion during the Saalian phase.

The Saalian deformation phase during the Stephanian and the earliest Permian is the final phase of the Variscan Orogeny. The NNW-SSE-oriented, compressive stress field was replaced by an E-W-oriented, extensional stress field during this phase. To the north of the Variscan Mountains, NW-SE-trending, predominantly dextral, strike-slip fault systems developed. In the map sheet area, transtensional fault movements resulted in uplift, tilting and erosion. The subcrop map of the Carboniferous (fig. 4.4) shows

Figure 13.2 Overview map showing the main structural elements in the Netherlands during the Late Carboniferous. The location of the map sheet area is outlined.



that erosion cut deepest in the northern and southern parts of the map sheet area, down to the Westphalian A deposits.

13.2.2 Permian

By the end of the Saalian tectonic phase in the Early Permian, an extensive landmass had formed. Intensive strike-slip deformation of this landmass was associated with widespread volcanic activity in, especially, the eastern part of the present-day Netherlands and in Germany, and caused severe deformation in other areas as well (Ziegler, 1990). By the end of the Early Permian, a combination of extensional stresses and cooling of these volcanic rocks led to the development of an extensive intra-cratonic continental basin: the Southern Permian Basin, in which the erosion products originating from the Variscan Mountains were deposited in a continental environment.

During most of the Permian, the map sheet area was located on the southern fringe of the basin. This long period was marked by major erosion of the Carboniferous deposits, which produced the present geological map configuration (fig. 4.4). During the Asturian and Saalian phases, erosion removed more than 1500 m of Limburg Group sediments from both the northern and southern parts of the map sheet area.

Not until the Late Permian did the map sheet area become part of the Southern Permian Basin (fig. 6.6). The aeolian and fluviatile sands and conglomerates of the Upper Rotliegend Group were deposited under arid climate conditions. Aeolian deposition started in the west, and gradually spread to the east (Map 1). The Variscan orogenic front more or less formed the southern limit of the depositional area. In the north-western part of the map-sheet area, aeolian sands were deposited (Slochteren Sandstone), as well as conglomerates. Because sedimentation in the Southern Permian Basin did not keep pace with regional subsidence, the basin gradually subsided below the sea level at that time (Glennie, 1986).

Rift formation in the North Atlantic/Arctic region, together with an eustatic sea-level rise led, during the Late Permian, to a connection opening up between the Barents Sea in the north and the, up to then continental, Southern Permian Basin. The basin had probably subsided below sea level by the time, thus allowing a very rapid transgression to flood the basin (Glennie, 1983, 1986). A large inland sea formed, in which cyclical sequences of carbonates and evaporites were deposited, because sometimes the influence of the arid climate prevailed, and then again the variable influx of Arctic seawater. Major transgressions mark the bases of the different cycles.

During deposition of the Z1 (Werra) Formation, transtensional movements, caused by the E-W extension, resulted in significant southward expansion of the sedimentation area. The resulting subsidence area formed a sub-basin of the Southern Permian Basin, which covered the entire map sheet area. The area of subsidence was composed of a series of relatively small pull-apart structures, grabens and half-grabens, in which, among other sediments, Z1 salt accumulated (Map 3, fig. 6.4a). North of the Raalte Boundary Fault, thick anhydrite sequences accumulated, since this area was part of the extensive anhydrite platform that extended far north-east of the map sheet area. The differential movements ceased during deposition of the Z1 (Werra) Formation; and the palaeo-relief was draped by the younger deposits of the Zechstein Group like a blanket (Geluk et al., 1997).

During the deposition of the Z2 (Stassfurt) to Z4 (Aller) Formations, the area of salt accumulation gradually shrank (fig. 6.4b to d). Initially, the Z2 salt still accumulated in the south-eastern part of the map sheet area. However, during accumulation of the Z3 and Z4 Formations, the area of salt accumulation was limited to the northern part of the map sheet area. At the same time, the southern part of the map sheet area became part of the fringe of the Southern Permian Basin where only clastic sediments were deposited. Moreover, deposition only took place during the initial transgressive stages. During the transgressions, normal marine conditions prevailed at the time of deposition of the Z1 (Werra) up to and including the Z3 (Leine) Formations, but the Z4 (Aller) Formation reflects a transition to continental depositional conditions. By the end of the Permian, the sedimentary environment changed; evaporites made way for lacustrine claystones and siltstones. The provenance area of these clastic sediments lay to the south. The Zechstein Upper Claystone Formation, which forms the transition to purely clastic sediments, disconformably overlies older deposits of the Zechstein Group.

13.2.3 Triassic

The Triassic was initially characterised by extremely uniform basin subsidence. The Southern Permian Basin persisted, and, therefore, it is often referred to as the Permo-Triassic Basin. Two phases of extensional tectonics changed the shape of the basin during the Triassic and also formed several NNE-SSW-trending elements, such as the Ems Low in the eastern part of the Netherlands, the *Off-Holland Low* just off the present-day coast of the Netherlands and the Central North Sea Graben (Ziegler, 1990). The Variscan Mountains situated to the south of the map sheet area, were the provenance area of the Triassic clastic sediments.

Sedimentation in the area initially took place in a lacustrine to playa environment, in a semi-arid climate. Uplift of the provenance areas of the sediments, in combination with water-level fluctuations in the basin, resulted in episodic progradation of river systems into the basin, depositing cyclic sequences of sand and clay/silt (Geluk & Röhling, 1997). During the Early-Triassic Hardegsen phase, several Variscan tectonic elements were reactivated. In the northern part of the map sheet area, a high developed: the Netherlands Swell. Here, a total of 300 m of sediment was eroded away. The erosion that marked the Hardegsen phase cut deeply into the underlying formations throughout the map sheet area. Owing to these movements, only the lowermost deposits of the Main Buntsandstein Subgroup have been preserved in the Roer Valley Graben (fig. 7.5).

The Hardegsen phase marked the onset of a long period of subsidence, lasting well into the Middle Keuper (Carnian). The Early Triassic structures subsided very evenly (Geluk et al., 1996), allowing the lacustrine deposits of the Solling Formation to cover the entire area. During the Middle Triassic, a connection with the Tethys Ocean opened up in the eastern part of the Permo-Triassic Basin. A eustatic sea-level rise (Vail et al., 1977) caused a slow transgression. The advancing transgression stagnated a number of times, and in these episodes, evaporites accumulated in the entire basin (Main Röt Evaporite, Upper Röt Evaporite and Muschelkalk Evaporite Members).

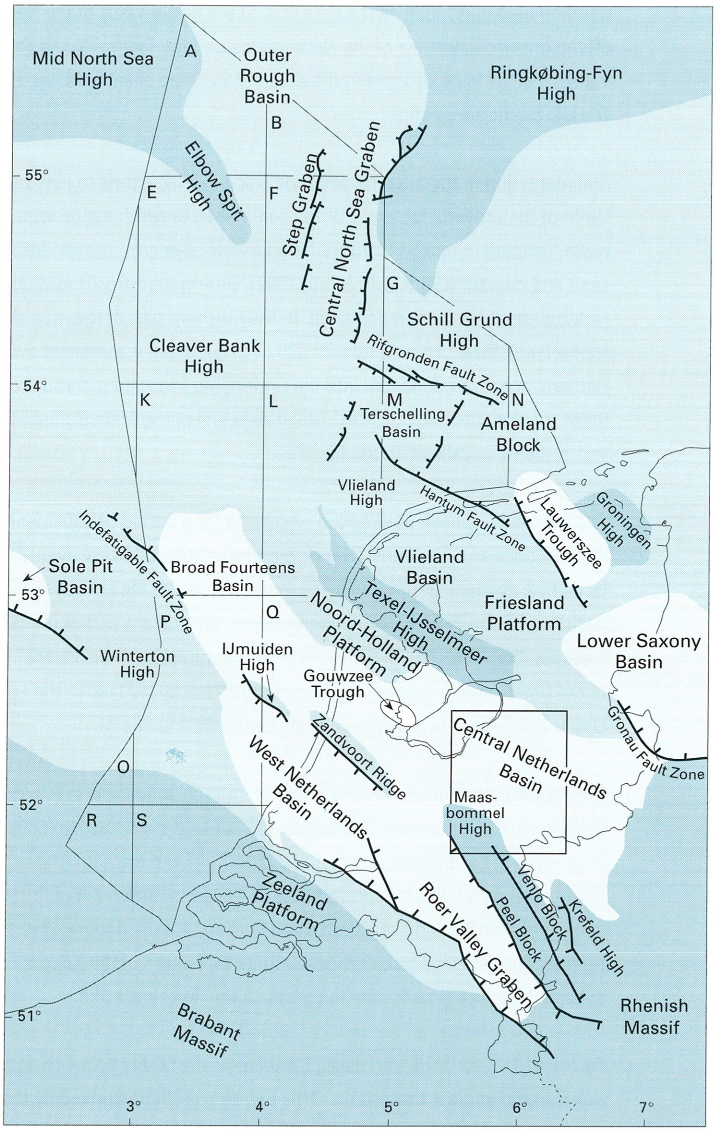
During the Late Anisian (Middle Triassic), marine conditions prevailed in the area. All around the map sheet area, the highs were flooded by the sea and the decreasing supply of clastic material allowed deposition of carbonates, marls and evaporites from the Late Anisian to the Ladinian (Muschelkalk Formation). Later erosion removed these deposits from most of the area. In the central part of the map sheet area, the Muschelkalk Formation was apparently deposited in a basin facies, with rock salt in the Middle Muschelkalk Marl Member. During deposition of the Keuper Formation, the area presumably subsided slightly slower than the areas to the north-east of it.

As from the Carnian (Late Triassic), a tectonically highly active period commenced which was to continue into the earliest Cretaceous. This period was characterised by the break-up of Pangaea and the onset of the opening of the Atlantic Ocean (Ziegler, 1990). This was manifested by four major extensional phases, the so-called Kimmerian phases, dominating the structural evolution of North-west Europe. For practical reasons, these phases have been related to major gaps in the stratigraphic record.

The first one, the Early Kimmerian tectonic phase, created a significant relief. Therefore, in the Central Netherlands Basin, only the oldest deposits of the Keuper, the Lower Keuper Claystone Member, have been preserved in the central and northern parts of the map sheet area.

The entire map sheet area remained part of a high for a long period; it was not until much later that the sediments of the Red Keuper Claystone and Dolomitic Keuper Members covered this relief. This was followed by the distinctive Rhaetian transgression, which laid down the marine sediments of the Sleen Formation in the map sheet area.

Figure 13.3 Overview map showing the main structural elements in the Netherlands during the Late Jurassic to Early Cretaceous. The location of the map sheet area is outlined.



13.2.4 Jurassic

The subsidence that started during the Rhaetian (latest Triassic) continued into the Early Jurassic. In combination with a sea-level rise, this resulted in the deposition of fine-grained, marine sediments. The deposits of the Early and Middle Jurassic have been considerably reduced in thickness in the map sheet area and are now found in apparently separate basins (Map 6). The deposits' uniform composition and fine-grained texture, however, point to contemporaneous deposition in a single, continuous, extensive basin, extending from the former Permo-Triassic Basin to the Paris Basin. In this marine basin, a high existed at the time to the south-east of the map sheet area, the Rhenish Massif, which, however, barely influenced sedimentation. At the end of the Early Jurassic (Toarcian), a period of stagnating water circulation in the marine basins resulted in the deposition of organic-rich sediments (Posidonia Shale Formation) across large parts of North-west Europe. In the map sheet area, these deposits have been preserved locally in the Central Netherlands Basin (fig. 8.4).

The Mid-Kimmerian tectonic phase, during the Middle Jurassic (Aalenian-Bathonian), mainly affected the areas to the north of the map sheet area. A large area was uplifted, including the central North Sea and the northern parts of the Netherlands and Germany (Ziegler, 1990). Sediments were transported from this elevated area to the basins situated further to the south. Remnants of these sediments have been encountered in the Central Netherlands Basin.

The Late Jurassic was characterised by major tectonic events: the Late Kimmerian tectonic phase, with a primary pulse occurring at the onset of the Late Jurassic, and a second at the Berriasian-Valanginian boundary. The ENE-WSW trending extensional stresses resulted in pronounced subsidence of several conspicuous structures in North-west Europe, such as the Central North Sea Graben, the West and Central Netherlands Basins and the Lower Saxony Basin.

The first pulse of the Late Kimmerian phase was marked by faulting and erosion. Erosion removed more than 600 m of sediments from the Central Netherlands Basin. Early Jurassic sediments are only preserved in the grabens, whereas elsewhere in the basin, deep erosion cut down to the sediments of the Upper Germanic Trias Group (Map 16). Owing to the major hiatus in the stratigraphic record, it is often not possible to reliably reconstruct the history of the Kimmerian and later erosion phases.

During the Portlandian (the final part of the Late Jurassic), the Central Netherlands Basin was connected with the Lower Saxony and West Netherlands Basins. This is indicated by the similar configurations and ages of the sedimentary successions. In the deeper central part of the basin, the Voorthuizen Trough, the sediments of the Schieland Group were deposited under fluviatile and paralic conditions. The facies of the sediments of the Niedersachsen Group, which have been encountered further north, is, however, very similar to that of the sediments of the Lower Saxony Basin, which were deposited in a brackish to marginal marine depositional environment.

13.2.5 Cretaceous

During the Cretaceous, a gradual sea level rise started, which culminated in a maximum highstand in the Late Cretaceous (Hancock & Scholle, 1975). At the same time, differential subsidence changed into regional subsidence. By the end of the Early Cretaceous, therefore, the depositional area had expanded across the entire map sheet area, with the exception of the far south-eastern corner. The Cretaceous transgression was probably a response to the increased rate of sea-floor spreading and the associated volumetric expansion of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979). Subsidence continued, until in the Late Cretaceous inversion movements associated with the Sub-Hercynian phase caused uplift of the basin areas and subsidence of the former highs.

At the end of the Early Cretaceous, basin subsidence affected a larger region and the depositional area thus expanded even further southward and eastward than during the Late Jurassic. The influx of brackish water in the northern part of the map sheet area indicates that, from time to time, open communication existed between the Vlieland Basin and the Central North Sea Graben; as evidenced by marine sediments of the same age in both basins. During the Valanginian, or possibly slightly later, the Central Netherlands Basin and the two basins mentioned above became connected because the sea level rose again.

The second pulse of the Late Kimmerian phase, during the Valanginian, accentuated the existing relief in the basin. The Dalfsen High, the Friesland Platform and the Maasbommel High experienced significant uplift and deep erosion. As a result, the Rijnland Group locally directly overlies the Limburg Group (Map 17). The erosion products were deposited in the central parts of the basin. Subsidence of the Central Netherlands probably continued uninterrupted. The depositional area expanded further during the Hauterivian and the Barremian, but did not yet cover the adjoining highs.

During the Aptian, a temporary regression occurred during the Austrian tectonic phase (Ziegler, 1990), which manifested itself in reactivation of the highs in the northern and southern parts of the map sheet area and consequently a hiatus in the stratigraphic record. On the Maasbommel High, Late-Aptian sediments directly overlie the Limburg, Zechstein, Upper Rotliegend or Lower Germanic Trias Group. On the Friesland Platform and the Dalfsen High in the north, Albian deposits directly overlie the Limburg, Zechstein, Lower Germanic Trias or Altena Group.

The movements of the Austrian tectonic phase were followed by regional subsidence of the area. During the Late Aptian and particularly the Albian, all the highs in and around the map sheet area were flooded by the sea. This Albian transgression has been identified throughout NW Europe (Crittenden, 1987). The sea level kept rising during the Albian to Turonian. The marine area in NW Europe expanded considerably. The influx of clastic material decreased; clays and marls (Upper Holland Marl) were deposited in a shallow sea, followed by thick marl and limestone sequences during the Cenomanian and Turonian. The maximum subsidence was still concentrated in the Central Netherlands Basin, but evidence from basins in NW Germany indicates that the differences in subsidence had drastically diminished and movement along the faults had virtually ceased (Baldschuhn et al., 1991).

This period of regional subsidence ended during the Coniacian. This was due to major plate reorganisation induced by ocean-floor spreading in the Arctic and North Atlantic Oceans (Coward, 1991); the collision of Europe and Africa (Ziegler, 1987) and other local factors (Baldschuhn et al., 1991). This resulted in a compressional tectonic regime throughout North-west Europe. During the Coniacian to Early Campanian period, this led to a reversal of the directions of movement along faults, inversion of the former Upper Jurassic/Early Cretaceous basins and significant subsidence of the former highs (Baldschuhn et al., 1991; Tantow, 1992). These highs subsequently formed the marginal troughs of the uplifted areas and the degree of subsidence is closely related to the degree of uplift of the adjacent basins (Voigt, 1963).

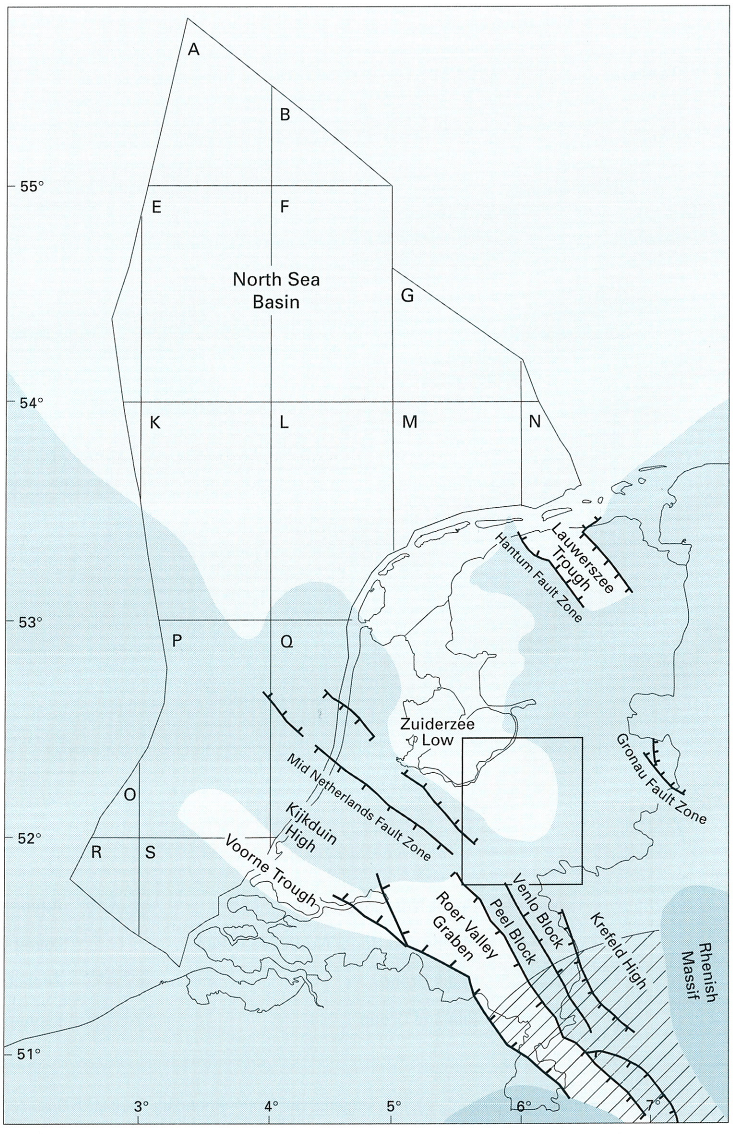
In the Central Netherlands Basin, uplift and erosion were more pronounced than the preceding subsidence. Consequently, virtually the entire Late Jurassic to Late Cretaceous stratigraphic record, as well as parts of the underlying deposits, are missing owing to erosion (Map 1 to 13). On the adjoining former highs, such as the Friesland Platform and the Maasbommel High, thick successions of the Chalk Group were deposited.

The gradually diminishing tectonic activity during the Campanian levelled the relief, which resulted in a fairly flat landscape. Elsewhere, chalk was deposited again during the Maastrichtian; the absence of these sediments in the map sheet area reflects non-deposition, rather than later erosion. Maastrichtian sediments have not been encountered anywhere underneath the Danian chalks. The Houthem Formation (fig.11.4) is present in the north-west of the map sheet area, overlying the Altena Group (Elberskirch & Wolburg, 1962). The same configuration is encountered in the adjoining part of Germany (fig. 11.4). After the Danian, the tectonic movements of the Laramide phase, which took place at the start of the Late Palaeocene, put an end to limestone deposition.

13.2.6 Cenozoic

The Tertiary and Quaternary evolution was mainly determined by the development of the North Sea Basin, which controls the sedimentation pattern up to the present day. During the Tertiary and the Quaternary, a rising sea level combined with continuing regional subsidence resulted in the deposition

Figure 13.4 Overview map showing the main structural elements in the Netherlands during the Cenozoic. The location of the map sheet area is outlined.



of over 3500 m of sediment in the central part of the North Sea Basin (Ziegler, 1990). Subsidence in the Zuiderzee Low in the north-western part of the map sheet area was not as pronounced, a mere 1500 m or so. Most of the map sheet area was situated along the eastern fringe of the basin, which is clearly reflected in the thickness development of the North Sea Supergroup (Maps 14 & 15).

During the Tertiary, sedimentation was predominantly controlled by sea-level changes and by a number of tectonic phases related to the Alpine Orogeny, such as the Pyrenean phase, at the transition from the Eocene to the Oligocene, and the Savian phase, at the transition of the Oligocene to the Miocene. The Pyrenean phase had a particularly significant impact in the map sheet area: the uplift of the Mid-Netherlands Fault zone resulted in deep erosion of the Maasbommel High, and of the Peel and Venlo Blocks (fig. 3.1d & 13.4). As a consequence, the stratigraphic record of the North Sea Supergroup is

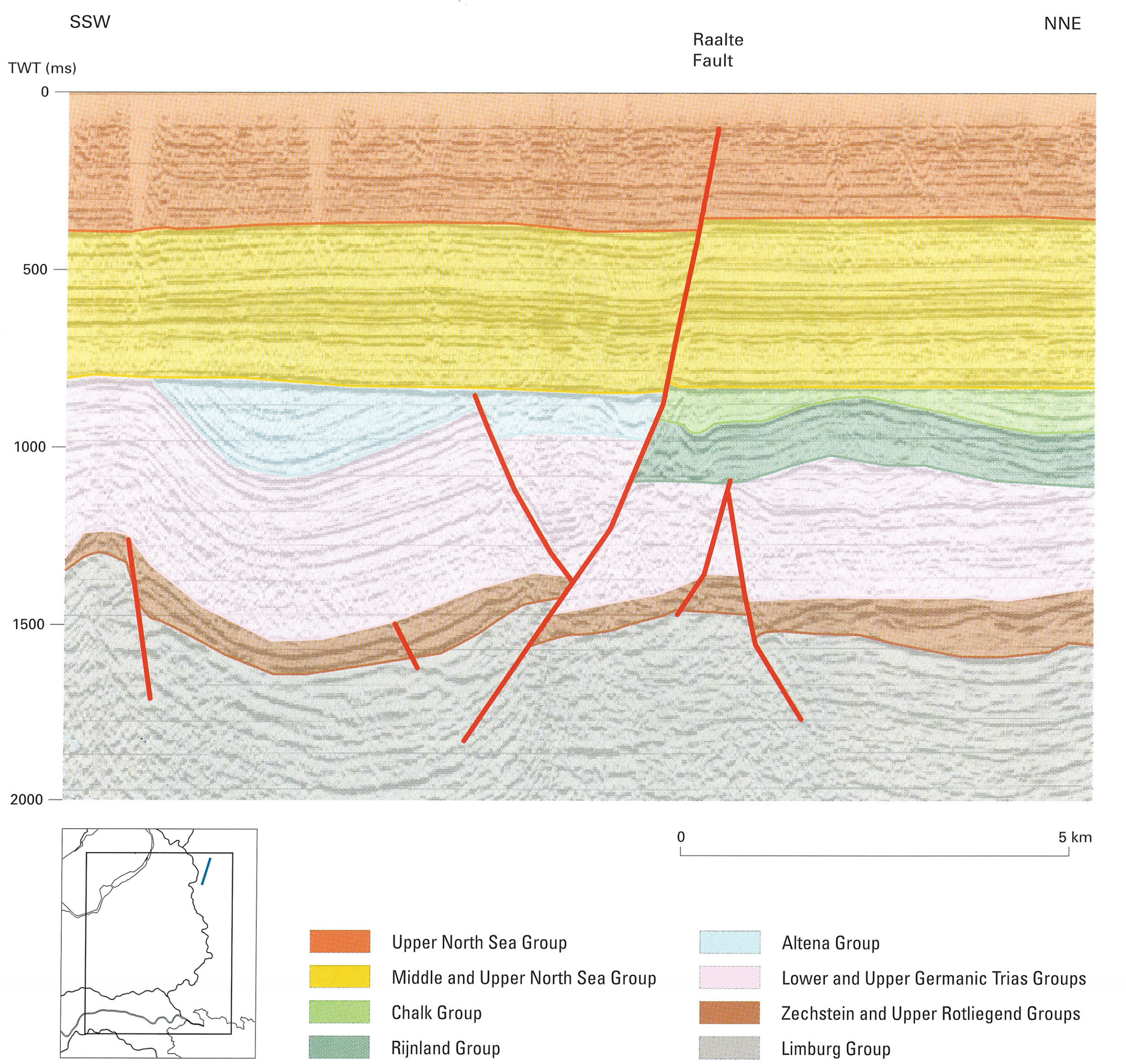


Figure 13.5 Seismic section showing the Raalte Boundary Fault with Cretaceous deposits to the NNE of it on the Friesland Platform. These deposits are completely absent on the SSW side of the fault in the Central Nederlands Basin.

marked by several disconformities and erosion phases. Although most strata were actually deposited within the map sheet area, they were subsequently removed again by erosion. This can be inferred from the sedimentary facies and isolated occurrences that are related to deposits outside the map sheet area.

During the Tertiary, fault movement was restricted to a few locations. These are related to reactivation of older faults, which originated during the tectonic phases mentioned above. The subsidence of the Zuiderzee Low, which lasted from the Miocene well into the Quaternary, however, was not related to faulting.

During the Pliocene, the sea began to withdraw from the map sheet area, commencing in the eastern part. During the Quaternary, marine conditions initially prevailed in the western part of the map sheet area, to be replaced later by continental conditions. The present-day topography of the map sheet area was created by several glacials and interglacials.

13.2.6.1 Neotectonics and glacial morphology

The Quaternary is characterised by a large number of glacial and interglacial periods. Several features of the Early Pleistocene sediments point to deposition by melt-water. The northern part of the Netherlands was covered by ice caps during two of the Middle Pleistocene glacial periods. The most recent ice cap, the Saalian, stayed in place for approximately 70,000 years, from 200,000 to 130,000 BP. It left behind a number of typical geomorphologic phenomena such as ice-pushed ridges, outwash plains and glacial basins, as well as a range of characteristic sediments, such as boulder clays, fluvio-glacial and glacio-lacustrine deposits.

The largest ice-pushed ridges, also referred to as glacio-tectonic ridges, are encountered in the central Netherlands and are locally up to 10 kilometres wide, 100 metres high and over 60 kilometres long. A good example is the eastern Veluwe, located within the map sheet area. The dimensions of the ridges further to the west, such as the 'Utrechtse Heuvelrug', are much smaller.

The glacio-tectonic ridges consist predominantly of fluviatile sands of a Middle Pleistocene age, and exhibit clear glacial deformation structures such as imbrications, upthrusts, overthrusts and folds (Van der Wateren, 1995).

The ice cap probably flowed fairly rapidly southward across the frozen soils of the northern part of the Netherlands. This speed was possible because of the fine-grained texture of the soil underneath the ice cap. In the fine-grained sediments underneath the ice cap, the water pressure increased significantly, reducing friction along the plane of movement.

In the central Netherlands and in the area of map sheet IX the soil consisted of coarser-grained sediments. This reduced the water pressure underneath the ice and slowed the advance of the ice mass. The increased friction at the base of the ice mass probably resulted in a thicker overall thickness of the ice mass (Schokking, 1989; De Mulder et al., 2003).

The large volumes of melt water that accumulated under the glacier terminus scoured out the underlying unconsolidated sediments. The ice mass would slump into these depressions. Subsequently, the ice cap's thickness would increase again. This process recurred a number of times, creating the typical U-shaped glacial basins.

The glacio-tectonic ridges surround the distal parts of the glacial basins (fig. 13.6). The long profiles of these glacial basins are asymmetrical, with the deepest parts on the northern sides of the basins. The floors of the basins are locally up to 100 metres below Amsterdam Ordnance Datum Level [the Dutch standard for normal average sea level, abbreviated to NAP] (De Gans et al., 1987). The glacial basins in the western part of the Netherlands are relatively small, which is consistent with the sizes of the local glacio-tectonic ridges.

Estimating the palaeo-thickness of the ice cap that covered the Netherlands during the Saalian is difficult. The depths of the basins and the elevations where glacial sediments still occur on top of the ice-pushed ridges suggest that in the deepest parts of the basins, the ice must have been at least 200 metres thick. The thickness of the ice cap further to the north would have depended on the distance of a particular location to the glacier terminus and on the composition of the local soil. Computer modelling suggests an ice-cap thickness of 600 metres at 5 kilometres distance from the ice terminus. At a distance of 10 kilometres, an ice cap would have been 1200 metres thick. These modelling findings, however, are not in agreement with observations on recent glaciers; these exhibit much smaller thicknesses (Schokking, 1989; de Mulder et al., 2003).

There is very little literature available in the Netherlands about the incidence of isostatic (rebound) effects, both during and after the ice ages. Faber assumed, as early as 1926, that the ice cap would have caused 'subsidence and emergence' of the surface. Teunisse postulated, in 1961, a relationship between the presence of glacial basins and faults in the Zuiderzee Basin, but this hypothesis cannot be confirmed. Nor is there any evidence of a relationship between ice-pushed ridges and faults (Van Balen et al, in press).

The valley of the river Rhine shifted southward from its former course through the IJssel valley, Zwolle and Alkmaar to its present-day course from Arnhem to Rotterdam. This happened prior to the Weichselian, when the ice front stagnated in Denmark. This shift has been attributed to a forebulge, i.e. a high area next tot an ice cap, the emergence of which would be due to isostatic movement (Törnqvist

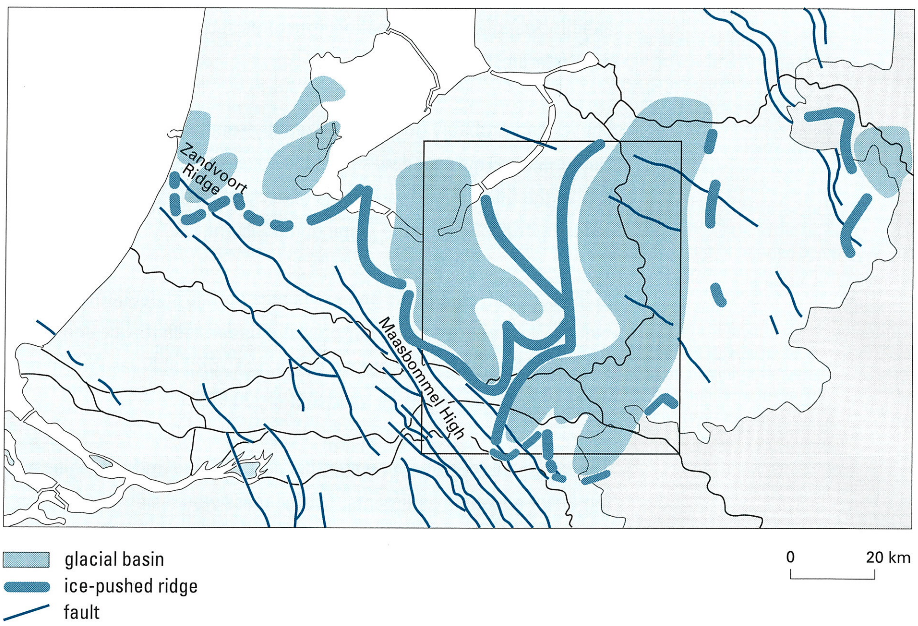


Figure 13.6 Locations of glacial basins, ice-pushed ridges, and the Mid-Netherlands Fault Zone in the Netherlands (after Van den Berg et al, 1987; De Gans et al, 1987).

et al, 2000). The anomalies in the sea-level curve as a result of glacio-hydro-isostatic rebound during the Late Weichselian and Holocene (Lambeck, 1995; Lambeck et al., 1998) are also attributed to this fore-bulge.

The existence of a hinge zone, i.e. an area that would have risen along existing fault planes in response to isostatic movements, has not been documented. It is, however, noteworthy that the southern boundary of the glacial basins and ice-pushed ridges in the Netherlands in the Saalian coincided with the northern flank of the northern Mid-Netherlands Fault Zone (De Gans et al., 1987; see also Rijks Geologische Dienst, 1984). This suggests that this zone, which included the Zandvoort Ridge and Maasbommel High, acted as a local barrier during the Saalian (fig. 13.6). The high may originally have protruded higher as a result of isostatic movement along fault planes. The border faults of the Mid-Netherlands Fault Zone are known to have been active during the Saalian, as well as later (Van Balen et al, in press), but the actual displacement is not known. Therefore, no conclusive evidence exists as yet for a possible relationship between the Mid-Netherlands Fault Zone, the glacio-tectonic phenomena and the southern limit of the ice during the Saalian.

14 Applied geology

14.1 Introduction

In addition to extracting resources such as oil, gas and salt, the subsurface can also be used for various other purposes. In the context of the Project Inventory Studies into Coal Resources in the Netherlands, phase 1, 1981 – 1985, well Joppe-1 was drilled in the map sheet area in the 1980s. Another well was drilled down to a depth of 700 m to explore for mineral-rich water. A large-diameter well was drilled to act as a reactor chamber for processing liquid organic waste. Strata at shallower depths are active fresh-water aquifers.

14. 2 Petroleum systems

14.2.1 Introduction

Up to the present day, no oil or gas accumulations have been discovered in the area of map sheet IX. It is, however, not impossible that such accumulations are present. This section discusses various factors that affect the potential presence or absence of petroleum systems in map sheet IX.
The five prerequisites that have to be met for a petroleum system to exist are: a source rock, a migration path, a reservoir, a seal, and a suitably timed geological evolution (timing).

14.2.2 Source rocks

The only rocks, penetrated in wells, with a high organic-matter content are Carboniferous coals, in particular in the Maurits, Ruurlo and Baarlo Formations. These coals would probably have mainly generated gas. The Baarlo Formation has been penetrated in wells in the southern part of the map sheet area. The coalification data available for six wells in or near map sheet IX indicate that, at the same depth, coalification is different in each well (fig. 14.1a). This demonstrates that the sediments did not coalify recently, there must have been an earlier coalification phase. This points to differences in burial history (fig. 14.2a). To assess the effects of these differences in coalification, a so-called "stratigraphic correction" has been applied, calibrating the coalification data in relation to the boundary between the Maurits and the Ruurlo Formations (fig. 14.1b). This correction shows that the coal-bearing strata in wells Zeddam-1, Dronten-1 and Zeewolde-1 are currently in the oil window (fig. 14.2b). That means that the degree of coalification of these sediments is high enough for them to have generated oil. However, the potential for oil generation is very limited as the coal beds consist of organic matter of a continental origin (Type III organic matter). The degree of coalification at these locations is too low for gas generation.

In well Joppe-1 (and to some extent in well Hellendoorn-1) the coal-bearing strata are predominantly in the gas window (fig. 14.2b); the degree of coalification of the sediments is high enough for these coals to have generated gas. Well Hellendoorn-1 shows a different coalification trend: at a depth of 1150 m (103 m above the boundary between the Maurits and the Ruurlo Formations), coalification is similar here to the coalification trends in wells Zeddam-1 and Zeewolde-1, and below that horizon, the coalification trend increases with depth much more rapidly than in the other wells. This is probably due to an intrusion, evidence of which has also been found in clay beds at a depth of approximately 1450 m (see section 4.2). The coalification of the sediments in well Dronten-1 shows a similar coalification trend. The complex tectonics that affected this location exclude a simple explanation. The degree of coalification of the coal-bearing strata in well Apeldoorn-1 is the highest at present, and most of them can be considered post-mature; i.e. gas generation must have taken place at a much earlier stage.

In addition to the Carboniferous coals beds, the Altena Group may also contain potential source rocks for either gas or oil, depending on the type of organic matter contained in them. The Altena Group is present in the central and northern parts of the map sheet area. No analyses have, however, been carried out to confirm the potential of these sediments. The most probable candidate source rock within the Altena Group is the Posidonia Shale Formation. The Posidonia Shale Formation has not been penetrated by any of the wells in the map sheet area, but seismic data suggest that the formation is present at several locations in the map sheet area (fig. 8.4). Analyses of samples from the Posidonia Shale Formation from other locations in the Netherlands have shown that the organic matter has a marine origin, which is classified as Type-II. Strata in the Sleen and Aalburg Formations may also contain sufficient organic material to act as source rocks, but this is less likely.

The organic-rich strata in the Niedersachsen Group are other possible source-rock contenders. The unit in this group that contains organic material is the Weiteveen Basal Clastics Member, which contains ubiquitous plant remains. (Van Adrichem Boogaert & Kouwe, 1993-1997). The unit has been encountered in a small area in the northern part of the map sheet area.

Is it questionable whether the organic-matter content of any of these Mesozoic deposits, with the exception, perhaps, of the Posidonia Shale Formation, is sufficiently high to generate substantial hydrocarbon volumes. Moreover, it is unlikely that the degree of maturity of these deposits is high enough for hydrocarbon generation.

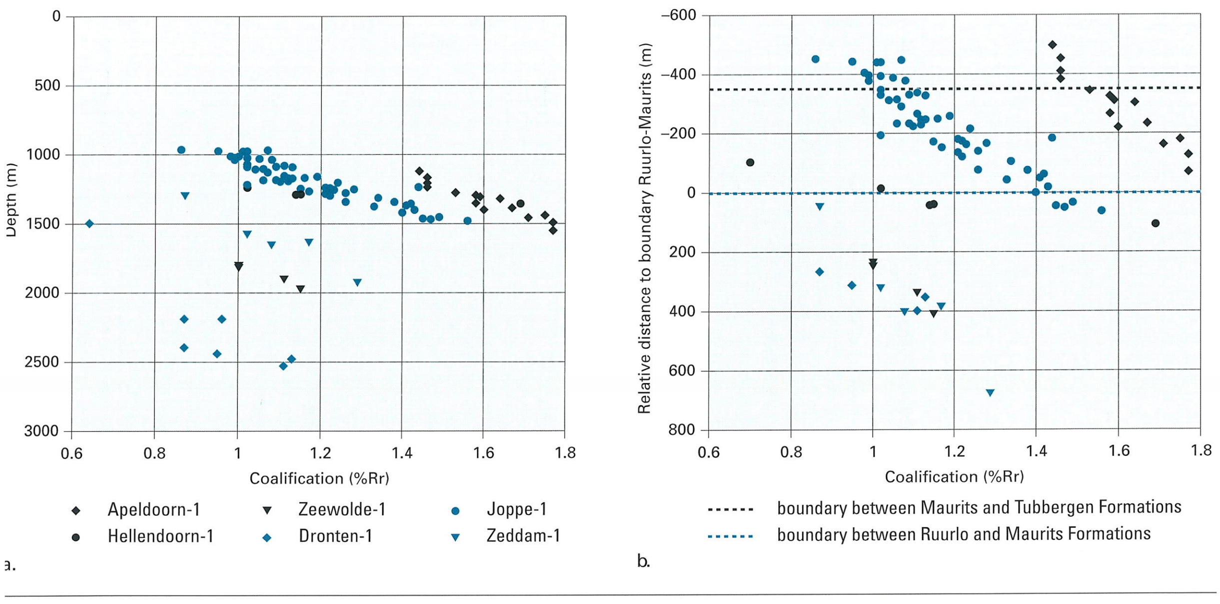
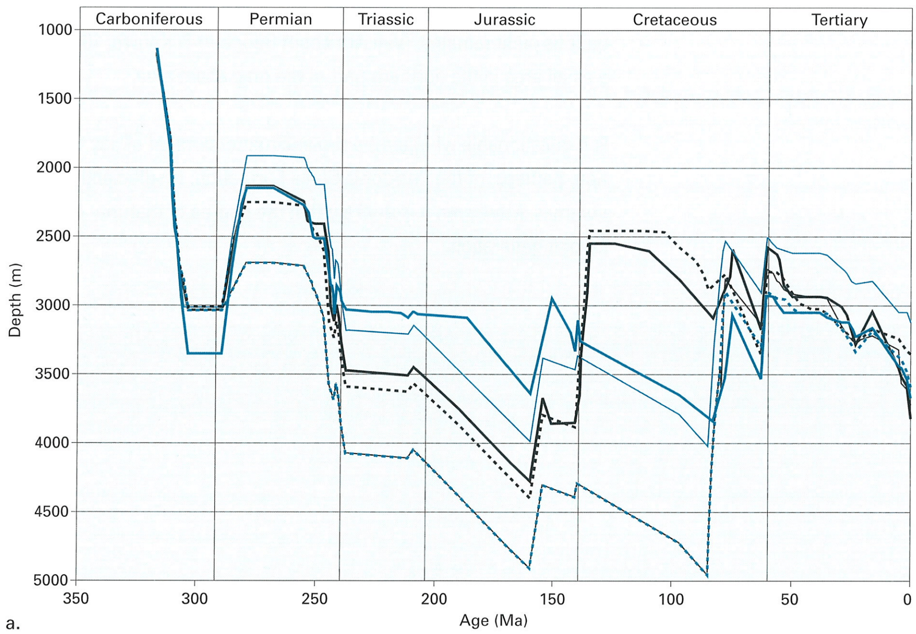


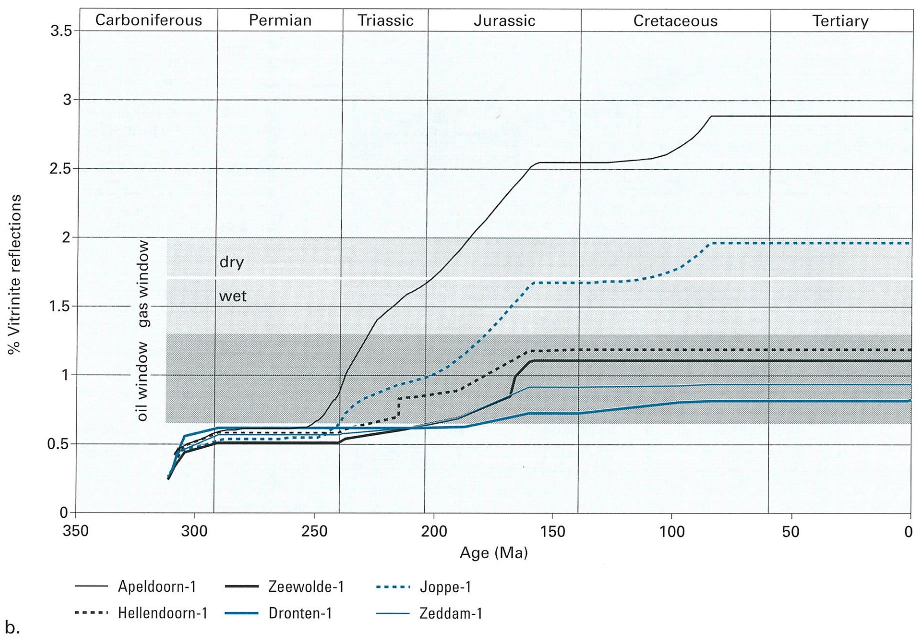
Figure 14.1a Measured vitrinite reflection values plotted against depth for wells Apeldoorn-1, Hellendoorn-1, Zeewolde-1, Dronten-1, Joppe-1 and Zeddam-1.
Figure 14.1b Measured vitrinite reflection values plotted against the depths calibrated in relation to the Westphalian stratigraphic boundaries.

14.2.3 Migration paths

Once hydrocarbons have been generated, these can migrate diffusely through the sediments overlying the source rock. Most migration will, however, have taken advantage of faults in the subsurface. Considering the burial history of the area, the bulk of the generated hydrocarbons will have, long ago, migrated straight up to surface.

Figure 14.2a Burial histories of wells Apeldoorn-1, Hellendoorn-1, Zeewolde-1, Dronten-1, Joppe-1 and Zeddam-1. The burial histories of Apeldoorn-1 and Joppe-1 are basically identical from the Carboniferous to the Late-Cretaceous Sub-Hercynian phase. *Figure 14.2b* Modelled coalification expressed in % vitrinite reflections of the wells over geological time.





14.3.4 Potential reservoirs

There are various potential reservoirs in map sheet IX. In particular the sandstones of the Tubbergen Formation, the Upper-Rotliegend Group and the Lower Germanic Trias Group have good reservoir quality for hydrocarbon accumulation. Other potential reservoir rocks are the Zechstein carbonates.

14.3.5 Seals

In particular the salt beds of the Zechstein Group, where they overlie the sandstones of the Upper Rotliegend Group, and the Röt Formation where it overlies the sandstones of the Lower Germanic Trias Group, would make good seals in map sheet IX.

14.3.6 Timing

Once the generated hydrocarbons have been expelled from the source rocks, suitable migration paths, reservoirs and seals must be present to allow oil or gas to accumulate. And if all these prerequisites have actually been met, the accumulated hydrocarbons still have to be preserved in the reservoir over geological time. The timing of the various geological events is therefore crucial. As an example of the timing of these events, the burial history of the sediments at the locations of wells Zeddam-1, Dronten-1, Zeewolde-1, Joppe-1 and Apeldoorn-1 has been reconstructed (fig. 14.2a). This reconstruction helps to understand how the variations in the degree of coalification arose (fig. 14.1a&b).

At the end of the Carboniferous, two prominent highs were present in the map sheet area: the Netherlands High (well Zeewolde-1) and the Achterhoek High (well Zeddam-1). During the Late Permian, the centre of the map sheet area was situated in a sub-basin of the Southern Permian Basin. As a result, the Upper Permian deposits are thicker here (wells Apeldoorn-1, Joppe-1, Hellendoorn-1, Dronten-1), than along the fringes of the basin (well Zeewolde-1). In well Zeddam-1, the Upper Permian deposits are even thinner, because here they were laid down on the edge of the South Netherlands Platform. In well Apeldoorn-1, burial of the Ruurlo Formation sediments during the Late Permian was already sufficiently deep to reach the oil window (fig. 14.2b).

From the Triassic up to the Middle Jurassic the region mainly experienced subsidence, apart from a few minor tectonic hiccups during the Hardegsen and Early Kimmerian phases. During the Late Kimmerian phase in the Late Jurassic, the map sheet area experienced some 600 m uplift, resulting in erosion of the major part of the sediments of the Altena Group. By the end of the Triassic, the Ruurlo Formation had subsided deep enough at the location of well Joppe-1 to reach the oil window (fig. 14.2b). The Carboniferous coals seams at the location of Apeldoorn-1 reached the gas window during the Early Jurassic. As a result of uplift during the Late Jurassic, the degree of coalification of these sediments barely increased during this period. During the Early Cretaceous, the Friesland Platform was uplifted and eroded during the second Late Kimmerian phase, with erosion cutting deeply down into the Triassic and Zechstein sediments. The present-day locations of wells Hellendoorn-1 and Zeewolde-1 were situated at the time on the edge of the Friesland Platform. The location of well Dronten-1 was also situated on the edge of this platform, but in addition to erosion, many reverse faults and normal faults have influenced the burial history of the sediments at this well location.

Unlike the Friesland Platform, the Central Netherlands Basin (wells Apeldoorn-1, Joppe-1 and Zeddam-1) experienced subsidence, rather than uplift, during the Early Cretaceous. Sediments of the Vlieland subgroup were laid down in the basin. This basin, and its fringe, subsequently subsided and sedimentation resumed throughout the area. By the end of the Late Cretaceous, the source rock strata had once again been buried sufficiently deep for maturation to continue.

During the Cretaceous, the area experienced inversion during the Subhercynian phase. Uplift was largest in the centre of the basin (wells Apeldoorn-1, Joppe-1 and Zeddam-1). During the inversion period, various locations in the map sheet area, e.g. the Apeldoorn High, were once again affected by deep erosion, with the result that Tertiary sediments now directly overlie Carboniferous sediments.

Uplift was less pronounced at the fringes of the basin (wells Hellendoorn-1 and Zeewolde-1). As a result, only Upper Cretaceous sediments were eroded off the basin fringe. After the inversion period, carbonates were deposited once again during the Late Cretaceous. However, these sediments were removed by erosion associated with the Laramide phase. From the Tertiary onwards, the basin mainly subsided, but the source rocks have not been buried sufficiently deep as yet to reach the *oil window.*

14.2.7 Synthesis

Through time, there has been plenty opportunity for gas to have been generated within the map sheet area. The above reconstruction shows that the Carboniferous sediments have been buried deepest in the centre of the basin (wells Joppe-1, Apeldoorn-1 and Zeddam-1). Burial along the basin fringes (wells Dronten-1, Zeewolde-1 and Hellendoorn-1) has obviously been much less deep, and the degree of coalification of the sediments there is therefore much lower.

The degree of coalification of the coal-bearing strata in the centre of the map sheet area was sufficiently high to generate gas. However, the timing of the events over geological time has not been favourable for forming accumulations. Once it had been generated, the gas would have accumulated in the sandstone beds of the Upper Rotliegend Group and the Lower Germanic Trias Group. However, many of these reservoir rocks must have been removed by erosion during the Cretaceous inversion phase. The gas that was present in those reservoir rocks that had escaped erosion would have leached away as a result of uplift and the associated pressure release, most probably along the faults that are present in this area. At the edges of the map sheet, the degree of coalification was most probably too low to generate an adequate volume of gas. Coalification did probably not occur during the Tertiary at all, because the present-day degree of coalification and the present-day depth show no correlation.

The hydrocarbon potential of the map sheet area therefore greatly depends on the preservation of suitable Cretaceous structures.

14.3 Hydrogeology

14.3.1 Introduction

The regional groundwater flow in the area covered by map sheet IX is controlled by major geomorphologic elements such as the 'Utrechtse and Gooise Heuvelrug', and the Veluwe. The water accumulations that are present in these structures can flow freely towards the flanks and towards the low-lying polder areas situated to the north and west (*TNO-NITG, 1996*). The Veluwe covers the largest area and affects the groundwater situation in a wide zone along its perimeter.

In terms of volume and depth of circulation, the Veluwe groundwater system knows four main exfiltration areas where the bulk of the infiltrated rainwater eventually seeps out at the surface as groundwater.

These areas are: the Flevo Polder in the north, the IJssel Valley in the east, the river district in the south, and the 'Gelderse' Valley in the west.

The 'Utrechtse Heuvelrug' forms a much smaller groundwater system, divided into two main parts; i.e. the western and south-western branch adjoining the lake and river districts, and the eastern branch, which may extend as far as the Eem and the Valley Canal, where groundwater seeps out at the surface. The digging of canals and water-level management in these canals and in other watercourses, and the reclamation of polders, etc., have caused considerable changes in groundwater flow patterns over the centuries. Major regional changes in groundwater flow have also been caused by the digging of the Amsterdam-Rhine Canal, by the reclamation of the low-lying polders west of the 'Utrechtse Heuvelrug', by the draining of the Flevo polders and by the creation of the Rim Lakes between the former Zuiderzee and its original coast.

The natural groundwater in the map sheet area is a virtually unpolluted calcium-bicarbonate type of water of varying hardness and low chloride content and is contained in aquifers underneath the ice-pushed ridges extending down to the Tertiary marine sediments (Oosterhout and Breda Formations); and underneath the Veluwe and the 'Utrechtse Heuvelrug'. The groundwater underneath the southern half of the Flevo polders, with the exception of the water in the aquifers overlying the glacial basin in South Flevoland, is fresh down to a depth of 100 metres. Deeper down, the groundwater is brackish. These types of water are generally separated by a transition zone containing sodium-bicarbonate type water, indicative of a freshening trend. The water hardness generally increases away from the higher sandy soils of the ice-pushed ridges, which act as infiltration areas. The impact of anthropogenic activity is clearly noticeable in the groundwater types that contain $CaSO_4$, CaMix, NaMix etc. Tongues of these groundwater types have penetrated as deep 50 metres below the surface.

14.3.2 Hydrogeology and major aquifer sequences

The general geological configuration of the shallow subsurface in the map sheet area (fig.14.3) is complex and heterogeneous. This heterogeneity is mainly due to the fluviatile deposits of Pleistocene age. The Central Netherlands has been shaped by rivers flowing from the south such as the Rhine and Meuse, as well as by rivers originating in Northern Germany. As a result, north-south cross-sections show very elongated and diachronous interfingering of formations and a wide range of lithologies. In a number of cases, sediments that had been deposited by rivers coming from the south have been reworked and redeposited by the eastern river system. Moreover, a major fault system, which is an extension of the Peel and Venlo Blocks, was still active during the Early and Middle Pleistocene, resulting in abrupt variations in formation thickness. Deep glacial erosion valleys were incised during the Saalian Ice Age, originally down to 100 metres or more below present-day sea level, but were later filled up again with clayey and silty melt-water deposits.

Figure 14.4 shows the west-east cross-section of the map sheet area that most clearly portrays the typical geological configuration of the map-sheet area. The main strata from which groundwater can be produced are of Pleistocene age and consist largely of fluviatile deposits locally containing ice-pushed zones. These Pleistocene fluviatile sandy strata overlie the marine Maassluis Formation of Early Pleistocene age. The hydrological basis is formed by the underlying clayey and silty Tertiary marine deposits such as the Oosterhout and Breda Formations.

The Drente Formation, deposited during the Saalian Ice Age, when the ice cap reached its maximum extension, consists of clayey sediments, mainly glacial tills, and acts as a semi-confining layer, obstructing groundwater flow. The Kreftenheye and Boxtel Formations overlying these tills act as aquifers, locally separated by the clayey interglacial intercalation of the Eem Formation. Figure 14.4 broadly outlines the geohydrological configuration (aquifers I to IV) commonly used in building numerical groundwater flow models.

As stated previously,.Saalian glacial erosion has cut deeply into the sedimentary record. Subsequently, thick clayey sequences have been deposited in the troughs scoured out by the ice lobes. As a result, the stratigraphic succession has been upset and lateral correlation of the geohydrological configuration is extremely complicated. The radical glacial processes have resulted in major heterogeneity and frequent interfingering of the clayey Quaternary sequences. The very nature of the Lower and Middle Pleistocene fluviatile formations, characterised by erosion by one river system and subsequent redeposition by another river system, makes it virtually impossible to trace the intercalated clay layers that separate groundwater flows, even on a local scale.

14.3.3 Distribution of fresh and saline groundwater

Figure 14.4 outlines the depth contours of the fresh/saline-groundwater interface (chloride content 150 mg/l). Underneath the Veluwe, the Gelderse Valley and the 'Utrechtse and Gooise Heuvelrug', the inter-

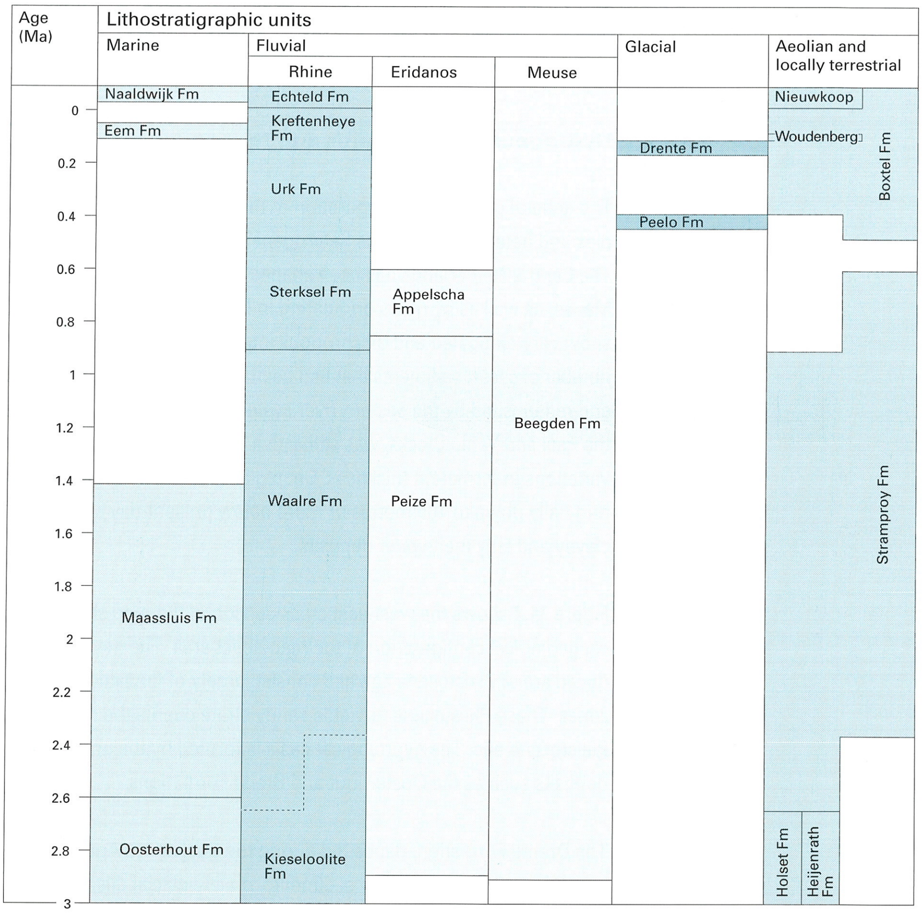


Figure 14.3 Lithostratigraphy of the Upper Tertiary and Quaternary deposits (after De Mulder et al., 2003).

face is located at depths of up to 300 metres below the surface. In the areas outside the ice-pushed ridges, for instance in the vicinity of Utrecht-IJsselstein-Culemborg and in the south-western part of Flevoland, the interface is also located at depths of over 200 metres below the surface. The situation in Flevoland is complicated by the presence of brackish and saline water, which overlies the deeper fresh groundwater, as a result of the Holocene transgression. Major bulges in the interface exist in the river district, along the Eem and the Valley Canal and in the IJssel Valley east of the present-day longitudinal axis of the valley.

The regional geometry of the fresh/saline groundwater interface is closely related to the prevailing groundwater flow systems. In infiltration areas, the interface is very deeply buried. In areas where groundwater flow branches, which lie very deep in the region in general, discharge at the surface, such as along the Eem, the Valley Canal, along the Langbroeker Wetering and along the eastern side of the IJssel valley, the interface is characterised by bulges that almost reach the surface. Local cones are associated with polders with controlled deep drainage levels and with areas of large-scale groundwater extraction. The bulges in the interface that are found locally in the river district (between Tiel-Rhenen

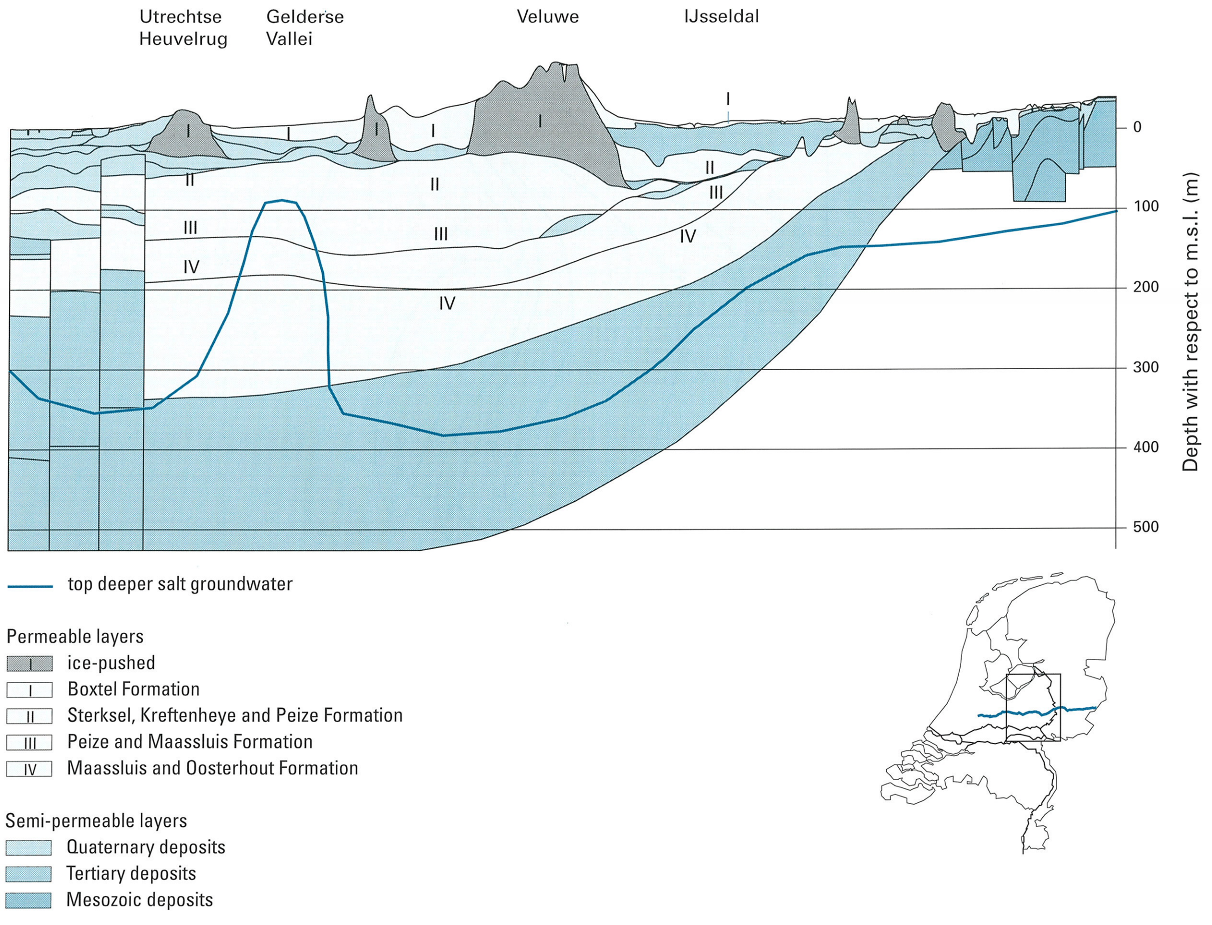
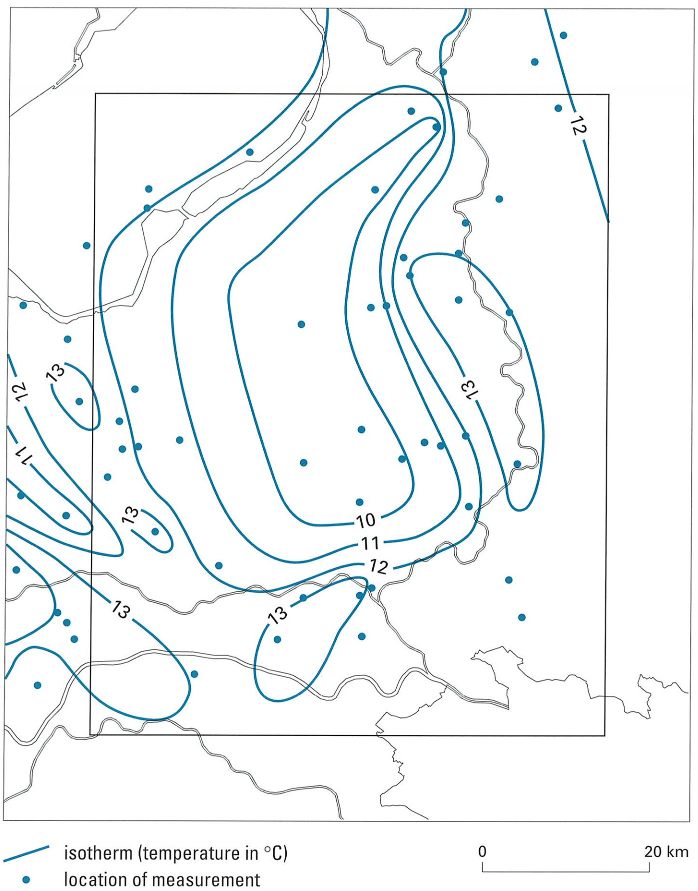


Figure 14.4 West-east geological cross-section through map sheet IX (for location see map insert), showing the geohydrological configuration (aquifers I - IV) and the approximate position of the fresh/saline interface (solid line).

and Nijmegen) cannot be related to groundwater flow. These cones are probably due to warmer saline groundwater welling up along the deep fault system that is an extension of the Peel Block.

Figure 14.5 shows the groundwater isotherms at a depth of 125 metres below the ground surface. Close to an extension of the Peel Block, the isotherm pattern suggests higher temperatures. Other areas where temperatures are locally higher are related to regional exfiltration areas, i.e. the end points of the groundwater flow paths along which the groundwater was heated geothermally during its migration through the deep aquifers. The areas of high groundwater temperatures correspond to the bulges in the saline/fresh groundwater interface. This may indicate volumetric compensation with deeper saline groundwater being expelled as large fresh water lenses form underneath the ice-pushed ridges. Temperatures in the infiltration areas, however, perfectly match the average annual temperature in the Netherlands.

Figure 14.5 Isotherms at a depth of 125 m below the surface (geothermal data supplied by TNO-NITG).



14.3.4 Regional groundwater systems

The cross-section, shown in fig. 14.6, outlines large regional groundwater flow systems and nested groundwater flow systems, which overlie larger-scale regional systems. The fresh/saline interface, discussed above, is regarded, in practice, as the lower boundary of the groundwater system. The locations where branches of two different groundwater systems adjoin one another and are curving upward, commonly referred to as 'hollow' groundwater divides, such as exist in the Gelderse Valley and in the IJssel Valley, coincide with upward bulges in the fresh/saline interface.

14.4 Thermal water

14.4.1 Introduction

During the past few decades, several wells have been drilled to explore for thermal mineral water. Groundwater may be called mineral water if the NaCl content exceeds 1000 mg/l or if a certain standard concentration of iron, iodine, hydrogen sulphide, fluoride or other minerals is exceeded. These standards have been laid down by the Deutschen Bäderverband and the Deutschen Fremdenverkehrsverband (Anonymous, 1979).

Well Sanadome-499, drilled in the map sheet area, near Nijmegen, on the edge of the Maasbommel High, struck thermal mineral water, which meets the German standards for Heilwasser (water suitable for a health spa).

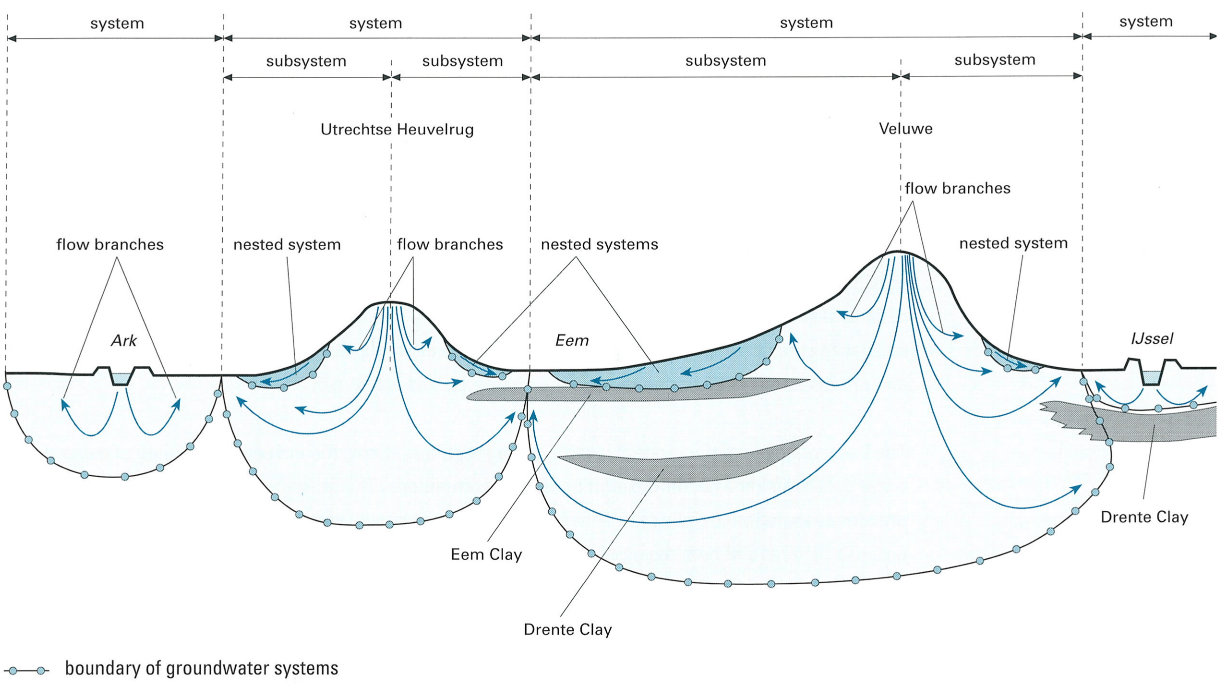


Figure 14.6 Schematic cross-section from the Amsterdam-Rhine Canal (Ark) to the IJssel Valley depicting the regional groundwater flow systems.

14.4.2 Sanadome Thermae; water from the Early Tertiary

Well Sanadome-499 was drilled in 1994 with the objective of extracting mineral water from limestones of a Late Cretaceous age. The sediments of the Ommelanden Formation were encountered at a depth of 700 to 755 m, and instead of chalk, these turned out to consist of grey-green marls of a Santonian age. Because of their high clay content, these deposits were unsuitable as aquifers. However, the deposits of an Early Tertiary age that overlie the Ommelanden Formation were more suitable. The base of the Landen Formation is formed by the Heers Member, consisting of fine-grained sand with a sufficiently high permeability to serve as an aquifer. The produced water is classified as 'iodide-containing thermal sole'. Bearing in mind the numerous faults in the subsurface and the very saline water (with a Na^+ content of 16,880 mg/l and a Cl^- content of 31,330 ml/g, according to Sanadome's own figures), the mineral water is probably derived from deeper sediments. The temperature in the producing layer would be would be approximately 33° C, in line with the normal gradient of 3°/100 m. The flow rate is approximately 1200 litres per hour.

A second well produces fresh water, from two sand bodies in the Oosterhout Formation at a depth of 70 metres. The spring water, which is used as drinking water, has a high iron content and a temperature of 12 °C.

14.5 Vertech well

14.5.1 Introduction

In 1992, VerTech Treatment Systems, now VAR BV, had a well, Apeldoorn-2, drilled down to a depth of 1272 m. The well penetrated Upper Carboniferous strata. The purpose of well Apeldoorn-2 was to drill a hole, of a large diameter, i.e. 17.5 inch or approximately 44 cm, which could be used for the environmentally friendly processing of dredge spoil, pig slurry, liquid manure and other liquid waste according to the Vartech process. This process takes advantage of the forces of nature in the subsurface such as pressure and temperature.

14.5.2 Wet oxidation process

Vartech processes liquid organic waste streams in a wet-oxidation process. The waste does not need to be drained and thickened first to create a sludge. The wet-oxidation process creates a significant reduction in volume; of the original volume of liquid organic waste processed each year, only 4% remains as residue in solid form. The remaining water is biologically purified. During the wet-oxidation process, the substances that are dissolved or suspended in the water are oxidised at high temperatures (180 – 374°C) and pressures (40 – 250 bar) in the aqueous phase by adding oxygen.

The basic principle of the process is that, under these conditions, the increased solubility of oxygen in water accelerates the decomposition of organic compounds. The pressure has to be sufficiently high to prevent evaporation of the water. The chemical reactions should take place in the aqueous phase, because they require both oxygen for oxidation and water for hydrolysis, which is decomposition by interaction with water. The speed at which the process occurs is predominantly determined by the temperature and the presence of catalysts such as iron and copper ions.

The substances treated are mainly organic compounds that are converted into carbon dioxide. A fraction of the initial material is converted into lower fatty acids that are easily biodegradable.

14.5.3 Reactor

The reactor consists of a 1280-m-long, concentric tubing system sunk vertically into the ground. The waste stream descends into the reactor through the down pipe. At the bottom, pure oxygen gas is added to trigger oxidation. The effluent - water mixed with ashes, the so-called 'sludge cake' - returns to the surface through the up pipe. The average turnaround time in the reactor is approximately 45 minutes. The temperature and the pressure curves show a straightforward profile: the input temperature is 20° C, the bottom-hole temperature is 280° C and the output temperature is approximately 85° C. The initial pressure is 12 bar, de bottom-hole pressure is 100 bar and the discharge pressure is 15 bar. By taking advantage of the natural properties of the subsurface, the Vartech principle consumes very little energy. The small quantities of carbon dioxide (CO_2) emitted and the solid residues that are left after the process are fully recyclable. This also applies to the heat that is generated in the process.

Appendices

Overview of seismic data used

Survey	*Year*	*Owner*	*2D/3D*
30*	1965/1988[1]	NAM	2D
31*	1965/1988[1]	NAM	2D
60*	1967/1988[1]	NAM	2D
7060*	1970	NAM	2D
7160*	1971	NAM	2D
7260*	1972	NAM	2D
7320*	1973	NAM	2D
7510*	1975	NAM	2D
ANE-78*	1978	AMC	2D
CN80*	1980	BPE	2D
CN81*	1981	BPE	2D
8134*	1981	NAM	2D
BW81-*	1981	ELF	2D
BW82-*	1982	ELF	2D
ZY83-*	1983	ELF	2D
84*	1984	NAM	2D
8430*	1984	NAM	2D
DG84*	1984	NAM	2D
DG85*	1985	NAM	2D
DG86*	1986	NAM	2D
8601E	1986	DG	2D
HA85-*	1985	ELF	2D
MZ85-*	1985	MOB	2D
MZ86-*	1986	MOB	2D
MZ88-*	1988	MOB	2D
AM86-*	1985	ELF	2D
AM87-*	1985	ELF	2D
Bronkhorst	1996	NAM	3D

AMC Amoco Netherlands Petroleum Co.
BPE British Petroleum Exploratie Maatschappij Nederland BV
DG Delft Geophysical
ELF Elf Petroland BV
MOB Mobil Producing Netherlands Inc.
NAM Nederlandse Aardolie Maatschappij BV

* Random number
[1] Reprocessed in 1988

Appendix B

Overview of wells used

Nr.	*Name well*	*Code*	*Owner*	*Total depth (m)*	*Year*
1.	Altforst-1	ALT-01	BPM	654	1944
2.	Apeldoorn-1	APN-01	BPE	1553	1971
3.	Apeldoorn-2	APN-02	VERT	1278	1992
4.	Arnhem-1	AHM-01	BPM	662	1944
5.	Barneveld-1	BNV-01	AMC	3066	1971
6.	Bronkhorst-1	BKH-01	NAM	2050	1999
7.	Doornspijk-1	DSP-01	NAM	2406	1964
8.	Doornspijk-2	DSP-02	NAM	1832	1966
9.	Dronten-1	DRO-01	CON	2504	1965
10.	Emmerich-1	EMMR-01	ELW	1449	1950
11.	Epe-1	EPE-01	CHE	1866	1971
12.	Ermelo-1	ERM-01	NAM	2650	1969
13.	Gewande-1-S1	GWD-01-S1	NAM	2324	1991
14.	Gewande-1	GWD-01	NAM	2355	1991
15.	Haarle-1	HLE-01	NAM	1747	1971
16.	Hellendoorn-1	HLD-01	NAM	1486	1976
17.	Hessum-1	HES-01	CON	2222	1968
18.	IJsselmuiden-1	IJD-01	BPE	2398	1968
19.	Joppe-1	JPE-01	RGD	1494	1985
20.	Knardijk-1	KRD-01	AMC	1524	1978
21.	Langenholte-1	LNH-01	NAM	2386	1977
22.	Lelystad-1	LEL-01	CON	2057	1970
23.	Lochem-2	LOM-02	BPM	1029	1944
24.	Maasbommel-1	MSB-01	NAM	1713	1951
25.	Maasbommel-2	MSB-02	NAM	1278	1953
26.	Nijmegen-Valburg-1	NVG-01	NAM	1277	1968
27.	Ommen-1	OMM-01	NAM	659	1943
28.	Oost-Flevoland-1	OFL-01	NAM	2390	1965
29.	Raalte-1	RAL-01	BPM	685	1943
30.	Raalte-2	RAL-02	BPE	1679	1983
31.	Sanadome-1 (40C499)	SNM-499	SAN	759	1994
32.	Voorthuizen-1	VHZ-01	NAM	1773	1950
33.	Wesepe-1	WEP-01	BPE	1902	1985
34.	Wijhe-1	WYH-01	NAM	1786	1965
35.	Zeddam-1	ZED-01	NAM	1965	1954
36.	Zeewolde-1	ZEW-01	CON	2000	1966
37.	Zwolle-1	ZWO-01	NAM	1058	1965

AMC Amoco Netherlands Petroleum Co.
BPE British Petroleum Exploratie Maatschappij Nederland BV
BPM Bataafse Petroleum Maatschappij
CHE Chevron
CON Continental Netherlands Oil Co.

ELW	Elwerath
NAM	Nederlandse Aardolie Maatschappij BV
RGD	Rijks Geologische Dienst
SAN	Sanadome Onroerendgoed BV
VERT	VerTech Treatment Systems

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Geological maps:

Maps compiled by
E.J.Th. Duin
C.M. Elmers-Kathmann
J.C. Doornenbal

Explanation:

Explanation compiled by
N. Witmans
E.J.Th. Duin
J.C. Doornenbal
F. van Bergen
F.H. Kloosterman
W. de Gans

Biostratigraphy
G.F.W. Herngreen
R.M.C.H. Verreusel

Figures
J.M. Rietstap
N. Witmans

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Th.E. Wong
R.J. van Leeuwen
J.C. Doornenbal
M.C. Geluk
G.F.W. Herngreen

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