Netherlands Institute of Applied Geoscience TNO - *National Geological Survey*

Explanation to map sheets XIII and XIV Breda-Valkenswaard and Oss-Roermond

Geological Atlas of the Subsurface of the Netherlands

Explanation to map sheets XIII and XIV Breda-Valkenswaard and Oss-Roermond

Netherlands Institute of Applied Geoscience TNO – *National Geological Survey*, Utrecht 2001

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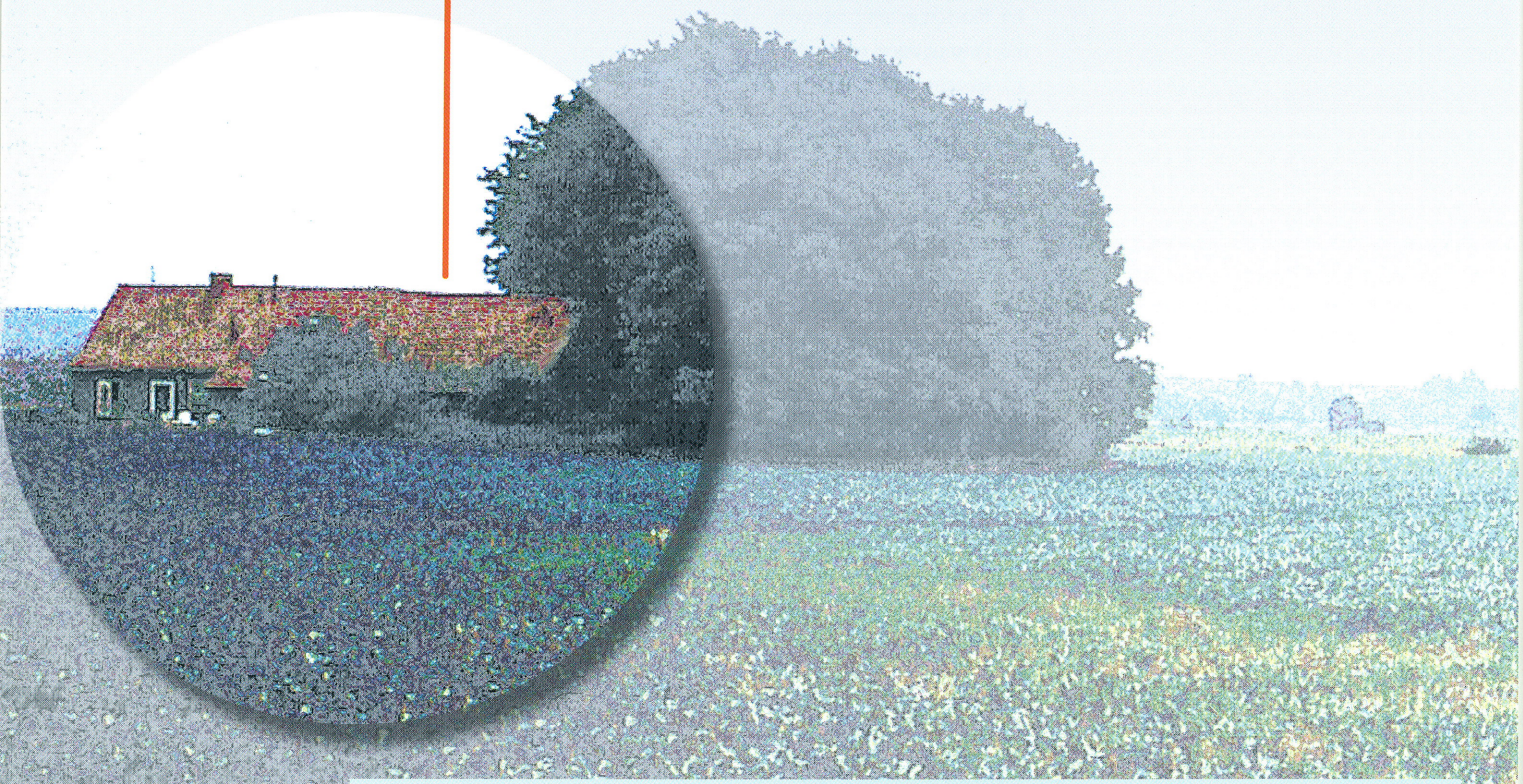
Farmhouse situated on top of the Peel Boundary Fault
Photos by Th.E. Wong and J. Schokker



Roer Valley Graben
Peel Block

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The publication of map sheet XIII and XIV by the Netherlands Institute of Applied Geoscience TNO – *National Geological Survey* marks a continuation of the map sheets constituting the Geological Atlas of the Subsurface of the Netherlands. In this series, unique map sheets of the subsurface of the Netherlands are made available, presenting an overall picture of its potential exploitation. With broad-based regional-geological knowledge of the subsurface of the Netherlands and surrounding countries at its disposal, the TNO-NITG has clearly enhanced the quality of these publications, which far exceeds that of routine mapping.

Reporting of information to the general public on the deeper subsurface geology (deeper than 500 m) was limited because of the status of the data required. These data are acquired from seismic investigations and deep drilling which are nearly exclusively carried out by oil companies. Because of the considerable commercial interests involved for the oil industry these data are classified, but are made available to the TNO-NITG as delineated in the mining act.

The existing mining legislation that applies to the Netherlands onshore area, does not permit the general release of this classified information. Agreement with industry concerning the use of these data enables the TNO-NITG to compile and publish this information, provided the data are older than 10 years. An exception is made for data from concession areas, with a restriction of 5 years. This agreement enables the TNO-NITG to bring the geology subsurface of the Netherlands to wider attention.

The Breda-Valkenswaard and Oss-Roermond map sheets of the Geological Atlas of the Subsurface of the Netherlands are the ninth and tenth sheets to be published in the framework of the systematic mapping of the subsurface of the Netherlands, for which purpose the Netherlands has been divided into 15 map sheets published on a scale of 1:250.000 (see figure 1.1 for an overview of the area of the map sheets). The present publication is the first time that two map sheets have been presented in one edition, with a combined explanation. This method of approach was chosen because both map sheets are dominated by a single geological structure, the Roer Valley Graben.

Each map sheet has its own features. The map sheets in question outline the geology of the largest part of the province of Noord-Brabant and of parts of the provinces of Limburg, Gelderland and Zuid-Holland. Maps and sections reveal that the present geological pattern of these provinces is dominated by a major graben, the Roer Valley Graben, and a number of high blocks which form the shoulders of this graben. This NW-SE oriented graben is characterised by periods of pronounced differential subsidence during the Triassic and the Jurassic and from the Oligocene on. During the Late Jurassic, pronounced differential subsidence occurred in the NW part of the Roer Valley Graben and during the Subhercynian phase (Coniacian-Campanian), inversion of the Roer Valley Graben took place. The erosion cut down as far as the Lower Jurassic or the Triassic deposits. The graben is bounded by a number of notable fault structures, of which the Peel Boundary Fault on the northeastern flank is the most prominent. Along this fault zone, at the basis of the Tertiary, normal faults extended down as far as 1000 m. In the Netherlands, most seismicity of natural origin occurs in the Roer Valley Graben. This seismicity is concentrated along the principal fault zones, such as the Peel Boundary Fault, which also applies to the Roermond earthquake of 1992.

The text broadly comprises three parts. The first part explains the research set up (Chapter 1), followed by an account of the exploration of mineral and natural resources (Chapter 2) and the structural framework (Chapter 3). The second part consists of a lithostratigraphic description of the rocks (Chapters 4-13) and the geological history of the map sheet area (Chapter 14). The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members, which are related to the major structural elements of the map sheet area. Each chapter devotes one section to

the depositional environment and the palaeogeography. In Chapter 15, special attention is given to various applied geological aspects, such as geochemistry, coal-bearing, petroleum systems, thermal energy and hydrogeology. Oil and gas-bearing reservoirs have been encountered in fluvial and aeolian sandstones of the Triassic.

The TNO-NITG anticipates that these map sheets, together with those already published or in progress, will contribute to a greater understanding of the structure and composition of the subsurface of the Netherlands. This is important not only to companies who are active in the fields of exploration and exploitation for mineral and natural resources, but also various governmental institutions and other interested parties. As from this year, the published maps may also be viewed digitally. TNO-NITG has developed a 3D viewer enabling the maps to be seen in three dimensions (see: http://dinoloket.nitg.tno.nl).

As well as those people acknowledged in the credit column who are directly responsible for compiling this map sheet, many other employees of the TNO-NITG have been involved, whose efforts are all greatly appreciated. Regular consultations have been held with Dr G. Drozdzewski and Dr V. Wrede of the Geologischer Dienst NRW, Krefeld (the former Geologisches Landesamt of Nordrhein-Westfalen) and Dr M. Dusar of the Belgian Geological Survey on the harmonisation of these map sheets with German and Belgian maps. Special thanks are due to the companies which provided exploration data used in these map sheets.

Utrecht, December 2001

1 Research set-up

1.1 Extent of area studied

The area covered by map sheets XIII (Breda-Valkenswaard) and XIV (Oss-Roermond) of the Geological Atlas of the Subsurface of the Netherlands comprises most of the province of Noord-Brabant and parts of the provinces of Limburg, Gelderland and Zuid-Holland (fig. 1.1). This explanation covers two map sheets; where the term "map sheet area" is used, the area encompassing both map sheets is intended. The map sheet area is bordered by the Belgian region of Vlaanderen in the south and the German federal state of Nordrhein-Westfalen to the east.

1.2 Data base

The mapping of the map sheet area has made use of seismic and well data acquired by industry, the Dutch Government and TNO-NITG. Both 2D and 3D seismics were available for map sheet XIII, whereas

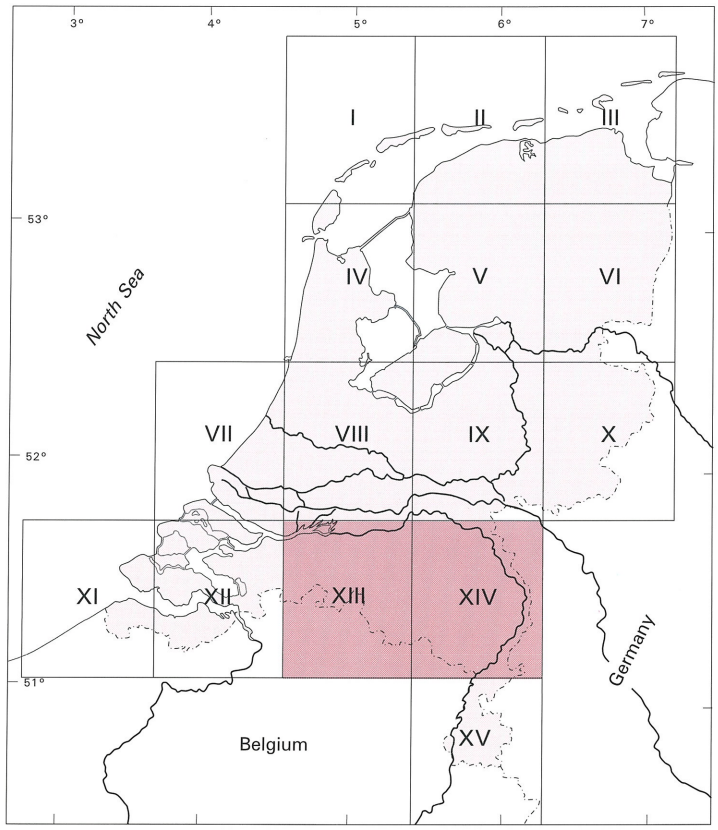


Figure 1.1 Subdivision of the regional map sheet areas of the subsurface of the Netherlands and geographical position of map sheets XIII and XIV.

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

the mapping of map sheet XIV had to rely exclusively on 2D seismics (fig. 1.2). A total of 109 boreholes were selected for the map sheets (34 in XIII and 75 in XIV). Where a cluster of boreholes occurs, only one of the wells was used. This only occurs in map sheet XIII. Use has also been made of published maps, wells and seismic data from the adjacent parts of Belgium and Germany (fig. 1.3, appendix B).

The majority of the data acquired from deep drilling was carried out by oil companies, the former Dienst der Rijksopsporing van Delfstoffen (ROvD) [*Government Institute for the Geological Exploration of the Netherlands*] and the State Collieries. The wells owned by these two latter bodies are situated in the southeastern part of the Peel and Venlo Blocks, and were drilled in order to take stock of exploitable coal seams. Finally, two additional deep wells were placed for mineral water and thermal water exploitation for health spas.

1.3 Geological research

The geological research focused on the lithostratigraphic composition of the rocks present in the map sheet area (fig. 1.4) and their geological history placed in a regional-geological context. Use was made

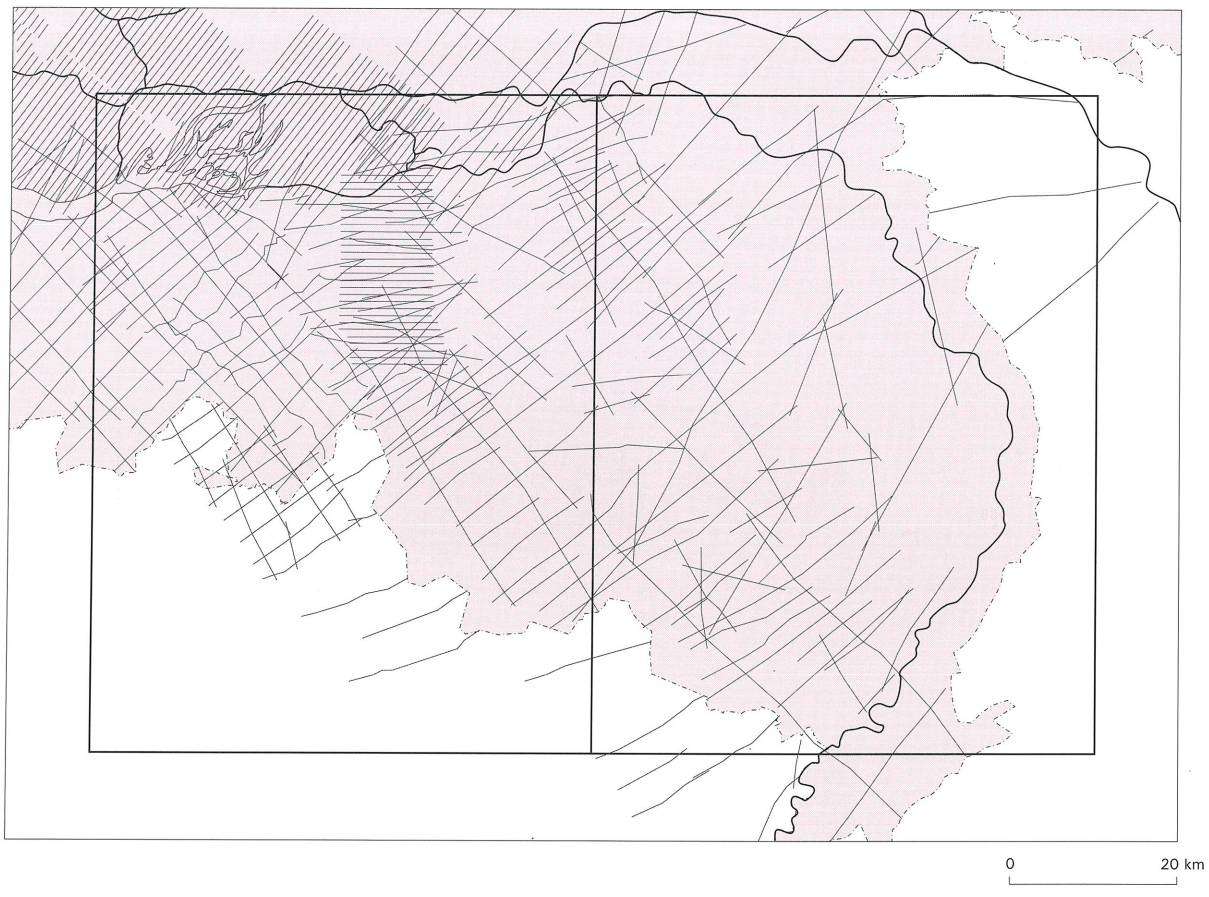


Figure 1.2 Location of the seismic lines used. Appendix A contains additional information on the owner and the year of the various surveys.

of the seismic sections and well-log data previously referred to. The lithostratigraphic units, which are indicated in figure 1.4, are discussed in greater detail in each chapter.
In the Explanation, particular attention has been paid to the tectonic development of the Roer Valley Graben and adjacent horsts. The associated neo-tectonics and earthquakes as well as the hydrogeology and the petroleum systems present in this area are also discussed in detail.

1.4 Seismic mapping

The mapping was carried out predominantly with 2D seismics; use of 3D seismics was restricted to the north of map sheet XIII (fig. 1.2; appendix A). In the area of the Peel and Venlo Blocks and the Maasbommel High, the density of the seismic lines is extremely sparse. An interpretation was made of a total of over 750 km^2 of 3D seismics and over 3200 km of 2D seismics.

The mapped reflectors form the boundaries between the lithostratigraphic units (groups and formations). Calibration of the seismic data was performed by means of acoustic logs and check-shot surveys. The

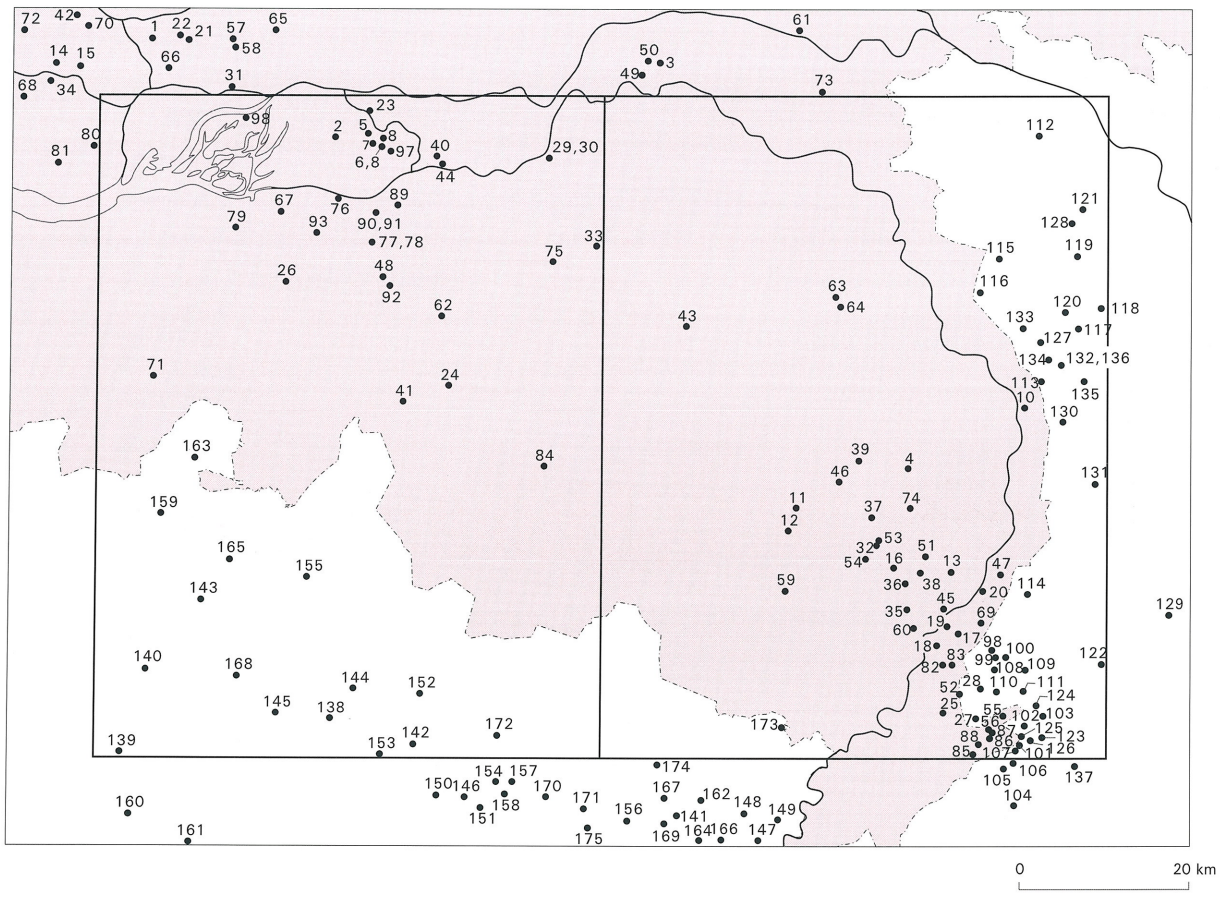


Figure 1.3 Location of the wells used for the mapping. For the numbering, reference should be made to appendix B where the name, owner, final depth and year of the well are given. In the case of the wells outside the country, final depth and literature source are given.

time-depth conversion of the seismic data was carried out per layer (the so-called layer-cake method). For this, a linear equation between the velocity and the depth of the layer was taken (table 1.1).

To guarantee consistency between adjacent map sheets, a countrywide velocity equation was formulated, for application to all the map sheets. The parameters of this countrywide equation were determined from the acoustic data from 61 wells located throughout the Netherlands. Application of this velocity distribution, however, gave rise to large deviations in the depths of the base of the Altena Group and the Lower Germanic Trias Group, particularly in the inverted areas, and consequently the equation was revised. A regional velocity distribution (TNO-NITG 2001) was determined from the acoustic data from over 600 wells located in the Netherlands onshore area. With respect to this area, this produced the velocity equation given in table 1.1.

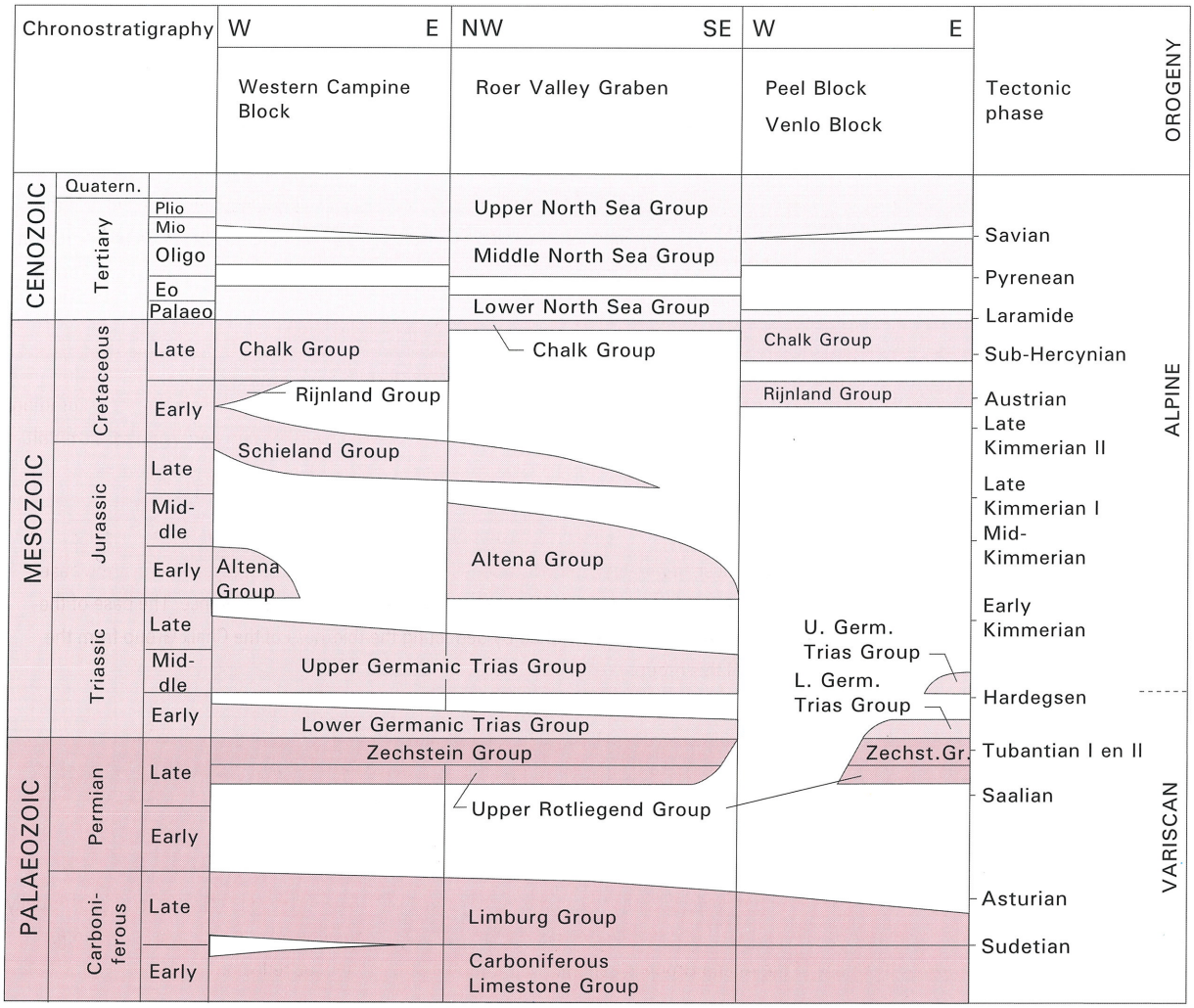


Figure 1.4 Diagram of the lithostratigraphic units and the main tectonic events for the geological development of the map sheet area.

Table 1.1 Applied velocity distribution

The velocity distribution in the map sheet area is based on $V_z = V_0 + k.z$
V_z: average velocity at depth z (m/s)
V_0: theoretical velocity at depth z = 0 (m/s)
k: specific constant (1/s)
z: depth (m)

Unit	V_0	*k*
North Sea Supergroup	1696	0.47
Chalk Group	2156	1.03
Rijnland Group	2026	0.73
Schieland Group	2770	0.53
Altena Group	2451	0.44
Lower and Upper Germanic Trias Groups	3097	0.47

The seismic, interpreted horizons are delineated by the bases of lithostratigraphic groups, namely the Upper North Sea Group, the North Sea Supergroup, the Chalk, the Rijnland, the Schieland and the Altena Groups (fig. 14.4). In addition, an interpretation has been made of the Posidonia Shale Formation, as this formation is in general clearly identifiable on seismic logs as a low-frequency band. This formation is also an important oil-source rock in this area.

The Upper North Sea Group is the youngest seismic unit and is characterised by typical seismostratigraphic phenomena such as downlaps, toplaps and onlaps, which are associated with a prograding sedimentary system. The Lower and Middle North Sea Groups constitute a comparatively uniform unit, in which clear continuous reflectors occur.

The base of the Chalk Group is manifested throughout the map sheet area as a very clear angular unconformity. However, in the Roer Valley Graben, this group is so thin that the reflectors of the base of the group and the overlying North Sea Supergroup caused reciprocal interference. The base of the North Sea Supergroup has been determined by deducting the thickness of the Chalk Group from the depth of the base of this group.

The Rijnland Group only occurs in two small parts of the map sheet area, where it is so thin that the group is difficult to identify on seismic logs. The Schieland Group is a unit with a large number of continuous reflectors. The group is encountered in complex tectonic structures.

In the Altena Group, three seismic units are identifiable in the Roer Valley Graben namely, top down, a unit with several reflectors frequently characterised at the base by a low-frequency band and two virtually reflector-less units, which are transected by a low-frequency band (the Posidonia Shale Formation). The base of the Altena Group is generally a prominent and continuous reflector.

The Permo-Triassic groups have been interpreted as a single unit exhibiting little difference in thickness. The unit often contains several continuous reflectors. The Zechstein and the Upper Rotliegend Groups here are so thin that they cannot be identified on the seismic profiles. Only in the northeastern part of the map sheet area is the Zechstein Group thick enough to enable seismic differentiation. The thickness

maps of the Zechstein Group and the Upper Rotliegend Group have therefore been principally derived from well-log data and knowledge of the regional geology. The base of the Permo-Triassic groups does not always permit easy interpretation, but this horizon can sometimes be recognised as a clear angular unconformity.

1.5 Biostratigraphic research

To clarify the geological research, use was made of a large number of biostratigraphic reports prepared within the framework of other research. A certain amount of supplementary biostratigraphic research was performed on units of the North Sea Supergroup and the Schieland and Limburg Groups (inter alia NITG-TNO 1998a, 1998b, 1999).

1.6 Petrophysical research

The reservoir rock characteristics within the map sheet area have also been taken into account. Well-log data and core analyses have been processed from 2 wells (Waalwijk Noord-1 and Waalwijk South-1) for the calculation of porosities; these have been categorised in appendix C. Appendix D exhibits a number of test data.

1.7 Geochemical research

A large number of vitrinite and RE analyses have been performed on the coal and potential source-rock of the Limburg Group in order to reconstruct the burial history and the petroleum geological development of the map sheet area. The procedures, the results of the analyses and the utilised modelling are discussed in section 15.1.

1.8 Maps and sections

The results of the mapping are shown on a scale of 1:250 000 in a series of depth maps and thickness maps of the lithostratigraphic units, on subcrop maps and in three sections (Maps 1 to 19). An overview of these units is given in figure 1.4. Depth maps have been plotted of the bases of the Upper Rotliegend, the Zechstein, the Lower Germanic Trias, the Altena, the Schieland, the Rijnland and the Chalk Groups, the North Sea Supergroup and the Upper North Sea Group.

The Upper Rotliegend and Zechstein Groups in the map sheet area are only thinly developed (0-50 m). The seismics are insufficient to map this interval separately. For the depth maps of the base of these groups, the base of the Lower Germanic Trias Group has therefore been taken, to which the thicknesses of the Zechstein Group and the Upper Rotliegend Group have been added.

Thickness maps were made of the Zechstein, the Lower and Upper Germanic Trias, the Altena, the Schieland, the Rijnland and the Chalk Groups. The depth and thickness maps only depict wells that have fully penetrated the interval in question (see section 1.2).

Subcrop maps have been made of the major unconformities at the bases of the Schieland and the Rijnland/Chalk Groups and the North Sea Supergroup, providing an impression of the degree of erosion preceding the deposition of these groups.

Finally, for both map sheets XIII and XIV, three structural sections with a NW-SE and SW-NE orientation have been depicted (Maps XIII-19 and XIV-19).

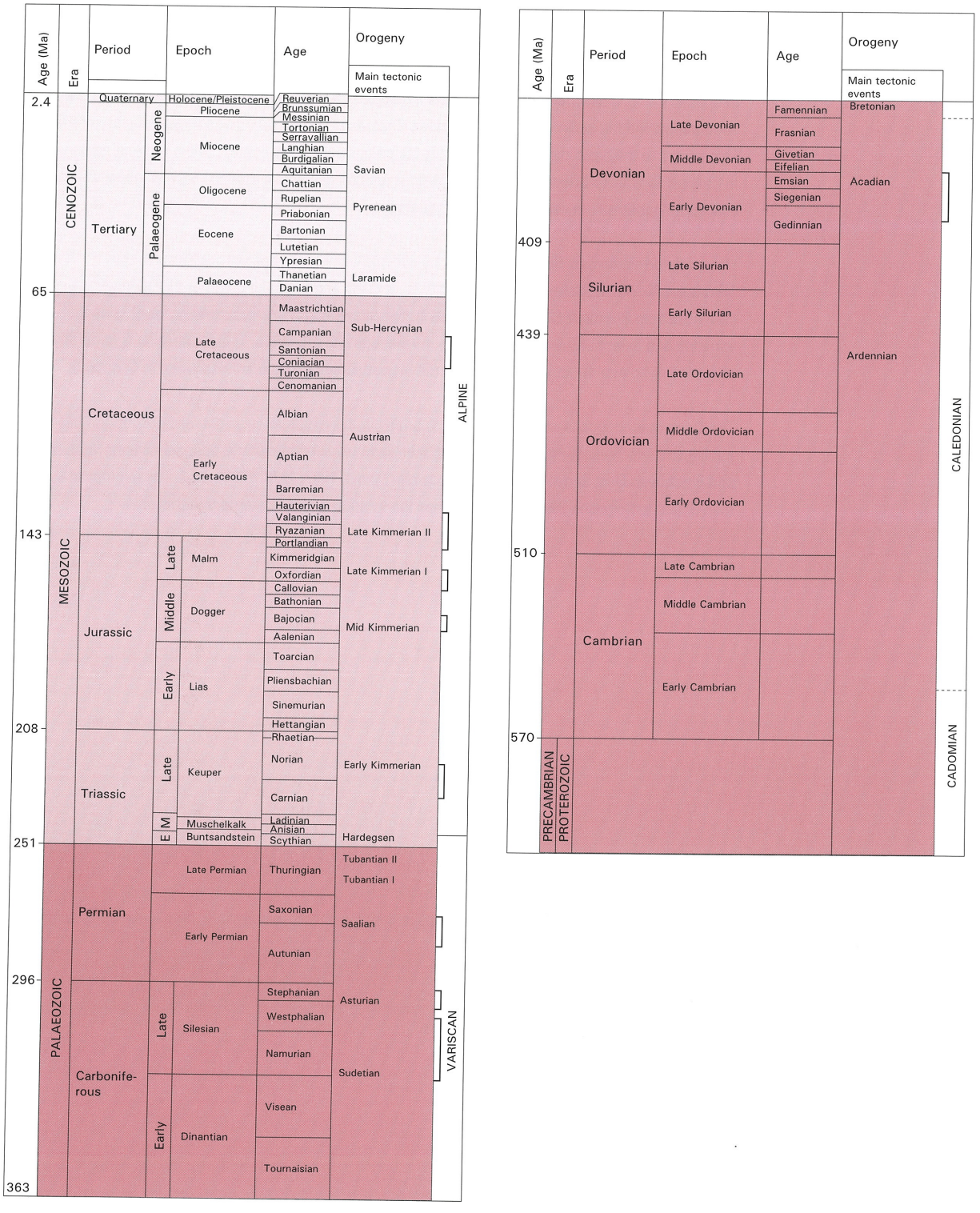


Figure 1.5 Geological timetable as used in the explanation. The tectonic phases which are referred to have been indicated in the figure.

1.9 Explanation

The explanation supplements the information provided by the geological maps and sections to form as complete a picture as possible of the geological structure and history of the map sheet area.
In Chapters 4-13, a description is given of the lithological successions, including an account of the lithostratigraphy and the sedimentary development. Chapter 14 focuses on the geological history of the area. This relates to the basin development and the tectonic events in the context of the regional tectonics.
In Chapter 15, special attention is given to various applied geological aspects, such as geochemistry, coal-bearing, petroleum systems and hydrogeology.

Unless stated otherwise, the lithostratigraphy and age of the units applied conforms to the "Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPA" (Van Adrichem Boogaert & Kouwe, 1993-1997). The lithostratigraphic descriptions emphasise the variation and extent of the different groups, formations and members. The distribution is generally related to the major structural elements of the map sheet area, which are described in Chapter 3.

The Quaternary deposits are only referred to briefly in this explanation. A detailed description has been published in de Toelichtingen bij de Geologische kaart van Nederland 1:50 000, map sheets Venlo West and Eindhoven Oost and West (Rijks Geologische Dienst, 1967, 1973, 1985 resp.). The geological surface map (Rijks Geologische Dienst, 1988) outlines the location of the Quaternary in this area.

2 Exploration history

Digging of peat by dry cutting began in the Peel and surrounding areas in the Middle Ages and went on until the middle of the nineteenth century. The ensuing exploration of coal in the area was initiated at the beginning of the twentieth century by the Dienst der Rijksopsporing van Delfstoffen (ROvD), with the investigation into the presence of exploitable quantities. The exploration of oil and gas subsequently became established by the middle of the century and led to the granting of a few concessions for the exploitation of natural gas and crude oil. In many places in the area, groundwater extraction from the surface is carried out. Finally, research into geothermal energy sources has been conducted.

2.1 Coal

On a basis of the presence of coal immediately across the border in Germany (Rheinland-Westfalen), surveys were carried out between 1903 and 1916 by the ROvD into the occurrence of exploitable quantities of coal in the Peel area. Thirteen deep wells and many shallow wells were placed. Based on the results obtained from these wells, the ROvD calculated the coal content of the Peel across an area of 19500 ha down to a depth of 1500 m with the maximum acceptable thickness of the overburden set at 900 m. This gave a figure of approximately 2500 million tons of coal, in seams of exploitable thickness (Van Waterschoot van der Gracht, 1918). During the Second World War, within the framework of the geologic research commissioned by the Gezamenlijke Limburgsche Steenkoolmijnen, a gravimetric survey was carried out in the Peel and adjacent area (De Sitter, 1949; Van Weelden, 1957). Half way through the twentieth century, twelve wells were drilled by the State Collieries.

In 1952, exploration of coal in the Peel area was intensified after the setting up of an advisory committee, which published a report of its findings eleven years later (Peelcommissie, 1963). The underlying geological research included shooting and interpreting 368 km of seismic data and drilling eight wells. These wells, which encountered the Carboniferous section at between 1100 and 1300 m, were almost completely cored. The commisssion calculated that in the areal extent studied to a depth of 1200 m, a geological coal stock of approximately 2100 millions of tons of coal occurs in coal seams over 50 cm thick. In the meantime, the construction of two shafts for the new Beatrix State Colliery was commenced here in 1952 (Kimpe, 1973). The advent of natural gas in the Netherlands (the Groningen gas field having been discovered in 1959 and concessions granted in 1963 after further evaluation had been conducted) and other parts of NW Europe, the low world-energy prices and the rising costs of coal exploration meant the collapse of coal mining in the Netherlands (Raedts, 1971). The construction of the Beatrix State Colliery was subsequently suspended in 1962.

In 1984, further investigations were carried out in the Peel area by the former Rijks Geologische Dienst (Geological Survey of the Netherlands) (RGD 1986; Pagnier et al., 1987), commissioned by the Ministry of Economic Affairs. Within the framework of this study, 7 seismic lines with a total length of 115 km were shot in the area. The results of the research confirmed the conclusions arrived at by the Peelcommissie. To the north of the Peel area, the Carboniferous section was also revealed to be represented by less productive coal-bearing seams of the Namurian and Westphalian A.

2.2 Oil and gas

The first hydrocarbon exploration (see section 15.2 for more information) in the map sheet area was carried out in 1944 by the Bataafsche Petroleum Maatschappij/Elwerath (BPM). However, this well, the Altforst-1, proved unsuccessful. After the war, the exploration was taken in hand by the NAM, which had drilled out a number of wells from 1949 to 1970. These wells were targeted at the southeastern extension of the oil finds in the Rijswijk concession. A limited number of successes were achieved: in the vicinity of Andel (in 1953) and in the Werkendam-1 well (in 1958), the Brabant Formation and

the Middle Werkendam Sandstone Member, respectively, were found to be oil-bearing. Attempts to trace this trend further into the Roer Valley Graben did not, however, produce the desired result (Asten-1, Dongen-1, Loon op Zand-1, Oisterwijk-1, Veldhoven-1, Waspik-1, Wijk-Aalburg-1). Nonetheless, oil traces were encountered in virtually all the wells in the Brabant or Werkendam Formation, though not in exploitable quantities. The wells drilled did not generally penetrate beyond the Aalburg Formation.

Fina drilled two wells in the Roer Valley Graben, Nederweert-1 (1965) and Sint Michielsgestel-1 (1969). Neither well was successful.

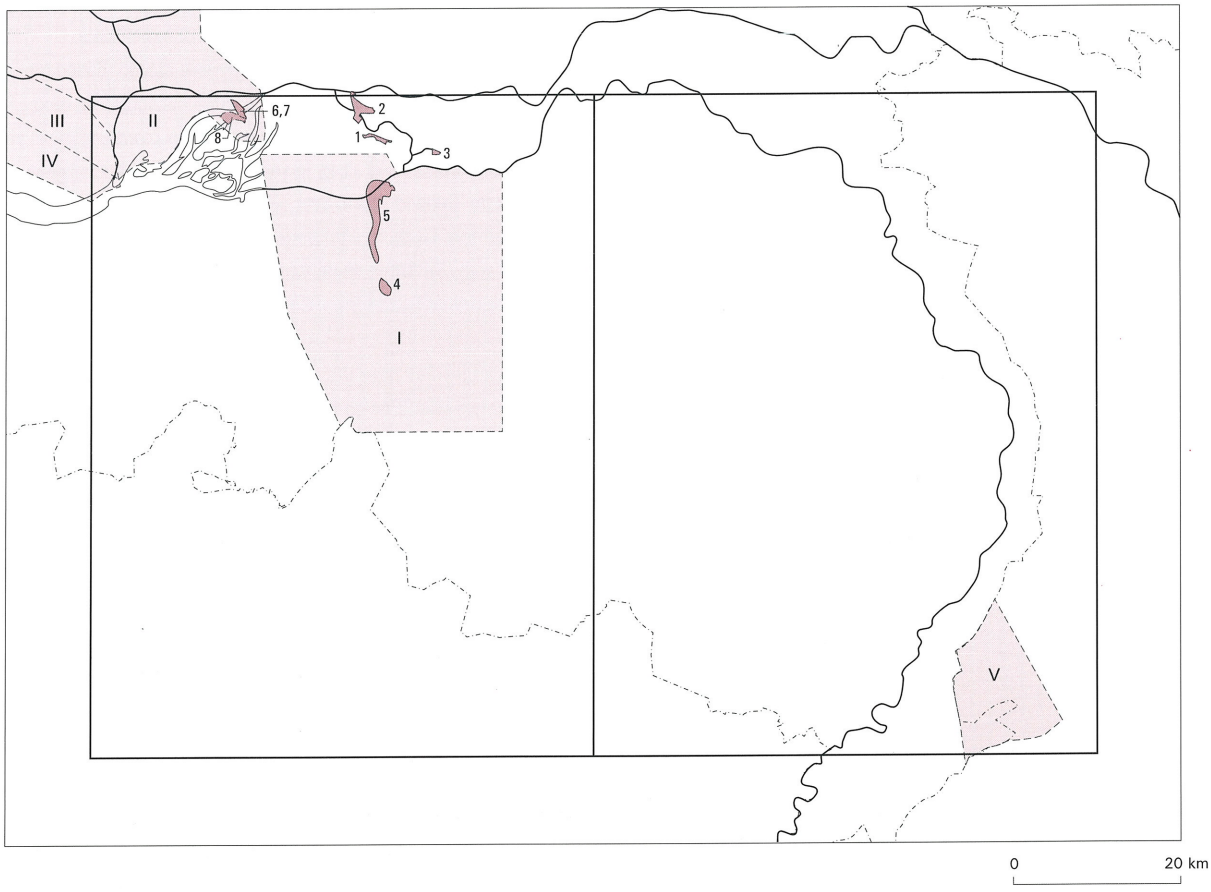


Figure 2.1 Overview map of the concession licence areas within the map sheet area.
I = Waalwijk concession, II = Rijswijk concession, III = Botlek concession, IV = Beijerland concession, V = Peel concession.
The following hydrocarbon accumulations have been encountered in the area:

1. Andel
2. Brakel
3. Kerkwijk
4. Loon op Zand
5. Waalwijk
6. Werkendam deep
7. Werkendam associated
8. Werkendam

In 1970, NAM drilled the only hydrocarbon exploration well in the Peel Block. This well, Grashoek-1, encountered oil traces in the Rupel Formation. This was also the case in older wells drilled by the ROvD (Van Waterschoot van der Gracht, 1918), as well as on the southwest flank of the Roer Valley Graben (Van Riessen & Vandenberghe, 1996).

Mid-1980, the exploration in the north of the map sheet area increased: a few wells were drilled by BP and Elf Petroland which, however, proved to be dry (Sprang-Capelle-1 and Steelhoven-1, respectively). The discovery by BP of natural gas in Triassic sandstone (Röt Formation and Main Buntsandstein Subgroup) in the Waalwijk-1 well in 1987 heralded a new phase in the exploration in the map sheet area. The focus of interest shifted from oil to gas. Supplementary wells and 3D seismic data have revealed that the Waalwijk field comprises two occurrences: Waalwijk-Noord and Waalwijk-Zuid (Winstanley, 1993). A concession for the exploitation of natural gas was granted in 1989.

After Waalwijk, the exploration of the Roer Valley Graben was continued: the Broekzijde-1, Heeswijk-1, Hilvarenbeek-1 and Keldonk-1 wells were drilled, initially by BP and later by Clyde, but none of these wells encountered gas. Exploration in the transition area of the Roer Valley Graben to the West Netherlands Basin achieved greater success. In a number of cases, gas was encountered in the Triassic sandstone, below the previously demonstrated oil occurrences, for example in the vicinity of Andel and Werkendam. Gas occurrences were also revealed by the Kerkwijk-1 and Brakel-1 wells.

In addition to the above-mentioned companies, Mobil also engaged in exploration activities in the area, while not actually drilling out any wells.

2.3 Groundwater

The Roer Valley Graben exhibits various aquifers, which are separated by poorly permeable sequences (see section 15.3 for more information). Here, the drinking water is principally extracted from the deeper (up to 400 m depth) coarse sands of the Kieseloolite Formation (Pliocene). These aquifers generally have an infiltrate area a considerable distance away (from the adjacent area in Germany) and the extracted water is therefore of a comparatively great age (Van Rooyen, 1989). In addition, in many places in the area, groundwater is extracted from the youngest continental formations, which are of Quaternary age.

2.4 Geothermal energy

Within the framework of geothermal research, the Asten-2 well was drilled in 1986-1987 by TNO-GG and the RGD (Heederik & Huurdeman, 1988, TNO-GG 1989). The aim was to ascertain the geothermal reserves of four potential reservoirs in the Tertiary. These four reservoirs are the Breda Formation (850-950 m), the Voort Sand (1050-1250 m), the Basal Dongen Sand (1500-1550 m) and the Houthem Formation (1630-1670 m). Particularly in the case of the deepest reservoir, and therefore with the greatest expectations, the assumption was that extra reservoir capacity would have been facilitated by karstification of the limestones in this formation. However, the Houthem Formation here proved to exhibit little or no karstification. In consequence, insufficient warm water was produced by this reservoir, which meant that exploitation would not be profitable.

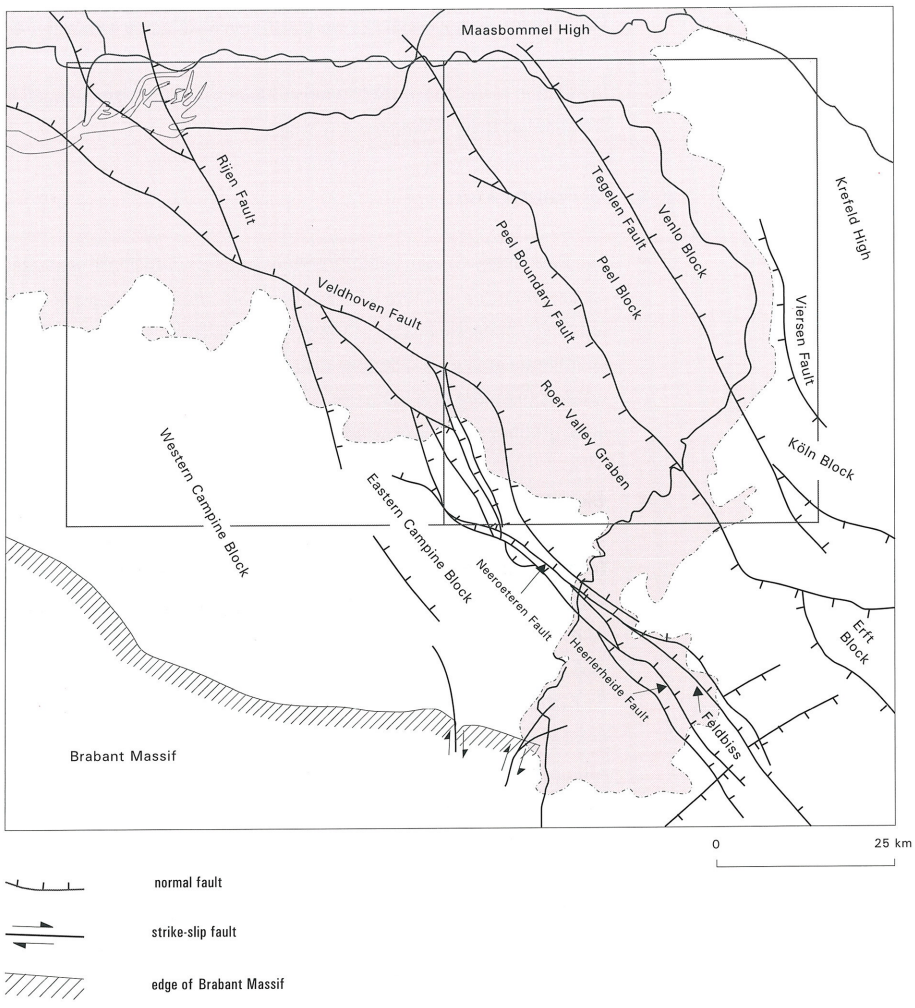
Within the framework of the mapping of this map sheet, the temperature data from the Asten-2 well and various coal and oil/gas exploration wells were modelled, resulting in changes to the geothermal map of the Netherlands at 2000 m (see section 15.4 for more information).

3 Structural framework

The geological history is illustrated by the structural elements differentiated in the map sheet area (fig. 3.1). The structural pattern is determined by the NW prolongation of the Rhine Graben, which is manifested by a system of thrust planes. These units comprise, to a greater or lesser degree, Variscan elements which were reactivated and modified during later tectonic phases. The map sheet area is dominated by a major graben, the Roer Valley Graben, and a number of high blocks forming the shoulders of the graben: the Eastern and the Western Campine, the Köln, the Peel and the Venlo Blocks and the Krefeld High.

The **Roer Valley Graben** is the most conspicuous element within the map sheet area. This NW-SE trending graben is characterised by periods of pronounced differential subsidence during the Triassic, Jurassic and from the Oligocene on. During the Late Jurassic pronounced differential subsidence took place in the NW part of the Roer Valley Graben. Inversion occurred during the Sub-Hercynian phase (Coniacian-Campanian). The erosion cut deep down as far as the deposits of the Lower Jurassic or the Triassic (Maps XIII/XIV-17). The Roer Valley Graben is defined by a number of prominent fault structures,

Figure 3.1 Structural units in the map sheet area.



the most prominent of which is the **Peel Boundary Fault** or **Peelrand Fault** (known in Germany as the "**Rurrand Sprung**") on the northeastern flank. Along this fault zone, at the base of the Tertiary, normal faults occurred of as much as 1000 m. At this level, the southwestern flank of the graben is bounded by several faults with a smaller offset, including the **Feldbiss** and the **Neeroeteren**, the **Hamont-Bocholt** and the **Rijen Faults**.

The **Campine Basin**, originating during the Variscan Orogeny, is a structure on the margins of the Roer Valley Graben and the Brabant Massif, which was differentiated by the absence of a comparatively young Carboniferous succession of the Brabant Massif and the Peel Block. The history of the development of this basin is principally related to the erosion of the flanks, and only in the youngest Westphalian, to sedimentation.

The **Eastern** and **Western Campine Blocks**, to the SW of the Feldbiss, are characterised by pronounced erosion during the Late Kimmerian period phases in the Late Jurassic/Early Cretaceous. During the Late Cretaceous, these blocks underwent relatively pronounced subsidence in relation to the Roer Valley Graben, whereas the subsidence during the Cenozoic was relatively slight. On the Eastern Campine Block, sediments of the Zechstein and the Lower and Upper Germanic Trias Groups are still found. The **Beringen Fault Zone** separates the Eastern and Western Campine Blocks, where deposits of the Chalk Group rest directly upon the Limburg Group. This fault zone comprises the Beringen, the Hoge Mierde and the Rauw Faults.

On the **Peel**, the **Venlo** and the **Köln Blocks** and the **Krefeld High,** to the north east of the Peel Boundary Fault, pronounced erosion took place during the Late Kimmerian phases. These blocks were subsequently distinguished by pronounced subsidence during the Late Cretaceous, followed by relatively slight subsidence during the Cenozoic with respect to the Roer Valley Graben. The first two blocks mentioned are separated by the **Tegelen Fault**; they are distinguished from each other by the more pronounced Neogene and Quaternary subsidence of the Venlo Block which is accordingly also referred to during this period as the Venlo Graben. Both blocks pass in a northwesterly direction into the **Maasbommel High**; during the Late Kimmerian phase, this high underwent deep erosion reaching as far as the level of the Carboniferous, followed by pronounced subsidence during the Late Cretaceous. On the **Krefeld High**, all the Permian and Mesozoic deposits were removed by erosion, as were many of the Upper Carboniferous deposits. The **Viersen Fault** here marks the separation from the Venlo Block.

In the extreme northwest of the map sheet area, the Roer Valley Graben runs into the **West Netherlands Basin**. This transition is difficult to indicate precisely, but is generally reflected by a change in the direction of the faults from NW-SE to a more WNW-ESE trending direction. In addition, the pronounced Tertiary subsidence, which characterises the Roer Valley Graben, diminishes significantly.

The **Central Netherlands Basin** is situated to the north of the Maasbommel High. This basin displayed strong differential subsidence in the Permian-Early Cretaceous period. During the Late Cretaceous, the basin became strongly inverted, with the result that virtually the entire Jurassic-Cretaceous succession has been removed by erosion.

The **Brabant Massif**, situated to the south and southwest of the map sheet area, is characterised by the occurrence of Caledonian folded Cambro-Silurian deposits immediately below the Chalk Group. During the Devonian and the Early Carboniferous, this massif was a high. After being partly covered by Upper Palaeozoic and Lower Mesozoic sediments, pronounced uplift resumed at the end of the Jurassic. During the Late Cretaceous, the massif was once again covered by sediments.

4 Cambro-Silurian, Banjaard group and Carboniferous Limestone Group

4.1 Introduction

While deposits older than the Limburg Group have not been penetrated within the map sheet area, they have, however, been encountered to the immediate east and south and have consequently been described in this explanation. The deposits comprise dark, dolomitised and silicified limestone of the Carboniferous Limestone Group (Early Carboniferous), clastic deposits of the Banjaard group (Late Devonian), clastic deposits and chalks of the Middle Devonian, dark shales of Silurian or Ordovician age and quartzites and schists of Cambrian to Silurian age.

The depth of the top of the pre-Upper Carboniferous deposits displays great variation (fig. 4.1). To the east of the map sheet area, these are encountered on the Krefeld High at a depth of 250 m (Hilden, 1988), while the depth in the Roer Valley Graben is presumed to exceed 10000 m (Bless et al., 1976). To the west and southwest of the Roer Valley Graben, the top of the Carboniferous Limestone Group is at depths of 3000 to 5000 m (fig. 4.1).

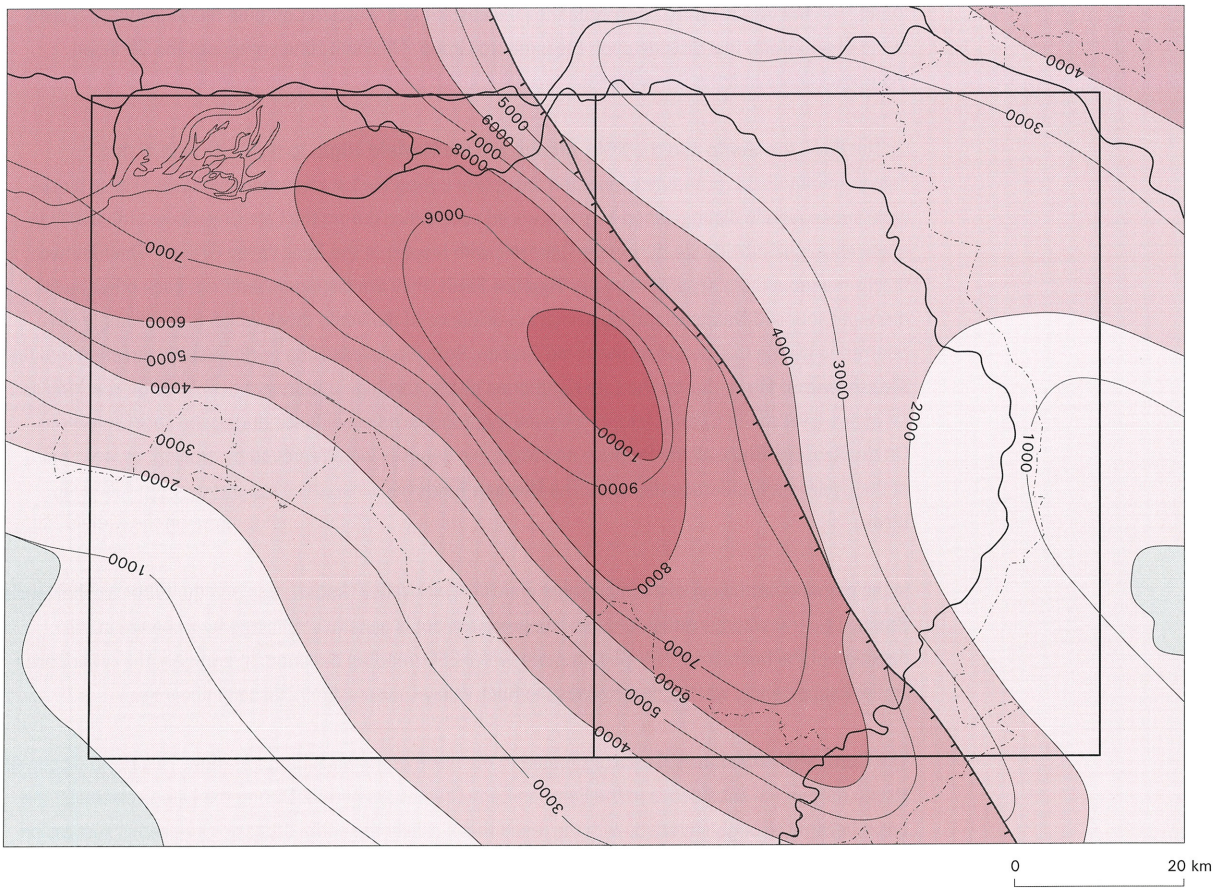


Figure 4.1 Depth map of the top of the Carboniferous Limestone Group. This map is based on literature and well-log data (Bless et al. 1976, Rijks Geologische Dienst 1984). Notice the great variations in the depth, which are indicative of the pronounced tectonic deformation. The top of the group is at a depth ranging from less than 500 m immediately to the east of the map sheet area to over 10000 m in the Roer Valley Graben.

4.2 Cambro-Silurian

Deposits of the pre-Devonian have been penetrated on the Brabant Massif (Legrand, 1968; De Vos et al. 1993). They consist of Caledonian folded shales, sandstones and quartzites of Cambrian to Silurian age. Ordovician rocks 50 km to the east of the map sheet area have also been documented (Soest-Erwitte-1/1A well; Clausen & Leuteritz, 1982). It may therefore be concluded that Silurian and Ordovician deposits also occur below the southern part of the map sheet area.

The Silurian/Ordovician deposits consist of dark, fine-grained shales containing intercalated thin, fine-grained sandstones. The fossil content and the sedimentological characteristics are indicative of a deep-water setting and deposition from turbidity currents (Verniers & Van Grootel, 1991). The Silurian/Ordovician deposits are unconformably overlain by the Devonian deposits.

4.3 Devonian

Devonian deposits have been encountered to the south and east of the map sheet area, and consequently are also assumed to occur below the entire map sheet area. These deposits, found on the Krefeld High and in the Namen Synclinorium, are coarse-clastic and comprise Middle and lowermost Upper Devonian. These deposits have not been defined in the Dutch lithostratigraphy. This Devonian succession is overlain by the Banjaard group.

4.3.1 Middle and lowermost Upper Devonian

The oldest deposits of the Devonian have been penetrated on the Krefeld High. They rest unconformably upon folded Cambrian-Silurian sediments and are overlain by the Banjaard group. The succession has been described by Ribbert (1998a,b). In the Viersen-1001 well, the deepest unit reached was a conglomerate consisting of phyllite (thickness > 100 m), followed by a claystone sequence with a thickness of approximately 250 m, containing intercalated thin sandstones and limestones. This sequence is of Givetian age (Ribbert, 1998a). The conglomerate was deposited in a shallow-marine environment to the west of the Krefeld High. The lithological succession indicates that folded Early Palaeozoic sediments on the high were outcropping (Neumann-Mahlkau & Ribbert, 1998). On the flank of the London-Brabant Massif, a 400 m-thick conglomerate has been identified (Booischot well; Legrand, 1968; Kimpe et al., 1978). This conglomerate, Frasnian in age, is partly younger than the conglomerate on the Krefeld High.

These clastic deposits are overlain by an over 400 m thick sequence, of Frasnian age (Ribbert, 1998b), consisting of reefal and nodular limestone and claystone. The carbonate component increases upwardly. To the north of the Brabant Massif, this sequence is over 100 m thick (Loenhout-Heibaart well; Kimpe et al., 1978). The sequence was deposited on a vast carbonate platform to the north of the Brabant Massif (Drozdzewski et al., 1998). During the Late-Devonian, the sedimentation area extended over the massif.

4.3.2 Banjaard group

The deposits of the Banjaard group in the area, of Famennian age, are represented by the *Condroz Sandstone*. This sandstone has been encountered in a number of German wells, including Wachtendonk-1 (Wolburg, 1963, 1970; Elberskirch & Wolburg, 1962) and Viersen-1001 (Ribbert, 1998a). The unit is also found on the northern flank of the Brabant Massif in the Loenhout-Heibaart well (Kimpe et al., 1978). The unit reaches a thickness of over 400 m in the Viersen-1001 well and in a northerly and westerly direction diminishes to approximately 200 m in the Wachtendonk-1 well and

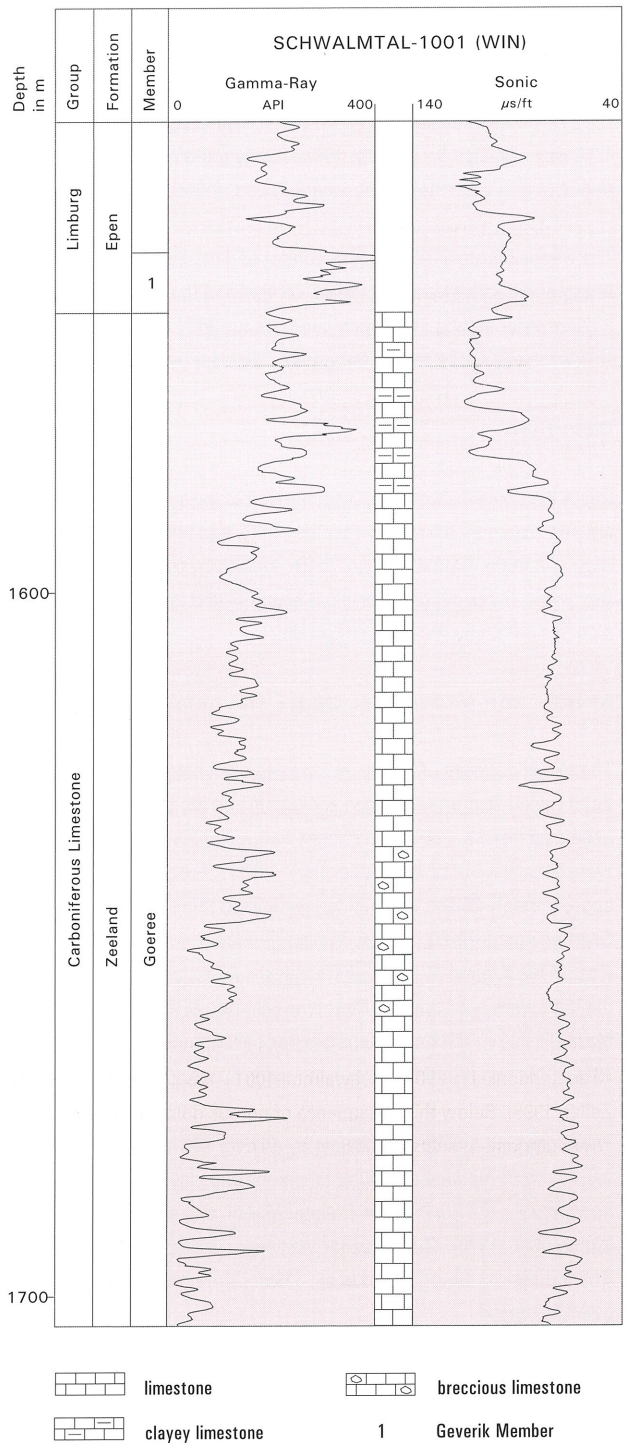


Figure 4.2 Stratigraphic division and log characteristics of the uppermost part of the Carboniferous Limestone Group in the Schwalmtal-1001 well. The succession here is overlain by the Epen Formation, separated by a hiatus, with the organic-rich deposits of the Geverik Member at the base.

136 m in the Loenhout-Heibaart well (Bless et al., 1976). To the southwest of the map sheet area, the sandstone rests unconformably on folded Cambro-Silurian deposits. The Condroz Sandstone was deposited in a tidally-influenced shallow-marine environment on the northern flank of the Rhenohercynian Basin (Ribbert, 1998a; Thorez et al., 1988; Ziegler, 1990).

4.4 Carboniferous Limestone Group

While deposits of the Carboniferous Limestone Group have not been identified within the map sheet area, they have however been encountered immediately beyond its areal extent. The top of the group forms a prominent, clearly distinguishable, high amplitude reflection, which is recognisable on seismic sections in the southwest and east of the area. The deposits are part of the *Zeeland Formation.* In Belgium, these limestones are known as the Campine Limestone. In the greater part of the area, the formation is conformably overlain by the Limburg Group. To the east of the map sheet area, the Chalk or the Middle North Sea Group rests unconformably upon the Carboniferous Limestone Group (Elberskirch & Wolburg, 1962). On the northern flank of the Brabant Massif, the Limburg Group rests unconformably upon the group. The base of the Carboniferous Limestone Group is diachronous: on the Krefeld High and to the east of the Brabant Massif, the oldest deposits are of Tournaisian age, whereas on the northern flank of the Brabant Massif, they are Viséan.

The Carboniferous Limestone Group has only been fully penetrated in the Loenhout-Heibaart well, where it is over 300 m thick. This, however, was a well on a local high, where the group exhibited a thinner and less complete development. The youngest Viséan in particular is absent here (Bless et al., 1976). In the nearby Turnhout-1 well, a succession exceeding 540 m of Viséan age was encountered, but the base was not reached, (Bless et al., 1976). The group here consists of light-grey limestone with intercalations of oolites and breccia-intervals. The top of the group, comprising dolomites of $V_{3\alpha}$ and $V_{3\beta}$ age, is strongly karstified and has clear reservoir potential in this area. The limestone becomes more fine-grained towards the base (Bless et al., 1976).

In the German wells, only incomplete successions were encountered, strongly resembling the Belgian sections. The youngest unit reached was a light-grey, partly oolitic limestone of Viséan age (Wachtendonk-1: >290 m, Schwalmtal-1001 >155 m; Bless et al., 1976; Elberskirch & Wolburg, 1962; Zeller, 1998). Below this, a sequence of porous dolomite was encountered, probably of Tournaisian age (Wachtendonk-1: >128 m; Bless et al., 1976).

The above-mentioned well logs in Belgium and Germany suggest substantial thicknesses of the Carboniferous Limestone Group in the map sheet area. The deposits of the Viséan in particular are presumed to be better developed, with $V_{3\gamma}$ and $V_{3\delta}$ deposits also occurring. The top of the group is expected to exhibit no karstification, or at any rate less than on the highs, where the wells have been placed. Seismic sections indicate the likelihood that in the Peel- and Venlo Blocks, a situation analogous to the northern flank of the Brabant Massif pertains and suggests that more severe karstification may be expected.

Deposition of the Carboniferous Limestone Group occurred on a vast carbonate platform, which extended around the Brabant Massif (Lokhorst, 1998) on the northern margin of the Rhenohercynian Basin (Ziegler, 1990). The deposition of carbonates here took place in a shallow, locally high-energetic setting. During the deposition, a transgression spread across the London-Brabant Massif, indicated by the diachronous character of the base of the Carboniferous Limestone Group.

4.5 Petrophysical data

No hydrocarbons have been found in the pre-Upper Carboniferous deposits in the area. On the northern flank of the Brabant Massif, however, the Carboniferous Limestone Group has proved to have good reservoir characteristics. This potential is being exploited in Belgium in, for example, underground gas storage in Loenhout-Heibaert and the geothermal Merksplas well. The so-called V_3 (Warnantian) deposits of the group in particular are characterised by good permeability, owing to palaeo-karstification. The data presented here have been derived from the literature. The average matrix porosity of the carbonates is low, around the level of 3-4%; the permeability is around 10 to 30 mD (Rijks Geologische Dienst, 1984). The maximum porosity, determined from logs, is 22% (Vandenberghe et al., 1986). Of greater importance, however, is the local permeability of 2-5 D. This arose through a system of fissures and solution cavities resulting from karstification. The open fissures have a diameter of 2 mm to 1 cm (Vandenberghe et al., 1986).

It is anticipated that in the greater part of the map sheet area, the Carboniferous Limestone Group displays less favourable characteristics; these have been revealed, amongst others, in the Geverik-1 well to the north of Maastricht (see, inter alia, NITG-TNO, 1999). Only on the Peel and Venlo Blocks are favourable characteristics anticipated, analogous to those in northern Belgium.

5 Limburg Group

5.1 Stratigraphy

The Limburg Group, of Namurian-Westphalian age, represents the Upper Carboniferous (Silesian). The Limburg Group is composed of an alternation of predominantly grey to black claystones, siltstones and sandstones, which are also red coloured in the youngest part with, especially in the middle part, a large number of intercalated coal seams. The group is subdivided into four subgroups. Each represent a particular phase of the Late Carboniferous regressive megasequence. The basal part, the Geul Subgroup, is characterised by several fossil-bearing marine bands in a predominantly fine-grained succession. The characteristic lithologies of the Caumer Subgroup are dark coloured claystone beds and coal seams. The Dinkel Subgroup consists largely of sandstone. Lastly, the Hunze Subgroup is composed mainly of

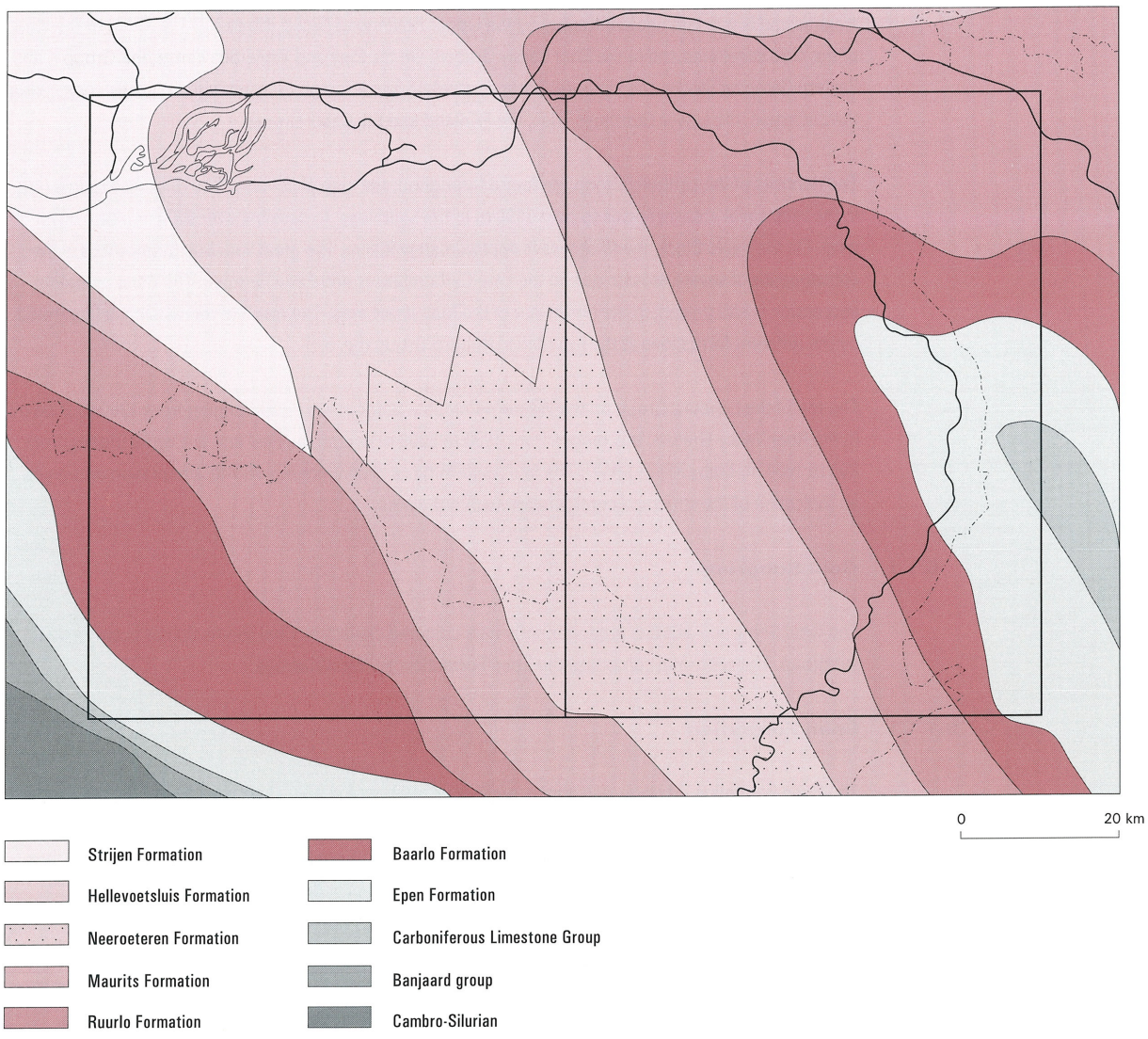


Figure 5.1 Subcrop map of the top of the Limburg Group. The map is based on Van Adrichem Boogaert & Kouwe (1993-1997, fig. C5), supplemented with new data derived from the current mapping.

red coloured claystones and in the map sheet area is only found on a limited scale. To illustrate the lithostratigraphy more clearly, marine bands and coal seams have also been correlated to give a better understanding of the chronostratigraphic relations pertaining.

The subdivision of the Limburg Group into formations is essentially based on log characteristics. However, on the Peel and the Venlo Blocks, a large number of older wells occur which have not been logged. To permit nonetheless a subdivision of these, often long, Carboniferous sequences, the following marine bands or coal beds have been adhered to as boundary markers. The Sarnsbank Marine Band for the Epen-Baarlo boundary (or the deepest coal seam), the Merl Band or the GB 13 coal seam for the boundary between the Baarlo and the Ruurlo Formations, and the Domina Marine Band for the boundary between the Ruurlo and the Maurits Formations.

The Limburg Group in the map sheet area rests upon the Carboniferous Limestone Group separated by a hiatus and is overlain unconformably by the Upper Rotliegend Group (Maps XIII-1 & XIV-1) in the west of the map sheet area and in the Roer Valley Graben. On the Peel and Venlo Blocks and the Western and Eastern Campine Blocks, the Limburg Group is overlain unconformably by younger deposits comprising the Zechstein, the Lower Germanic Trias, the Rijnland and the Chalk Groups.

The deposits of the Limburg Group are found throughout the map sheet area. The thickness of this unit in the map sheet area increases to over 3000 m in the southwest to possibly over 6000 m in the northwest. On the Venlo Block, the thickness is approximately 900 m. The great variation in thickness is the consequence of severe erosion during the Late Carboniferous and Early Permian. The most complete succession is still present in the northwest of the map sheet area. The result of the erosion is illustrated by the different formations at the top of the Limburg Group (fig. 5.1)

The top of the Limburg Group on the Western Campine Block is at a depth ranging from 1200 to 2000 m. In the Roer Valley Graben, this ranges from 1000 to 5000 m and on the Peel and the Venlo Blocks, from 800 to 1600 m (Maps XIII-1, XIV-1). The fault pattern has a predominantly NW-SE orientation and gives an indication of the structural configuration within the area.

5.1.1 Geul Subgroup

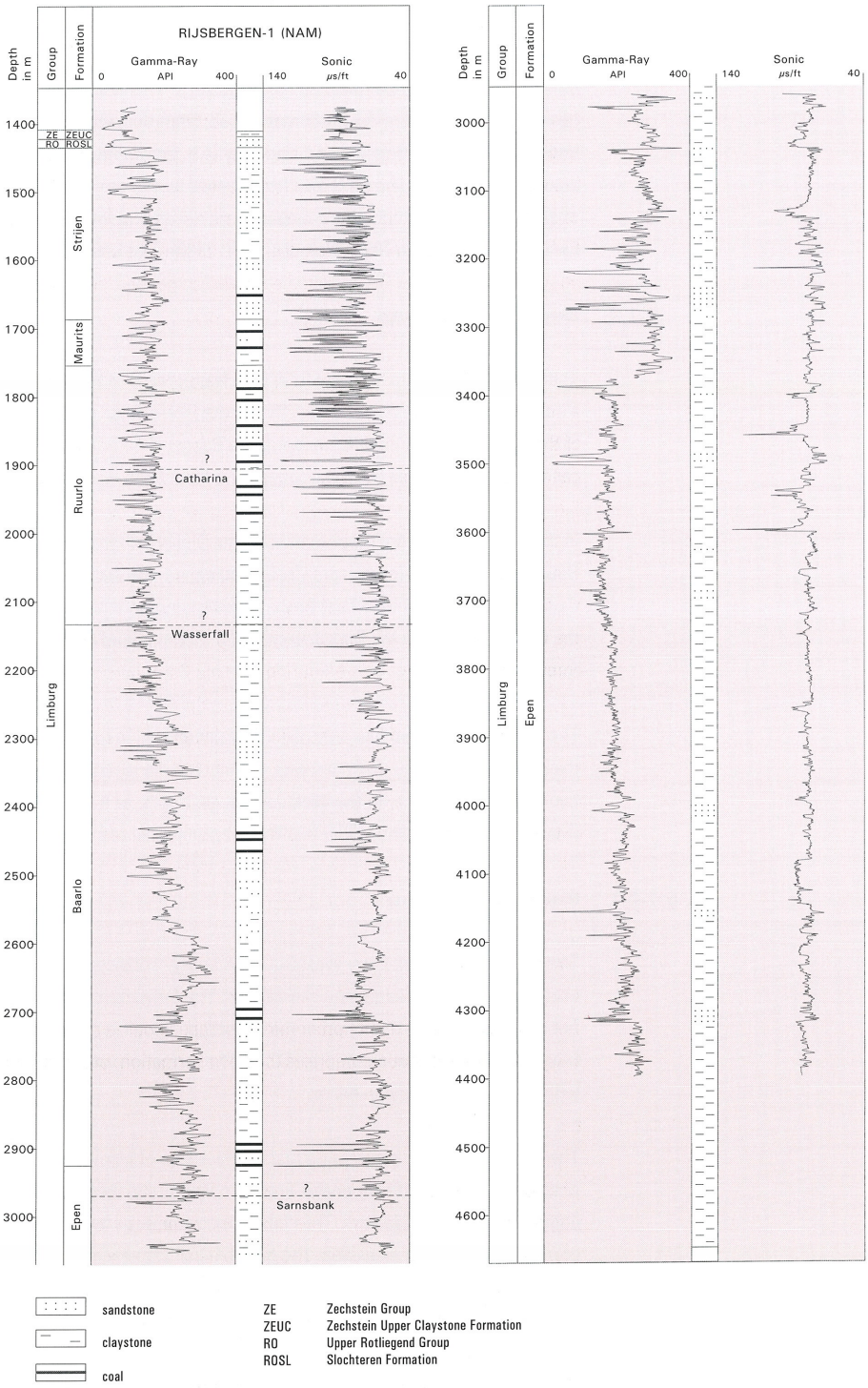
The Geul Subgroup exhibits predominantly dark coloured claystone. Coal seams do not occur in this subgroup. The subgroup comprises the Epen Formation, of Namurian age.

5.1.1.1 Epen Formation

The Epen Formation, of Namurian age, is present throughout the map sheet area. However, the formation has been penetrated by only a few wells owing to its great depth (e.g., Rijsbergen-1 and Belfeld-14). Comparable deposits have been described in documentation from South Limburg (e.g. Van Adrichem Boogaert & Kouwe, 1993-1997), the Campine Basin (Langenaeker & Dusar, 1992) and Germany (Drozdzewski et al., 1985). The formation rests unconformably upon the Carboniferous Limestone Group and is overlain either conformably by the Baarlo Formation (e.g. in Rijsbergen-1) or unconformably by younger formations (e.g. the Houthem Formation in Belfeld-14). The thickness of the Epen Formation increases from around 800 m in Campine Basin to over 1700 m in the north of the map sheet area.

The Epen Formation consists predominantly of dark coloured claystone and siltstone and only a very small percentage comprises sandstones. In a southwesterly direction, the proportion of sand increases (Langenaeker & Dusar, 1992). The formation is characterised by the frequent occurrences of beds

Figure 5.2 Stratigraphic division and log characteristics of the Limburg Group in the Rijsbergen-1 well. The principal marine bands have been indicated.



containing marine fossils. These beds are situated at the base of cyclical successions of coarsening-upward sequences with a thickness of 50 to 100 m. A sandstone sequence, ranging in thickness from a few metres to over 10 m, forms the top of the sequences. Within the formation in the map sheet area, only the *Geverik Member* has been distinguished. This unit is situated at the base of the formation and has not been reached in the Rijsbergen-1 well. From documentation on the Geverik-1 well (South Limburg) and various wells in Belgium and Germany (e.g. Schwalmtal-1001, fig. 5.4) adjacent to the map sheet area, this member is known to be characterised by the occurrence of *hot shales* (claystones with a high organic material content) alternating with siltstones and fine-grained sandstones (RGD 1987a; Langenaeker & Dusar, 1992; Wolburg, 1963, 1970). This unit is locally 50 to 100 m thick.

5.1.2 Caumer Subgroup

The Caumer Subgroup, ranging from Late Namurian C to Early Westphalian C in age, is composed of a succession of dark coloured claystones with intercalated sandstones and coal seams. The Caumer Subgroup comprises three formations, the Baarlo, the Ruurlo and the Maurits, which all occur throughout the map sheet area, with the exception of the Venlo Block and the Krefeld High (fig.5.1).

In the central part of the map sheet area, the Dinkel Subgroup rests conformably upon the Caumer Subgroup. In the southwest, the Upper Rotliegend, the Zechstein or the Chalk Groups rest upon the Caumer Subgroup. On the Peel Block, the overlying units are the Upper Rotliegend, the Zechstein or the Chalk Groups. On the Maasbommel High, the Rijnland Group rests unconformably upon the Caumer Subgroup.

The Caumer Subgroup has only been fully penetrated in the Rijsbergen-1 well (fig. 5.2), where it has a thickness of over 1200 m. In this well, a fault (Van Adrichem Boogaert & Kouwe, 1993-1997) may have had a strong influence on the thickness development, as it has been documented from the literature (Stancu-Kristoff & Stehn, 1984) that the subgroup may reach a thickness of 2000 m.

5.1.2.1 Baarlo Formation

The Baarlo Formation, Early Westphalian A in age, consists of dark coloured claystone with frequent occurrences of coal seams and sandstones. The formation is present throughout the map sheet area, but has only been encountered in the Rijsbergen-1 well, a number of wells in Belgium (Langenaeker & Dusar, 1992) and wells on the Peel Block. The formation was fully penetrated in the Rijsbergen-1 well, with a thickness of nearly 800 m.

The sandstones in this formation reach a thickness of 30 m and occur predominantly at the top of coarsening-upward sequences. From the Peel wells, these sandstones are known to contain various conglomeratic intercalations. The coarsening sequences have a thickness ranging from a few tens of metres to 300 m on occasion. The base of such sequences, contain claystones with marine to brackish-water fossils (goniatites, *Lingula*).

5.1.2.2 Ruurlo Formation

The Ruurlo Formation, of Westphalian A to Early Westphalian B age, comprises a thick succession of predominantly light-grey silty or argillaceous claystones with intercalated coal seams and grey to pink sandstone beds. In the formation, while fining-upward sequences prevail, there are also a few coarsening-upward sequences. The sandstones reflect channel sandstone deposits as well as sand layers developed with good lateral continuity.

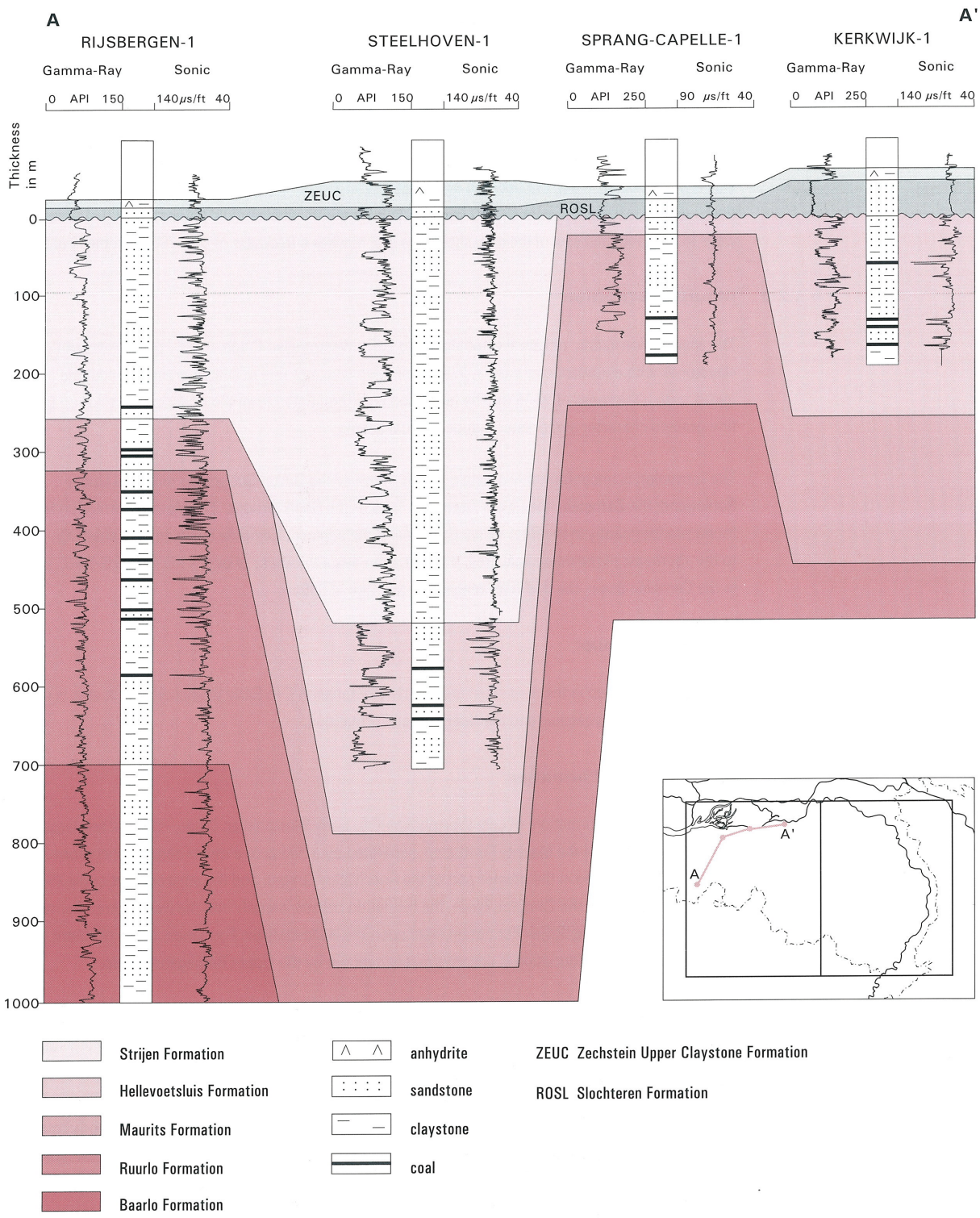


Figure 5.3 Stratigraphic section A-A' of the Limburg Group between the Rijsbergen-1, Steelhoven-1, Sprang-Capelle-1 and Kerkwijk-1 wells. The reference level is the base of the Upper Rotliegend Group.

The formation rests conformably on the Baarlo Formation and is also overlain conformably by the Maurits Formation or unconformably by the Upper Rotliegend, the Zechstein or the Chalk Groups (fig. 5.3 & 5.4). The formation is found virtually throughout the map sheet area but is absent on the northern rim of the Brabant Massif, on the Venlo Block and the Krefeld High. The Ruurlo Formation contains the equivalents of two major marine bands, namely the Catharina Marine Band, which reflects the Westphalian A/B boundary, and at the top of the formation the Domina Marine Band, at the boundary of the Lower and Upper Westphalian B (fig. 5.4). The Catharina Marine Band is clearly identifiable from well logs (Schuster, 1968), but because of the scarcity of logged wells in the map sheet area, its correlation potential is here limited in extent. The Ruurlo Formation has been fully penetrated in the various wells in the south and east of the map sheet area and reaches a thickness of over 700 m on the Peel Block.

5.1.2.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Early Westphalian C age, mainly comprises light-grey claystones with abundant coal seams. In addition, thin layers of fine to coarse-grained sandstone are found, with a thickness of 10-15 m. The formation is differentiated from the underlying formation by its fine-grained character and greater number of coal seams.

The formation is unconformably overlain by the Hunze or the Dinkel Subgroups or by the Upper Rotliegend, the Zechstein, the Lower Germanic Trias or the Chalk Groups. The Maurits Formation is found predominantly in the Roer Valley Graben and the adjacent Campine Basin. In map sheet XV, to the southeast of the map sheet area, the formation has a thickness of over 1100 m (NITG-TNO, 1999). In the Campine Basin, the thickness reaches an average of 900 m.

5.1.3 Dinkel Subgroup

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

5.1.3.1 Hellevoetsluis Formation

The Hellevoetsluis Formation, of Late Westphalian C to Early Westphalian D age, is composed largely of sandstone and lies on the Maurits Formation, separated by a hiatus or a minor angular unconformity. The formation is found in the greater part of the Roer Valley Graben and the adjacent part of the West-Netherlands Basin. In the Campine Basin, the formation passes laterally into the Neeroeteren Formation. In the western part, the Strijen Formation rests upon the Hellevoetsluis Formation. In the northern part of map sheet XIII, the formation is unconformably overlain by the Upper Rotliegend Group (fig. 6.1, Map XIII-1).

The formation comprises an alternation of sandstone beds 10 to over 30 m thick, even reaching 100 m in the central part of the formation. The individual sandstone beds are separated by 5 to 40 m thick claystone/ siltstone intervals (fig. 5.3). Sandstone beds constitute 50% to 80% of the formation. The lithology consists of medium-coarse, very fine to conglomeratic immature sandstone, comprising poorly rounded grains, predominantly light-grey in colour. In the map sheet area, the Hellevoetsluis Formation has been encountered in five wells in the Roer Valley Graben, with a maximum thickness of 200 m.

5.1.3.2 Neeroeteren Formation

The Neeroeteren Formation, of Westphalian D age, consists of massive, white, coarse-grained to gravel-bearing, arkosic sandstones with fine-grained material and the occasional coal seam. This unit is

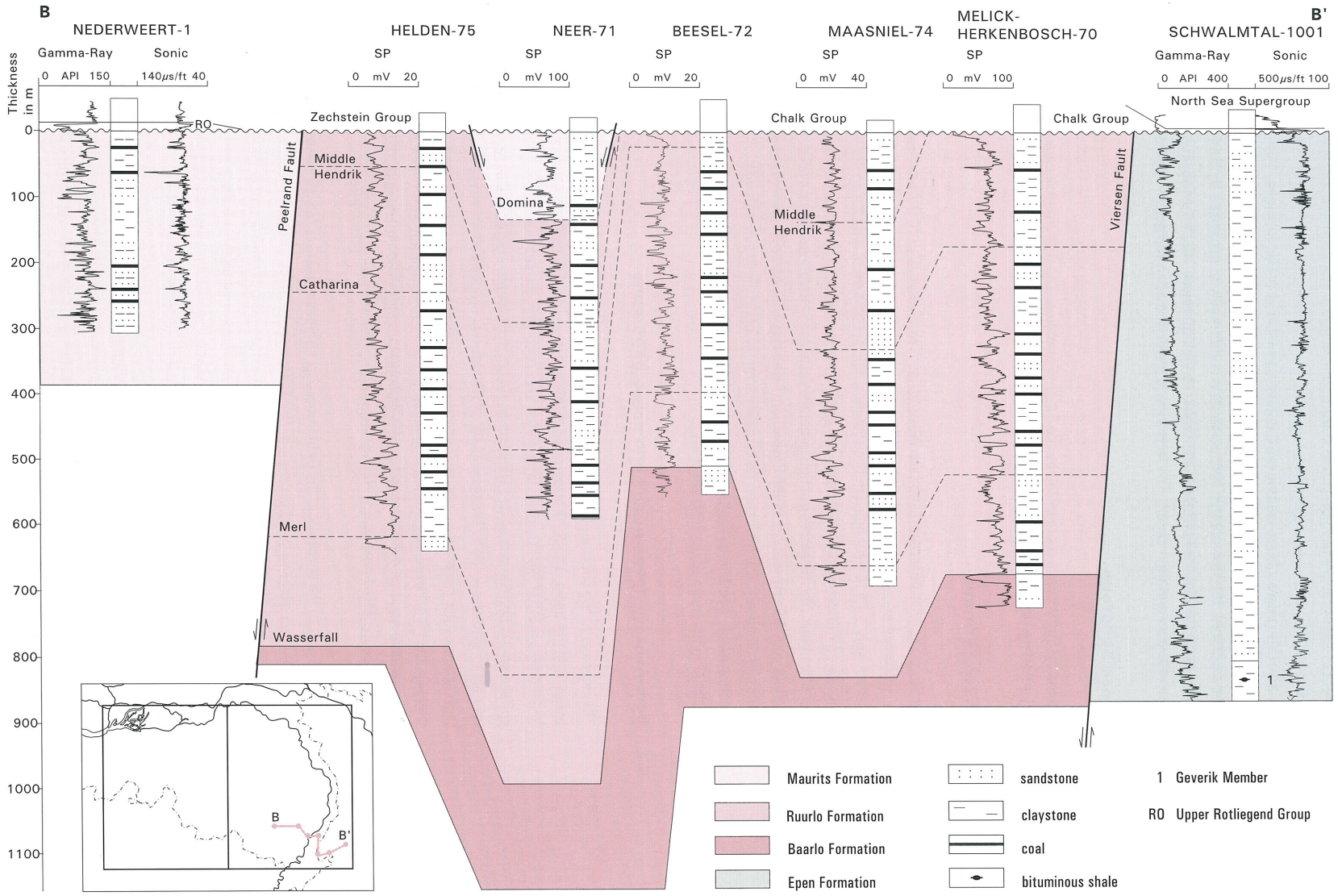


Figure 5.4 Stratigraphic section B-B' of the Limburg Group between the Nederweert-1, Helden-75, Neer-71, Beesel-72, Maasniel-74, Melick-Herkenbosch-70 and Schwalmtal-1001 wells. The reference level is the top of the Limburg Group. To the east of the Viersen Fault, only the Epen Formation has been preserved.

present to the north of the Feldbiss and in the Campine Basin. The estimated thickness is 300 to 500 m; the formation has not been encountered by drilling in the Netherlands. The Neeroeteren Formation has only been documented from wells in the Campine Basin (Dusar & Houlleberghs, 1981; Dusar et al., 1987b).

In the southeast, the Neeroeteren Formation rests conformably or separated by a minor angular unconformity upon the Maurits Formation and further to the northwest, interfingering with the top of the Hellevoetsluis Formation occurs. The formation is unconformably overlain by the Rotliegend Group.

5.1.4 Hunze Subgroup

The Hunze Subgroup is represented by the Strijen Formation. The Subgroup is Late Westphalian C up to and including Westphalian D in age.

5.1.4.1 Strijen Formation

The Strijen Formation, comprising Late Westphalian C to Westphalian D, is found in the northwest of the map sheet area. This formation consists of a succession of reddish-brown and occasionally greenish-grey, silty to very fine-sandy claystones. The succession of claystones contains 5 to 15 m thick sandstones with fair lateral continuity. The base of the formation is formed by a claystone sequence over 50 m thick. The Strijen Formation generally rests conformably upon the massive sandstones of the Hellevoetsluis Formation. In the Rijsbergen-1 well (fig. 5.2), however, where the Hellevoetsluis Formation is absent, the formation rests unconformably upon the Maurits Formation. The formation is unconformably overlain by the Upper Rotliegend Group. The formation reaches a maximum thickness of 200 m in the north of the map sheet area.

5.2 Sedimentary development and palaeogeography

The deposits of the Limburg Group reflect a paralic and continental sedimentation in an east-west oriented foreland basin. The thick succession displays only gradual transitions between the different facies, which indicates that the rate of sedimentation kept pace with the subsidence. For a long period, the land surface lay around the palaeo-sea level, which meant that a slight sea-level rise effected flooding over vast areas, where marine or brackish-water sediments were deposited (marine bands). In addition, the high groundwater table led to extensive marshes, where peat formation took place. On the occurrence of a sea-level fall, fluvial systems again extended over the area. The Brabant Massif was largely covered by sediments and had only a negligible palaeogeographic significance. The area with maximum surface subsidence migrated northwards during the Late Carboniferous (Drozdzewski, 1992).

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 lacustrine deposits, with large-scale peat formation in marshes situated on a delta plain (Van Amerom & Pagnier, 1990). In the top part of the succession, the Dinkel Subgroup, braided rivers extended from the south and east over the area, depositing coarse-grained sediments (Neeroeteren Sandstone). Between these rivers, marshes were able to develop (Thorez & Bless, 1977; Wouters & Vandenberghe, 1994).

During deposition of the youngest part of the Late Carboniferous, a pronounced climate change occurred; the humid tropical setting prevailing during the Namurian and the Westphalian A and B made way during the Late Westphalian C for a warm climate with an alternation between wet and dry seasons (monsoons).

6 Upper Rotliegend Group

6.1 Stratigraphy

The Upper Rotliegend Group is represented entirely by sands and conglomerates of the Slochteren Formation. According to the most recent perceptions, the group in the Netherlands is of Late Permian age (Van Adrichem Boogaert & Kouwe, 1993-1997; Geluk, 1999a).

The Upper Rotliegend Group rests unconformably upon the Limburg Group, separated by a hiatus, and is overlain conformably by the Zechstein Group (Maps XIII/XIV-2). The group is absent on the Krefeld and Maasbommel Highs owing to subsequent erosion, and also absent locally on the Eastern Campine and Peel Blocks. Owing to non-deposition, the group is also absent to the east of the map sheet area. The absence of the group cannot always be incontrovertibly determined from borehole descriptions. The depth of the base of the group ranges from under 1000 m on the Peel Block to over 5000 m in the Roer Valley Graben (Maps XIII-1 and XIV-1).

The group has a thickness of over 50 m in the north of the map sheet area; however, in the greater part of the map sheet area, the group is only a few metres thick (figs. 5.2, 5.3 & 6.1).

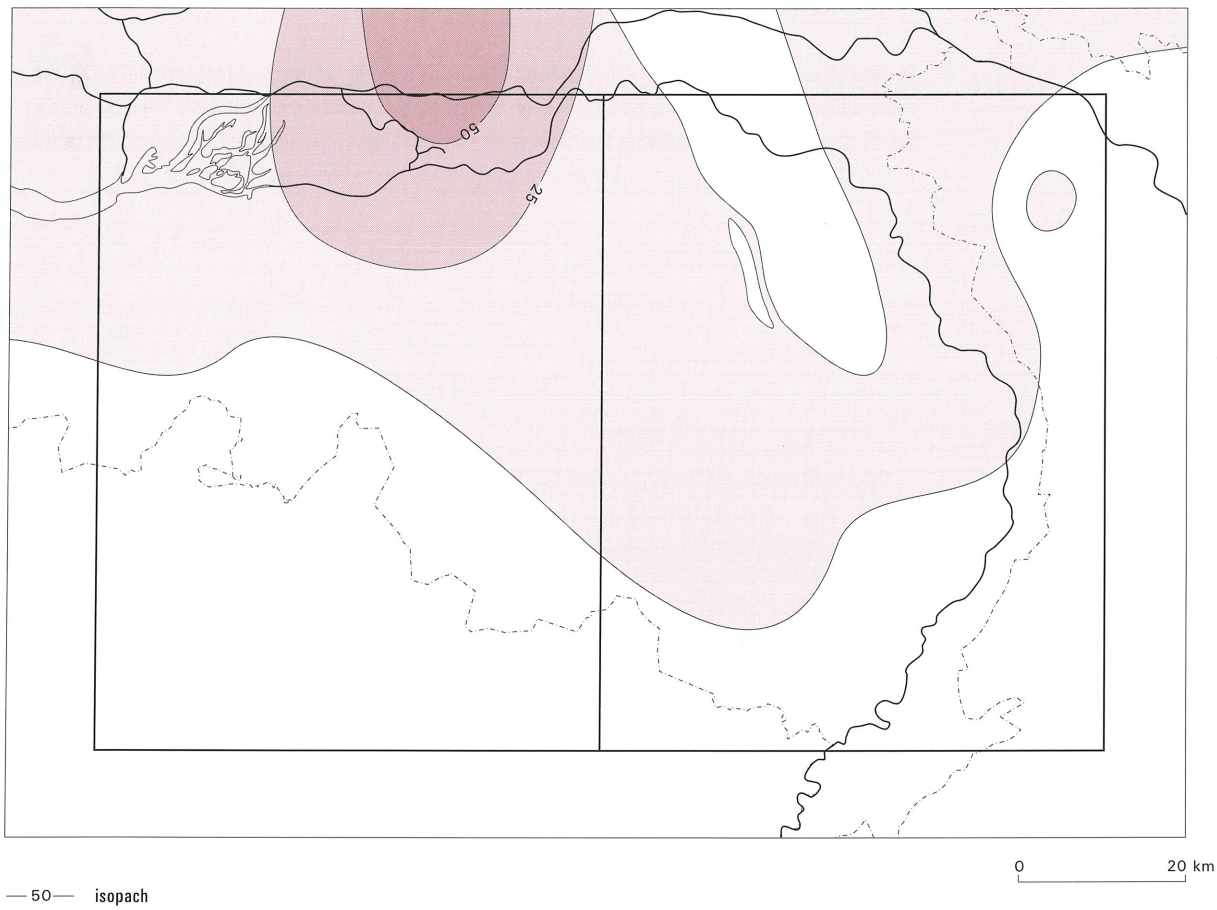


Figure 6.1 Thickness map of the Upper Rotliegend Group in the map sheet area, based on wells and the literature (after Geluk et al., 1996).

6.1.1 Slochteren Formation

The Slochteren Formation consists entirely of purple to reddish-brown and yellowish-grey sandstones and conglomerates. In the north of the map sheet area, three informal units can be distinguished locally within the massive sandstone on a basis of the dip-meter log. The bottommost and uppermost part of the formation is characterised by a disjointed pattern of stratification. The middle part of the formation (approximately 20 m) has a consistent pattern of cross stratification with angles of over 30°.

6.2 Sedimentary development and palaeogeography

The deposits of the Upper Rotliegend Group constitute the erosional products of the Variscan hinterland situated to the southeast. The conglomerates and sandstones of the Slochteren Formation were deposited by braided river systems, wadis and sheetfloods. The foreset-bedded sandstone represents aeolian sediments. Deposition of poorly sorted, conglomeratic thick sandstone layers followed intense, brief periods of precipitation in an arid climate (Glennie, 1983). The deposits indicate mass transport of sand and gravel within a proximal fluvial range. The direction of flow of the fluvial systems and wadis in the map sheet area is predominantly northwards (Van Wijhe et al., 1980).

6.3 Petrophysical data

In contrast to the northern part of the Netherlands, the sandstones of the Slochteren Formation do not form the reservoir rocks in the map sheet area. However, this is not on account of the reservoir properties of the sandstone, but rather to the absence of good sealing layers. In the northeast of the map sheet area, in the Nijmegen-Valburg-1 well, the average porosity of the Slochteren Formation has been set at 18% (RGD 1989).

7 Zechstein Group

7.1 Stratigraphy

The Zechstein Group is of Late Permian age (RGD 1994a) and consists of the equivalents of four evaporite cycles, the Z1 (Werra) to Z4 (Aller) Formation and a sealing claystone, the Zechstein Upper Claystone Formation. The basis of the formations is characterised by a transgression.

The Zechstein Group rests conformably upon the Upper Rotliegend Group (Maps XIII/XIV-1 & XIII/XIV-2) and is conformably overlain by the Lower Germanic Trias Group (Maps XIII-5 & XIV-5) and in the east and west unconformably by the Chalk Group (Maps XIII-17 & XIV-17). On the Peel and the Eastern Campine Blocks, the group locally rests unconformably upon the Limburg Group. The group is absent as a result of erosion on the Krefeld and the Maasbommel Highs, the Western Campine Block and the eastern part of the Peel and Venlo Blocks. The base of the Zechstein Group ranges in depth from under 1000 m on the Peel and the Venlo Blocks to over 5000 m in the Roer Valley Graben (Maps XIII-2 & XIV-2). The thickness of the group increases in a northeasterly direction to over 200 m in the Central Netherlands Basin to the east of the map sheet area (fig. 7.1). Tectonic activity was responsible for a differentiation in the palaeogeography within the area; on the Peel and the Venlo Blocks, a few NW oriented faults were active, which caused differences in thickness (Map XIV-3).

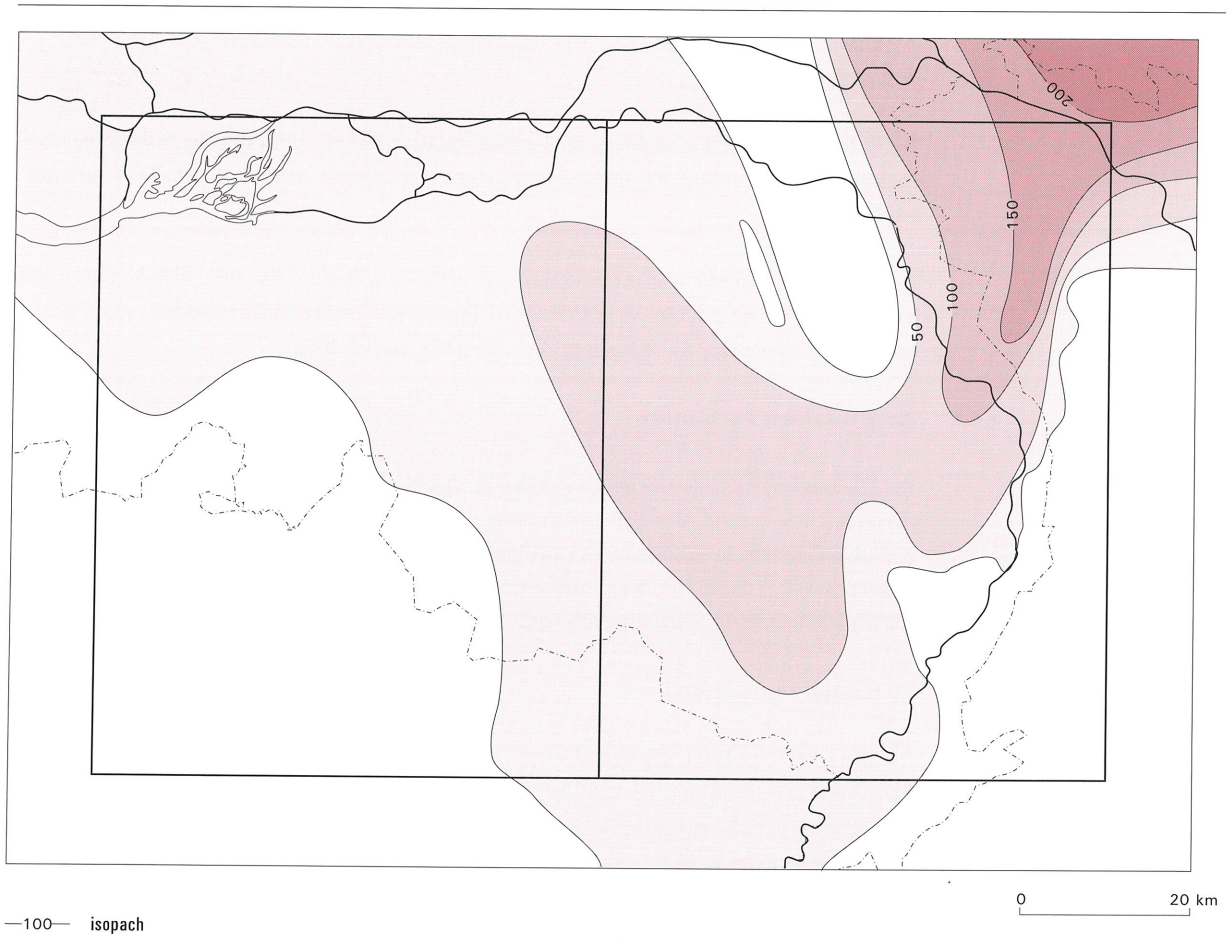


Figure 7.1 Thickness map of the Zechstein Group. This map is based on wells and the literature (Geluk et al., 1996).

7.1.1 Z1 (Werra) Formation

The Z1 (Werra) Formation is composed of the Coppershale, the Z1 Fringe Carbonate, the Z1 Anhydrite, the Z1 Middle Claystone and the Z1 Salt Members. The formation reaches its greatest thickness in the northeast of the area, over 70 m. In the west of the map sheet area, the unit is absent.

The *Coppershale* is an approximately 1-m thick, bituminous, fine-laminated brownish-black shale at the base of the Zechstein Group with a characteristic high peak on the gamma-ray log. The Coppershale is only found on the Peel and the Venlo Blocks and in the adjacent part of Germany (Wolburg, 1957; Teichmüller, 1957).

The *Z1 Fringe Carbonate* is a greyish-brown, oolitic limestone, 1 to over 40 m thick. The unit reaches considerable thicknesses, particular to the east of the Roer Valley Graben. On the Peel Block and in the adjacent parts of Germany, this unit contains Bryozoa reefs (Visser, 1955; Teichmüller, 1957; Geluk, 2000). In the Roer Valley Graben, the member rests upon the Upper Rotliegend Group, separated by a hiatus and disconformably upon the Limburg Group in the Eastern Campine Block. In the Belgian Campine, the unit comprises a fine, calcareous, cross-bedded sandstone (Dusar et al., 1987a).

The *Z1 Anhydrite* consists of a maximum of 50-m thick white to grey anhydrite. The unit only occurs in the adjacent part of Germany, where the unit displays major, fault-bound differences in thickness (Wolf, 1985).

The *Z1 Middle Claystone*, a maximum of 15 m thick, consists of a red to grey coloured laminated claystone. The unit contains anhydrite nodules and desiccation cracks, and thin sand beds and lenticles may also occur.

The *Z1 Salt* is only encountered in the adjacent part of Germany (Teichmüller, 1957; Hilden, 1988), where it consists of rock salt, a maximum of 100 m thick. The member displays major thickness variations owing to synsedimentary active faulting. (Wolf, 1985; M.A. Ziegler, 1989).

7.1.2 Z2 (Stassfurt) Formation

The Z2 (Stassfurt) Formation is composed of the Z2 Middle Claystone Member. The thickness is minimal, achieving a maximum of 20 to 25 m in the central and northeastern parts of the map sheet area. The *Z2 Middle Claystone* consists of a red to grey coloured, laminated claystone. The unit contains anhydrite nodules as well as desiccation cracks. Anhydrite nodules occur mainly in the basal part of the member and mark the boundary with the underlying Z1 Middle Claystone Member.

7.1.3 Z3 (Leine) Formation

The Z3 (Leine) Formation is subdivided into the Grey Salt Clay and the Z3 Carbonate Members. The formation is only found on the Eastern Campine Block, in the eastern part of the Roer Valley Graben, the Peel and Venlo Blocks and the Central Netherlands Basin. The formation exceeds a thickness of 30 m in the extreme northeast of the area.

The *Grey Salt Clay* consists of a 1-to-8 m thick, grey dolomitic claystone.

The *Z3 Carbonate* (Platy Dolomite) is composed of a beige to light-brown limestone with a thickness of 10 m to over 20 m.

7.1.4 Z4 (Aller) Formation

The Z4 (Aller) Formation only occurs in the extreme northeast of the area. Here, the formation comprises the *Red Salt Clay* with a thickness of 2 to 10 m.

7.1.5 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation in the map sheet area rests disconformably upon the Upper Rotliegend to Z4 (Aller) Formations. The formation consists of a succession of claystones and micaceous sandstones, with a characteristic low acoustic velocity. The thickness in the map sheet area ranges from 10 to 15 m. The formation is overlain by the Lower Germanic Trias Group, separated by a small hiatus.

7.2 Sedimentary development and palaeogeography

During deposition of the Zechstein Group, the map sheet area was situated near the southern margin of the Southern Permian Basin. However, the Brabant Massif, which flanked the southern margin of this basin, exhibited scarcely any relief in view of the absence of influx of coarse-clastics along the margin. During this period, subsidence in the area was slight, causing deposition of an incomplete section of the group, consisting of carbonates and fine-clastic sediments.

The succession of the Zechstein Group began with the deposition of the Coppershale in response to a major transgression. Deposition was restricted to the Peel and the Venlo Blocks; the Roer Valley Graben and the Western Campine Block were not overlain with sediment until a later stage. The Z1 Fringe Carbonate was deposited in a shallow, open-marine setting; the cross-bedded sandstone encountered on the Eastern Campine Block is indicative of a shallow-marine environment subjected to tidal conditions (Dusar et al., 1987). Subsequently, hypersaline conditions prevailed owing to a restriction in the circulation in the basin and the sedimentation area diminished. In the basin, the first to precipitate were the sulphates, which have only been encountered in the former deeper parts to the east and northeast of the map sheet area. The occurrence of rock salt is also restricted to fault-related structures to the east of the map sheet area (Wolf, 1985). The majority of the map sheet area underwent regular periods of drying out of the plains with fine-grained sediments.

The transgression of the Z2 (Stassfurt) Formation caused a restriction in clastic sedimentation. Anhydrite formed in a sabkha environment in response to a high groundwater table and the arid climate. Fine-grained plains subsequently extended over the area again following falling water levels.

With the transgression of the Z3 (Leine) Formation, a thin sequence of claystones was deposited throughout the area. Clastic sedimentation was restricted to the margin of the basin, and the Z3 Carbonate was deposited in a shallow-marine setting throughout the area. Subsequently the evaporite sedimentation retreated to the areas situated further towards the basin. Following the transgression at the beginning of the Z4 cycle, the red Salt Clay was deposited. The sediments of the Zechstein Upper Claystone Formation subsequently rested upon the Z3 (Leine) or Z4 (Aller) Formations, separated by a hiatus.

7.3 Petrophysical data

No oil or gas reservoirs are found in the Zechstein Group in the map sheet area. This is largely attributed to the absence of a good sealing layer overlying the group. In the eastern part of the map sheet area, however, thermal water has been extracted from the Zechstein Group (Arcen-1 well). The water production is carried out from the Z1 Fringe Carbonate and the Z3 Carbonate (see section 15.3).

8 Lower and Upper Germanic Trias Groups

8.1 General

The Triassic deposits, of youngest Late Permian to Norian age, consist predominantly of red and green coloured clastics and grey coloured carbonates, marls and evaporites. The deposits are subdivided into the Lower and Upper Germanic Trias Groups.

The Triassic deposits are found in a large part of the map sheet area. (Maps XIII/XIV-5). The absence of these sediments on the Brabant Massif, the Peel and the Venlo Blocks and on the Krefeld and the Maasbommel Highs is mainly the result of subsequent erosion. The depth of the base of the deposits ranges from approximately 600 m on the Peel Block to over 5000 m in the Roer Valley Graben. The structure of the base of the Triassic is dominated by a number of NW-SE-trending faults. The deposits rest conformably upon the Zechstein Group and are unconformably or disconformably overlain by the Altena, the Schieland, the Rijnland or the Chalk Groups or by the North Sea Supergroup (Maps XIII/XIV-16, -17 & -18). Locally on the Peel and Eastern Campine Blocks, the Triassic deposits rest unconformably

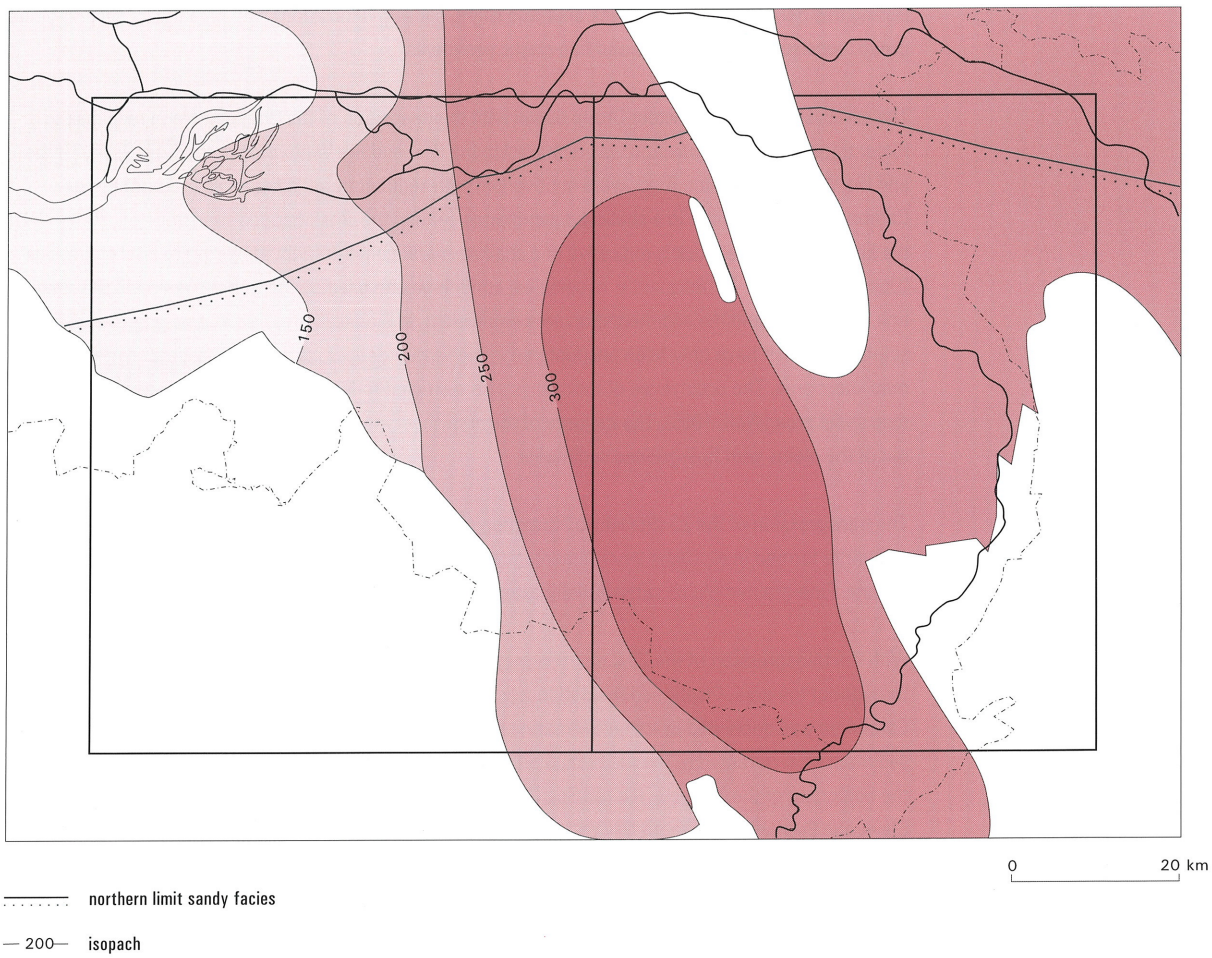
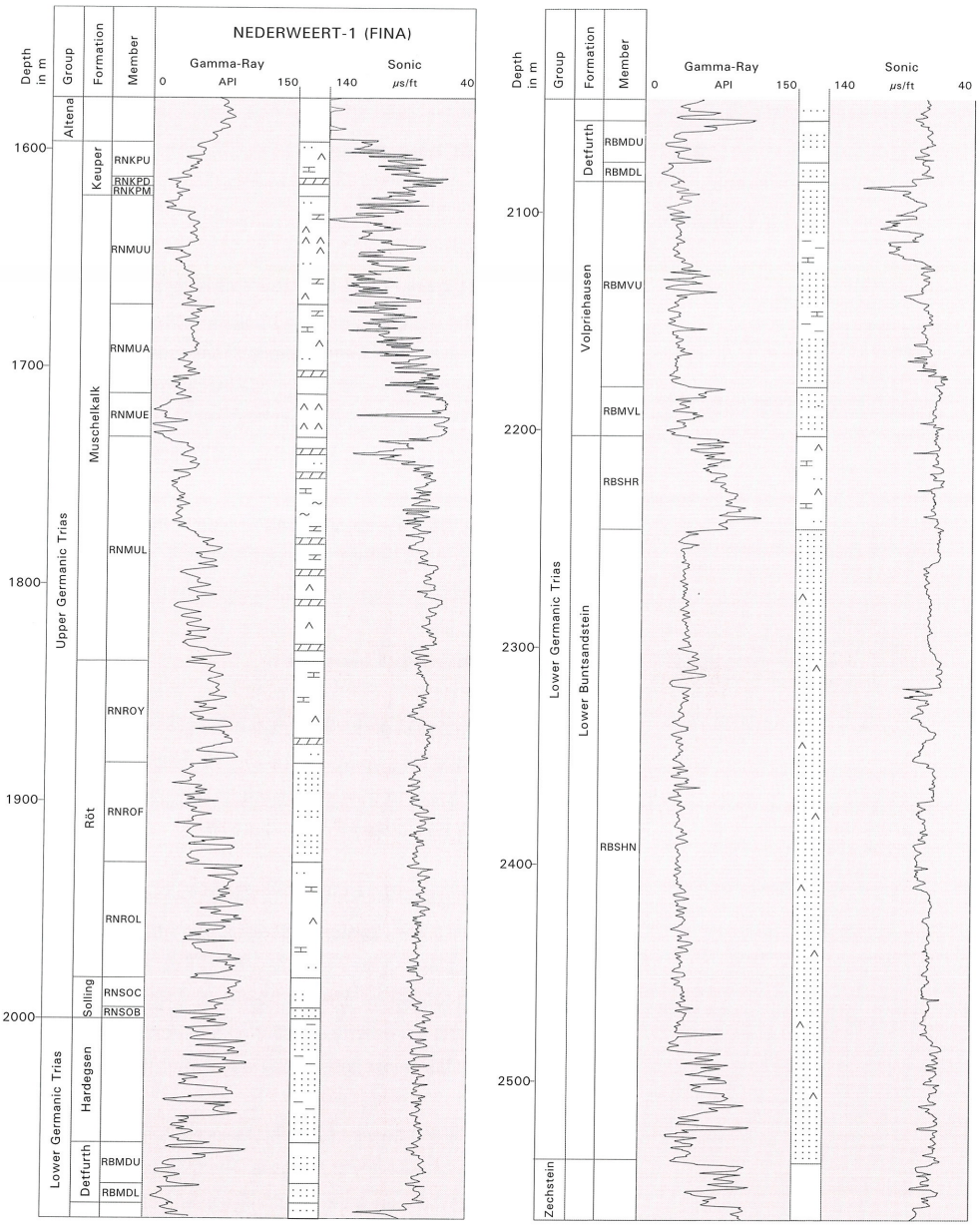


Figure 8.1 Thickness map of the Lower Buntsandstein Formation. The northern limit of the massive sandstone in this formation, the Nederweert Member, has been indicated. The formation reaches a considerable thickness, over 300 m, in the Roer Valley Graben.

Figure 8.2 Stratigraphic division and log characteristics of the Lower and Upper Germanic Trias Group in the Nederweert-1 well.



RNKPU Upper Keuper Claystone Mb
RNKPD Dolomitic Keuper Mb
RNKPM Middle Keuper Claystone Mb
RNMUU Upper Muschelkalk Mb
RNMUA Middle Muschelkalk Marl Mb
RNMUE Muschelkalk Evaporite Mb
RNMUL Lower Muschelkalk Mb
RNROY Upper Röt Fringe Claystone Mb
RNROF Röt Fringe Claystone Mb
RNROL Lower Röt Fringe Claystone Mb
RNSOC Solling Claystone Mb
RNSOB Basal Solling Sandstone Mb
RBMDU Upper Detfurth Sandstone Mb
RBMDL Lower Detfurth Sandstone Mb
RBMVU Upper Volpriehausen Sandstone Mb
RBMVL Lower Volpriehausen Sandstone Mb
RBSHR Rogenstein Mb
RBSHN Nederweert Sandstone Mb

upon the Limburg Group. A complete succession of the Lower and Upper Germanic Trias Group is found in the Roer Valley Graben and the West Netherlands Basin; beyond this areal extent, the thickness is drastically reduced and only the oldest deposits of the group have not been affected by erosion. The lithostratigraphic succession of the Triassic is illustrated by two stratigraphic sections (figs. 8.2 & 8.3).

8.2 Lower Germanic Trias Group

8.2.1 Stratigraphy

Within this group in the map sheet area, four formations can be distinguished, the Lower Buntsandstein, the Volpriehausen, the Detfurth and the Hardegsen Formations. The formations are composed predominantly of sandstone, with a few intercalations of siltstone. The three last-mentioned formations are referred to in combination as the Main Buntsandstein Subgroup. Within the group, minor unconformities occur at the base of the Volpriehausen and Detfurth Formations, which may well have caused some tens of metres of erosion locally (Geluk & Röhling, 1997, 1999).

The Lower Germanic Trias Group, of youngest Late Permian to Scythian age, rests conformably on the Zechstein Group, and is unconformably overlain by the Upper Germanic Trias (fig. 8.3), the Schieland, the Rijnland, or the Chalk Groups, or by the North Sea Supergroup (Maps 16, 17 & 18).

8.2.2 Lower Buntsandstein Formation

This formation is composed of the Nederweert Sandstone, the Main Claystone and the Rogenstein Members. The formation is overlain by the Main Buntsandstein Subgroup via a sharply defined boundary marking a minor unconformity, or unconformably by the Schieland or the Chalk Group. The thickness exceeds 300 m in the Roer Valley Graben (fig. 8.1).

The *Nederweert Sandstone* is composed of a thick sequence of light coloured sandstones. The base of this member contains a few claystone intercalations. This member occurs throughout the area, with the exception of a strip of land in the north (figs. 8.2 & 8.3), and is composed of massive or cross-bedded, carbonate-cemented sandstone. The member is conformably overlain by the uppermost part of the Rogenstein Member; in a northerly direction, the Nederweert Sandstone passes laterally into the Main Claystone and the bottommost part of the Rogenstein. The sequence reaches a thickness of over 250 m.

The *Main Claystone* is composed of a cyclical succession of 20 to 35 m thick, fining-upwards clay-siltstone sequences, with sandstone beds at the base. The member is only found in the extreme north of the area. Towards the south of the map sheet area, these sandstone beds increase in thickness and the sequence passes into the Nederweert Sandstone. The complete member is over 110 m thick.

The *Rogenstein* consists of red and green coloured fine-sandy claystones and siltstones with abundant mica. The member also contains a few oolite beds; in the northern part of the area, several sand beds are also found (fig. 8.3). In a southerly direction, the bottommost part of the sequence passes into the Nederweert Sandstone. The thickness ranges from a few tens of metres in the southern part of the Roer Valley Graben to over 120 m in the north of the area.

8.2.3 Main Buntsandstein Subgroup

This subgroup, consisting primarily of sandstone, is only found in the Roer Valley Graben and the West Netherlands Basin. The greatest thickness, over 200 m, occurs in the Roer Valley Graben (fig. 8.4). Within

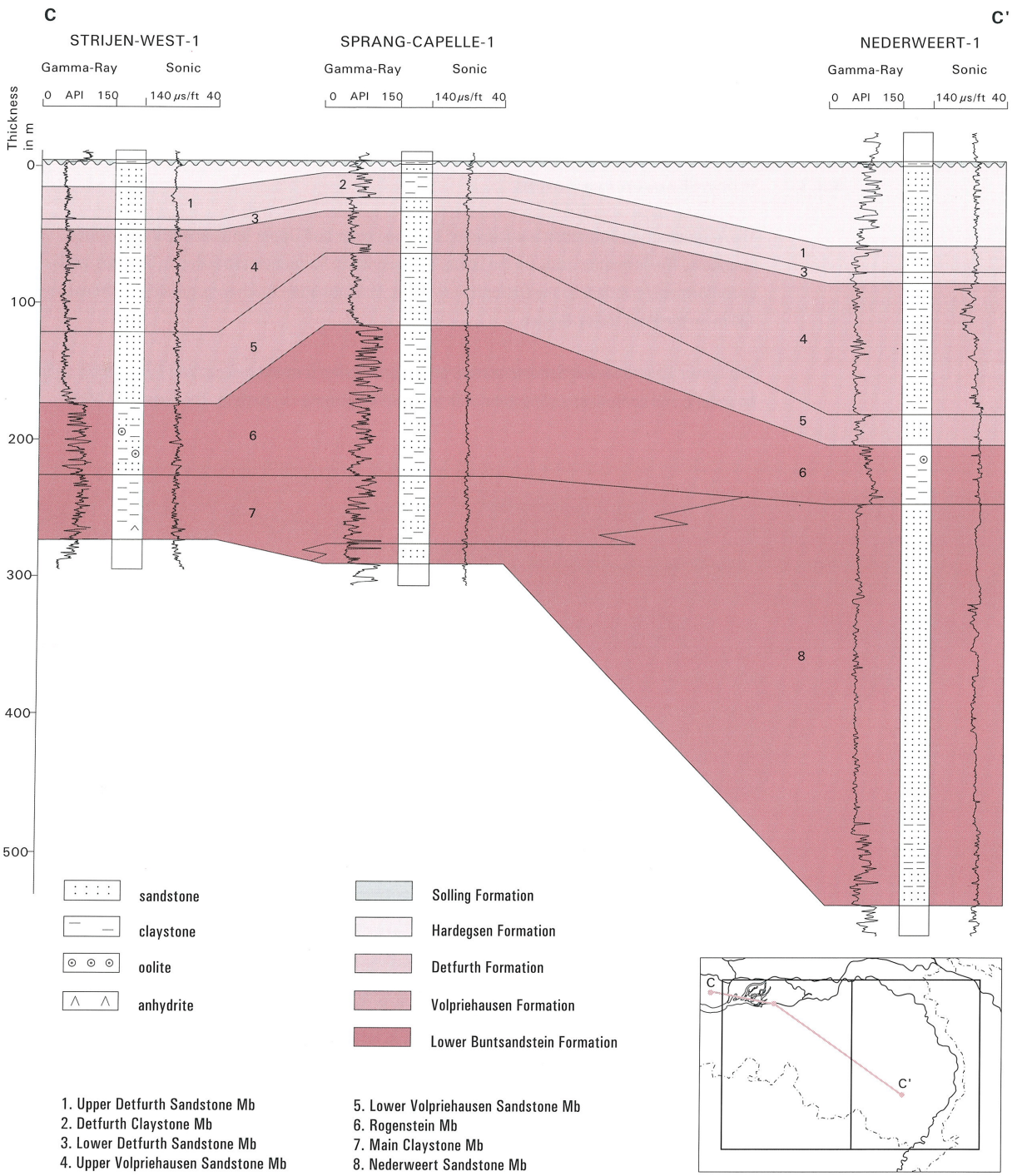


Figure 8.3 Stratigraphic section C-C' of the Lower Germanic Trias Group and the Solling Formation in the Strijen-West-1, Sprang-Capelle-1 and Nederweert-1 wells. The reference level is the base of the Solling Formation. This section shows the lateral transition within the Lower Buntsandstein Formation of the fine-grained facies in the northwest to a sandy facies in the Roer Valley Graben.

the subgroup, three formations can be distinguished, the Volpriehausen, the Detfurth and the Hardegsen Formations. The subdivision of this formation relies mainly on log characteristics.

The Main Buntsandstein Subgroup rests on the Lower Buntsandstein Formation separated by a sharply defined boundary marking a minor unconformity, and is unconformably overlain by the Upper Germanic Trias Group or by younger sediments.

8.2.3.1 Volpriehausen Formation

The Volpriehausen Formation is subdivided into the Lower and Upper Volpriehausen Sandstone Members. The formation rests on the Lower Buntsandstein Formation separated by a hiatus, and is unconformably overlain by the Detfurth Formation. The formation reaches its greatest thickness, over 130 m, in the Roer Valley Graben.

The *Lower Volpriehausen Sandstone* rests on the underlying formation separated by a sharply defined boundary, and comprises a sandstone with a block-like gamma-ray pattern. The basal part of the

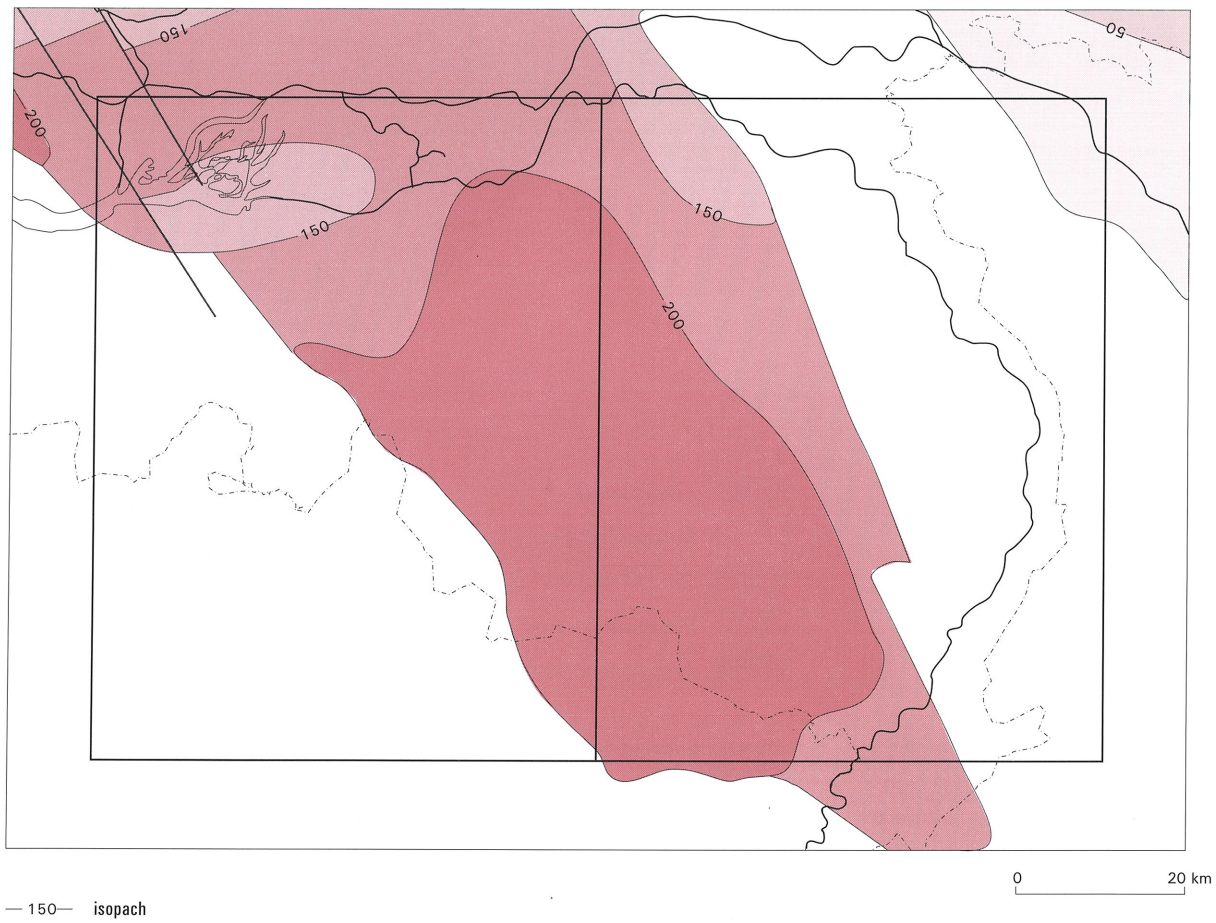


Figure 8.4 Thickness map of the Main Buntsandstein Subgroup. This map is based on wells and the literature (Geluk, 1999b; Geluk et al., 1996).

member is in general fine-grained and strongly cemented with calcite (Geluk et al., 1996). The sequence thickness, approximately 35 m, is comparatively constant. The sandstone has a 50% quartz content.

The *Upper Volpriehausen Sandstone* consists of a cyclically composed sequence of light coloured sand-siltstone beds. The sand-siltstone is cemented with dolomite and ankerite. The base of this member is characterised by a laminated siltstone, approximately 40 cm thin, which can be correlated regionally. The most complete succession, over 100 m, has been preserved in the Roer Valley Graben; beyond the graben, the thickness decreases to approximately 50 m.

8.2.3.2 Detfurth Formation

The Detfurth Formation is subdivided into the Lower and Upper Detfurth Sandstone Members and the Detfurth Claystone Member. The Detfurth Formation rests upon the Volpriehausen Formation separated by a minor unconformity, and is overlain conformably by the Hardegsen Formation. The formation reaches its greatest thickness, over 30 m, in the Roer Valley Graben.

The *Lower Detfurth Sandstone* consists of a complex of medium-fine to coarse-grained, light coloured sandstones. The quartz content in the sandstone may be as much as 60% (Geluk et al., 1996). This unit is generally characterised by the lowest gamma-ray values in the Main Buntsandstein. The thickness of the sandstone increases in a southwesterly direction from approximately 5 to over 20 m.

The *Upper Detfurth Sandstone* is composed of two sandstone intervals, separated by claystone. The thickness is comparatively constant and ranges from 20 to 30 m.

The *Detfurth Claystone* is composed of fine-sandy or silty, predominantly reddish brown coloured claystone. The claystone contains some fine to medium sandstone beds cemented with carbonate or quartz. The maximum thickness of the unit reaches 30 m in the northern part of map sheet XIII.

8.2.3.3 Hardegsen Formation

The Hardegsen Formation consists of a medium-coarse sandstone, cemented with carbonate or quartz. The deposits are grey in colour. The thickness of the formation is determined by the extent of the pre-Solling erosion and reaches a maximum of 75 m in the Roer Valley Graben.

8.3 Upper Germanic Trias Group

8.3.1 Stratigraphy

The Upper Germanic Trias Group, of Late Scythian to Norian age, is composed of four formations, namely the Solling, the Röt, the Muschelkalk and the Keuper Formations. The Solling and the Röt Formations are known in combination informally as the *Upper Buntsandstein*. The group is mainly found in the Roer Valley Graben, the West and Central Netherlands Basin (figs. 8.5 & 8.6). The group rests unconformably upon the Lower Germanic Trias Group and is conformably overlain by the Altena Group or unconformably by the Schieland, the Rijnland or the Chalk Groups or by the North Sea Supergroup (Maps 16, 17 &18).

8.3.2 Solling Formation

The Solling Formation, of Late Scythian age, occurs within the areal extent of the Upper Germanic Trias Group. The formation is subdivided into the Basal Solling Sandstone and the Solling Claystone Members. The formation rests unconformably on the Main Buntsandstein Subgroup. Throughout the

map sheet area, this sequence is under 20 m thick. In the adjacent part of Germany, the thickness is much greater, over 80 m (Geluk, 1999b).

The *Basal Solling Sandstone* consists of a succession of one or more fine-grained sandstone layers and thin claystone layers. The sandstones have a block-like appearance on the gamma-ray log. With the exception of a few areas in the north and south, the Basal Solling Sandstone is always present in the formation. The thickness of the sandstone ranges from a few metres to 15 m.

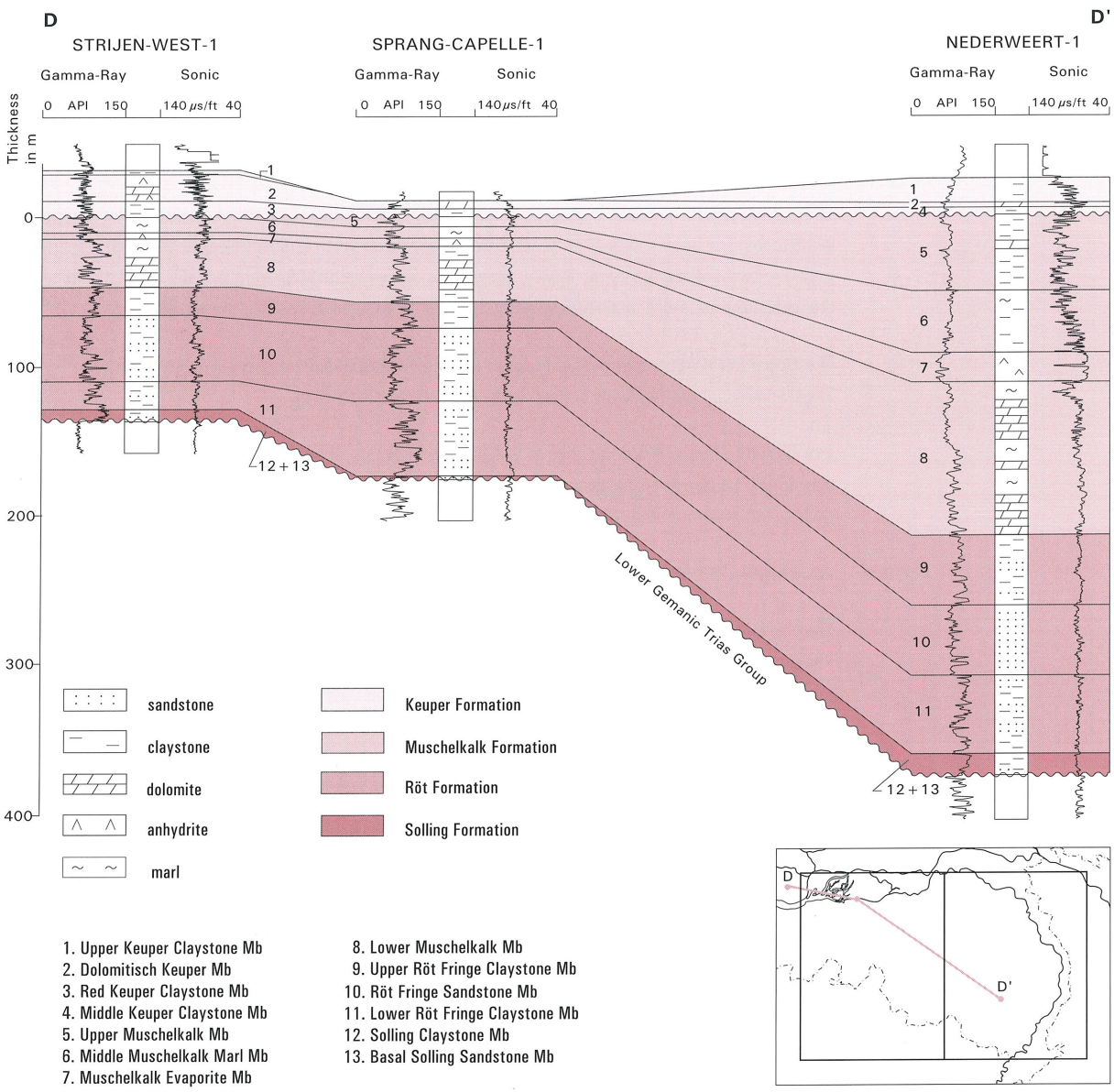


Figure 8.5 Stratigraphic section D-D' of the Upper Germanic Trias Group in the Strijen-West-1, Sprang-Capelle-1 and Nederweert-1 wells. The reference level is the Early Kimmerian Unconformity at the base of the Red Keuper Claystone.

The *Solling Claystone* represents the largest part of the formation and consists of reddish-brown, sometimes green-mottled claystone. The lower parts of the member contain grey layers, which are characterised by a high gamma-ray log reading. In the middle part of the member, a few silty and sometimes sandy layers are found. The claystone also contains anhydrite concretions.

8.3.3 Röt Formation

The Röt Formation, of Early Anisian age, is subdivided into the Main Röt Evaporite and the Upper Röt Claystone Members. In the greater part of the map sheet area, however, the last-mentioned sequence contains a sandstone, as a result of which this sequence can be further subdivided in the Lower Röt Fringe Claystone, the Röt Fringe Sandstone and the Upper Röt Fringe Claystone Members.

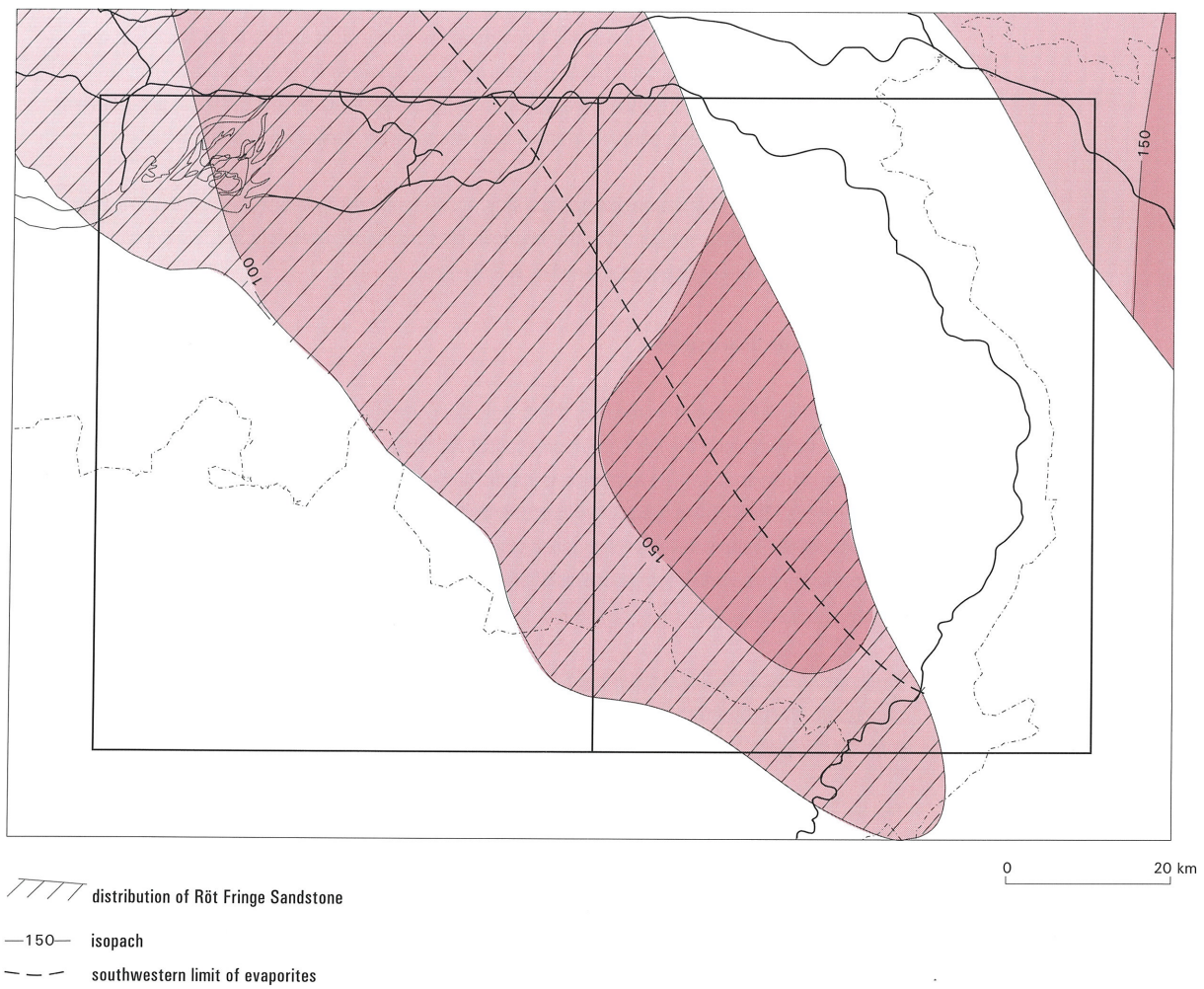


Figure 8.6 Thickness map of the Röt Formation. The occurrence of the Röt Fringe Sandstone Member is limited to the Roer Valley Graben. This map is based on wells and the literature (Geluk, 1999b; Geluk et al., 1996).

The Röt Formation occurs within the entire areal extent of the Upper Germanic Trias Group. The greatest thickness, over 150 m, is reached in the Roer Valley Graben (fig. 8.6). The thickness decreases in a north-westerly direction.

The *Main Röt Evaporite* is only found in the Roer Valley Graben, in a zone close to the Peel Boundary Fault. The member is also found in the most northeasterly part of the area. Here, the unit is composed of an anhydrite bed several metres thick. Beyond the areal extent of the Röt Fringe Sandstone, the member is overlain by the Upper Röt Fringe Claystone, and elsewhere by the Lower Röt Fringe Claystone Member.

The *Lower Röt Fringe Claystone* occurs throughout the areal extent of the Röt Fringe Sandstone. The unit comprises a reddish-brown, silty claystone. The base of the unit frequently contains a thin anhydrite or an anhydrite-cemented sandstone. On the southern border of the areal extent, the member is over 20 m thick; the greatest thickness, over 50 m, is reached in the southwest of the Roer Valley Graben.

The *Röt Fringe Sandstone* occurs virtually throughout the entire areal extent of the formation (fig. 8.6). The unit is composed of alternating beds of grey, arkosic sandstone and reddish-brown claystone. These claystone beds allow good regional correlations. In a northerly direction, the thickness and grain size diminishes, and to the north of the map sheet area, the member passes into the Röt Claystone.

The *Upper Röt Fringe Claystone* comprises a silty, occasionally sandy claystone. A few small dolomite layers are found in the member. The thickness increases from approximately 30 m on the southwestern flank of the Roer Valley Graben to over 50 m at its centre.

8.3.4 Muschelkalk Formation

The Muschelkalk Formation in the map sheet area, deposited in the Middle Anisian to Ladinian period, rests conformably upon the Röt Formation and is, separated by the Kimmerian Unconformity, overlain by the Keuper Formation. The formation is subdivided into the Lower Muschelkalk, the Muschelkalk Evaporite, the Middle Muschelkalk Marl and the Upper Muschelkalk Members. The formation occurs in the Roer Valley Graben, the West Netherlands Basin and the extreme northeast of the area (figs. 8.7 & 8.8). The formation has a maximum thickness of over 170 m near the Peel Boundary Fault. In the northeast, only the bottommost part of the formation is present.

The *Lower Muschelkalk* is composed of an alternation of greyish-white limestone/dolomite beds and grey marls, the proportion of dolomite beds decreasing towards the top. The member reaches its greatest thickness, over 70 m, in the vicinity of the Peel Boundary Fault.

The *Muschelkalk Evaporite* consists of a 5 to 15 m thick anhydrite in the greatest part of the map sheet area. An exception to this is a narrow zone in the vicinity of the Peel Boundary Fault, where rock salt also occurs. Here, the sequence reaches its greatest thickness, over 50 m.

The evaporite is overlain by the 20 to 30 m thick *Middle Muschelkalk Marl*, consisting of light-grey, sometimes greenish to brownish-grey marls and claystone with a few anhydrite beds near the base. This sequence displays a characteristic, upwardly increasing, gamma-ray reading. The thickness is 15 to 20 m.

The topmost calcareous unit, the *Upper Muschelkalk*, is composed of an alternation of grey and greenish-grey dolomite, limestone and marl layers. The proportion of dolomite beds decreases

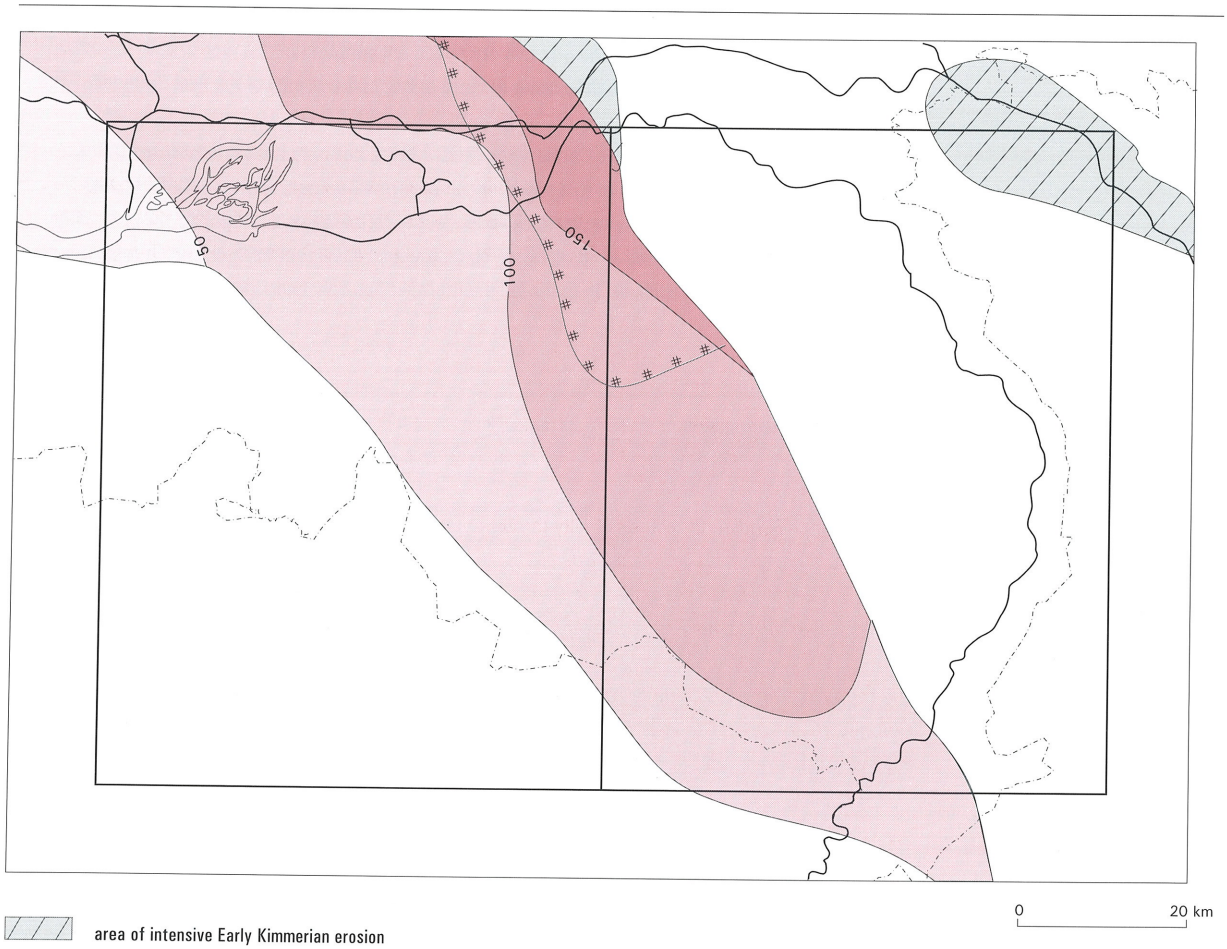


Figure 8.7 Thickness map of the Muschelkalk Formation. The areal extent of salt within the Muschelkalk Evaporite has been given. The most complete succession is encountered in a zone in the immediate vicinity of the Peel Boundary Fault. This map is based on wells and the literature (Geluk, 1999b; Geluk et al., 1996).

upwardly. The base is formed by a massive dolomite bed, the so-called *Trochitenkalk*. The member is only locally complete, in the vicinity of the Peel Boundary Fault, with a thickness of 50 m. Elsewhere, the thickness was drastically reduced by the Early Kimmerian erosion.

8.3.5 Keuper Formation

The Keuper Formation consists predominantly of claystone and dolomite layers. Throughout the area the formation is subdivided into the Red Keuper Claystone, the Dolomitic Keuper and the Upper Keuper Claystone Members, of Norian age. Locally, in the vicinity of the Peel Boundary Fault, erosional remains of the Lower Keuper Claystone and the Middle Keuper Claystone, of Late Ladinian and Carnian age, are also found. In the greatest part of the area the formation is 30 to 50 m thick.

The *Lower Keuper Claystone* consists of greenish-grey and reddish-brown, dolomitic claystones with anhydrite in thin beds and nodules. The unit has only been encountered in one well (Asten-1), with a thickness of 28 m. The unit is presumed to occur at more places in the vicinity of the Peel Boundary Fault.

The *Middle Keuper Claystone*, of Late Carnian age (RGD 1994b), has only been encountered in the Nederweert-1 well. The occurrence of this member can be termed unique, on account of its great distance from other demonstrated occurrences in the central Netherlands and the Eifel (Knapp, 1999; Geluk, 1999b). The unit comprises a red coloured clay sequence a few metres thick, which rests unconformable on the Upper Muschelkalk. In this well, the member has only been identified by palynological

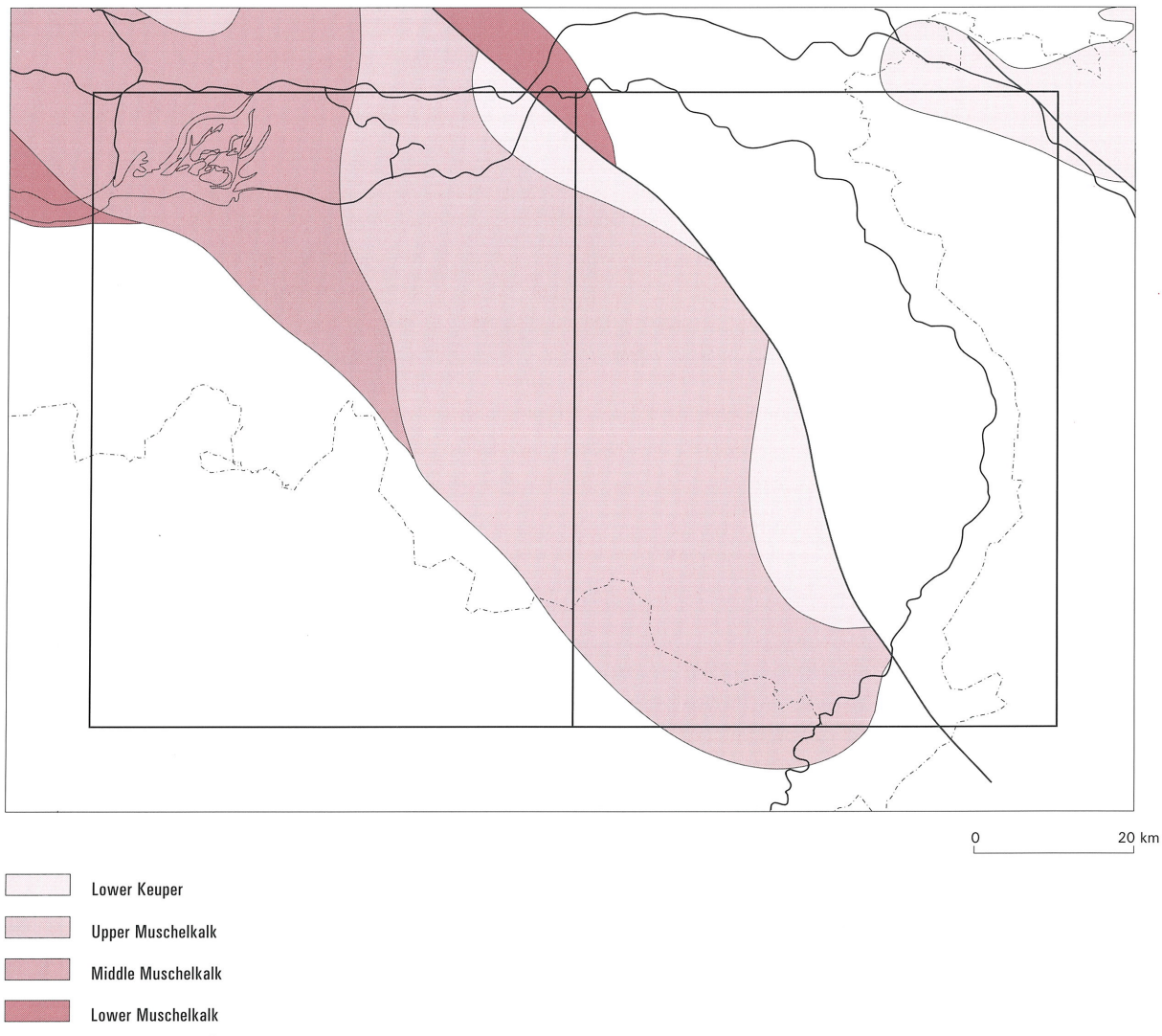


Figure 8.8 Subcrop map below the base of the Early Kimmerian Unconformity at the base of the Red Keuper Claystone. In a zone bordering the Peel Boundary Fault, erosional remains of the Lower Keuper Claystone are encountered in a few places. This map is based on wells and the literature (Geluk, 1999b; Geluk et al., 1996).

studies; the possibility can therefore not be excluded the Middle Keuper Claystone may also occur at a number of other places in the area.

The *Red Keuper Claystone* rests, in many cases unconformably, upon the Muschelkalk Formation. The member has a thickness of 2 to 15 m. In addition to red-coloured claystone, green claystone is also found. This member is of great importance in carrying out regional correlations, owing to the presence of the Early Kimmerian Unconformity at the base (Geluk, 1999b).

The *Dolomitic Keuper* is composed of an alternation of claystone with several anhydrite and dolomite beds. The member is characterised by a conspicuous light colour. The thickness decreases towards the southwest. The maximum thickness is 50 m in the east of the map sheet area. In Germany, this unit, in combination with the Red Keuper Claystone, is known as the *Steinmergelkeuper.*

The *Upper Keuper Claystone* varies in thickness from a few metres to a maximum of 20 m in the north of the Roer Valley Graben. The member mainly comprises grey silty claystones and marls.

8.4 Sedimentary development and palaeogeography

The incipient influx of clastics from the south at the end of the Zechstein was prolonged in the Triassic. During the Triassic, initially continental depositional conditions prevailed, which acquired an increasingly marine character owing to a gradual sea-level rise. The highstand reached its maximum during deposition of the Muschelkalk Formation. Tectonic movements occurred during two phases: the Hardegsen phase, which gave rise to a hiatus between the Lower and the Upper Germanic Trias Groups and the Early Kimmerian phase, initiating an unconformity within the Upper Germanic Trias Group.

The Lower Buntsandstein Formation in the map sheet area consists predominantly of fluvial deposits, possibly with aeolian intercalations. In the northern part of the area, these deposits pass into lacustrine deposits. Sediment influx took place from the southeast. The cyclical character displayed by these deposits is ascribed to climatic cycles, the so-called Milankovitch cycles, with a periodicity of 100,000 years (Geluk & Röhling, 1997, 1999).

During the deposition of the Main Buntsandstein Subgroup, the map sheet area formed an extensive flood plain, where fluvial and aeolian sands were deposited. Fine-grained deposits document the brief expansion of the lake over this flood plain. At the base of the formations, minor unconformities have been revealed; before the deposition of the Detfurth Formation in particular, relatively pronounced erosion occurred, which resulted in the absence of the top part of the Volpriehausen Clay-Siltstone (Geluk & Röhling, 1997, 1999).

The Solling Formation reflects a transgression from an easterly direction. Closing of the connection with the sea and evaporation of the water present in the basin resulted in the deposition of the anhydrite of the Main Röt Evaporite in the deepest part of the Roer Valley Graben in the vicinity of the Peel Boundary Fault. Subsequently, during the deposition of the topmost part of the Röt Formation, the last influx of clastic material from the south occurred and the Röt Fringe Sandstone was deposited in a fluvial to aeolian environment. In the topmost part of the Röt Formation, a transgression was initiated. The sediment source area became increasingly submerged by the sea and clastic sediment deposition changed over to a carbonate dominated succession of the Muschelkalk Formation. The Lower Muschelkalk was deposited in a marine to supratidal setting, while the renewed closing of the connection between the Northwest European Basin and the Tethys facilitated deposition of the Muschelkalk Evaporite and the Middle Muschel-kalk Marl. Subsequently, the Upper Muschelkalk was deposited, again during normal-marine conditions.

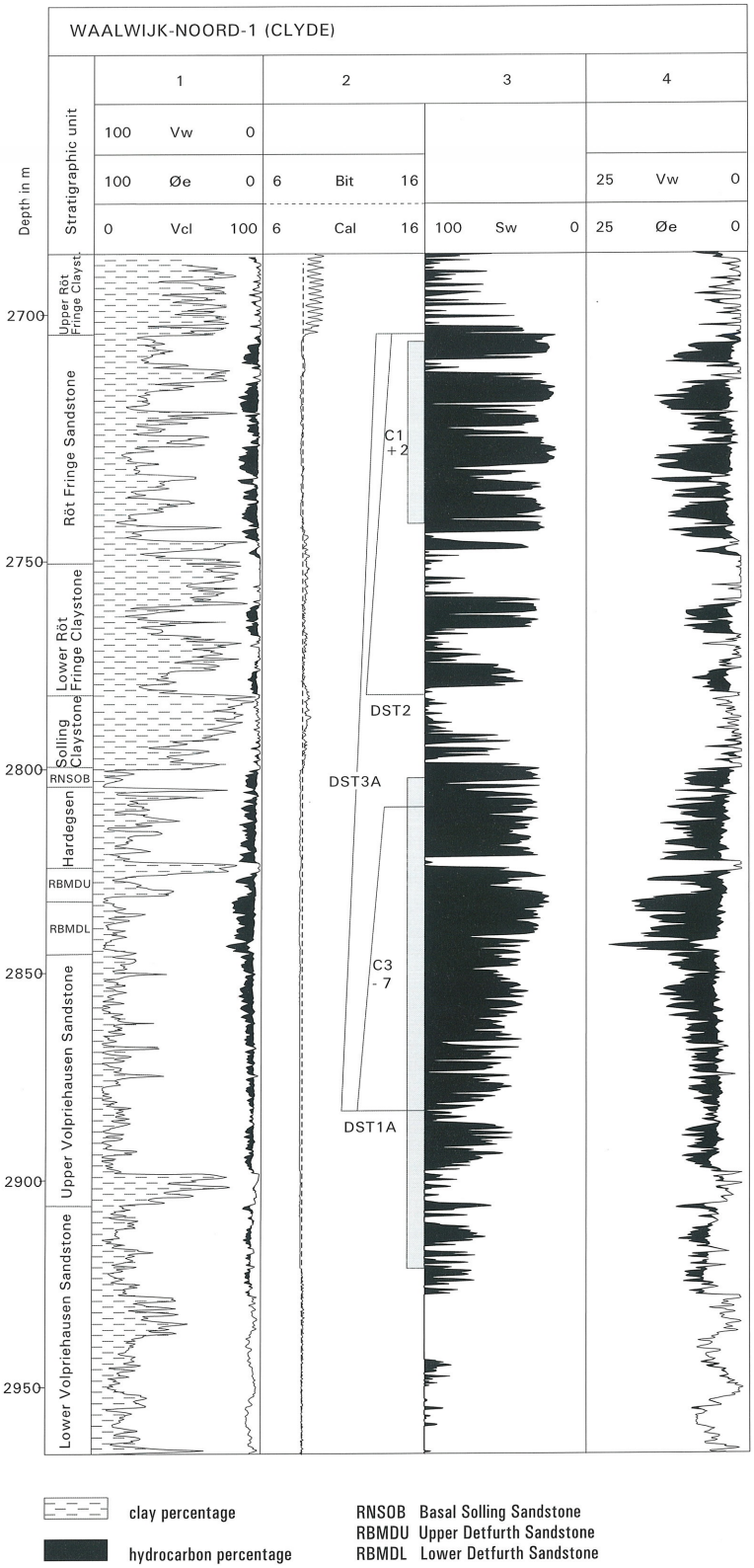


Figure 8.9 Petrophysical evaluation of the sandstones of the Lower and Upper Germanic Trias Groups in the Waalwijk-Noord-1 well.
Column 1: clay content V_{cl}, effective porosity Φ_ε and pore volume water V_w, all given in percentages.
The clay content was determined with the use of gamma-ray logs.
The effective porosity was obtained by the use of a shaly sand model (density log/neutron log), in which the calculated log porosity was corrected for the clay and the hydrocarbons present.
Column 2: drill hole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the cored interval is indicated a grey bar.
Column 3: water saturation S_w in percentages. The Indonesia formula was applied to determine the water saturation (Fertl, 1987).
Column 4: effective porosity Φ_ε (left curve) and the volume of water in the pores V_w (right curve), both in percentages. In the left-hand column, the boundaries of the formation are indicated.
The depths are the true depths.

The Keuper Formation was deposited in shallow-marine, marginal marine to evaporitic depositional conditions. During deposition of this formation, strong tectonic movements took place, which initiated a large hiatus in the succession.

8.5 Petrophysical evaluation

In 1987, BP discovered natural gas in the Waalwijk-1 well in the Trias sandstones (Röt Formation and Main Buntsandstein Subgroup). Further exploration revealed two gas fields in the Triassic deposits, the Loon op Zand field and the Waalwijk field, located in the northwest of map sheet XIII. The Waalwijk field consists of two occurrences: Waalwijk-Noord and Waalwijk-Zuid (Winstanley, 1993).

The deposits of two wells in the map sheet area have been petrophysically evaluated (appendix C. These wells, Waalwijk Noord-1 and Waalwijk South-1, are the demonstration wells of the Waalwijk and the Loon op Zand field. In both wells, the sandstones of the Lower Germanic Trias Group have been found to be gas-bearing (appendix D). Core analysis data are available from both selected wells.
To illustrate a log-evaluation of the reservoir sequence of the Lower and Upper Germanic Trias Group, the Waalwijk Noord-1 well is given (fig. 8.9).

9 Altena Group

9.1 Stratigraphy

The Altena Group, of youngest Late Triassic to Middle Jurassic age, consists predominantly of dark coloured claystones with, in the upper part, sandstone, limestone and marl, and was deposited in a marine environment. The group is subdivided into the Sleen, the Aalburg, the Posidonia Shale, the Werkendam and the Brabant Formations. The geographical extent and the stratigraphic succession of these formations are illustrated in figures 9.1 and 9.2 respectively.

Within the map sheet area, the Altena Group rests on the Upper Germanic Trias Group, separated by a minor hiatus (fig. 9.3). The deposits occur predominantly in the Roer Valley Graben and the transition to the West Netherlands Basin (Maps XIII-6 and XIV-6). The group reaches its greatest thickness, over 1200 m, in the northwestern part of the Roer Valley Graben (Maps XIII-7 and XIV-7). The deposits, which

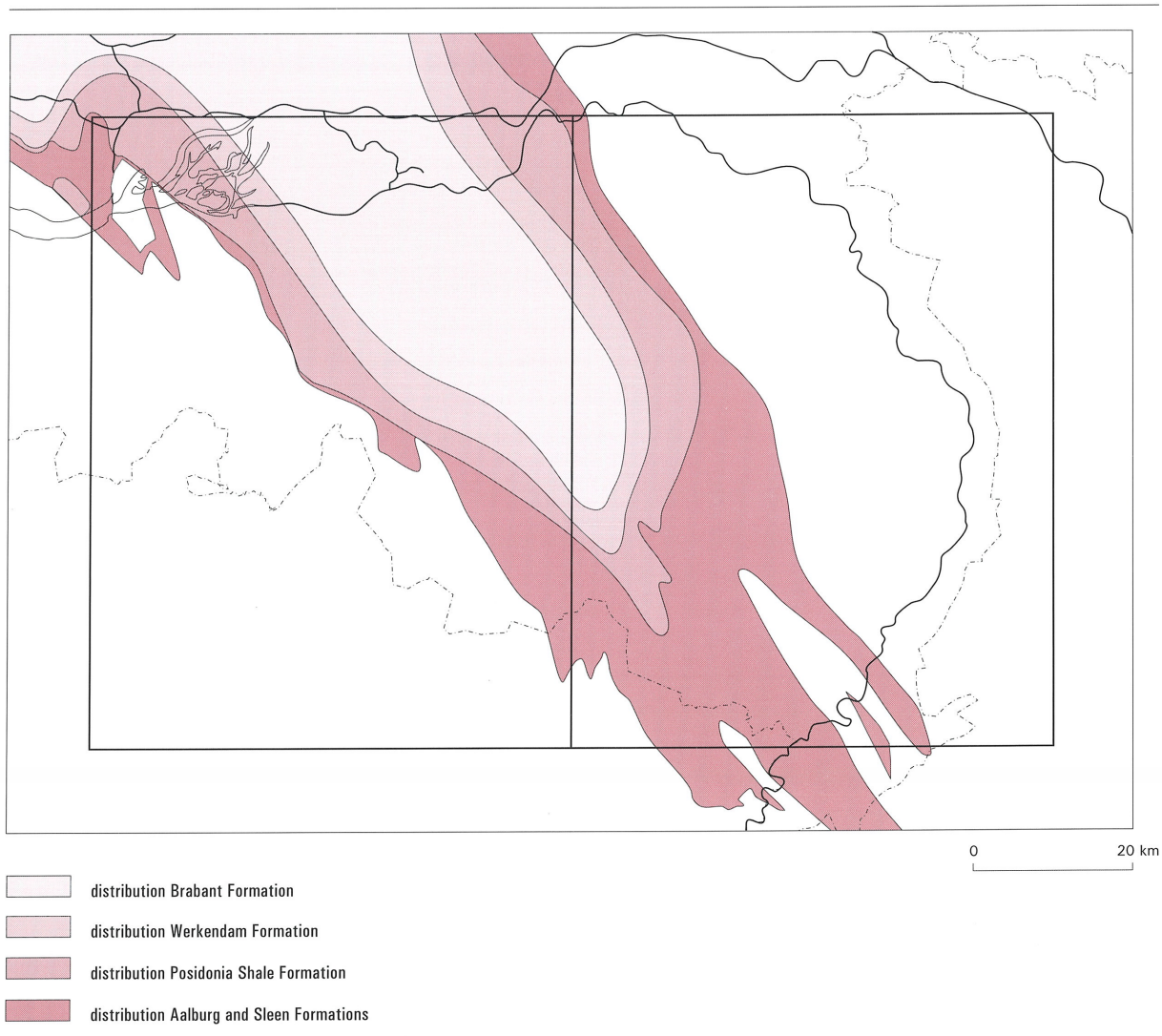


Figure 9.1 Subcrop map of the top of the Altena Group.

are separated by the Late Kimmerian unconformity, are covered by the Schieland or the Chalk Group, and locally by the North Sea Supergroup.

The base of the group is intensively faulted and exhibits major differences in depth. In the Roer Valley Graben, the basin lies at depths in excess of 3700 m and along the flanks of the graben at 2000-2500 m (Maps XIII-6 and XIV-6).

9.1.1 Sleen Formation

The Sleen Formation, of Rhaetian age, occurs within the entire areal extent of the Altena Group. The Formation rests, separated by a hiatus, on the Upper Germanic Trias Group (fig. 9.3) and is conformably overlain by the Aalburg Formation. The deposits comprise black, sometimes bituminous claystone and shale, with abundant pyrite, fossil and plant remains in patches. The formation is subdivided into two parts by a thin sandstone. The topmost part of the formation may have a red flamed appearance. The formation is 20 to 45 m thick.

9.1.2 Aalburg Formation

The Aalburg Formation, of Hettangian to Pliensbachian age, is also found throughout the areal extent of the Altena Group. The formation rests conformably on the Sleen Formation and is conformably overlain by the Posidonia Shale Formation or unconformably by the Schieland, the Chalk Group or the North Sea Supergroup. Lithologically, the formation has a monotonous character and comprises greenish-grey to black, sometimes calcareous claystone with thin limestone beds. In addition, a few organic-rich claystone beds are found in the bottommost part of the formation (Herngreen & De Boer, 1974). In the formation there are abundant occurrences of ammonites, belemnites and molluscs. The maximum thickness of the formation is 700 m. Locally, there are pronounced differences in thickness as a result of synsedimentary faults.

9.1.3 Posidonia Shale Formation

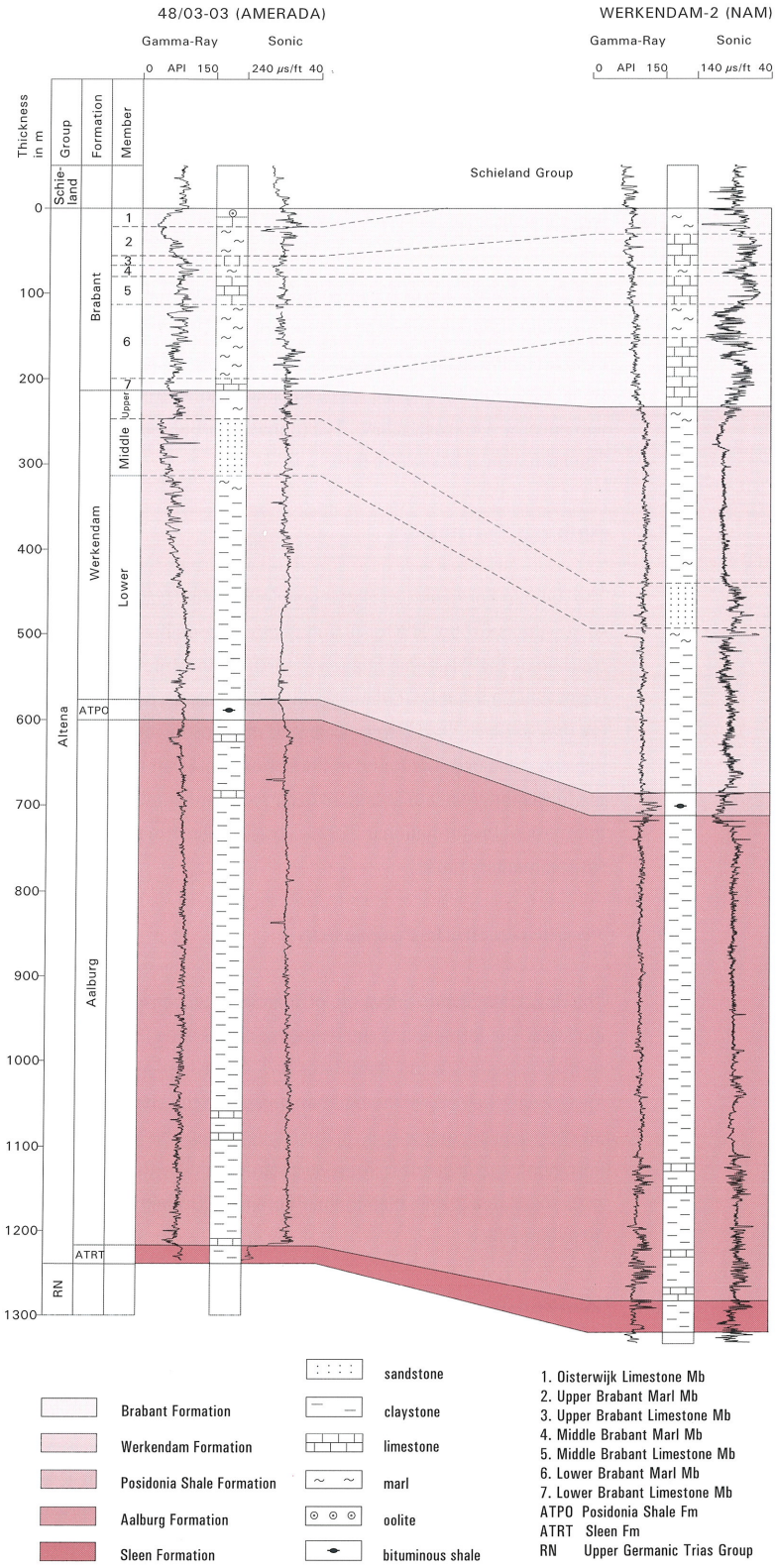
The Posidonia Shale Formation, of Toarcian age, consists of a dark organic-rich shale with a few carbonate beds. The formation is clearly distinguishable by its characteristic peak on gamma-ray logs. The formation is also clearly identifiable on seismic logs as a result of the strong reflection, caused by the low acoustic velocity of the bitumen present in the shale. The presence of the bitumen makes the shales an important oil-source rock. in the Netherlands. The formation rests conformably on the Aalburg Formation and is overlain, likewise conformably, by the Werkendam Formation. The formation in the map sheet area is restricted to the Roer Valley Graben and the West Netherlands Basin. The formation is 30 to 50 m thick.

9.1.4 Werkendam Formation

The Werkendam Formation, of Late Toarcian up to Early Bathonian age, consists of grey, marly claystone with, in the middle of the section, a more calcareous, silty to sandy interval. The formation is subdivided into three members.

The *Lower Werkendam Member* consists of predominantly of dark coloured, occasionally silty, claystone, with alternations of light coloured marls and a few bands containing iron oolites. The member is manifestly less calcareous than the overlying Middle Werkendam Member. The thicknesses vary variably and may exceed 250 m in an uneroded section.

Figure 9.2 Correlation of the Altena Group in the Werkendam-2 well with the 48/03-03 well in the English section of the southern North Sea. The reference level is the top of the Altena Group. Despite the fact that these wells are at a distance of 330 km from each other and are situated in two separate geological basins, the groups display a similar composition. This indicates that during the deposition of the Altena Group, these wells were in a single sedimentary basin.



The *Middle Werkendam Member* consists of an alternation of calcareous siltstones and sandstones, has manifestly higher sonic and resistance values in comparison with the underlying and overlying members. There are considerably variations in thickness, from 20 to over 100 m.

The *Upper Werkendam Member* consists of a homogeneous section of grey, somewhat marly claystones, resting on the calcareous sediments of the Middle Werkendam Member with a conformable contact. The member may reach thicknesses of over 200 m.

The Werkendam Formation in the map sheet area is only present in the Roer Valley Graben and the transition to the West Netherlands Basin. The formation has virtually the same areal extent as the Posidonia Shale Formation (fig. 9.1). Where the formation is complete, the thickness is a maximum of approximately 500 m. The Werkendam Formation rests conformably on the Posidonia Shale Formation and is conformably overlain by the Brabant Formation or unconformably by the Schieland or the Chalk Groups and locally by the North Sea Supergroup.

9.1.5 Brabant Formation

The Brabant Formation, of Bathonian up to Oxfordian age, comprises an alternation of limestone, marl and claystone, which in general displays a sandy character. On a basis of alternating carbonate/sand quantities, the formation can be subdivided, in stratigraphic order. into seven members.

The *Lower Brabant Limestone Member* consists of an alternation of marls and limestones, in which the number of limestone beds upwardly increase. The thickness ranges from 30 to 90 m.

The *Lower Brabant Marl Member,* with sandy marl deposits, contains ferrugineous sediments at the top. Locally, thin, sandy limestone beds may be intercalated. The member is 30 to 70 m thick.

The *Middle Brabant Limestone Member* consists of a unit of extremely sandy, fossil-rich limestones with an intercalation of sandy marls. The thickness ranges from 20 to 50 m.

The *Middle Brabant Marl Member* comprises sandy marls, which are ferrugineous at the base. The thickness is 10 to 65 m.

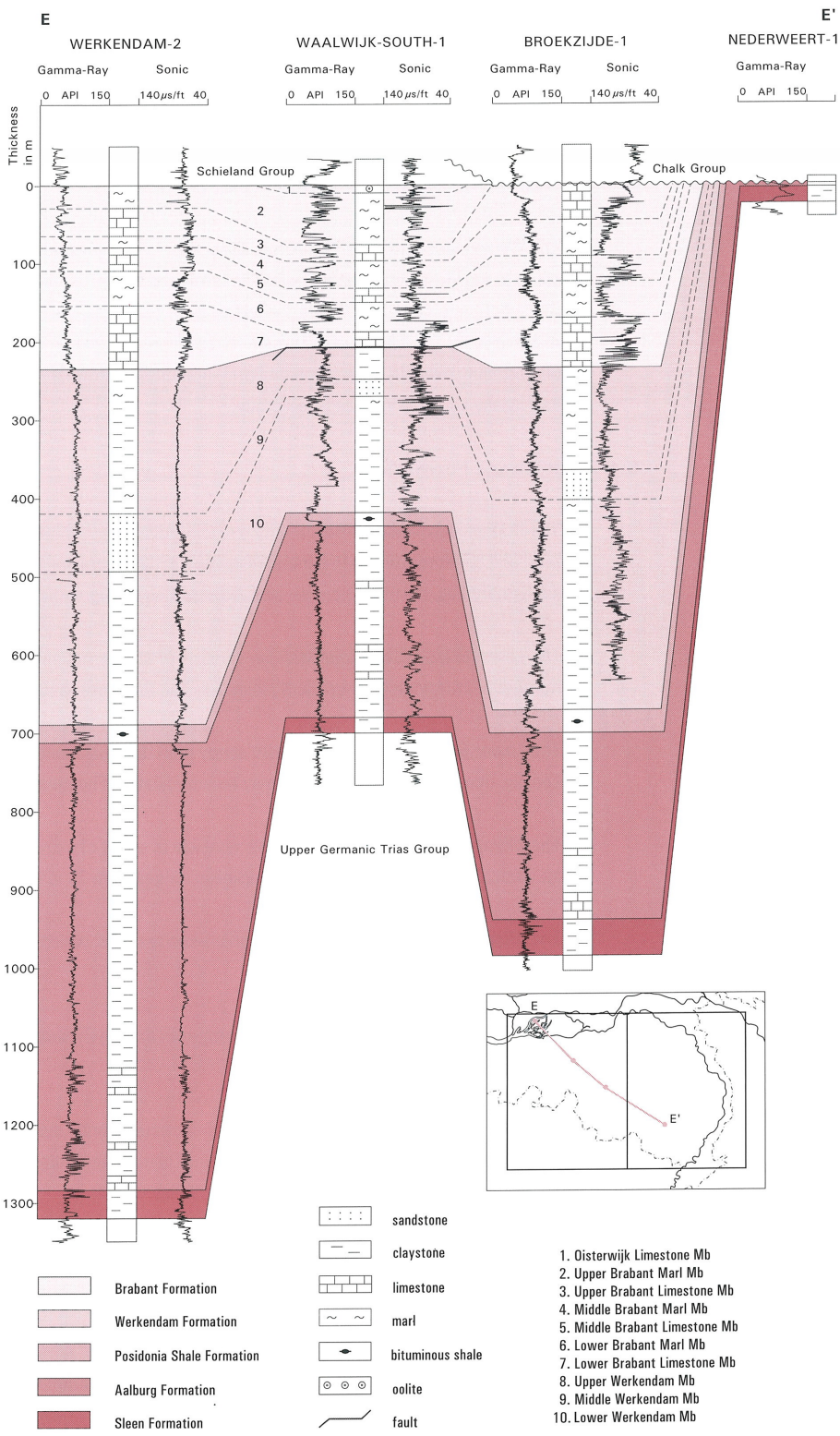
The *Upper Brabant Limestone Member* comprises extremely sandy limestones with a total thickness of 10 of 50 m.

The *Upper Brabant Marl Member* is a unit of extremely sandy marls with sandstone layers at the base. The sand content upwardly decreases content. The total thickness is 10 to 100 m, with the greatest thickness occurring in the central part of the Roer Valley Graben.

The *Oisterwijk Limestone Member* has only been penetrated in a few wells in the surroundings of the type-well Oisterwijk-1. The member is composed of massive oolitic limestone beds. The member is 5 to 20 m thick.

The Brabant Formation rests conformably upon the Werkendam Formation. The areal extent has been strongly determined by erosion (fig.9.1) as indicated by the considerable differences in the thickness of the various members. The formation is unconformably overlain by the Schieland or the Chalk Group or by the North Sea Supergroup. Where the formation is complete, the maximum thickness is slightly over 350 m.

Figure 9.3 Stratigraphic section E-E' of the Altena Group between the Werkendam-2, Waalwijk South-1, Broekzijde-1 and Nederweert-1 wells. The reference level is the top of the Altena Group.



9.2 Sedimentary development and palaeogeography

After a long period of continental or shallow-marine depositional conditions, a transgression during the Late Triassic (Rhaetian) favoured an open-marine depositional environment which extended over a large part of North Western Europe. This marks the beginning of the deposition of the Altena Group. The uniformity of the deposits is demonstrated by log correlation between the Werkendam-2 well in the map sheet area and well 48/03-03 situated in the English section of the North Sea (fig. 9.2). The homogeneous, fine-grained development of the Sleen, Aalburg and Posidonia Shale Formations clearly indicate that deposition took place in a single, continuous marine area. The Werkendam and the Brabant Formations also permit good correlation. It should, however, be observed that there is no certainty as whether the sandy Middle Werkendam Member in these wells correspond; the sands in the English well would generally appear to belong to a stratigraphically higher level. The Brabant Formation is developed far more argillaceously in the English well than in the Werkendam-2 well.

The sedimentation of the Altena Group in the map sheet area commenced with the transgressive deposits of the Sleen Formation. A brief regressive period at the end of the deposition of this formation gave the top of the Sleen Formation more of a lagoonal character, superseded by a sea-level rise and deposition of the open-marine sediments of the Aalburg Formation. The thin organic-rich layers indicate stagnation of the circulation in the basin. The greatest subsidence was initiated in the west of the map sheet area. The Early Toarcian is marked by a major period of euxinic sedimentation.

10 Schieland Group

10.1 Stratigraphy

The Schlieland Group, Kimmeridgian up to Barremian in age, is represented by the Delfland Subgroup, of which only the Nieuwerkerk Formation is encountered (fig. 10.1). The lithology consists predominantly of an alternation of dark to variegated claystones and sandstones with lignite beds. In the map sheet area, the group rests unconformably upon deposits of the Altena or the Upper Germanic Trias Group. The Schieland Group is unconformably overlain by the Rijnland or the Chalk Group. The group is found exclusively in the Roer Valley Graben and the West Netherlands Basin (Maps XIII-8,-9 and XIV-8,-9).

The depth of the base of the Schieland Group in the map sheet area is between 900 to approximately 2300 m. The thickness development is determined by a number of prominent NNW oriented fault blocks. These blocks display pronounced differences in thickness from one another (Maps XIII-9, XIV-9). The greatest thickness, over 1500 m, occurs in the northwestern part of the Roer Valley Graben at the transition to the West Netherlands Basin.

10.1.1 Nieuwerkerk Formation

The Nieuwerkerk Formation in the map sheet area is represented entirely by the Alblasserdam Member. The member comprises dark to light-grey, red and variegated claystones/siltstones, and fine to medium-grained sandstones. These sandstones may reach a thickness of several metres. Thicker, coarse-grained sandstone beds are also found. Coal seams and lignite are associated with the grey claystones. The red coloured sediments are restricted to the bottommost part of the member, while the grey coloured, organic-rich sediments predominate in the uppermost part. The total thickness of the member varies considerably, ranging from a few metres to over 1500 m. This great variation in thickness is the result on the one hand of the synsedimentary tectonics and on the other, of erosion during the subsequent basin inversion.

The intercalated sandstones in general display slight lateral continuity. The sand/shale ratio in the Roer Valley Graben and the West Netherlands Basin was demonstrated by Den Hartog Jager (1996) to diminish from the southeast to the northwest. The same trend can be observed in the direction of the adjacent horst blocks.

Based on biostratigraphic research of the Alblasserdam Member in the Oisterwijk-1 well (NITG 1999), this study documented that this unit was of Kimmeridgian age, thereby stating explicitly that no indications have been found for the Portlandian and younger Cretaceous in this well.

10.2 Sedimentary development and palaeogeography

The sediments of the Alblasserdam Member were deposited during the Late Jurassic in the relatively rapidly subsiding Roer Valley Graben and the West Netherlands Basin (Van Adrichem Boogaert & Kouwe, 1993-1997 and Den Hartog Jager, 1996). This subsidence was of a highly differentiated character. The bottommost ("red bed") section represents a depositional system of braided rivers which flowed via the longitudinal axis of the subsiding rifts. This was accompanied by rapid sedimentation of channel sandstones. These sand bodies were of limited areal extent and owing to the rapid subsidence of the basins, were stacked on top of each other at the basin centre. Initially, a semi-arid climate prevailed, which gradually became more humid. This was accompanied by a decrease in the differential subsidence. The braided river system made way for a pattern of meandering rivers flowing in flat valleys. Sand was deposited in channels, while sand, in the form of crevasse splays, as well as clays and lignite were also deposited in flood plains. Owing to the lateral accretion of channels, a number of continuous sand

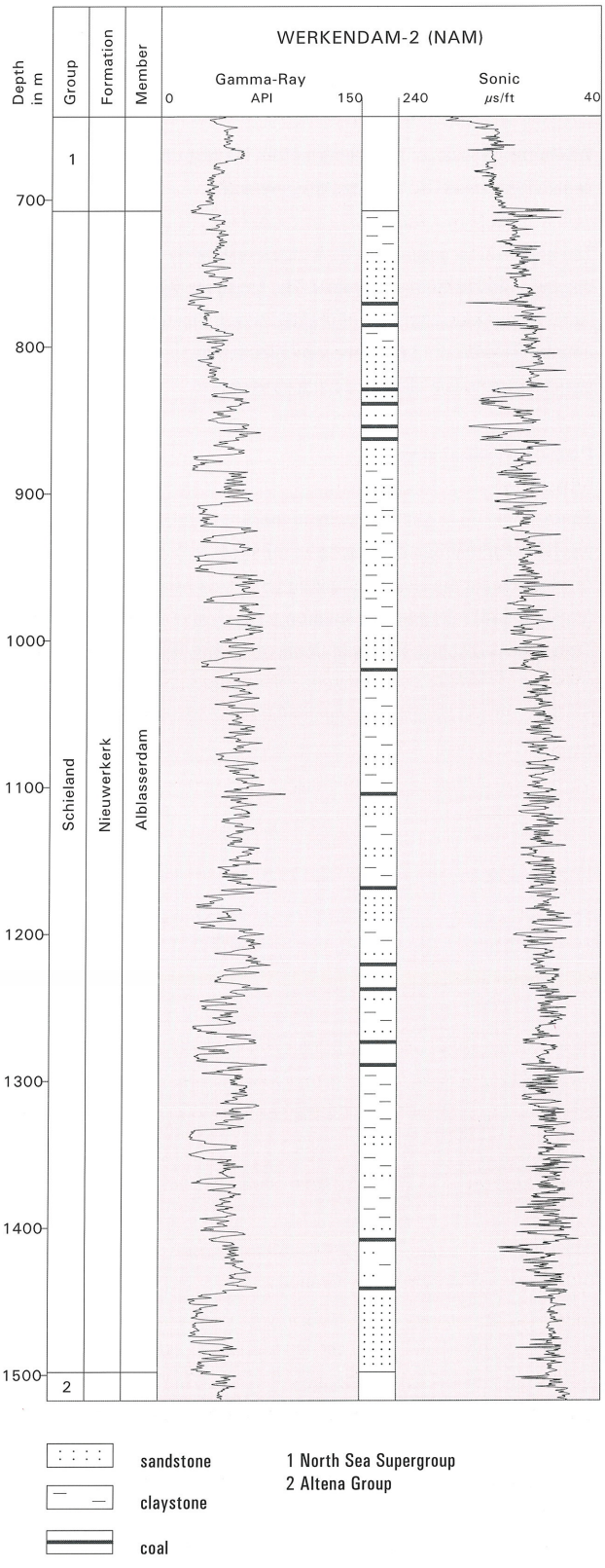


Figure 10.1 Stratigraphic division and log pattern of the Schieland Group in the Werkendam-2 well.

bodies developed. Likely areas of provenance of the detritus are thought to be the Brabant Massif, the Ardennes and the Rhenish Massif.

10.3 Seismic facies

Within the deposits of the Alblasserdam Member, two seismic facies are differentiated by Den Hartog Jager (1996) based on their seismic character.

The bottommost seismic facies is characterised by low amplitudes, where the reflectors generally display a discontinuous character. The facies represents the "red beds" facies within which sandstones were deposited in channels of braided rivers. The uppermost seismic facies is characterised by high amplitudes and comparatively continuous reflectors. This facies represents the alternation of coal seams, organic-rich claystones and sandstones.

10.4 Petrophysical data

There are no oil or gas reservoirs in the Schieland Group in the map sheet area. However, to the northwest of the map sheet area, in the West Netherlands Basin, oil is exploited from the sandstones of this group in the IJsselmonde/Ridderkerk oil field. Considerable differences in permeability (<100 tot 3000 mD) and cementation are typical of the sediments of the Nieuwerkerk Formation. The porosity displays values of under 10 to 27% (Racero-Baena & Drake, 1996).

11 Rijnland Group

11.1 Stratigraphy

The Rijnland Group in the map sheet area, of Late Barremian up to Albian age, comprises glauconite-bearing sandstones, siltstones, claystones and marls. The group is subdivided into the Vlieland Sandstone, the Vlieland Claystone and the Holland Formations. The two first-mentioned formations together form the informal Vlieland subgroup.

The deposits of the Rijnland Group are only found in the northeastern and northwestern parts of the map sheet area. The group has not been penetrated in any part of the map sheet area; unlike the immediately adjoining area. Based on the seismic mapping, the Vlieland subgroup and Holland Formations cannot always be clearly differentiated from each other. The depth of the group in both areas lies between 1000 and 2000 m (Maps XIII-10, XIV-10). The group reaches a maximum thickness of 250 m on the Maasbommel High (Maps XIII-11, XIV-11).

In the northwest, the group rests conformably or with a small hiatus upon the Schieland Group and in the northeast, unconformably upon older deposits. The Rijnland Group is conformably or unconformably overlain by the deposits of the Chalk Group.

11.1.1 Vlieland subgroup

The Vlieland subgroup, latest Barremian in age, is present in the northwestern and northeastern parts of the map sheet area. Elsewhere, the succession is completely absent owing to non-deposition and erosion during the Late Cretaceous or Tertiary.

Within the subgroup, the Vlieland Sandstone Formation and the Vlieland Claystone Formations can be distinguished. For the development of the subgroup in the West Netherlands Basin immediately beyond the areal extent of the map sheet area, reference should be made to Bodenhausen & Ott (1981), Van Adrichem Boogaert & Kouwe (1993-1997) and Den Hartog Jager (1996).

11.1.1a Vlieland Sandstone Formation

To the west and northwest of the map sheet area, the Vlieland Sandstone Formation, of Late Barremian age, is only represented by the De Lier Member. The thickness is approximately 20 m. The member comprises an alteration of often bioturbated, glauconite-rich, argillaceous sandstones and sandy claystones with shell debris.

11.1.1b Vlieland Claystone Formation

The Vlieland Claystone Formation, of Late Barremian age, is presumed only to occur in the map sheet area on the northeastern part of the Venlo Block. The thickness is expected to be only a few tens of metres.

11.1.2 Holland Formation

The Holland Formation consists predominantly of grey and reddish-brown marl and claystone deposited during the Aptian to Early Cenomanian. The formation is subdivided into the Lower Holland Marl, the Holland Greensand, the Middle-Holland Claystone and the Upper Holland Marl Members.

In the northwest, the formation rests conformably or with a small hiatus upon the Vlieland subgroup and in the northeast, unconformably upon the Upper Germanic Trias Group. The formation is overlain conformably or with a small hiatus by the Chalk Group or unconformably by the North Sea Supergroup.

The occurrence of the formation is restricted to the margin of the Central and West Netherlands Basin and to the Maasbommel High. Owing to the lack of well logs documenting the Holland Formation in the map sheet area, the lithological composition and thickness development of the adjacent areas have been taken as basis.

The *Lower Holland Marl* is composed of a grey, sometimes reddish-brown, argillaceous marl of Aptian age.

The *Holland Greensand*, of Late Aptian up to Early Albian age, consists of an alternation of dark, silty and sandy clay and glauconite-rich sands (greensands) and calcareous sands. The Holland Greensand rests on the Lower Holland Marl and is overlain by the Middle-Holland Claystone.

The *Middle Holland Claystone*, of Early to Middle Albian age, comprises a grey, marly clay. The clay content is higher than that of the underlying and overlying successions, which is reflected by a higher natural radioactivity. The thickness ranges from a few metres to 30 m.

The *Upper Holland Marl*, of Middle Albian up to presumably earliest Cenomanian age, comprises a grey to reddish-brown argillaceous marl. In the uppermost part lighter colours are also found. A characteristic feature of the sequence is the upwardly decreasing clay content, reflected in a decreasing natural radioactivity. The member rests on the Middle Holland Claystone and is unconformably overlain by the Chalk Group or the North Sea Supergroup. The maximum thickness of the member is over 100 m on the Maasbommel High.

11.2 Sedimentary development and palaeogeography

At the onset of the deposition of the Rijnland Group, the development was controlled by two subsidence regions, the Central and West Netherlands Basins. As the greater part of the map sheet area lay beyond these basins, only a thin, incomplete succession of the group is present.

The initiation of deposition of the Vlieland subgroup is marked by a major transgression, which terminated the lacustrine and fluvial conditions of the Schieland Group and preluded a long period of marine sedimentation, which is only represented in this map sheet by shallow-marine deposits.

During deposition of the Holland Formation, argillaceous marls and clays were deposited in the basins (Lower Holland Marl and Middle Holland Claystone), while along the margins, glauconitic sands were deposited in a shallow-marine realm (Holland Greensand and slightly further to the west, the Spijkenisse Greensand). This was superseded by a prominent sea-level rise resulting from the Albian transgression, identified throughout Western Europe (Crittenden, 1987). This transgression only reached the north and northwest of the map sheet area. In general, the coastline lay to the north of the map sheet area.

12 Chalk Group

12.1 Stratigraphy

In the map sheet area, the Chalk Group exhibits considerable variation in composition. On the Maasbommel High and the area to the west of the Rijen Fault, the group consists of a succession of well cemented, light-coloured, fine-grained chalks and marly chalks. A characteristic feature of these sediments is that the main constituents are calcareous skeletons of planktic and benthic organisms with very little influx of terrigenous material (Van Adrichem Boogaert & Kouwe, 1993-1997). On the Peel, the Venlo, the East and West Campine Blocks however, the Chalk Group is composed partly of argillaceous deposits; here, limestones are only found in the topmost part of the group. The Chalk Group is subdivided into the Texel, the Ommelanden and the Houthem Formations. In a large part of the map sheet area, by analogy with South Limburg (Felder, 1975, 1996; Felder et al., 1985; NITG-TNO, 1999), a further subdivision of the Chalk Group is made into the Aken, Vaals, Gulpen, Maastricht and Houthem Formations. The Oploo Formation has been added to this subdivision by Gras & Geluk (1999). In the Roer Valley Graben, the group consists of predominantly calcareous deposits of the Maastricht and Houthem Formations.

The Chalk Group is present virtually throughout the map sheet area (MapsXIII/XIV-12). Only in the northeast and in the extreme northwest of the map sheet area does the group rest conformably on the Rijnland Group; elsewhere, the group rests unconformably upon the Schieland, the Altena, the Lower Germanic Trias, the Upper Germanic Trias, the Zechstein or the Limburg Group (Map XIII/XIV-17). On the Krefeld High, the group rests unconformably upon the Carboniferous Limestone Group (Elberskirch & Wolburg, 1962). The group is overlain conformably or separated by a small hiatus by the Lower North Sea Group; however, in the north and west of the map sheet area, the Lower North Sea Group rests unconformably upon the Chalk Group. To the east of the area, the Middle North Sea Group rests unconformably upon the group (Hilden, 1988). A number of unconformities also occur within the group, of which the one at the base of the Maastricht Formation can also be distinguished on seismics (Gras & Geluk, 1999).

The depth of the base of the Chalk Group is the least in the southeastern part of the Venlo Block and the greatest, over 2000 m, in the Roer Valley Graben. Fairly analogous is the depth to the west of the Rijen Fault and on the Maasbommel High (Maps XIII/XIV-12).

The thickness of the Chalk group was strongly influenced by inversion tectonics and ranges in thickness from over 1500 m in the northeast to only a few tens of metres in the Roer Valley Graben. West of the Rijen Fault, the thickness is over 500 m (Maps XIII/XIV-13). On the Maasbommel High, the formation displays notable, fault-related thickness differences (Gras & Geluk, 1999). The Peel and Venlo Blocks were subject to synsedimentary movements of a maximum of some tens of metres. The group is of Cenomanian up to Danian age.

12.1.1 Texel Formation

The Texel Formation, of Cenomanian age, is only found on the Maasbommel High and in the Central and West Netherlands Basins. The formation is also found locally in the vicinity of the Rijen and Veldhoven Faults (Dongen-1, Hilvarenbeek-1 wells). In the majority of the area, the formation was not deposited. Within the formation, the Texel Greensand, Texel Marlstone and Plenus Marl Members can be distinguished. The thickness of the formation in the vicinity of the Rijen Fault is over 100 m. On the Maasbommel High, the thickness is over 80 m. In the West Netherlands Basin, the thickness rapidly diminishes in a southerly direction, from 100 m in the surroundings of Rotterdam to 0 m to the northwest of the map sheet area.

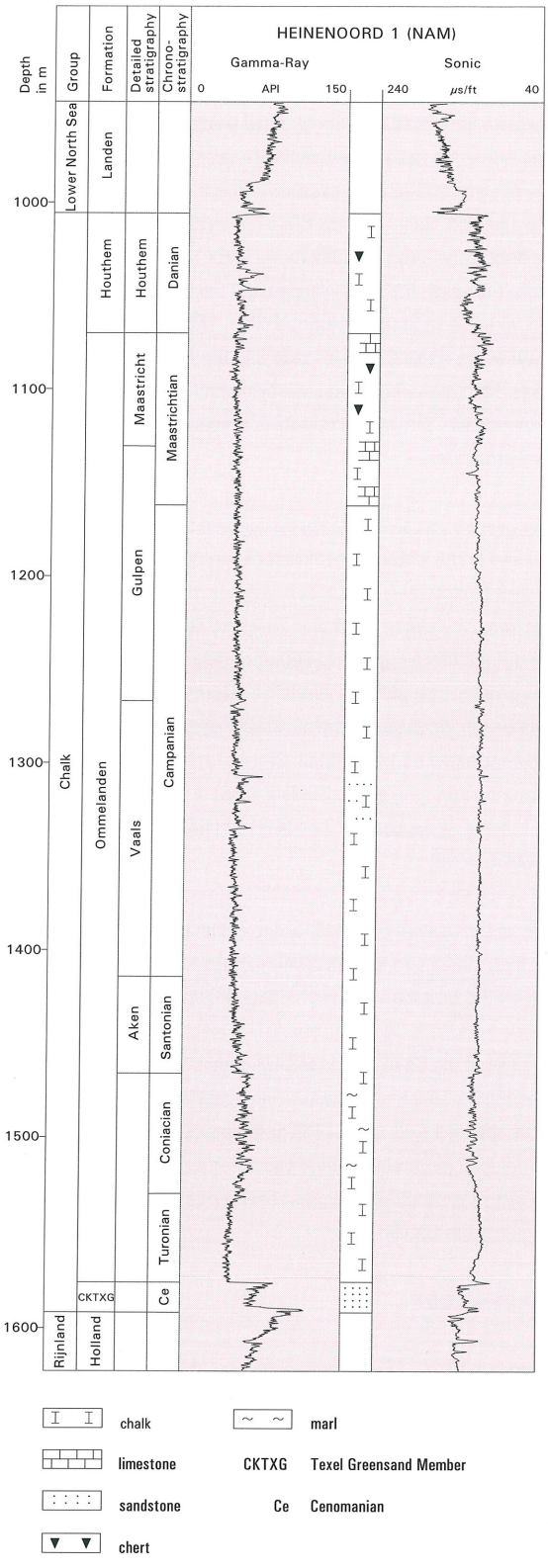


Figure 12.1 Stratigraphic division and log characteristics of the Chalk Group in the Heinenoord-1 well. This well is located in the western overlap of the map sheet area and displays the complete development of the group. The ages and the detailed stratigraphy have been determined on a basis of log correlation with Belgian wells (Felder et al., 1985).

The *Texel Greensand* consists of glauconite-rich sands. This member is only encountered close to the Rijen Fault and on the margin of the West Netherlands Basin. The thickness ranges from 10 to 40 m.

The *Texel Marlstone*, consists of an alternation of white marl sequences with a few limestone beds. This member is encountered on the Maasbommel High, with a thickness of over 80 m. This interpretation deviates from that arrived at by Gras (1995), who, on a basis of his log interpretations, estimates a thickness of over 30 m for the Texel Formation.

The *Plenus Marl*, of latest Cenomanian age, consists of a calcareous, dark coloured laminated claystone, clearly distinguishable by the kick on the well logs caused by its high gamma-ray. The sequence is generally a mere 1 to 2 m thick.

12.1.2 Ommelanden Formation

The Ommelanden Formation occurs throughout the map sheet area. In the greater part of the area, a further subdivision of the formation can be made analogous to that in South Limburg (Felder, 1975, 1996). In the northwestern part, the formation is not subdivided into members, but log correlation supported by biostratigraphic datings facilitates identification of the different Cretaceous stages (fig. 12.2).

The formation consists, at the base, of massive chalk of Turonian age, succeeded by a more marly sequences of Coniacian and Santonian age. These, in turn, are overlain by a calcareous succession of the Campanian which, in the lower part, consists of consolidated calcareous sand, upwardly grading into massive chalks. At the top of the Ommelanden Formation, limestones of Maastrichtian age occur, containing abundant chert nodules.

12.1.3 Aken Formation and Oploo Formation

The Aken and Oploo Formations, both of Santonian age, consist predominantly of clastic deposits. The formations are each others' lateral equivalents. The Aken Formation is differentiated by the occurrence of brown coal, soil horizons and wood remains

The Aken Formation is only found in the most southeasterly part of the Peel Block and on the Eastern and Western Campine Blocks (Felder et al., 1985). On the Peel Block, the unit rests unconformably upon the Limburg Group and is overlain by the Vaals Formation separated by a small hiatus; on the Eastern Campine Block, the unit rests upon the Limburg, the Zechstein or the Lower Germanic Trias Groups. At the base, the formation is composed of an alternation of brownish-grey sandstones, siltstones and claystones, which in places contain wood remains, root soil horizons and thin brown coal layers. Cross-bedded, channel sands were subsequently deposited. The formation has a maximum thickness of 50 m.

The Oploo Formation is found on the northern part of the Peel and the Venlo Blocks and the transition with the Maasbommel High (Gras & Geluk, 1999). The formation rests unconformably upon deposits of the Lower and Upper Germanic Trias, the Altena or the Rijnland Groups. The Vaals Formation rests on the Oploo Formation separated by a hiatus. The last-mentioned formation consists, at the base, of greenish-grey, glauconite-rich, fine-grained argillaceous sandstone. Sandy bioclastic limestones may also occur. In this sandstone, conglomerate beds containing iron ore may also occur (Van Waterschoot van der Gracht, 1918). The uppermost part of the formation consists of fine-grained sandstone, locally argillaceous. The formation reaches a thickness of over 200 m in the northwestern part of the Peel Block (Oploo-16 well) and further to the northwest, grades laterally into the chalks and marls of the Ommelanden Formation.

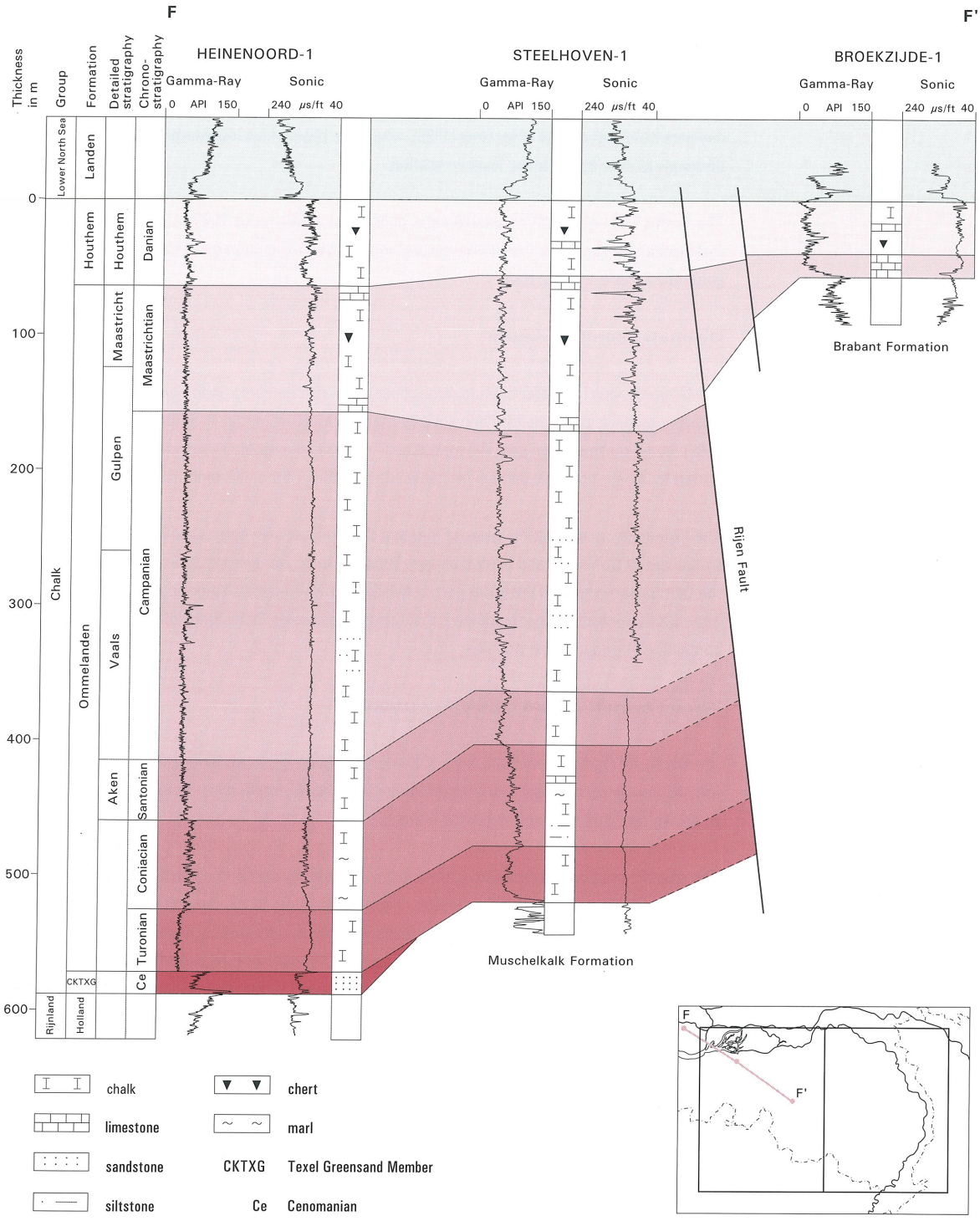


Figure 12.2 Stratigraphic section F-F' of the Chalk Group between the Heinenoord-1, Steelhoven-1 and Broekzijde-1 wells. This section displays the thickness and complete succession of the Chalk Group to the west of the Rijen Fault and the thin succession in the Roer Valley Graben as a consequence of inversion tectonics. The reference level is the base of the Landen Formation.

12.1.4 Vaals Formation

The Vaals Formation, of Campanian age, is found in the non-inverted areas beyond the Roer Valley Graben: the Peel and Venlo Blocks on the northeastern side and the Eastern and Western Campine Blocks to the southwest and west side. The formation is also found on a few fault blocks on the flank of the Roer Valley Graben, between the Grote Brogel and the Hamont-Bocholt Faults (Demyttenaere & Laga, 1985).

The formation rests conformably on the Aken or Oploo Formation; beyond the areal extent of these formations, the Vaals Formation rests unconformably upon the Limburg, the Zechstein or the Lower Germanic Trias Group. The formation is unconformably or disconformably overlain by the calcareous deposits of the Gulpen or Maastricht Formations. The thickness on the Peel Block increases in a north-westerly direction from 20 to over 200 m (Oploo-16 well. On the Eastern and Western Campine Blocks, the thickness ranges from 40 to 80 m (Felder et al., 1985). During deposition of this formation, minor faulting occurred here (Rossa, 1986).

The Vaals Formation comprises marine, yellowish to greenish-grey, fine, glauconitic sands and silty and argillaceous marly sands, with a fining-upward cyclicity. At the base, a thin, sandy conglomerate is found, consisting of well-rounded quartz pebbles. (Peelcommissie, 1963). In a northwesterly direction, the formation grades laterally into the chalks of the Ommelanden Formation.

12.1.5 Gulpen Formation

The Gulpen Formation, of Late Campanian up to Early Maastrichtian age, is also found in the non-inverted areas on both sides of the Roer Valley Graben. Within the formation, an unconformity occurs, and consequently the oldest part of the formation is not always found; an unconformity also occurs at the base of the overlying Maastricht Formation, which truncates the uppermost part of the Gulpen formation (Felder, 1996; Gras & Geluk, 1999). As a result, the formation has a drastically alternating thickness and is not always present (Peelcommissie, 1963). On the Western Campine Block, the formation consists of light coloured, fine-grained limestone. In the bottommost part of the formation, glauconite is found, while in the uppermost part, flint nodules occur. In the vicinity of the inverted Roer Valley Graben, on the Peel Block and the Eastern Campine Block, the formation developed as a glauconitic marl, containing some sand and silt. These sediments were termed the pre-Valkenburg Strata by Felder et al. (1985).

The Gulpen Formation rests, locally, unconformably upon the siliciclastic Vaals Formation. The Maastricht Formation rests unconformably upon the Gulpen Formation, via a small hiatus. The thickness of the formation on the Peel Block varies considerably: less than 10 m in the southeast to 95 m in the Oploo-16 well. The formation is absent locally. On the Eastern and Western Campine Blocks, the thickness of the formation increases drastically in a northerly direction from approximately 30 to over 200 m (Felder et al., 1985). In a northwesterly direction, the formation grades into the chalks and marls of the Ommelanden Formation.

12.1.6 Maastricht Formation

The Maastricht Formation comprises light-yellow to light-greyish-yellow, carbonate deposits. As the first formation of the Chalk Group to be deposited, the Maastricht Formation occurs virtually throughout the areal extent. Owing to non-de position, the formation is absent in places in the Roer Valley Graben. In this graben, the formation rests unconformably upon the Upper Germanic Trias, the Altena or the

Schieland Groups. On the Eastern and Western Campine and the Peel Blocks, the formation rests unconformably upon the Gulpen Formation. On the Venlo Block, the formation in the northwest rests unconformably upon the Gulpen Formation. Owing to an angular unconformity, in a southeasterly direction the formation rests on increasingly older sediments, as far as the Limburg Group. To the east of the map sheet area, the formation on the Krefeld High rests unconformably upon the Carboniferous Limestone Group (Elberskirch & Wolburg, 1962). The Houthem Formation overlies the formation, separated by a small hiatus. At the base of the Maastricht Formation, a glauconitic layer with fossil hash occurs. The bottommost part of the formation predominantly consists of fine-grained carbonates, whereas the uppermost part comprises coarse-grained limestones with bioclastic grains of silt and sand grain size. This type of limestone is also termed tuffaceous chalk (Zijlstra, 1995). In addition, hard limestone nodules, hardground and fossil hash layers are present in the formation. On the Krefeld High, the formation encountered comprised a porous reef limestone, Maastrichtian in age (Wachtendonk-1 well); the principal

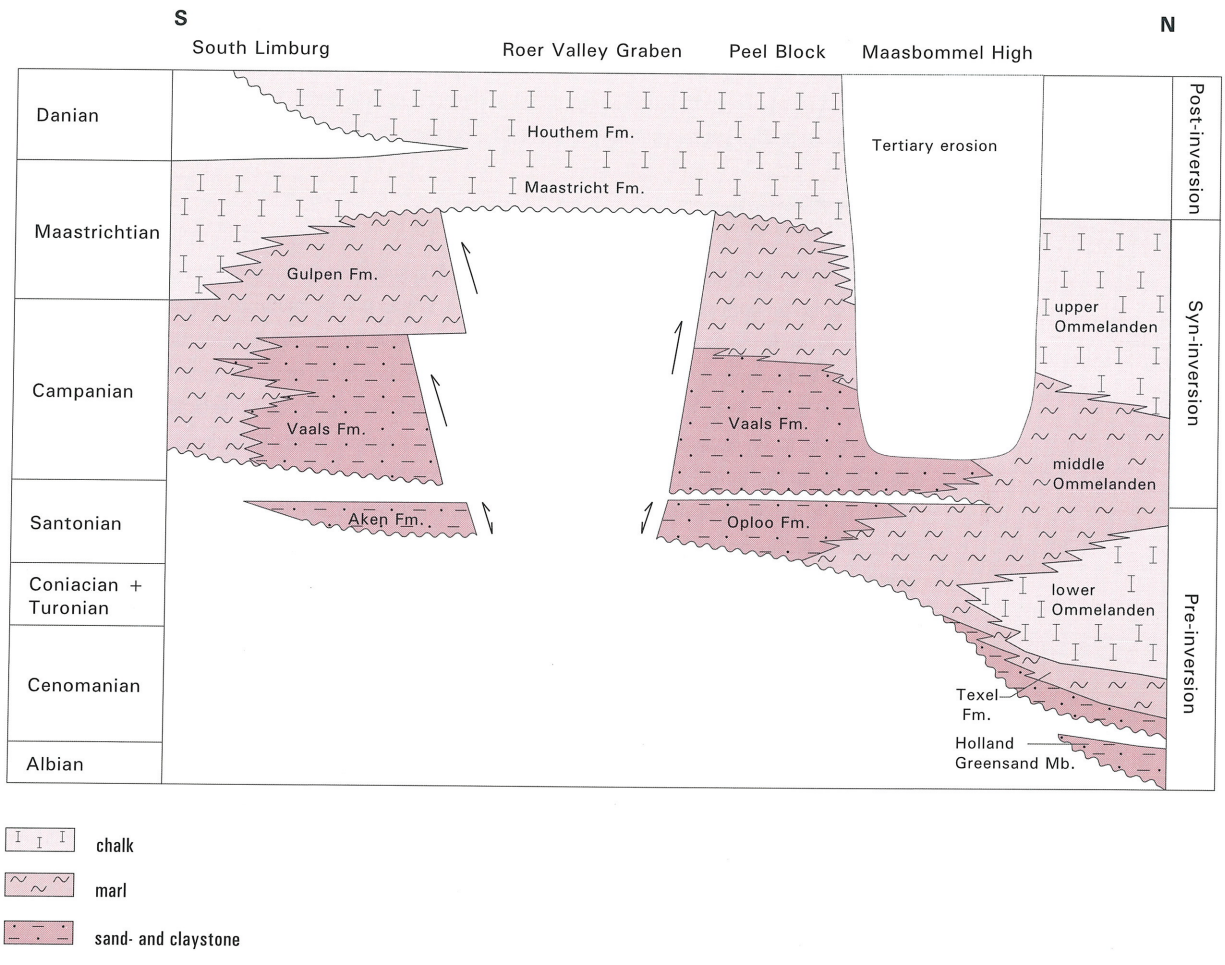


Figure 12.3 Diagram of the succession of the Chalk Group in the principal structural elements. In the inverted areas, the youngest deposits of the group (Maastrichtian-Danian) rest upon older deposits, separated by a large hiatus, whereas in non-inverted areas, the main deposits present are of Santonian up to Maastrichtian age. In the immediate vicinity of the inverted Roer Valley Graben, sands were deposited during the Santonian and Campanian. After Gras (1995).

reef-forming organisms identified were bryozoa and algae (Elberskirch & Wolburg, 1962). These were erosional relics with a thickness of only 4 m beneath the Middle North Sea Group.

The formation is a few metres thick in the Roer Valley Graben and reaches a maximum of 40 m on the Peel Block to over 100 m on the Western Campine Block. The Maastricht Formation consists only of deposits of the Late Maastrichtian, to possibly earliest Danian (Gras, 1995).

12.1.7 Houthem Formation

This formation, of Danian age, comprises soft, light-grey to light-yellowish-grey, fine to coarse-grained limestones, with the occurrence of hard limestone nodules, hardgrounds and fossil hash layers. At the base, the formation contains glauconite. The bottommost part of the formation is characterised by the occurrence of glauconite. The formation is found virtually throughout the map sheet area, with the

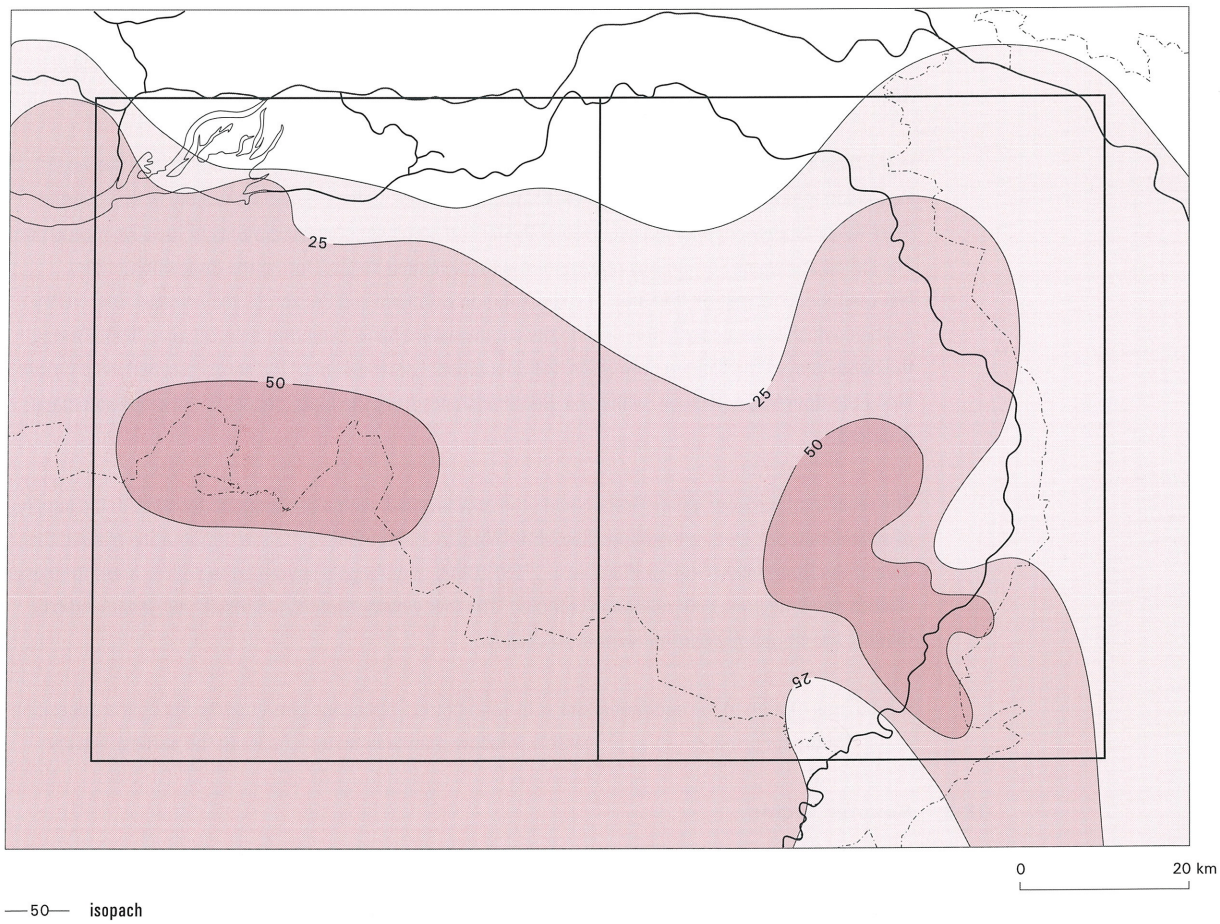


Figure 12.4 Extent and thickness of the Houthem Formation in the map sheet area. This formation, which forms an important aquifer, overlays the palaeorelief in the area. The absence of the formation in the northern part of the area is attributed to subsequent uplift.

exception of the northern part of the Roer Valley Graben and the southwestern part of the Western Campine Block (Felder et al., 1985).

The Houthem Formation rests upon the Maastricht Formation, separated by a hiatus, or, in the extreme northwest, upon the Ommelanden Formation. In the Roer Valley Graben, the deposits rest unconformably on the Limburg, the Lower Germanic Trias, the Upper Germanic Trias, the Altena or the Schieland Groups. To the northeast of the map sheet area, the formation in the Central Netherlands Basin rests unconformably upon the Altena Group. The formation reaches a thickness of approximately 50 m. The formation is overlain, unconformably or separated by a hiatus, by the Lower North Sea Group.

In the Houthem Formation, on the northern Peel Block, a penetrated aquifer generated an artesian spring in the Oploo-16 well (Tesch, 1913). The natural outflow here had a discharge of over 1 m^3/s.

12.2 Sedimentary development and palaeogeography

The deposition of the Chalk Group in the map sheet area was determined by the interaction of two external factors, namely a transgression from the north, as a result of which the base of the group becomes younger towards the south and the inversion of former Jurassic-Cretaceous basins during deposition of the group. The inverted basins, in the map sheet area formed predominantly by the Roer Valley Graben, constituted the main source area of sediment (Bless, 1991; Bless et al. 1987).

In the vicinity of the former coastline, greensands were initially deposited, as is the case in the Texel Formation in the north and northwest of the map sheet area. In the immediate vicinity of the inverted Roer Valley Graben, deposition occurred of fluvial and limnic/lagoonal sediments of the Aken Formation. The Oploo and Vaals Formations represent marine deposited sands. During the deposition of the last-mentioned formation, the area of sedimentation extended slightly across the inverted Roer Valley Graben; which is particularly the case on the southwestern flank (Demyttenaere & Laga, 1995). During the deposition of the Gulpen Formation, the depositional areal extent of the sands receded even further along the Roer Valley Graben, while at a greater distance from the high, deposition of chalk and marls occurred.

The relief in of the Roer Valley Graben had gradually levelled, with a consequent decrease in the supply of clastic material. During the deposition of the Maastricht Formation, the sea temporarily invaded the area of the Roer Valley Graben (Bless et al., 1987, 1993), thus largely covering the source areas for these clastics and limestone sedimentation resumed. The many hardgrounds and fossil hash layers indicate that the sea frequently became extremely shallow.

A brief interruption to the sedimentation at the end of the Cretaceous was superseded by the deposition of the Houthem Formation, in a comparable, shallow-marine limestone facies in the earliest Tertiary.

12.3 Seismic facies

Within the deposits of the Chalk Group, three seismostratigraphic units have been distinguished on a basis of seismic characteristics by Gras (1995) and Gras & Geluk (1999):

Seismic facies I occurs on the Peel and the Venlo Blocks. This facies has a transparent character with only a few discontinuous reflectors. This facies represents the sandy deposits of the Oploo, Vaals and Gulpen Formations. Towards the northwest, the number of continuous reflectors increases, and the facies grades laterally into facies II.

Seismic facies II occurs on the Maasbommel High, and also to the west of the Rijen Fault. This facies is characterised by an alternation of a few continuous reflectors with transparent sequences. This facies represents the alternation between the marly and calcareous sequences of the Ommelanden Formation.

Seismic facies III is present in the greater part of the map sheet area. The species comprises one or more continuous high-amplitude reflectors, running parallel to those of the North Sea Super Group. Locally, this facies is truncated by the base of this group. The facies rests unconformably upon facies I or II; on the Venlo Block, in a southwesterly direction, the entire facies I has been truncated by this facies. This facies represents the Maastricht and Houthem Formations.

13 North Sea Supergroup

13.1 Stratigraphy

The North Sea Supergroup is subdivided into the Lower, the Middle and the Upper North Sea Groups and is composed almost entirely of sands and clays. The three groups are separated from each other by unconformities; within the groups, unconformities may also occur. The North Sea Supergroup rests conformably or unconformably upon the Chalk Group, or unconformably upon older lithostratigraphic units, such as the Rijnland, the Altena and the Upper Germanic Trias Groups. The sedimentation was to a large extent influenced by a combination of regional tectonics and eustatic sea-level changes. Marine conditions, however, were predominant during virtually the whole of the Tertiary, with the exception of the Neogene in the southeast of the area, where continental depositional conditions prevailed.

The three groups of the North Sea Supergroup are found throughout the area, but the depth, almost analogous to the thickness, varies considerably. In the Roer Valley Graben, the Supergroup reaches the greatest thickness of over 1700 m. To the west of the Rijen Fault, the thickness is over 1000 m and on the Peel and Venlo Blocks, from 500 to over 800 m (Maps XIII/XIV-14).

Besides in-house interpretations based on logs and seismics, the descriptions and extensional limits of distribution used in this chapter derive largely from data originating from Letsch & Sissingh (1983), Zagwijn (1989), Van Adrichem Boogaert & Kouwe (1993-1997), NITG-TNO (1999), Verbeek et al. (in press) and the explanations accompanying the map sheets Rijks Geologische Dienst (1967, 1973, 1984, 1985) of the Geologische Kaart van Nederland. These last-mentioned references provide considerable information on the youngest sediments in particular.

13.1.1 Lower North Sea Group

The Lower North Sea Group, comprising the Landen and Dongen Formations, occurs throughout the map sheet area. The deposits rest unconformably upon the Chalk or upon the Rijnland, the Altena and the Upper Germanic Trias Groups. The Lower North Sea Group was deposited during the Late Palaeocene and the Eocene.

13.1.1.1 Landen Formation

The Landen Formation, of Late Palaeocene age, is found virtually throughout the map sheet area. In the western part of the Roer Valley Graben, the formation is absent locally, presumably as a consequence of erosion. The formation has its greatest thickness, 120 m, in the southeast of the area, where it displays its most complete sequential development with sands at the base and the top, with intermediary marl and clay. The formation is composed of the Swalmen, the Heers, the Gelinden, the Landen Clay and the Reusel Members.

The *Swalmen Member* consists of a sandy and argillaceous sequence containing a few small brown coal seams. This deposition has only been documented in the southeast of the map sheet area. The thickness is a maximum of 35 m in the Molenbeersel-198 well.

The *Heers Member* is composed of a fine-grained, glauconitic sand, which may be regarded as the transgressive sand at the base of the formation. The thickness ranges from 10 to 25 m.

The *Gelinden Member* comprises greyish-white to yellowish-brown, argillaceous marls with yellow concretions. The base generally consists of dark green, marly clay. The member has a limited distribution in the southeast of the map sheet area. The thickness ranges from 5 to 20 m.

The *Landen Clay Member* consists of a green, silty clay and is found throughout the area with a thickness of 50 to 100 metres.

The *Reusel Member* has a sandy development and may be over 70 m thick on the Peel Block, while in the adjacent parts of the Roer Valley Graben, thicknesses of over 40 m have been documented.

13.1.1.2 Dongen Formation

The Dongen Formation, of Eocene age, occurs throughout the area, with the exception of the Peel Block and the southeastern part of the Roer Valley Graben. The Dongen Formation rests conformably on the Landen Formation and is unconformably overlain by deposits of the Middle North Sea Group. The thickness of the formation is strongly dependent on tectonic movements and erosion during the Pyrenean and Savian phases. The formation is composed of the Basal Dongen Sand, the Ieper, the Brussels Sand and the Asse Members. The member is over 300 m thick in the Dongen-1 well.

The *Basal Dongen Sand*, of Early Eocene age, consists of a fine-grained, sometimes glauconitic sand. The thickness is a maximum of 10 m.

The *Ieper Member*, of Early Eocene age, consists of brownish-grey and reddish-brown clay at the base and sandy clay at the top and may contain pyrite, shells, coalified plant remains and benthic foraminifera locally. The fat clays contain sandy and silty horizons. The topmost part of the unit comprises greenish-grey, glauconitic and marly sand intercalations. The member may exceed a thickness of 300 m.

The *Brussels Sand* consists of fine-grained, glauconitic sands which, on the Campine Block, may attain a thickness of approximately 110 m.

The *Asse Member* is a highly plastic and greenish-grey to bluish-grey calcareous clay. The member may reach a thickness of 80 m.

13.1.2 Middle North Sea Group

The Middle North Sea Group, of Oligocene age, rests unconformably on the Lower North Sea Group and is overlain, also unconformably, by the Upper North Sea Group. In the map sheet area, the group consists of the Rupel and Veldhoven Formations. Both formations consist of fine-grained sands and clays.

13.1.2.1 Rupel Formation

The Rupel Formation, of Rupelian and Early Chattian age, occurs throughout the map sheet area and may reach thicknesses of approximately 150 m. The formation is composed of the Vessem, the Rupel Clay and the Steensel Members. The *Vessem Member* consists of fine-grained and glauconitic sands, which may be regarded as the transgressive base of the formation. These sands display several, coarsening-upward cycles. The thickness of the member is limited and ranges from a few metres to 30 m. The overlying *Rupel Clay* consists of an alternation of silty and argillaceous deposits. This member is rich in pyrite in places. In the southeastern part of the map sheet area, the top of this unit contains the *Steensel Member*. This member comprises, at the base, an alternation of clays and silty clays with thin sands and upwardly grades into a fine-grained sand. The presence of this member is difficult to demonstrate, even on logs. The *Steensel Member* has a thickness of approximately 20 m in the map sheet area.

13.1.2.2 Veldhoven Formation

The Veldhoven Formation, of Late Oligocene age, is absent in the southwest, while its presence in the west is doubtful. The formation is composed of the Voort, the Veldhoven Clay and the Someren Members. The thickness of the formation shows pronounced variations. In the southeastern part of

the Roer Valley Graben, the formation may be extremely thick (>400 m), but is absent on the Western Campine Block and in the West Netherlands Basin.

The *Voort Member* exceeds a thickness of 230 m in the southeast of the map sheet area. The member comprises a succession of coarsening-upward units. Towards the west, the unit becomes much thinner (<10 m), displaying more the character of a transgressive sand at the base of a sedimentary cycle.

The overlying *Veldhoven Clay Member* also reaches its greatest thickness (>140 m) in the southeast of the Roer Valley Graben and, towards the northwest, rapidly decreases in thickness to a few tens of metres. This member consists of silty clays and, at the top, sandy clays.

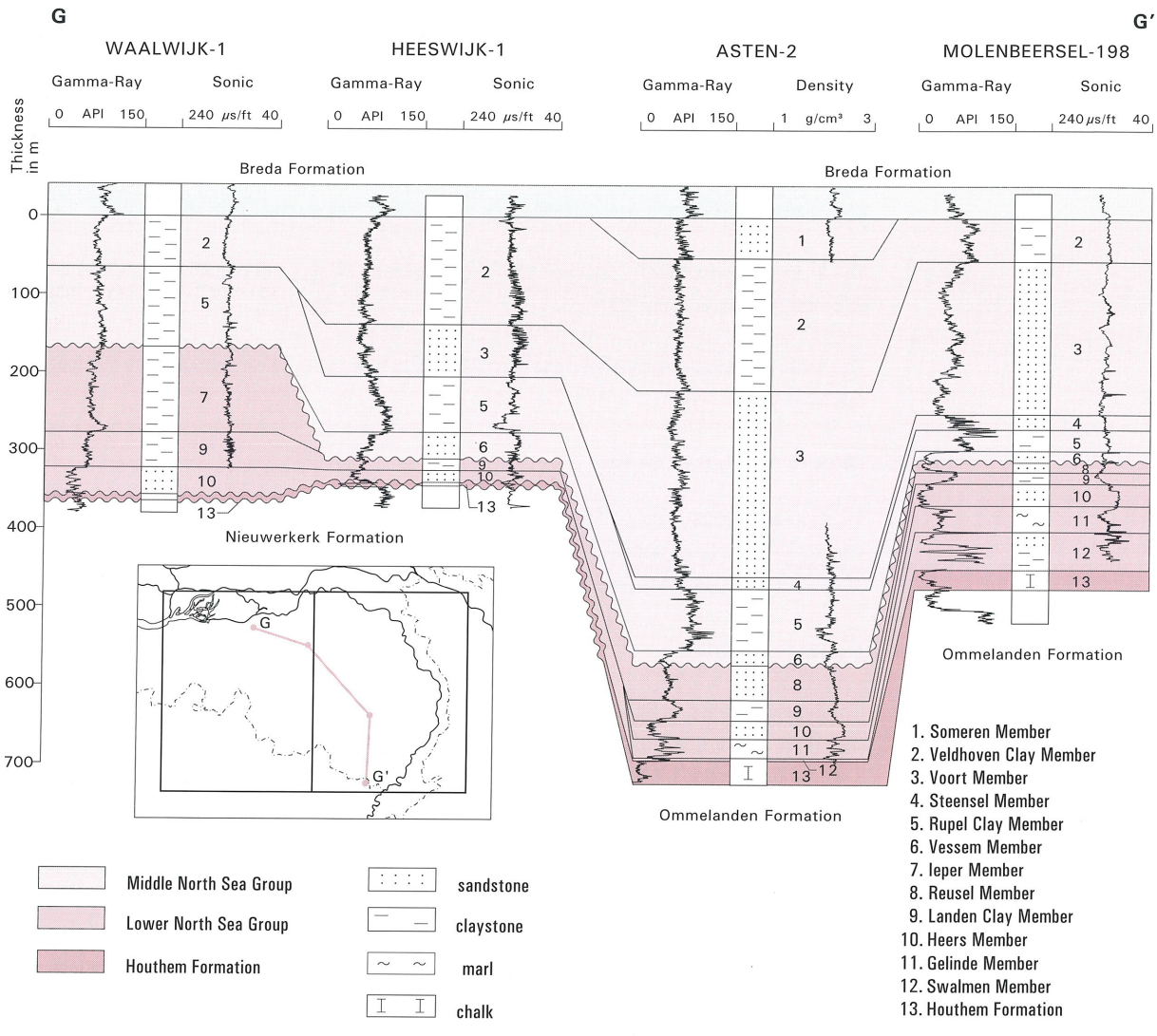


Figure 13.1 Stratigraphic section G-G' of the Lower and Middle North Sea Group between the Waalwijk-1, Heeswijk-1, Asten-2 and Molenbeersel-198 wells. This section clearly illustrates the complete thickness development of the Middle North Sea Group (numbers 1-6) in the Roer Valley Graben. The reference level is the base of the Breda Formation.

The youngest member, the *Someren Member*, consists of argillaceous sands which upwardly grade into fine-grained sands. Beyond the Roer Valley Graben, this unit is difficult to differentiate on logs.

13.1.3 Upper North Sea Group

In the map sheet area, the Upper North Sea Group, of Miocene to Quaternary age, comprises the Breda, Ville and Oosterhout Formations and Quaternary deposits. The group rests unconformably upon the Middle North Sea Group or disconformably upon older deposits. The depth of the base of the group, as well as the thickness of the group, varies considerably. On the Peel and Venlo Blocks, the thickness is 100 to 300 m; in the Roer Valley Graben over 1200 m (Maps XIII/XIV-15).

13.1.3.1 Breda Formation

On a basis of in-house interpretations of the gamma-ray log and seismic data, the formation in the map sheet area can in general be subdivided into three large seismostratigraphic units (fig. 13.1): a basal argillaceous interval overlain by two sandy intervals. The formation, which was deposited during the Miocene, reaches its greatest thickness, around 600 m, in the Roer Valley Graben. The basal, argillaceous interval here is approximately 200 m thick. This unit consists of a few, coarsening-upward sequences. The sandy part shows a bipartition, each of which displays a prograding character on seismic records. The boundary between the two sandy units coincides with the Serravallian-Tortonian boundary (NITG 1998a). Particularly towards the west, the units decrease in thickness. In the map sheet area, the sandy units pinch out or are absent locally as a result of erosion. In the westernmost part of the map sheet area, on the Campine Block, the Breda Formation is absent and the Oosterhout Formation rests immediately upon the Rupel or the Veldhoven Formation.

13.1.3.2 Ville Formation

The Ville Formation, of Early to Middle Miocene age in the map sheet area, only comprises the *Heksenberg Member*. This sandy unit occurs exclusively in the southeast of the Roer Valley Graben. Abundant plant remains are found in the unit, but the conspicuous brown coal seams have only been found in the extreme southeast of the map sheet area. The formation is approximately 80 m thick.

13.1.3.3 Oosterhout Formation

The Oosterhout Formation, of Pliocene age, is a predominantly sandy, glauconite-rich formation, which is absent in the southeast of the map sheet area. The eastern part of the formation consists of aggregating sands, while in the western part, large prograding sedimentary units reaching a thickness of over 250 m can be distinguished. In a few places, a clear erosive contact with the underlying Breda Formation can be observed. Towards the west, there is a gradual increase in clay content in the formation.

13.1.3.4 Maassluis Formation

The Maassluis Formation, of Pleistocene age, is only found in the western and northern parts of the map sheet area, with a maximum thickness of a few tens of metres. The formation consists of poorly glauconitic, fine-to coarse-grained sands with shell fragments, and the occasional local intercalation of sandy clay and clay lenticles

13.1.3.5 Upper Miocene to recent continental deposits

The oldest continental formation is the Kieseloolite Formation, which occurs throughout the area. The lower boundary is not isochronous. In the southeastern part of the map sheet area, an interfingering with

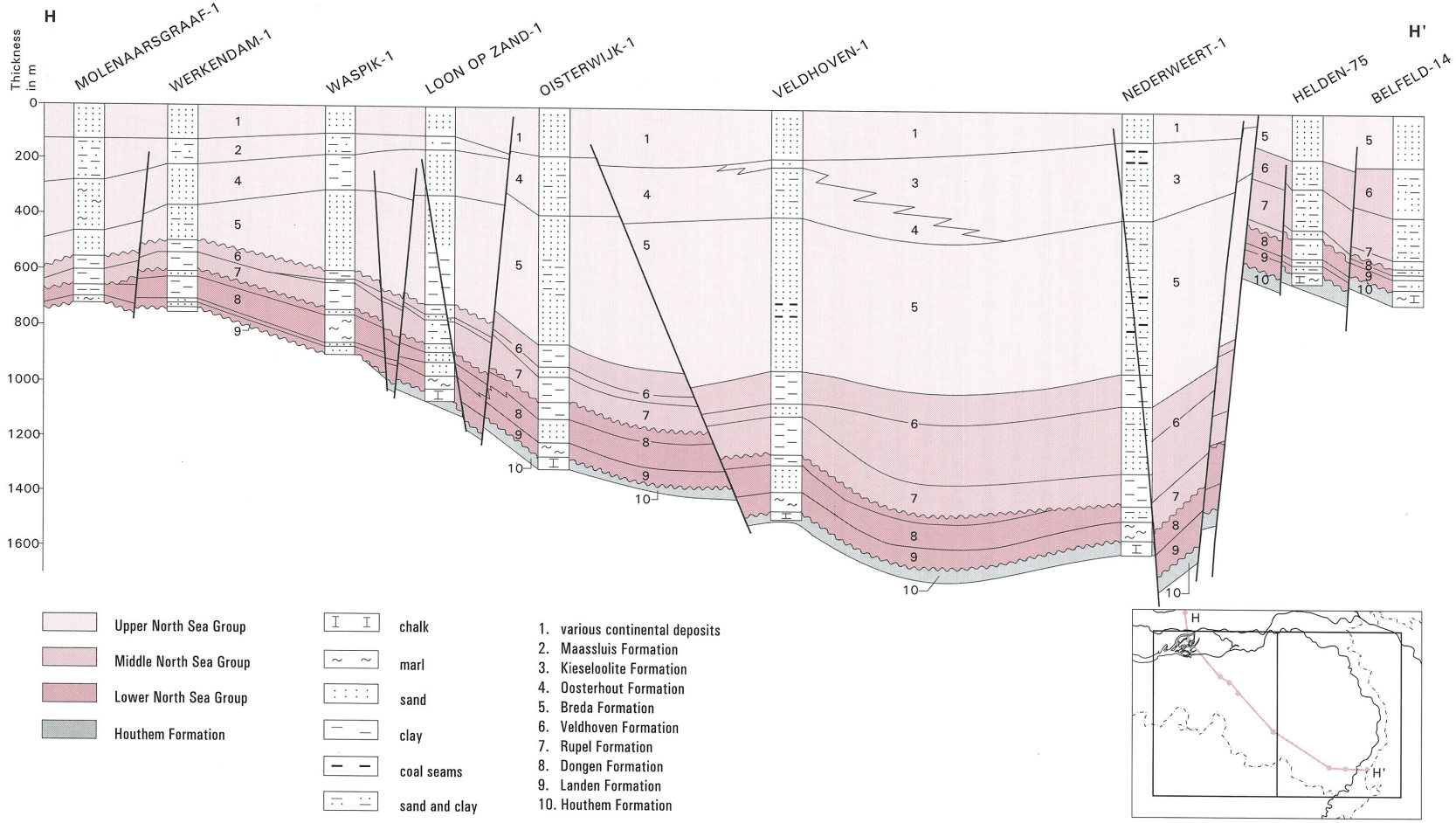


Figure 13.2 Section H-H' through the Cenozoic deposits in the Roer Valley Graben and on the Peel Block. The section clearly illustrates the great difference in thickness and composition between these structural elements (after RGD 1982).

the Breda Formation occurs and the lower boundary is Late Miocene in age. To the west, interfingering occurs with the Oosterhout Formation and the lower boundary is Pliocene in age. The westernmost areal limit of the formation is situated, in a southwest to northeast line, to the west of Eindhoven (Rijks Geologische Dienst, 1985).

The Quaternary continental formations are, in succession, the Tegelen, Kedichem, Sterksel and Veghel Formations. These formations consist of clay, sand and gravel and are differentiated by their mineral content and grain size. The units evolved as a result of the deposition of degradated material from the hinterland by the large rivers. Peat layers may also occur in these formations.

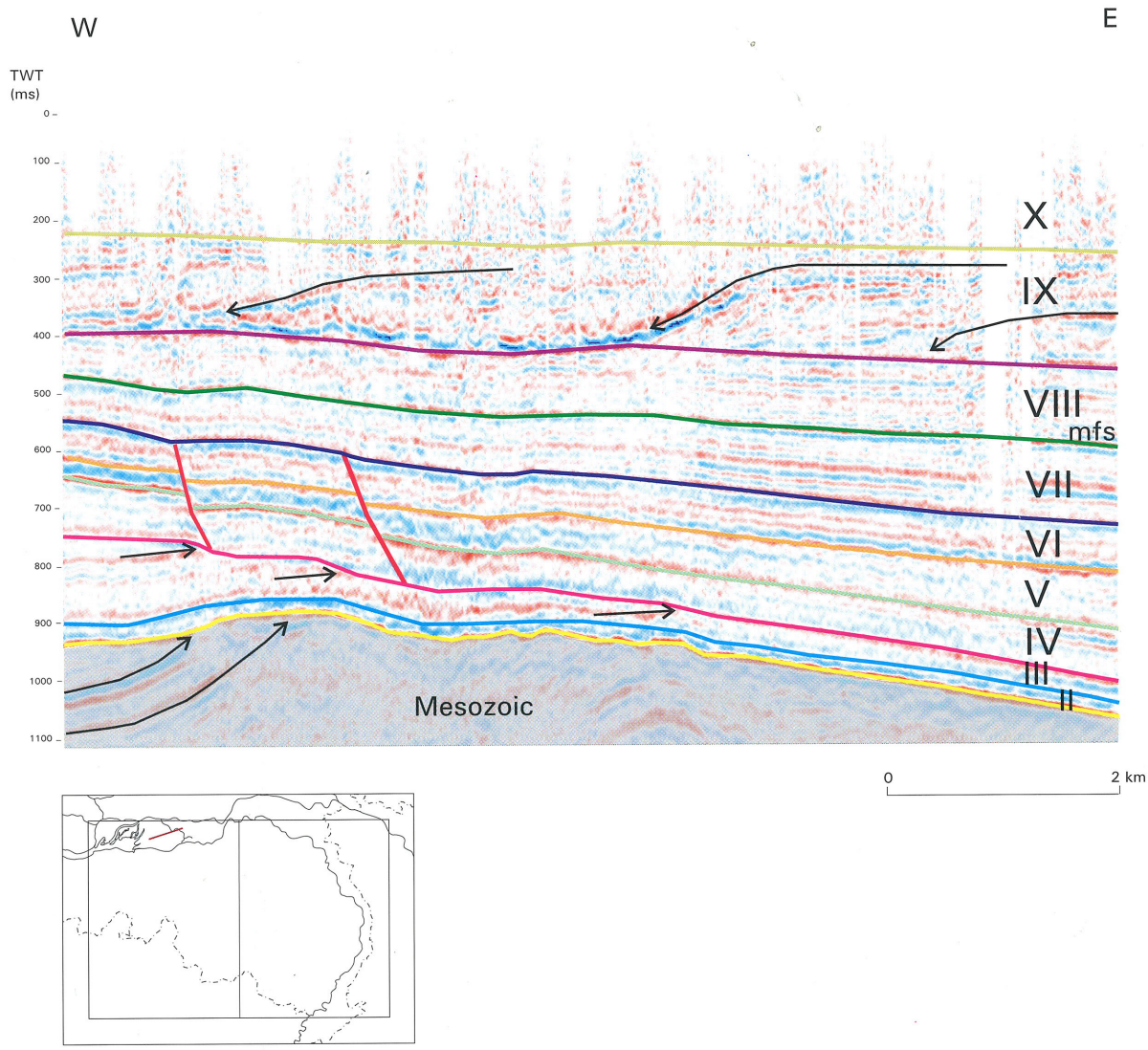


Figure 13.3 Seismostratigraphic section through the Cenozoic deposits in the Roer Valley Graben. For an explanation of units II-X reference should be made to table 13.1. Unit I is absent in this section. (mfs = maximum flooding surface)

13.2 Sedimentary development and palaeogeography

During deposition of the North Sea Supergroup, the map sheet area lay on the southern margin of the North Sea Basin. Owing to this position, the deposition of the supergroup was largely controlled by tectonic surface movements and eustatic sea-level fluctuations. In particular, the tectonic movements of the Roer Valley Graben and surrounding horst blocks played an important role.

In the Palaeocene and the Early Eocene, the North Sea Basin was still connected to the Paris Basin, but uplift of the Artois Axis terminated this contact (Ziegler, 1990). During the Late Palaeocene, the sediments of the Landen Formation were initially deposited under lacustrine and lagoonal conditions. The persevering transgression facilitated deposition of the marine sands, clays and marls of the Dongen Formation. At the end of the Eocene, the Pyrenean tectonic phase caused an uplift of a NW-SE oriented

Table 13.1 Overview of characteristics of the seismo-stratigraphic units

Seismic unit	*Chrono-stratigraphy*	*Litho-stratigraphy*	*Sedimentary facies*	*Seismic facies*				
				amplitudes	*continuity*	*frequency*	*lower boundary*	*upper boundary*
X	Quaternary	Various	fluvial-peri-glacial	high	limited	high	conform	
IX	Pliocene	Oosterhout/ Kieseloolite Formation	marine-deltaic-fluvial	high	limited, clinoforms shingled to complex sigmoid	high	conform, downlap	conform, toplap, incision
VIII	Late Miocene	(upper) Breda Formation	marine-deltaic	low to medium	limited, clinoforms shingled	high	conform, onlap, downlap	conform, toplap, incision
VII	Middle Miocene	(middle) Breda Formation	marine-deltaic	medium	limited, clinoforms shingled	high	conform, onlap, downlap	conform, toplap
VI	Early Miocene	(lower) Breda Formation	marine	high	large	high	conform	conform
V	Late Oligocene	Veldhoven Formation	marine	low	large	low	conform	conform, incision
IV	Early Oligocene	Rupel Formation	marine	low	very large	low	conform	conform
III	Eocene	Dongen Formation	marine	high (upper part) and low (lower part)	limited (upper part) and large (lower part)	high (upper part) and low (lower part)	conform	conform, incision, truncation
II	Early Palaeocene	Landen Formation	marine	low	large	low	conform	conform
I	Early Palaeocene	Houthem Formation	marine	high	limited	high	conform	conform
	Mesozoic							conform, truncation

zone in the centre and southeast of the Netherlands (the Southern Early Tertiary High, cf. Van Adrichem Boogaert & Kouwe, 1993-1997). The erosion incised profoundly into the sediments, which accounts for the absence of the Eocene in large parts of the map sheet area. In the Roer Valley Graben and on the Peel and Venlo Blocks, only the Palaeocene was preserved from erosion. To the east of the map sheet area, these sediments have also been eroded and the Oligocene deposits rest immediately upon the pre-Tertiary (Hilden, 1988).

The deposits of the Rupel Formation reflect the resumption of sedimentation in the map sheet area in the earliest Oligocene. Initially, the conditions were shallow-marine and lagoonal, and later open-marine. There are no indications of differential subsidence of the area and the uniform character of the Rupel Clay suggests deposition in a vast marine realm. At the beginning of the Late Oligocene, the Roer Valley Graben fault system was reactivated (Zagwijn, 1989; Geluk et al., 1994), causing, during the sedimentation, considerable differences in the thickness of the Upper Oligocene and younger formations in the graben and on the flanking horst blocks. This is also indicated by the pattern of the depth of the base of the Upper North Sea Group (Maps XIII-15 and XIV-15).

On the transition Oligocene-Miocene, regional uplift occurred, related to the Savian phase. This, together with a low stand, culminated in regional erosion during the Early Miocene, which incised most particularly on the Peel and the Venlo Blocks. Initially, the sedimentation only persisted in the deepest part of the Roer Valley Graben. Subsequently, the deposition extended to the more elevated flanking highs (Zagwijn, 1989).

The basin-margin position of the area studied was accentuated during the Miocene and the Pliocene with the withdrawal of the sea from the east and southeast of the map sheet area. The Quaternary was marked by intensified upheaval of the hinterland, including the Ardennes. Subsequently, in an alternately glacial and moderate climate, rivers formed the terrace landscape now visible in the south of the map sheet area.

13.3 Seismic facies

Verbeek et al. (in press) have differentiated ten seismostratigraphic units in the Tertiary section of the Roer Valley Graben (fig. 13.3). Table 13.1 shows characteristics and ages of these units.

14 Geological history

14.1 Introduction

This chapter describes the geological history of the map sheet area, from the Cambro-Silurian to the Quaternary. Data on the pre-Carboniferous in the map sheet area are scarce. For this period, the description is based entirely upon publications on the surrounding areas. For details of the Quaternary of the map sheet area, reference should be made to the publication by Zagwijn (1989), the geological map, map sheets Venlo West, Eindhoven Oost and West (Rijks Geologische Dienst, 1967, 1973, 1985).

The geological history of each subsequent period is illustrated by the different tectonic phases that were active in the map sheet area and environment (fig. 1.5). During the Early Palaeozoic, these phases were the Ardennian and Acadian phases, both characterised by a compressive stress field. These phases

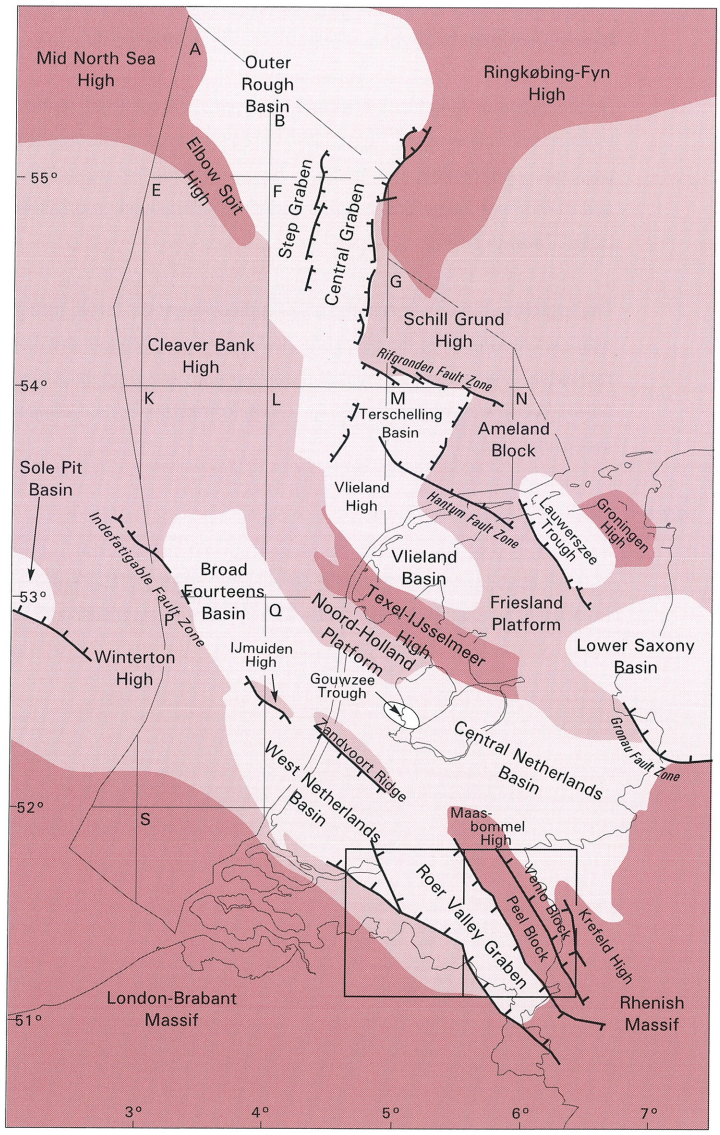


Figure 14.1 Overview of the principal structural elements in the Netherlands during the Late Jurassic to Early Cretaceous. The position of the map sheet area has been outlined.

preluded the consolidation of the Brabant Massif and the Krefeld High. The Late Carboniferous to earliest Permian period was characterised by the Variscan Orogeny, related to the forming of the Variscan Mountains to the south and east of the map sheet area. During these tectonic phases, the broad outlines of the structural framework were formed. The Late Triassic to earliest Cretaceous period was marked by the Kimmerian extensional tectonic phases, which were related to the disintegration of Pangaea and were responsible for the formation of major structural units in the Mesozoic. The Sub-Hercynian phase during the Late Cretaceous and the Early Palaeocene Laramide phase displayed a compressive stress field, causing a brief change (inversion) in the direction of movement of the major fault systems and structural elements. Subsequent tectonic phases during the Tertiary were associated with the Pyrenean and Savian events of the Alpine Orogeny and initiated the Roer Valley Rift System. The tectonic phases, together with the climate changes and associated sea level fluctuations (Haq et al., 1987), were the determining factors in the geological development of the area.

The specific development of the map sheet area has been examined in a regional context (fig. 14.1). The major tectonic structures discussed in this chapter are illustrated in figure 3.1.

14.2 Basin development, sedimentation and tectonics

14.2.1 Cambro-Silurian

During the Early Palaeozoic, the map sheet area was situated on the microcontinent Avalonia (fig. 14.2a). The collision of Avalonia with Baltica at the end of the Ordovician resulted in the Ardennian phase of the Caledonian Orogeny, initiating folding and uplift of the Cambro-Ordovician Ardennes Basin (Wouters & Vandenberghe, 1994; De Vos, 1998). To the north of this uplifted area, the Brabant Depression developed, as a foredeep. Continuing plate movement closed the Iapetus Ocean and merged Laurentia-Greenland and Fennoscandia-Baltica into a single continent, Laurussia (Ziegler, 1989). This was associated with further Late Caledonian deformation. The Acadian phase in the Early Devonian initiated folding and uplift of the Brabant Depression (of which the map sheet area is a part), defining the Brabant Massif (Van Grootel et al., 1997; the Vos, 1998). In the northwest the incipient Cadomian (Precambrian) Midland micro.craton became connected to the Brabant Massif (Ziegler, 1990). Together, they formed the London-Brabant Massif, which was to play an important role in the subsequent geological development of the Netherlands, Belgium and the Southern North Sea. During this phase, the Krefeld High also came into existence (Drozdzewski et al., 1998).

14.2.2 Devonian

During the Caledonian Orogeny, a vast landmass was formed in the present North Sea region, known as the *Old Red Continent*. During the Early Devonian, a regime of extensional stresses, in a back-arc position, initiated the formation of a large basin in Central Europe, the Rhenohercynian Basin (Ziegler, 1990). Owing to an increase in surface subsidence and a cyclical rise in sea level, the area of marine sedimentation extended significantly during the Middle and early Late Devonian.

During the Devonian, the map sheet area was situated on the northwestern margin of the Rhenohercynian Basin. The area was surrounded by two highs, the Brabant Massif and the Krefeld High (Drozdzewski et al., 1998). In the immediate vicinity of these highs, conglomerate was deposited in grabens or in half grabens during the youngest Middle Devonian (Givetian) (Muchez & Langenaeker, 1993; Neumann-Mahlkau & Ribbert, 1998). A major transgression occurred during the Frasnian (oldest Late Devonian). Upon and to the north of the Brabant Massif, deposition of clays and limestones took place (Ribbert, 1998b). The conglomerates are presumed to have been deposited in the vicinity of

synsedimentary faults. The Campine Basin formed a large half graben, bounded on the southern flank by a fault (Muchez & Langenaeker, 1993). A drop in sea level at the beginning of the Famennian (Kimpe et al., 1978) brought an end to the sedimentation of limestones and was followed by the deposition of sands in a shallow-marine environment (Condroz Sandstone). The supply of the sands originated from a northeasterly direction (Paproth et al, 1986).

14.2.3 Carboniferous

The Carboniferous is dominated by the Variscan Orogeny. This orogeny during the Late Carboniferous was characterised by the collision between Gondwana and Laurussia, which was responsible for the formation of the supercontinent Pangaea, whose contours can be seen in figure 14.2b. The first contact with Laurussia occurred at the end of the Devonian (Wouters & Vandenberghe, 1994), and preluded the Variscan Orogeny. In this orogeny, three orogenic deformation-phases can be identified in Northwest Europe: Bretonian, Sudetian and Asturian tectonic phases, during which the deformation front migrated increasingly further to the north; this was manifested by the migration of the depocentre in a northerly

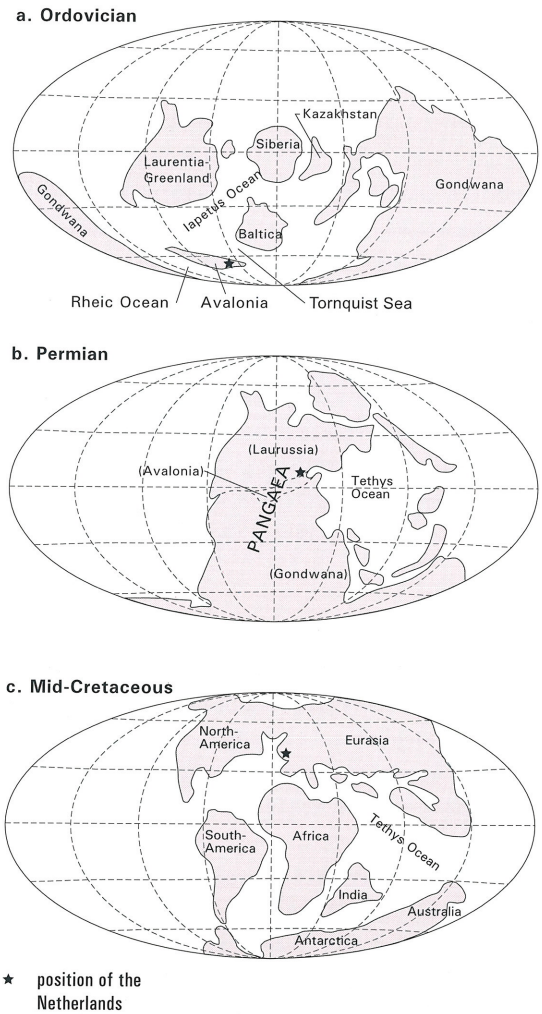


Figure 14.2 Position of the continents and oceans during the Ordovician, Permian and Middle Cretaceous (after Scotese, 1991; Scotese & McKerrow, 1990). In the middle figure, the elements from which Pangaea was formed are given in brackets.

direction, from the Ruhr Basin to the east of the map sheet area in the Namurian and oldest Westphalian into the Ems Low to the northeast of the map sheet area during the youngest Westphalian and Stephanian (Drodzdzewski, 1992).

The first phase of the Variscan Orogeny, the Bretonian phase, only produced limited uplifts and hiatuses in the succession locally, in the vicinity of the London-Brabant Massif. During the Early Carboniferous, a further rise in the sea level drastically restricted the influx of clastic material. Around the London-Brabant Massif and the Krefeld High, a vast carbonate platform was created. More distally, the carbonate platform passed into deeper water (Ziegler, 1990). Under starved basin sedimentary conditions, a thin sequence of euxinic claystones was deposited here, often containing some carbonate or silicic acid. Initially, stratified cherts (lydites) were deposited. This type of sedimentation is presumed to have

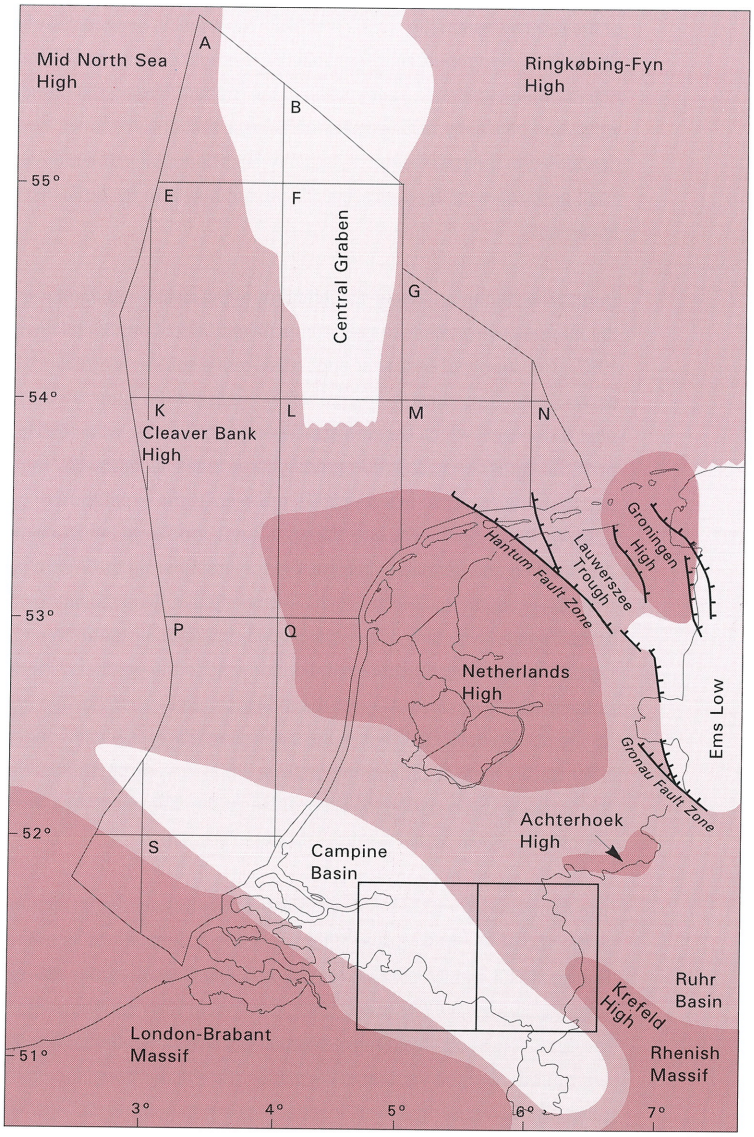


Figure 14.3 Overview of the principal structural elements in the Netherlands during the Late Carboniferous. The position of the map sheet area has been outlined.

occurred both to the east of the Krefeld High (Wolburg, 1970) and in the area between the Brabant Massif and the Krefeld High. During the Viséan/Namurian transition, the platforms became situated above the palaeo sea-level, which resulted in extensive karstification. In the basins between these highs, the sedimentation persevered without interruption and a thick limestone sequence was deposited.

The Sudetic phase of the Variscan Orogeny occurred at the beginning of the Late Carboniferous. The N-S oriented compressive stress field initiated the development of an E-W trending mountain chain transecting Europe. In isostatic response to this pressure, the foreland basin to the north of this mountain chain deepened (fig. 5.4). This basin contained the Ruhr Basin, which extended westwards into the Campine Basin. The previously formed Krefeld High was part of this basin (Drozdzewski & Zeller, 1998). This basin displays a clear change in direction of the basin axis, from ENE in the Ruhr Basin to WNW in the Campine Basin. This change in direction occurs in the vicinity of the later Peel Boundary Fault, which is an indication that this fault may also be a Caledonian element. The orientation of the Campine Basin is determined by the structure of the Brabant Massif, which was a rigid element on the southern margin of the foreland basin (fig. 14.3). This basin became the depocentre of erosion products from the Rhenohercynian mountain chain. Initially, during the Namurian, these consisted of deep-marine clays, rich in organic material. To the north of the Brabant Massif, the Campine Basin became rapidly deeper, which can be clearly distinguished on seismic sections. It should, however, be mentioned that this deepening in the basin is not necessarily fault-bounded in the manner displayed in the Hoogstraten Fault postulated by Vandenberghe (1984), but may also be explained by a flexure above a Caledonian lineament.

During the Namurian, under the influence of the clastic sedimentation, the basin became shallower and the marine environment passed from a deltaic into a continental environment (Langenaeker & Dusar, 1992). The supply of sediment originated from a southerly direction. During the Westphalian A, B and early C, lacustrine clays were predominantly deposited, alternated by deltaic and fluvial sands and vast peat sequences, which became coalified into coal seams when subsequent burial occurred. Episodically, brief transgressions occurred spanning large areas, facilitated by the very flat relief in the basins. These deposits, the so-called marine bands, are seen as the expression of glacio-eustatic sea-level rises (Ziegler, 1990). During the later Westphalian C, the fluvial influence on the sedimentation became more pronounced and ultimately became predominant during the Westphalian D, when the Asturian deformation phase began to manifest itself. This resulted in the deposition, under fluvial conditions, of coarse, arkosic sands, with only a few intercalated coal seams (Neeroeteren Formation). During the youngest Carboniferous, the climate became drier owing to the gradual northward drift of the area away from the equator and to an obstruction in the Monsoon rains caused by the uprising mountains. This is reflected by the occurrence of caliches in the succession (Pagnier & van Tongeren, 1996). As a result of the northwardly migrating deformation front, little or no sedimentation is presumed to have occurred in the Campine Basin during the Stephanian. In the map sheet area, this heralded a long period of non-deposition, which would last until the Late Permian.

The Asturian deformation phases initiated the northward migration of the Variscan orogenic front, at the end of the Westphalian. There are various perceptions as to the precise position of the front: Franke (1990) and Drozdzewski & Wrede (1994) place the front entirely to the east of the map sheet area, whereas in the view of Kockel (1998), the Krefeld High and the Venlo Block also formed part of the Variscan deformed area. Franke postulates a NNW oriented fault to the east of the Krefeld High as western boundary of the Variscan deformation (the *Niederrhein Lineament*). Drozdzewski & Wrede base their perception on observed overthrust tectonics in mines and wells, whereas Kockels interpretation is based on large-scale structures. In Kockel's opinion, the Peel Boundary Fault plays an important role as tear fault along which the front is highly offsetted. The origin of this offsetting could well be related to the

post-Variscan wrench deformation during the Early Permian. To the southeast of the map sheet area, a number of low-angle overthrust planes occur, which can be regarded as the northern boundary of the Variscan front, with a SW-NE strike (NITG-TNO, 1999). The direction of the overthrust planes in South Limburg indicates that the palaeo-compressive stress fields had a NW-SE orientation.

In the adjacent part of Germany, during the youngest phase of the Variscan Orogeny, a system of ENE oriented synclines, anticlines and overthrusts was established which is separated from the Campine Basin on the west by the NNW oriented Krefeld High and the Venlo and Peel Blocks. The origin of these NNW oriented structures would appear to be related to volcanic intrusiva in these units. Their presence is deduced from anomalies in the coalification pattern, gravity and magnetism (Buntebarth et al., 1982; Bredewout, 1989; Bosum, 1965 resp.). These intrusiva are associated with the post-Variscan wrench-deformation. Uplift related to these intrusions initiated profound erosion on the Peel and Venlo Blocks and the Krefeld High.

The areas of uplift and subsidence during the Variscan Orogeny are regarded as precursors of large-scale structural elements, which would also be manifested during the Permian, the Triassic and the Jurassic (Roer Valley Graben). Although these structural elements had different orientations and boundaries in subsequent geological periods, they were nonetheless bounded by the same fault systems.

14.2.4 Permian

The Permian in the map sheet area is characterised by a large hiatus. Only the youngest Permian is represented by sediments. During the Early Permian, the compressive stress fields of the Variscan Orogeny made way for east-west trending extensional changes. To the north of the Variscan mountain chain, NW-SE and W-E trending transverse movements were triggered (Ziegler, 1990). During the Early Permian, intensive wrench-deformation of this area in Germany induced extensive volcanic activity (Ziegler, 1990) are also presumed to occur below the Krefeld High. At the end of the Early Permian, a combination of extensional stresses and cooling of these volcanic rocks led to the development of vast intracratonic continental basins: the Northern and the Southern Permian Basins. In this latter basin, the erosion products originating from the Variscan Mountains were deposited in a terrestrial environment. The oldest sediments in this basin have been identified in northeast Germany, from where the sedimentation area expanded to the west and south (Plein, 1995). During the hiatus, which spans the entire Early Permian and the oldest part of the Late Permian, a number of tectonic pulses occurred: the Saalian and the Altmark I, II and III (Plein, 1995). These pulses together initiated the unconformity at the base of the Upper Rotliegend Group. Not until the deposition of the youngest part of this group did sedimentation of conglomerates and sands transported by wadis take place in the map sheet area. In depressions in the north of the map sheet area, aeolian sands accumulated. The deposition area was roughly bounded by the Variscan front (Geluk, 1999a); sedimentation only took place to its north.

Graben formation in the North Atlantic/Arctic region combined with a eustatic sea-level rise as a consequence of the melting of the Gondwana ice cap (Ziegler, 1990) initiated the forming of an open connection between the present Barentsz Sea area in the north and the intracratonic Northern and Southern Permian Basins. In response to this, a very rapid transgression occurred in the basins, which had already subsided below the palaeo sea-level (Glennie, 1998). This initiated the forming of a large inland sea, in which cycles of carbonates and evaporites were deposited, as a result of a combination of the arid climate on the one hand and an alternating influx of sea water from the Arctic area on the other. Major transgressions mark the bases of the different cycles. Owing to the position of the map sheet area on the edge of this inland sea, only an incomplete succession was deposited, consisting predominantly of clastics and carbonates.

The first extensional pulse during the Late Permian, the Tubantian I pulse, caused a modification in the pattern of highs and lows. This pulse initiated a depression bounded by NW-SE oriented faults in the adjacent part of Germany, where rock salt was also deposited (Wolf, 1985; Hilden, 1988; M.A. Ziegler, 1989). During this period, the Roer Valley Graben formed an elevated block together with the Eastern Campine Block, while the Peel and Venlo Blocks occupied an intermediary position. There are indications from seismic records that the Peel Boundary Fault and the Tegelen Fault bordered these units. A second rift pulse during the Late Permian, the Tubantian II, caused slight uplift of the west and northwest of the map sheet area; here, the youngest deposits of the Zechstein Group rest unconformably upon older deposits of the Zechstein Group, or even of the Upper Rotliegend Group (Geluk et al., 1997).

14.2.5 Triassic

The Triassic was characterised initially by extremely uniform basin subsidence. The Southern Permian Basin continued in essence to exist and is therefore often referred to as the Permo-Triassic Basin. The sedimentation area extended southwards. The Triassic is characterised by two phases of extensional tectonics, namely the Hardegsen and Early Kimmerian phase (Ziegler, 1990), delineating the disintegration of the supercontinent Pangaea.

The beginning of the Triassic is characterised by a prominent influx of clastic material, which originated from the Variscan Mountains. Contemporaneously, accelerated subsidence was initiated in the map sheet area, in particular in the Roer Valley Graben (Zijerveld et al. 1994; Geluk et al., 1996). A vast, sandy flood plain formed, where wadis alternated with sand dunes and which, in a northerly and northwesterly direction, passed into a playa lake. The main supply of clastic material took place through the Roer Valley Graben towards the West Netherlands Basin (Geluk et al., 1996). The most pronounced subsidence occurred in the Roer Valley Graben. Uplift of the source areas of sediment, in combination with fluctuations in the water table in the basin, favoured the episodic progradation of fluvial systems in the basin, initiating a cyclical succession of sand and clay/silt (Geluk & Röhling, 1997, 1999). In the map sheet area, these cycles were predominantly deposited as sand. The Hardegsen phase during the Scythian facilitated uplift of areas to the north and east of the Roer Valley Graben, which was marked by erosion of a part of the deposits of the Main Buntsandstein Subgroup. This phase was completed in three pulses, the strongest of which was the pulse preceding deposition of the Solling Formation. The first tectonic pulse facilitated differential subsidence of the Roer Valley Graben, as a result of which a thick succession of the Volpriehausen Formation has been preserved. Subsequently, the Roer Valley Graben formed part of a stable platform on the southern margin of the basin (Geluk et al., 1996). Lacustrine clays of the Solling Formation overlay the relief.

During the Anisian, the eastern part of the Permo-Triassic Basin achieved a connection with the Tethys ocean, and a major transgression was triggered (Ziegler, 1990). This transgression flooded the main source areas of terrigeneous sediments (Röt Formation) and made way for carbonates and marls (Muschelkalk Formation). The disruption of this connection for a short period facilitated the deposition of evaporites. During the Anisian, the first movements of the Early Kimmerian phase manifested themselves, which would culminate during the Carnian. These movements heralded a tectonically highly active period, which was to continue until the earliest Cretaceous. This period was characterised by the disintegration of Pangaea, when the opening of the northern Atlantic Ocean commenced. The Kimmerian phases are reflected by major hiatuses in the stratigraphic succession. In the map sheet area, the effects of the Early Kimmerian phase during the Late Triassic were restricted to a few differential movements along the Peel Boundary Fault. The Roer Valley Graben and the West Netherlands Basin consisted of large-scale NE dipping half grabens, fault-bounded along the northern edge (Geluk, 1999b). This configuration is particularly clearly displayed by the areal extent of the evaporites in the Röt and

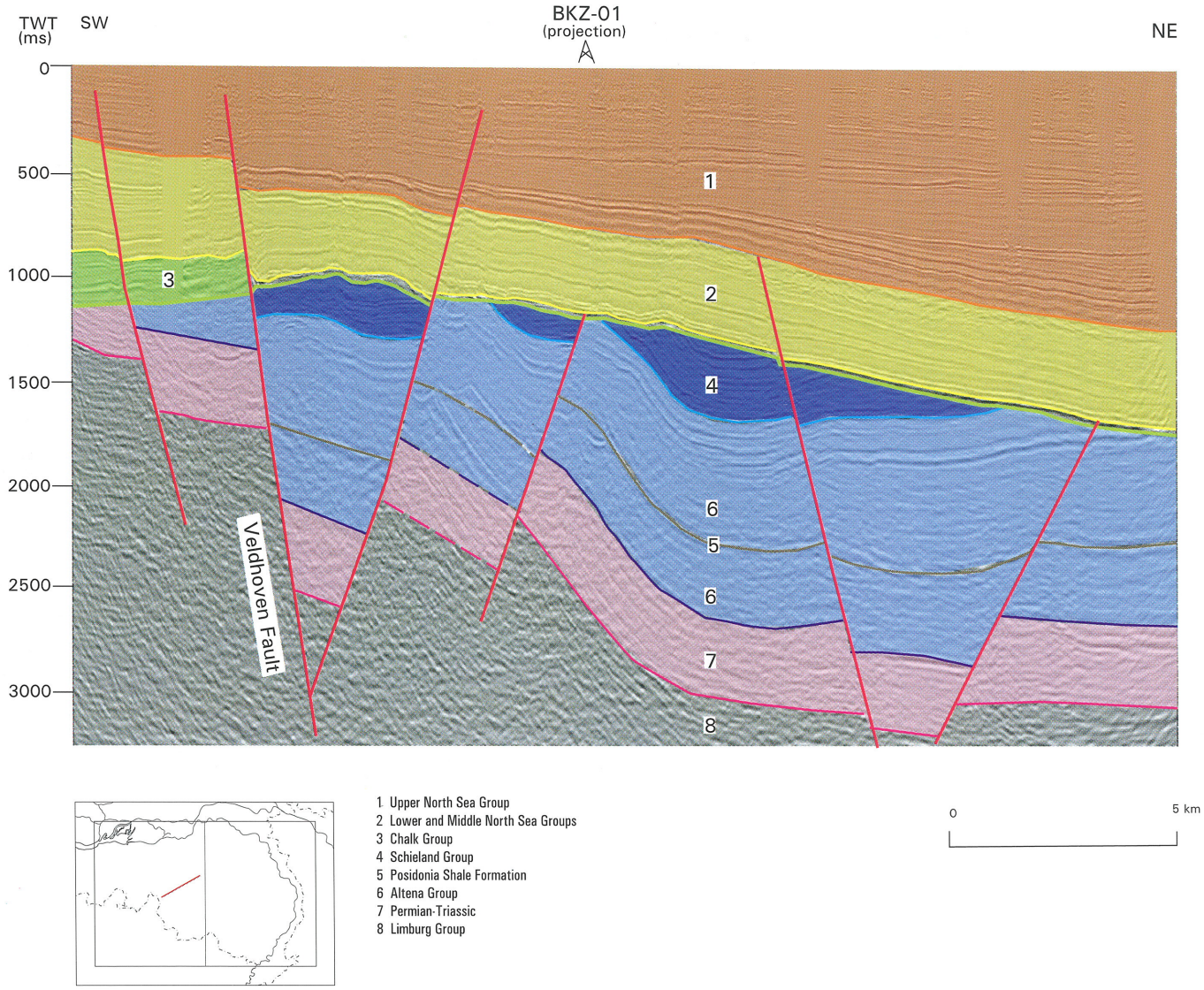


Figure 14.4 Seismic section through the southwestern part of the Roer Valley Graben. At this point, the Veldhoven Fault marks the limit of the graben. The interpreted lithostratigraphic units have been indicated, for a description of which, reference should be made to section 1.4. The great variation in thickness of the Chalk Group in relation to the Veldhoven Fault is notable. Furthermore, this structure demonstrates the more pronounced faulting of the Mesozoic deposits compared with those of the North Sea groups.

the Muschelkalk Formations (figs. 8.5, 8.6 & 8.7) in the vicinity of these faults. Uniform thickness characterises the Triassic on seismic sections (fig. 14.4).

During the Early Anisian, the area was characterised by vast plains covered by fine-grained sediment. Flood plains with braided rivers and sand dunes extended across these plains, constituting the last sandy influx from the south. During the Late Anisian, the transgression further restricted the clastic supply to the southeast, and in the map sheet area, limestones and marls were deposited in a shallow-marine environment. Via the Roer Valley Graben and the Trier Embayment, a connection formed with the Paris Basin, which was to persist until the Middle Jurassic (Ziegler, 1990). The brief disruption of this connection with the ocean, possibly in response to a tectonic pulse (Geluk et al. 2000) culminated in the deposition of evaporites throughout the area. In the north of the map sheet area, this was accompanied by the deposition of rock salt.

A regression during the Ladinian, in combination with the uplift of the Fennoscandia Shield, caused renewed deposition of clastics in the basin (Ziegler, 1990). The map sheet area was situated at a considerable distance from the source area, with the result that only fine-grained shallow-marine to deltaic deposits are encountered. Further tectonic movements during the Ladinian and Carnian are difficult to reconstruct owing to the absence of sediments. A local occurrence of a thin Carnian succession in the vicinity of the Peel Boundary Fault suggests that the differential movements along this fault continued. The previously discussed large-scale tilting of the Roer Valley Graben was accentuated, as displayed in the subcrop map over the Early Kimmerian unconformity.

During the Norian, the tectonic movements decreased sharply and sedimentation resumed. The deposits of the Red Keuper Claystone and the Dolomitic Keuper Members mark the Early Kimmerian unconformity. During the Rhaetian, a striking transgression heralded a long period of marine sedimentation which would persist until the Middle Jurassic.

14.2.6 Jurassic

During the Jurassic, regional subsidence of a large part of northern Europe, which had commenced at the end of the Triassic, initially continued. A connection with the Arctic Sea was established via the North Sea rift system which, in combination with a sea-level rise, initiated the deposition of fine-grained marine sediments. The deposits of the Early and earliest Middle Jurassic were deposited in a single continuous vast area, encompassing the area of the Permo-Triassic Basin and the Paris Basin. This can be inferred from the uniform and fine-grained character of the deposits. The Brabant Massif was also contemporaneously covered by the sea. During the Hettangian to Pliensbachian, clays and silts were deposited in an open-marine environment, below the wave base. Some stagnation in the circulation in the basin caused euxinic depositional conditions.

During the early Middle Jurassic, tectonic movements of the Mid Kimmerian Phase were responsible for differential fault movements. The structuration during the Triassic of large-scale NE dipping half grabens in the Roer Valley Graben and the West Netherlands Basin persevered in essence. The westerly boundary fault of the Waalwijk structure also resumed activity, as did a number of fault zones in the West Netherlands Basin, triggering the formation of NE-dipping faults in the half grabens, as a result of which the Roer Valley Graben and the West Netherlands Basin were transformed from simple half grabens into a series of grabens. This is demonstrated by the differences in thickness of the intervals between the Posidonia Shale Formation and the base of the Altena Group on the seismic section in figure 14.4. This pattern subsequently increased further in complexity during the Late Kimmerian Phase, owing to the markedly different subsidence patterns displayed by these faults blocks (see below).

During the Toarcian, the marine basins were characterised by a period of stagnation, presumably owing to a thermo-haline stratification of the water (Ziegler, 1990), initiating deposition of organic-rich clays of the Posidonia Claystone Formation in large parts of Northwestern Europe. During the Middle Jurassic, the circulation in the basin was restored and during the Aalenian to Bajocian, clays and sands were deposited in a marine environment. These sands appear to be related to the uplift of the highs (Brabant Massif, Rhenish Massif) surrounding the basin during the Mid Kimmerian Phase. During the Bathonian to earliest Oxfordian, limestones, marls and clay were deposited in shallow-marine conditions. The excellent correlation properties of these deposits with those in the Sole Pit Basin reveal that sedimentation in essence occurred in a large marine area spanning the Sole Pit Basin, the West Netherlands Basin, the Central Netherlands Basin, the Roer Valley Graben and the Paris Basin. A regression terminated the deposition (Gianolla & Jacquin, 1998).

The Late Jurassic is a period characterised by major tectonic events: the Late Kimmerian phase, with a primary pulse occurring at the beginning of the Late Jurassic, and a second at the Ryazanian-Valanginian boundary in the earliest Cretaceous (Late Kimmerian I and II; Rijks Geologische Dienst, 1991). The stretching of the crust under the graben was accommodated by transtensional dextral strike-slip movements along a system of reactivated NW-SE-trending fault systems. This initiated a further structural modification of the Roer Valley Graben and the West Netherlands Basin. Faults also developed on the southwestern margin of these basins. The movements of the Late Kimmerian phase were accompanied by volcanic activity, which was concentrated in the time around the two pulses (Werkendam 1: tuff/dyke rocks, Hauterivian; Heinenoord 1: mafic to ultramafic volcanites, Late Jurassic).

During the Late Kimmerian rift phases, the areas on the edge of the rifts as well as the Brabant Massif (Vercoutere & van den Haute, 1993) were strongly uplifted. Profound erosion also took place on the northwestern shoulders of the Roer Valley Graben. In the two basins themselves, the erosion was restricted. In the Roer Valley Graben, the erosion increases in a southeasterly direction; the graben flanks also became accentuated and were marked by severe erosion. During the Kimmeridgian, transtentional movements in the north and northwest of the map sheet area triggered the formation of small rift related basins, where thick sequences of fluvial sands and lacustrine clays were deposited. During the Portlandian, the differential subsidence diminished and sedimentation extended from these basins further across the area.

The Waalwijk structure was formed during this period. The structure developed on the transition of the southern fault zone of the West Netherlands Basin to the Roer Valley Graben. Characteristic of the structure is the N-S orientation of the main faults of this structure, for example the Rijen Fault. Secondary faults in the structure are in a roughly E-W direction. The Nieuwerkerk Formation in the Waalwijk structure is extremely thickly developed. The structure can be explained by dextral transtensional tectonics on the southern NW-SE oriented boundary faults of the West Netherlands Basin and the Roer Valley Graben. The overstep between the two basins initiated a pull-apart regime with N-S oriented faults, facilitating accelerated subsidence, as a result of which abnormal thicknesses may occur in the Nieuwerkerk Formation. The reactivation of the faults in the basement as a result of dextral transtension indicates that the sub-horizontal principal stress direction associated with this structure were roughly NNW-SSE.

14.2.7 Cretaceous

The Cretaceous was marked by a gradual sea-level rise, which was to reach its maximum high stand in the Late Cretaceous (Hancock & Scholle, 1975). The Cretaceous transgression was presumably a response to the increased rates of sea-floor spreading which were positioned between the components

of Pangaea broken into parts and the associated enlargement in volume of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979).

The second pulse of the Late Kimmerian phase, during the Valanginian, favoured an accentuation of the relief around the basins and other regional uplifts in Northwestern Europe. In the map sheet area, the flanks of the Roer Valley Graben and the West and Central Netherlands Basin were drastically upheaved. This was followed by a termination in the differential surface subsidence. In the Roer Valley Graben, fluvial and deltaic sediments were deposited during the Ryazanian and Valanginian, which, in a northerly direction, pass into marine sediments outside the map sheet area.

During the Cretaceous, the map sheet area was situated on the southern margin of the basin. A transgression prograded from the north, but did not reach the northern part of the map sheet area until during the Barremian. The Aptian was characterised by a brief regression associated with the Austrian tectonic phase (Ziegler, 1990), favouring the deposition of greensands on the flank of the West and Central Netherlands Basin. During the Albian, the transgression persevered, until the entire Maasbommel High was flooded. This Albian transgression has been identified throughout Western Europe and attributed to a pronounced sea-level rise (Crittenden, 1987). Deposition of marine sediments is also presumed to have taken place in the northern part of the Roer Valley Graben but erosion associated with the inversion tectonic movements makes this impossible to ascertain with any degree of certainty.

The Cretaceous transgression continued to prograde. Thereby, the distance between the source areas of the clastics and the map sheet area increased, reducing its surface extent. During the Cenomanian and Turonian, the sedimentation spread from the Central and West Netherlands Basin and the Maasbommel High further towards the south (Gras & Geluk, 1999). Sedimentation also occurred in the area to the west of the Rijen Fault.

This period of regional subsidence came to an end during the Coniacian. Europe underwent major plate reorganisation (fig. 14.2c) induced by an extensional stress regime and graben formation associated with the sea-floor spreading in the Arctic and North Atlantic Ocean (Coward, 1991), the collision of Africa and Europe (Ziegler, 1990) as well as a number of local factors (Baldschuhn et al., 1991). This initiated a compressive tectonic regime. During the Coniacian to Early Campanian period, this led to a reverse direction of movement along faults resulting in inversion of the former Upper Jurassic/Lower Cretaceous basins in the area and pronounced depression of the former highs. This inversion was completed in a series of pulses which have been grouped in two main phases: the Sub-Hercynian phase during the Santonian and Campanian, and the Laramide phase at the beginning of the Tertiary. The seismic section (fig. 14.4) illustrates the reactivation of the Veldhoven Fault.

The inversion of the Roer Valley Graben and the West and Central Netherlands Basin occurred in the Santonian and Early Campanian (Kuyl, 1983; Bless et al., 1987; Gras & Geluk, 1999). During this period, the non-uplifted areas surrounding these former basins began to subside profoundly. The most pronounced subsidence occurred alongside the most prominently uplifted area is in the north and northwest of the map sheet area (XIII/XIV-13). The inverted basins formed a separation between the now subsiding former highs, supplying them with sediment. During the Santonian, the sea spread over these adjacent areas. In the southeast of the Peel Block and on the Eastern and Western Campine Blocks, lacustrine to lagoonal sands were deposited during the Santonian, while further to the northwest, marine greensands were deposited. During the Campanian, the relief in the inverted basins had already partially levelled and predominantly sandy limestones were deposited around these areas. A slow onlap of the inversion area also commenced. Not until the Late Maastrichtian did the Roer Valley Graben again become

invaded by the sea, and carbonate sedimentation occurred. The carbonate sedimentation continued, with a brief interruption, across the entire area into the Danian.

The inversion tectonics were not restricted to the basins; beyond them, faults were reactivated on the Eastern and Western Campine Blocks (Rossa, 1986) and the Maasbommel High, Peel and Venlo Blocks (Geluk & Gras, 1999). In these areas, a number of active faults were reactivated as reverse faults during the Late Cretaceous. This is the case in, for example, the Tegelen Fault (Geluk & Gras, 1999). Contemporaneous to the inversion, NW oriented tilting of the Venlo Block occurred; in the southeast, the Maastrichtian deposits rest immediately upon the Limburg Group, while in a northwesterly direction, a thick sequence of Santonian to Campanian deposits is intercalated. Between these sequences, seismic records display an intraformational hiatus between the post and pre-inversion deposits.

14.2.8 Cenozoic

After the Laramide tectonic phase at the beginning of the Early Palaeocene, which was accompanied by a pronounced sea-level fall, the North Sea Basin was formed. The extensive calcareous sedimentation still present during the Late Cretaceous and earliest Tertiary, came to an abrupt end. Only in the north of the map sheet area did the phase induce any aftereffects in the inverted basins. These movements, which occurred virtually without any fault movement, culminated in the erosion of the post-inversion deposits of the Chalk Group in the Central and West Netherlands Basin, with the uplifted area encompassing the basin margins. The Maasbommel High was also affected by erosion (Gras, 1995). In the Palaeocene and the Early Eocene, the North Sea Basin was still connected to the Paris Basin, but this contact was terminated with the uplift of the Artois Axis (Ziegler, 1990). Although the present map sheet area lay on the margin of the North Sea Basin, major tectonic activity from the Oligocene onwards resulted in pronounced subsidence of the Roer Valley Graben, in which 2000 m of Cenozoic sediments accumulated (fig. 14.6).

During the Cenozoic, the Atlantic Ocean opened further. The sea between Norway and Greenland was formed and graben formation in the North Sea area ceased. The collision of the Eurasian and the African lithospherical plates persisted, reflected in the primary activity of the Alpine Orogeny. This resulted in NW oriented compressive stress fields.

During the Late Palaeocene, lacustrine and lagoonal sediments were deposited initially. The continuing transgression subsequently facilitated the deposition of marine sands, clays and marls. At the end of the Eocene, the Pyrenean tectonic phase caused the uplift of a NW-SE oriented zone in the centre and south-east of the Netherlands, termed the Southern Early Tertiary High by Van Adrichem Boogaert & Kouwe (1993-1997). Locally, small-scale reverse-fault reactivation occurred along E-W faults in the northern part of the Roer Valley Graben. The ensuing erosion incised profoundly into the sediments. The Eocene is therefore absent in large parts of the map sheet area. In the Roer Valley Graben and the Peel Block, only the Palaeocene has been preserved from erosion. To the east of the map sheet area, erosion also occurred to these sediments, and Oligocene deposits rest immediately upon the pre-Tertiary (Hilden, 1988).

In the earliest Oligocene, sedimentation resumed in the map sheet area, initially shallow-marine and lagoonal, and later full-marine. There are no indications of differential subsidence of the area and the uniform character of the Rupel Clay points to deposition in a large marine realm. At the beginning of the Late Oligocene, the Roer Valley Graben fault system was reactivated (Zagwijn, 1989; Geluk et al., 1994), causing, during the sedimentation, considerable differences in the thickness of the Upper Oligocene and younger formations in the graben and on the flanking horst blocks. This is also indicated by the pattern

of the depth of the Upper North Sea Group (Maps XIII/XIV-15). Movement has taken place along the faults of this system up to the present time, as demonstrated by terrain steps and scarps and drainage patterns influenced by faults (Van den Berg et al., 1994) as well as by the earthquakes in Limburg and surrounding areas (Camelbeek et al., 1994; Ahorner, 1994).

On the transition Oligocene-Miocene, regional uplift occurred, related to the Savian phase. This, together with a low stand, culminated in regional erosion during the Early Miocene, which incised predominantly into the Peel and Venlo Blocks. Initially, the sedimentation only persisted in the deepest part of the Roer Valley Graben. Subsequently, the deposition extended to the more elevated flanking highs (Zagwijn, 1989).

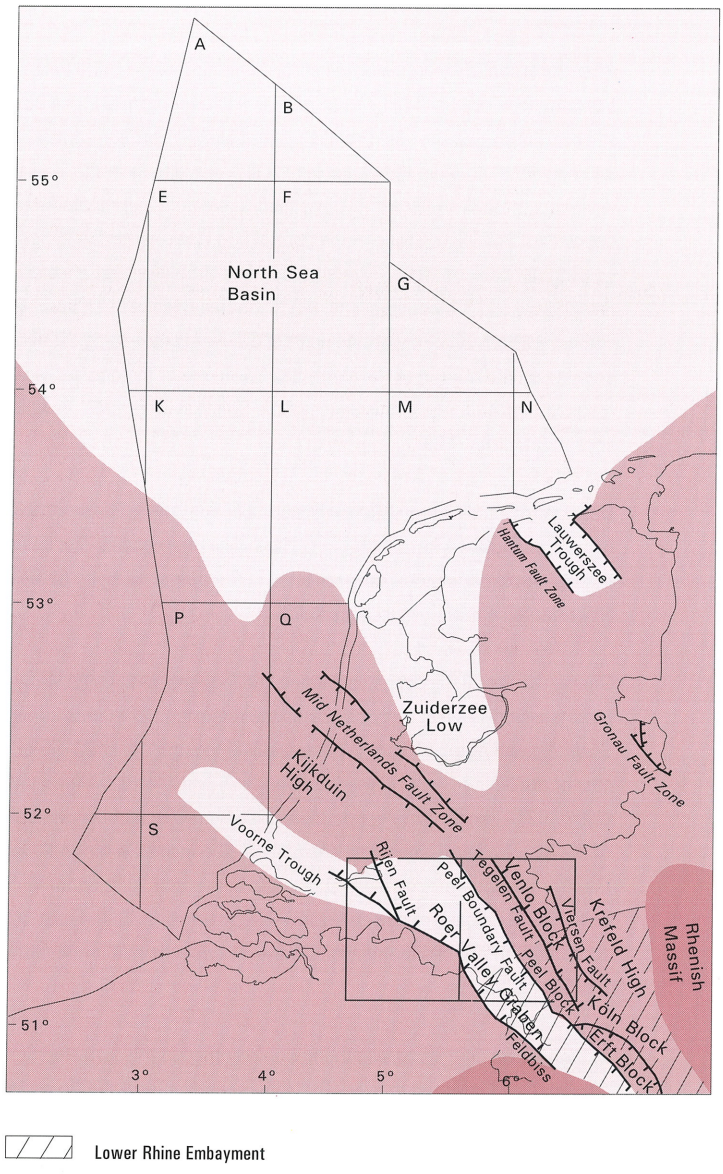


Figure 14.5 Overview of the principal structural elements in the Netherlands during the Cenozoic. The position of the map sheet area has been outlined.

The basin-margin position of the area studied was accentuated during the Miocene and the Pliocene with the withdrawal of the sea from the east and southeast of the map sheet area. In the Quaternary, intensified upheaval of the hinterland, including the Ardennes, ensued. Subsequently, in an alternately glacial and moderate climate, rivers formed the terrace landscape still to be seen in the south of the map sheet area. The faults in the Roer Valley Rift System have a right-lateral component within generally extensional forces (Van den Berg, 1994).

14.3 Neotectonics of the Roer Valley Graben

The Roer Valley Graben is a part of an active rift system encompassing numerous fault blocks situated in the southern part of the Netherlands, the northeastern part of Belgium and the adjacent part of Germany (figs. 14.5 & 14.6). The Roer Valley Rift System is subdivided into three tectonic units: the Eastern and Western Campine Blocks in the southwest, the Roer Valley Graben in the centre and the Peel and Venlo Blocks in the northeast. The Roer Valley Graben is separated from the adjacent blocks by the Feldbiss zone in the south and the Peel Boundary Fault zone in the northeast. On a larger scale, the Roer Valley Rift System forms part of a rift system in the Lower Rhine Bight, which itself is part of a mega rift system transecting Western Europe (fig. 14.5; Ziegler, 1992).

The Roer Valley Rift System is superimposed on the basins of Mesozoic and Palaeozoic age (Geluk et al., 1994). The rifting in the Roer Valley Rift System commenced in the Late Oligocene. Since then, the Roer Valley Graben has subsided 1000 to 1200 m and the Peel Block, a maximum of 200 m (Geluk et al., 1994). During the Quaternary, the average subsidence rate of the Roer Valley Graben was 60 to 90 m/Ma. However, subsidence did not proceed at a constant rate. A subsidence analysis of two wells in the Roer Valley Graben without correction for compaction reveals that the subsidence rate might have increased by 25 to 30% during the Quaternary (Geluk et al., 1994). Furthermore, both wells are characterised by hiatuses in the Lower and Middle Pleistocene, which suggests the existence of periods of negligible subsidence or of uplift. Houtgast and Van Balen (2000) have carried out a detailed study of the subsidence history of the Roer Valley Rift System during the Quaternary in six wells, situated on the three tectonic blocks. The result of these analyses reveals three subsidence phases. Rapid subsidence took place during the Early Pleistocene (2.4 to 1.8 Ma). The second phase, up to 0.35 Ma, is characterised by slow subsidence. The wells in the Roer Valley Graben and on the Peel Block demonstrate accelerated subsidence starting from 0.35 Ma. However, this acceleration is not apparent in wells of the Western and Eastern Campine Blocks (see Houtgast & Van Balen, 2000).

The Peel Boundary Fault and the Feldbiss are the most active fault zones during the Quaternary. The average displacement rate along these fault zones ranges from 5 to 80 m/Ma (Houtgast & Van Balen, 2000). Periods of high and low displacement rates alternate. The subsidence rate in the Roer Valley Graben is roughly equivalent to the displacement rate of the fault zones. This means that the subsidence, particularly in the graben, is particularly caused by displacement along faults, and to a lesser degree by other subsidence processes in extensional basins, for example compaction and thermal contraction of the lithosphere (Houtgast & Van Balen, 2000).

Results of lineament analyses of satellite images and topography (Sesören, 1976; Van den Berg, 1994; Houtgast & Van Balen, 2000) indicate that two fault directions could be active in the Roer Valley Rift System, a NW-SE oriented set and a N-S to NE-SW oriented set. The NW-SE oriented faults were triggered during the final period of the Variscan Orogeny; they are found in the Palaeozoic basement of the Roer Valley Rift System, and were also reactivated, for example during the Mesozoic and the Early Cenozoic. The N-S to NE-SW oriented faults, however, would have been less active during these periods. However, this N-S to NE-SW direction, was not recognised during the mapping of the Tertiary sediments.

Lineament analyses and geophysical data indicate that N-S to NE-SW oriented faults are present in the Caledonian Brabant Massif to the south of the Roer Valley Rift System (see Van Balen et al., 2000). This may mean that this fault direction also occurs in the pre-Variscan basement below the Roer Valley Rift System. The fact that Palaeozoic faults were repeatedly reactivated during the Mesozoic and Cenozoic indicates that these faults are fundamentally brittle zones in the lithosphere.

During the Late Tertiary and Quaternary, tectonic movements influenced the course and incision of the Rhine and Maas (e.g. Rijks Geologische Dienst, 1973; Van den Berg, 1994; Van Balen et al., 2000; Houtgast & Van Balen, 2000). One example of the effect of the northwardly oriented tilting during the Middle Pleistocene was that the Rhine and Maas abandoned the Roer Valley Graben, to follow a more northwardly course transecting the Roer Valley Rift System (the Rhine slightly further to the east in the Lower Rhine Bight). The fault action also influences the present-day morphology: minor fault scarps characterised the major fault zones and little streams run parallel to faults (Van den Berg, 1994; Houtgast & Van Balen, 2000).

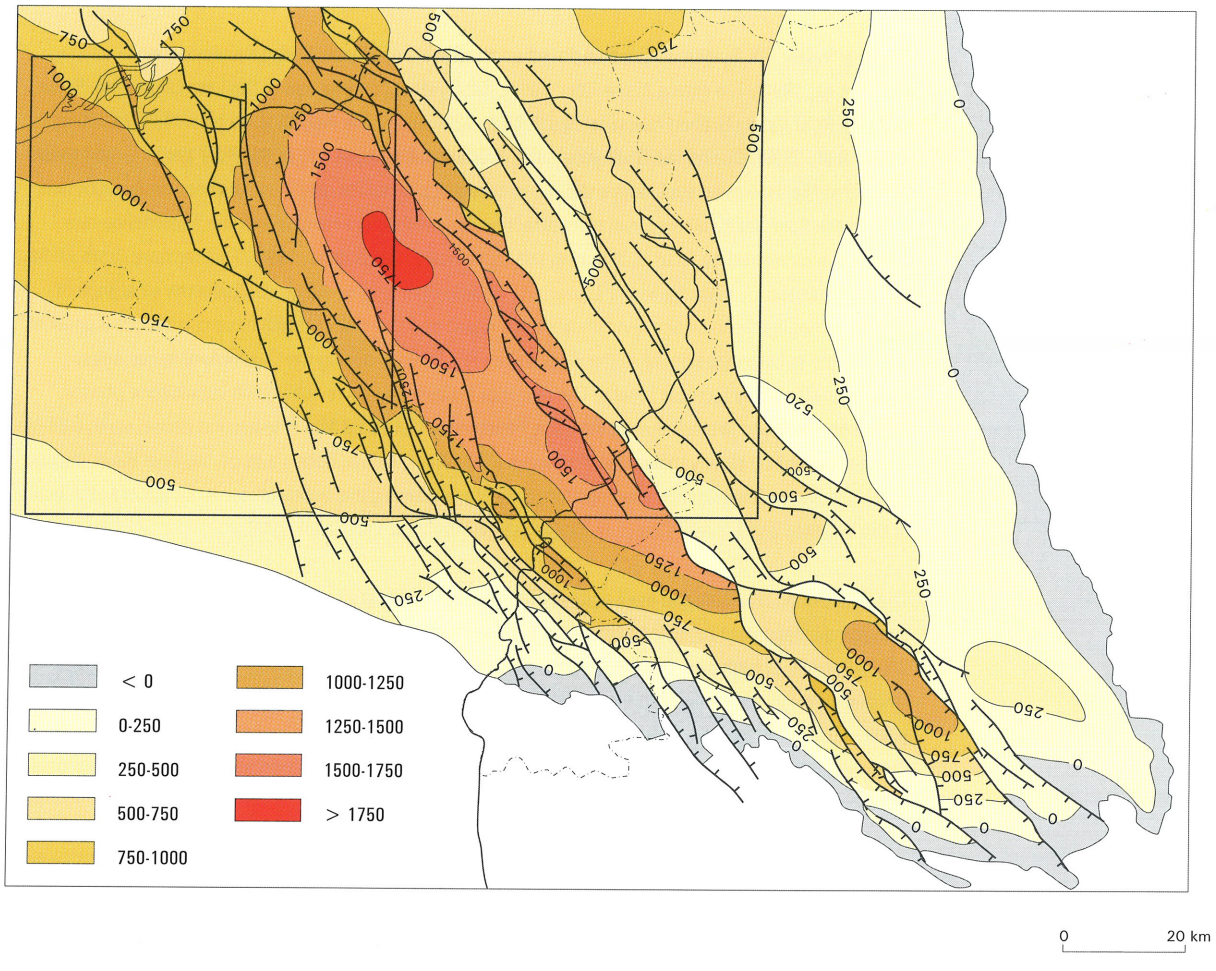


Figure 14.6 Depth of the base of the clastic Tertiary (North Sea Supergroup and equivalent deposits) in the Lower Rhine Bight. This map was compiled partly on a basis of data derived from Hilden (1988) and Demyttenaere & Laga (1988).

14.4 Seismicity of the Roer Valley Graben and environment

The majority of the seismicity in the Netherlands of natural origin occurs in the Roer Valley Graben, a northwesterly extension of the Rhine Valley Graben. The recent earthquakes in the Roer Valley Rift System are caused by the rifting which commenced during the Late Oligocene. This seismicity was concentrated along the major fault zones (fig. 14 7; table 14.1; Ahorner, 1962; Camelbeeck & Meghraoui, 1998). The Roermond earthquake in 1992, for example, occurred along the Peel Boundary Fault (Van Eck & Davenport, 1994). The present rates of displacement, determined by geodesy along faults (Groenewoud et al., 1991) are 10 to 100 times greater than the rates which can be deduced from the sedimentation history of the Roer Valley Rift System. This can be explained by a great variation in rates of displacement during the course of time caused by fault stress interactions, whereas the sedimentation history is only able to establish an average speed.

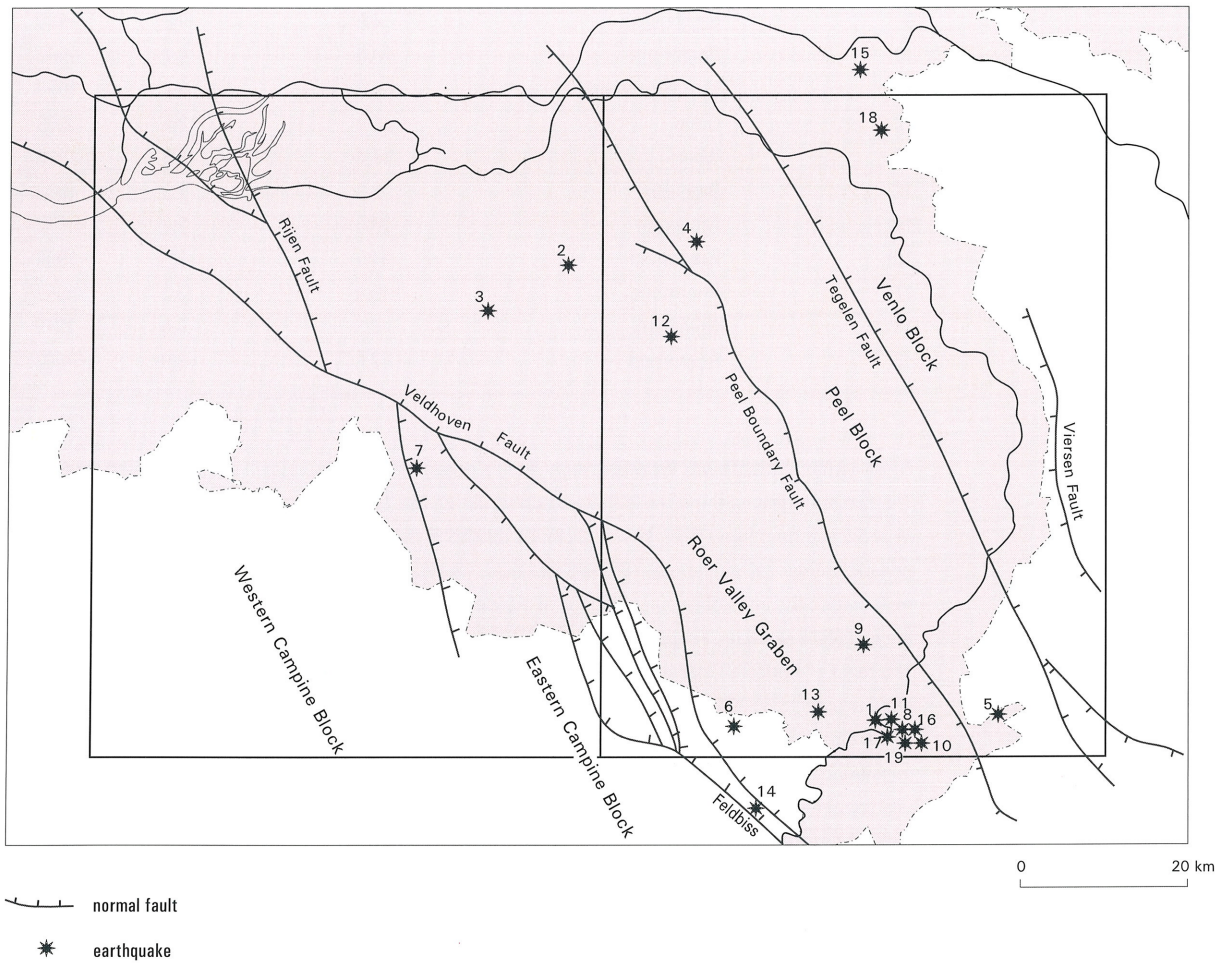


Figure 14.7 Epicentres of earthquakes in the Roer Valley Graben with a magnitude greater than 3.0. For the explanation of the figures, reference should be made to table 14.1.

Table 14.1 Summary of the epicentres of earthquakes in the southern part of the Netherlands

The earthquakes are ranked in order of magnitude greater than 3.0. The location numbers refer to figure 14.7.

Location number	*Location*	*Depth (km)*	*Magnitude (M_L)*	*Year*
1	Roermond	15.4	5.8	1992
2	Uden	16.3	5.0	1932
3	Meyel	3.4	4.5	1932
4	Vught	18.9	4.3	1932
5	Roermond/Herkenbosch	15.0	4.3	1935
6	Stamproy (B)	15.1	4.2	1960
7	Bladel	10.1	4.0	1932
8	Roermond	7.7	4.0	1992
9	Heythuysen	4.9	3.8	1980
10	Roermond	28.0	3.7	1992
11	Linne/Roermond	10.6	3.4	1993
12	Uden	11.5	3.4	1999
13	Weert	17.4	3.3	1976
14	Bree (B)	9.9	3.3	1983
15	Nijmegen	28.0	3.2	1972
16	Roermond	14.9	3.1	1992
17	Roermond	13.0	3.1	1992
18	Nijmegen	18.3	3.0	1979
19	Roermond	12.8	3.0	1992

Of the two boundary faults (Peel Boundary and Feldbiss), the Peel Boundary Fault is the most active. The two strongest earthquakes to have occurred during the 20th century (Uden, 20 November 1932, $M_L = 5.0$ and Roermond 1992, $M_L = 5.8$) can be related to this fault. The Roermond earthquake (1992) generated over 200 aftershocks (Camelbeeck et al., 1994), a notable aspect of which is that they were not restricted to the immediate surroundings of the main shock, but also occurred 40 km to the southeast of the epicentre along the Feldbiss. All the aftershocks were, however, confined to the area of the graben. The focus of both the Uden and the Roermond earthquakes lies at a depth of approximately 16 km and implies a dip of 60-70 degrees of the Peel Boundary Fault. This is in accordance with the determination of the dip of the fault from seismic data derived from the first 3 km and suggests a constant angle of inclination. Two observations are particularly striking. Firstly, the epicentres of the aftershocks in the vicinity of the main shock area display a trend that deviates from the lateral extent of the Peel Boundary Fault at the surface, while the focal mechanism of the main shock displays a strike parallel to the direction of the Peel Boundary Fault. Secondly, the aftershocks do not extend to the northwest in the direction of Uden. Increased knowledge of the structure of the earth's crust between 3 and ca. 16 km depth might well throw light on a possible cause of these observations. Although a series of deep seismic lines were shot across the Netherlands at the beginning of the eighties, a general interpretation was made (Remmelts & Duin, 1990) which in fact provided little in the way of fresh evidence. Further research, by shooting one or more deep seismic lines, under the Peel Boundary Fault in the epicentral area, would increase the insight in the detailed structure of the crust between 3 and 20 km depth. Subsequent to 1992, the seismicity in the Roer Valley Graben remained concentrated around the epicentre of the

Roermond earthquake, with occasional widespread activity across the rest of the graben. An earthquake of a magnitude of 3.4 in the vicinity of Uden on 9 November 1999, the first in the area since 1932, is notable.

Practically all the focal mechanisms of earthquakes in this area display a normal fault, in which the central part of the graben subsides. This is in accordance with the seismo-tectonic model for the region, in which a SW-NE extension occurs.

On a basis of the historical seismicity in the area, the maximum possible magnitude can be estimated. De Crook (1996) calculates a magnitude of 6.3. The historic time series is, however, too short in the case of larger earthquakes, with a repeat time of several thousands of years. A solution may possibly be found in palaeoseismology. In 1999/2000, a trench was dug across the Peel Boundary Fault, and traces of sudden displacements were found in the Holocene sediments, which could have been caused by earthquakes of a greater force than the maximum magnitude in the history of seismicity (Van den Berg et al., in press). However, results from one of the trenches do no more than offer an indication and a working hypothesis. Further research is required for this hypothesis to be tested.

15 Applied geology

15.1 Coal from the Peel Block

In connection with potential coal exploitation, the eastern part of the map sheet area (Peel and Venlo Blocks and the adjacent areas in Germany and Belgium) has been extensively studied with the aid of seismics, several deep wells and a large number of shallow wells (see Chapter 2). The principal objective in drilling these wells was to acquire a better understanding of the Coal Measures of the Limburg Group (Westphalian age) in the Peel area as well as to accurately map the stratigraphy and quality of the coal. Chemical and coal petrographic research was carried out on the coal seams in the cored Carboniferous sequences.

For the calculation of the geological coal stock by the Peelcommissie (1963), the area was divided into 12 fields. Some of these fields are situated on German territory, but are subject to Dutch concession law (Peelcommissie, 1963). The total geological coal stock to a depth of 1500 m was estimated at 2.9 billion tons. A recent inventory of the coal stock on the Peel Block (TNO-NITG 2000) arrived at a slightly higher figure.

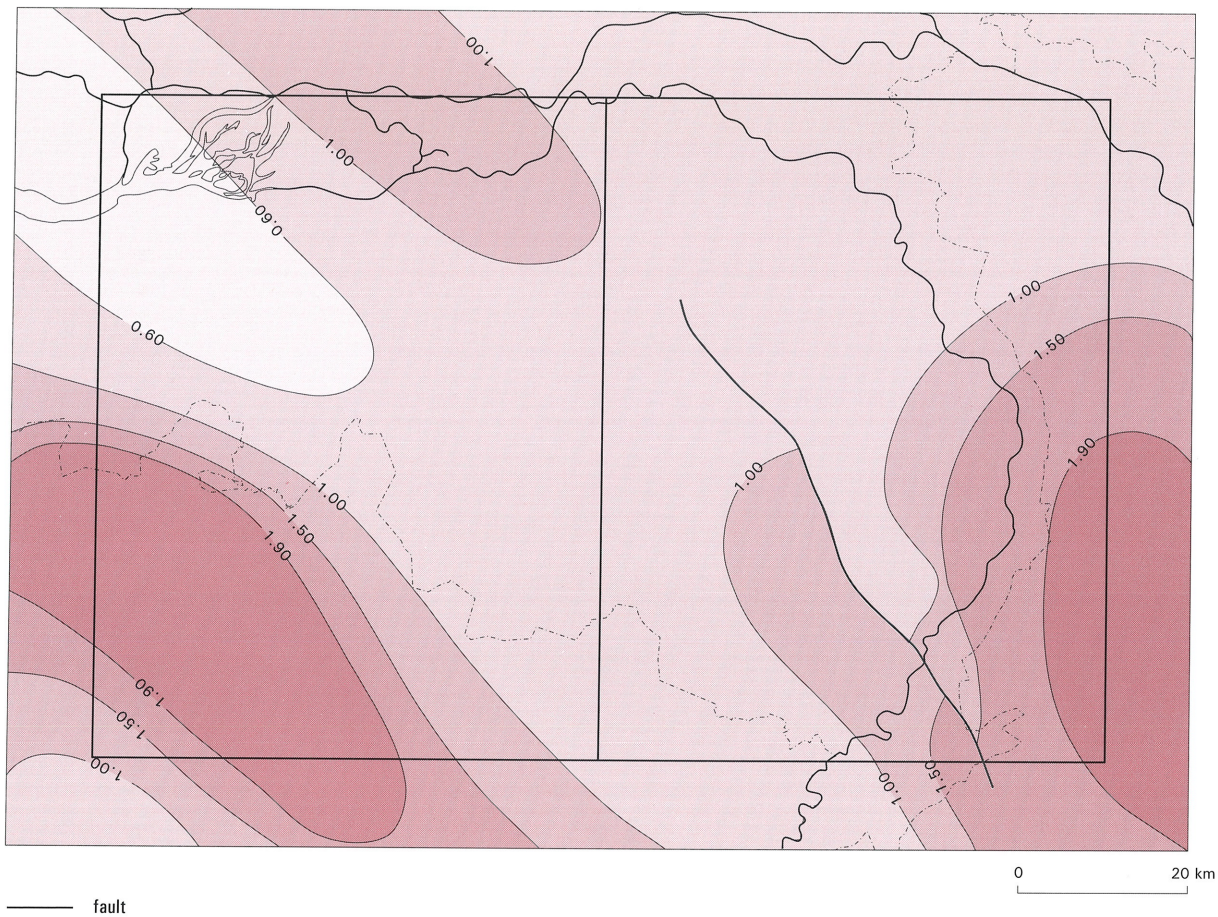


Figure 15.1 Coalification map of the top of the Carboniferous (after Winstanley, 1993).

Table 15.1 Overview of the wells studied giving the coalification rank at the top of the Limburg Group

Well	*Depth Top Limburg Gr.*	*Coalification (%Rr)*
Beesel-72	683.60	1.18
Belfeld-14	668.00	1.82
Elmpt-77	708.70	1.45
Elmpt-78	571.55	1.47
Helden-20	705.00	0.94
Helenaveen-5	913.90	0.92
Kessel-10	687.00	1.17
Maasbree-13	872.65	1.35
Maasniel-74	668.70	1.52
Melick-Herkenbosch-70	479.30	1.68
Maris-18	837.00	0.78
Nederweert-1	2638.00	0.97
Neer-71	700.00	1.03
Reuver-76	593.50	1.88
Swalmen-21	659.00	1.27
Swalmen-73	661.70	1.37

Production of the adsorbed gas in the coal, coal bed methane, may become an economically viable proposition in the near future, if necessary with the aid of simultaneous CO_2 injection. The injected CO_2 enhances the production of the methane and is stored permanently in the coal (Novem, 2001).

15.1.1 Coalification of the Peel Block

For the purposes of the survey reported on by the Peelcommissie (1963), the coal rank of the Carboniferous was determined on a basis of volatile matter. In the eighties, a new analysis, this time petrographical (vitrinite reflections), was carried out on the coal rank of the sample material. There proved to be a good correlation between the coalification measured by means of volatile matter and the coalification measured using vitrinite reflection. In addition, new measurements were performed in seven wells.

Based on these coalification data, the coalification trend of the Limburg Group was determined from information derived from all the wells in the Peel area. Table 15.1 gives an overview of the wells studied. These trends were extrapolated to the top of the Carboniferous surface, which resulted in a coalification map of the top of the Carboniferous (fig. 15.1). This map reveals that the coalification trend at the top of the Carboniferous in the Roer Valley Graben is relatively slight and that the coalification increases in an easterly and southeasterly direction to over 1.8% Rr (fig. 15.2). This increase is to some degree analogous with the increasing age of the top of the Carboniferous from Westphalian C in the Roer Valley Graben to Namurian in an easterly direction and to Westphalian A in a southeasterly direction (fig. 5.1). The coalification is not primarily determined by the stratigraphic position, as the coalification of the Catharina band, a marine band, manifests an increase in coalification in a southeasterly direction within the layer as well. These coalification trends may be accounted for by differences in burial depth at the moment of deepest burial and/or local temperature differences.

The burial history of coal-bearing sequences of Westphalian age has been reconstructed on the Peel Block and in the Roer Valley Graben. The original depositional thickness of these deposits only varied marginally (see Chapter 5). During the Early Permian, the Peel and Venlo Blocks underwent pronounced differentiated uplift, during which the degree of erosion increased in an easterly direction from 450 m to over 1950 m. From this reconstruction, it is evident that only in the Roer Valley Graben was the uplift

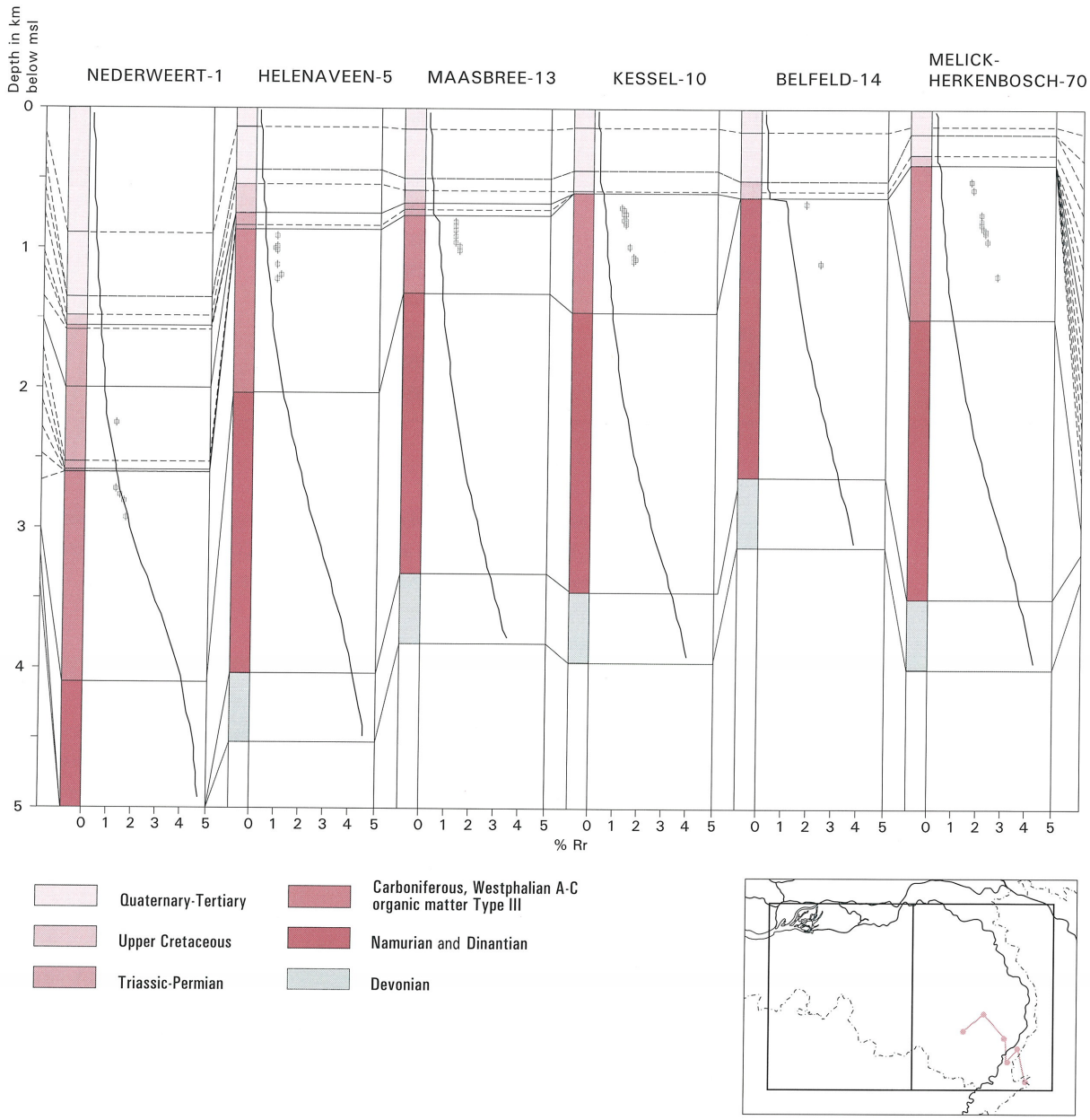


Figure 15.2 Modelled and measured coalification values of the Nederweert-1, Helenaveen-5, Maasbree-13, Kessel-10, Belfeld-14 and Melick-Herkenbosch-70 wells. The location of the section is NW-SE of the Roer Valley Graben towards the Peel Block. The difference between the modelled coalification (line) and the measured coalification (points) becomes increasingly larger in a SE direction. This is attributed to the Erkelenz intrusive.

exceeded by subsequent subsidence. The coal seams on the Peel Block reached their greatest depth at the end of the Carboniferous (fig. 15.3). This period of deepest burial was also characterised by the principal coalification phase on the Peel Block. Consequently, the differential uplift during the Early Permian was insufficient to account for the differences in coalification. The differences in burial depth would therefore appear not to have been of importance.

The second factor relates to local temperature differences. Temperature plays an influential role in the coalification of the sediments. The temperature is determined by the following four parameters: 1. heat flow from the subsurface, 2. temperature at the surface, 3. rock characteristics (radioactivity, conductivity) and possibly 4. lateral heat flow. There is no reason to presuppose the existence of regionally large differences over the ages as far as the first three parameters are concerned.

Assuming equal values for these parameters, the coalification history of five wells on the Peel Block and one well in the Roer Valley Graben have been modelled. Figure 15.2 demonstrates a good fit between the calculated coalification (line) and the measured coalification (points) in the Nederweert-1 well in the Roer Valley Graben. The deviation between the calculated and the measured coalification increases in a southeasterly direction.

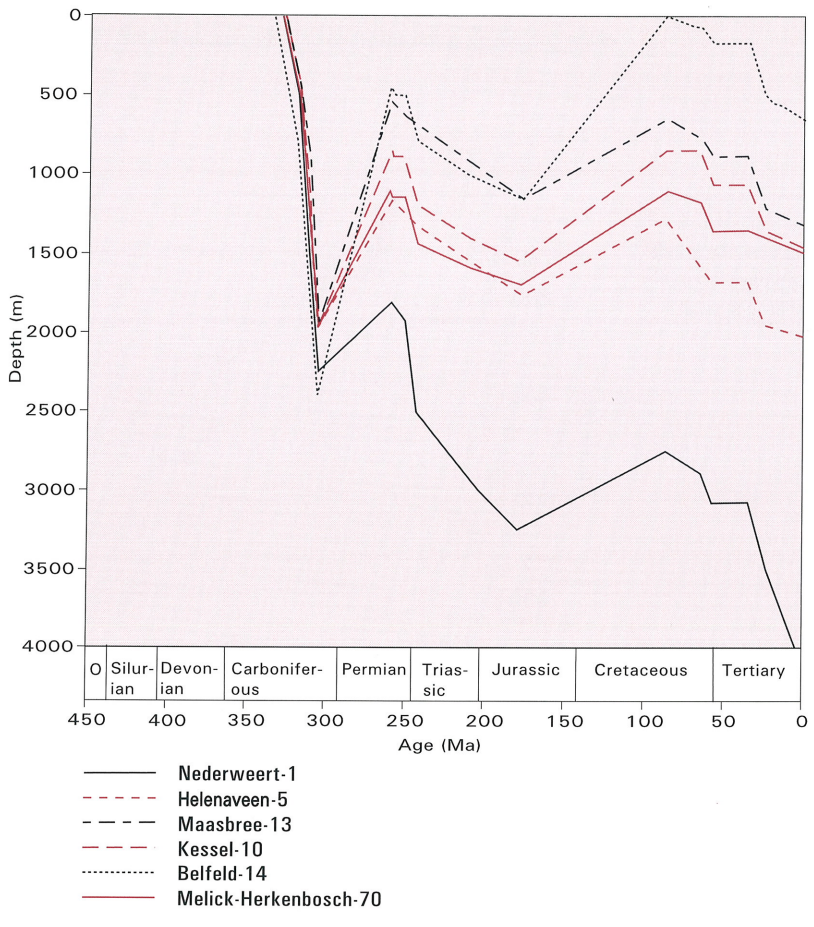


Figure 15.3 Burial history of the Limburg Group of five wells on the Peel Block and one well in the Roer Valley Graben.

A possible reason for this supply of heat could be a hot fluid influx, as has been postulated by Buntebarth et al (1982) to account for the anomalous coalification pattern around the Krefeld High to the southeast of the Peel Block. The source of this hot fluid flow is suggested as being a large intrusive body (Erkelenz intrusive) in the subsurface. Indications of the presence of such an intrusive below the Krefeld High are measured anomalies in the gravity and magnetic fields (Bosum, 1965, Bredewout, 1989) and observed volcanic intrusions in the coalfields.

15.2 Petroleum systems in the Roer Valley Graben

In the northwestern part of the Roer Valley Graben, hydrocarbon accumulations have been encountered, while none on the Peel Block are present. This can be clarified by evaluating the petroleum systems. A classical petroleum system consists of a source rock, a migration route, a reservoir and a sealing rock overlying the reservoir. All these elements are of essential importance to the preservation of hydrocarbons through geological time.

The source rock for gas, the coal seams of the Limburg Group, are found in the Roer Valley Graben as well as on the Peel Block. The reconstruction of the burial history of the Peel Block and the modelled generation of hydrocarbons reveals that peak generation was reached prior to the pre-Permian uplift phase. At the time of this peak generation of hydrocarbons, no reservoirs were present. In consequence, the hydrocarbons generated during this period disappeared from the Peel Block area, with the exception of the gas, which is still adsorbed onto the coal itself (coal bed methane).

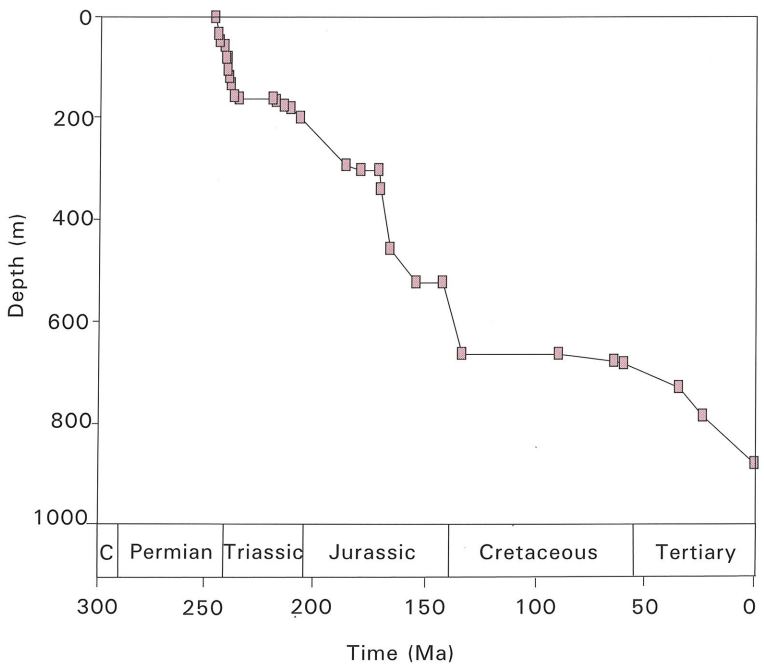


Figure 15.4 Subsidence history of the Sprang-1 well, derived from backstripping analyses. The results are based on the present-day sedimentary succession in this well.

The Roer Valley Graben, in contrast, has experienced an entirely different burial history from that of the Peel Block (Zijerveld et al., 1992, Geluk et al., 1994), as is illustrated by the eastern part of the graben (Nederweert-1 well) in figure 15.3. The pattern of the *tectonic* subsidence of the western part from the Late Permian on is illustrated by a burial depth history diagram of the Sprang-1 well (fig. 15.4). The deepest burial was achieved from the Tertiary up to the present time. In this timespan, migration paths as well as reservoirs and sealing layers were present.

Two different plays have been identified in the Roer Valley Graben: a gas and an oil play. In order to account for the presence of hydrocarbons in the graben, a model has been used relating the time spans of generation and migration to the tectonic evolution of the basin. The plays have been modelled using the I.F.P. software program TemisPack, on a basis of the section in fig.15.5. For details of the procedure involved, reference should be made to Van Balen et al. (2000). The results have been calibrated using present-day temperatures and vitrinite reflections from reference wells. The data for the Waalwijk concession have been derived from Clyde Petroleum Exploration B.V. In the eastern part of the Roer Valley Graben, coalification data are available from one well only (Nederweert-1).

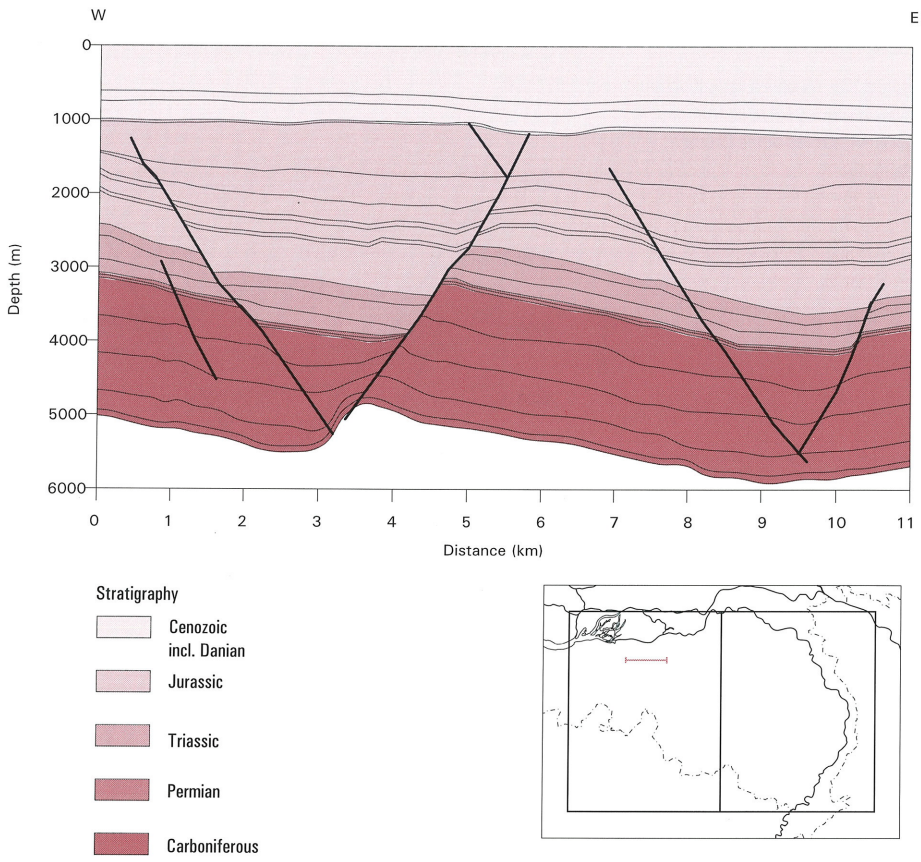


Figure 15.5 The modelled W-E section in the Roer Valley Graben.

15.2.1 The Triassic gas play

In Waalwijk-Noord, gas was first discovered by BP in 1987 (fig. 2.1). Subsequently, in the early nineties, the presence of oil and gas in the vicinity of Loon op Zand was revealed by Clyde (Winstanley, 1993). The reservoir rocks in the Waalwijk and Loon op Zand fields are sandstones belonging to the Main Buntsandstein Subgroup and the Röt Fringe Sandstone Member (Winstanley, 1993). The hydrocarbon accumulations in the Triassic reservoirs are located in tilted fault blocks in a comparable configuration to the Triassic occurrences in the West Netherlands Basin (De Jager et al. 1996; Geluk et al. 1996; Van Balen et al., 2000).

The most important gas-source rock in the western part of the Roer Valley Graben is formed by the coal seams of the Caumer Subgroup (Type III source rock). The present saturation that has been predicted by modelling the Westphalian gas-source rock is shown in fig.15.6. It transpires that gas generated from the coal seams is captured in reservoirs in the Main Buntsandstein Subgroup and Röt Formation. The accumulations on either side of the profile are due to the pre-conditions of the model. The model reproduces the well-known occurrence in the Loon op Zand field. The time span of gas generation has been shown in fig. 15.7a. The generation history is analogous to that in the West Netherlands Basin (Van Balen et al., 2000). Generation commenced approximately 210 Ma ago, subsequently accelerated and then levelled off in 120 Ma when maximum burial depth was achieved. The high generation velocity

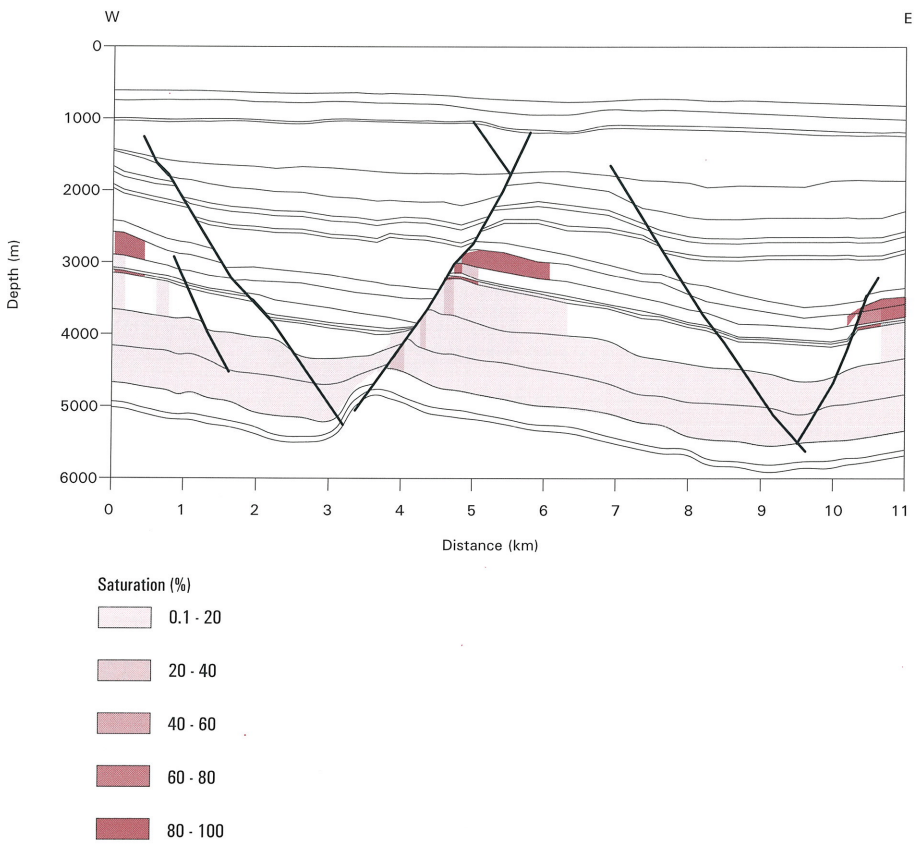


Figure 15.6 Modelled saturation for hydrocarbons generated from the gas-source rocks of the Caumer Subgroup.

between 180 and 120 Ma can be attributed to the rapid burial and the high heat flow during the Late Jurassic – Early Cretaceous rift phase. The history of the filling of the reservoir has been depicted in fig. 15.7b. This commenced in 130 Ma and was completed in 100 Ma. In other words, the reservoir was filled prior to the Sub-Hercynian inversion.

A second potential source of the gas is a layer rich in organic material belonging to the Geverik Member, at the base of the Epen Formation (Namurian). Lower Namurian source rocks have been penetrated in wells located further to the south (Langenaeker, 1998) and in wells to the east of the study area (NITG-TNO, 1998; Van Balen et al., 2000). Furthermore, the palaeogeographic circumstances during the Early Namurian and Westphalian (Lokhorst, 1998; Cameron & Ziegler, 1997) suggest the likelihood of Lower Namurian and Westphalian profiles as important oil-source rocks in the West Netherlands Basin and the Waalwijk area (De Jager et al., 1996; Van Balen et al., 2000). These marine deposits (Type II organic material) will initially have predominantly generated oil. In the model, it has been assumed that oil, originating at an early stage, did not survive the high temperatures and pressures occurring during burial and was transformed into gas by a process of secondary cracking. According to the model, this gas was captured in the same structures in which the gas from the Caumer Subgroup is trapped (fig. 15.8). The generation history (fig. 15.9a) shows that hydrocarbons were generated between 300 and 160 Ma, consequent to burial during the Late Carboniferous, Permian and the Mesozoic. However, the history of the accumulation in the reservoir demonstrates (fig. 15.9b) that these hydrocarbons did not reach the reservoir until 160 Ma. This is approximately the same time interval as the commencement of the accumulation of the Westphalian gas in this reservoir. Compared with the West Netherlands Basin, the generation of hydrocarbons from the Epen Formation in the Roer Valley Graben began much later, owing to the difference in burial history during the Carboniferous. The burial depth was considerably shallower in this part of the Roer Valley Graben than in the West Netherlands Basin. The mechanisms ultimately resulting in the present situation can only be ascertained with the aid of supplementary geochemical research.

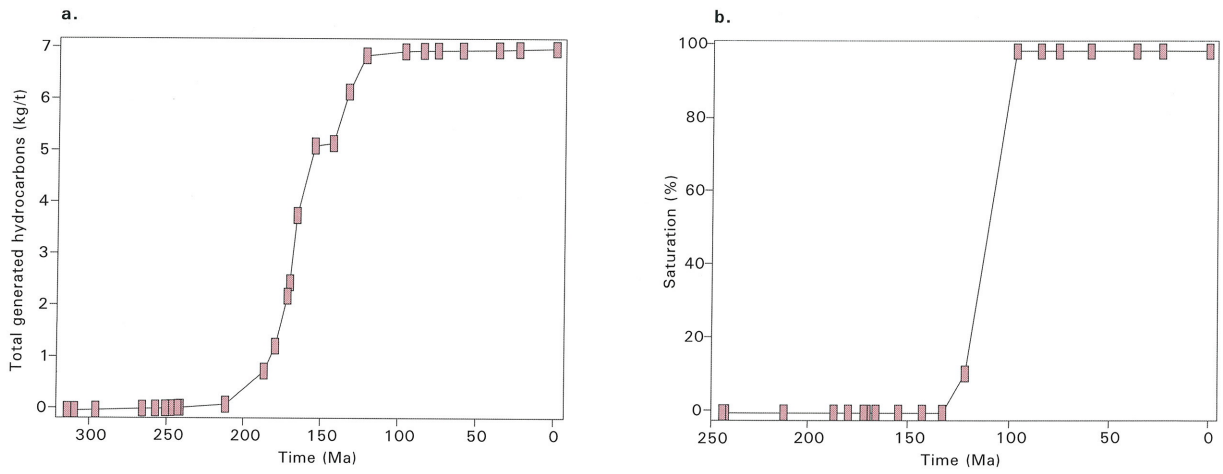


Figure 15.7 a) Generation history and *b)* accumulation history. The saturation history relates to the Triassic sandstone in the Waalwijk South-1 well. The generation history relates to the deeply buried Westphalian source rocks to the east of the well.

15.2.2 The Triassic oil play

The provenance of the oil encountered in the Triassic sandstone reservoirs of the Loon op Zand field (Winstanley, 1993) is still unclear. The most obvious source rock (Type II) for oil, the organic-rich marine deposits of the Posidonia Shale Formation and possibly the Aalburg Formation, form part of the Altena Group. According to Winstanley (1993), the Posidonia Shale Formation in the western part of the Roer Valley Graben is not mature enough for oil generation. Furthermore, the geochemical signature of the oil does not correspond to that of the Posidonia Shale Formation, which makes this improbable as provenance (Winstanley, 1993).

An second alternative is that the oil was generated from terrestrial deposits (Type III) with a high organic content. According to Winstanley (1993), the geochemical signature points to a terrigenous oil-source rock within a marine shale sequence. Correlation of the geochemical characteristics of the oil with those of the Sleen Formation indicate this formation to be a likely source rock. However, the Sleen Formation is too thin to have been capable of generating the large quantities of oil in the Loon op Zand field (Winstanley, 1993). Furthermore, the migration path of oil from the Sleen Formation to the underlying Triassic reservoirs is highly problematic, unless juxtaposition of two fault blocks occurred.

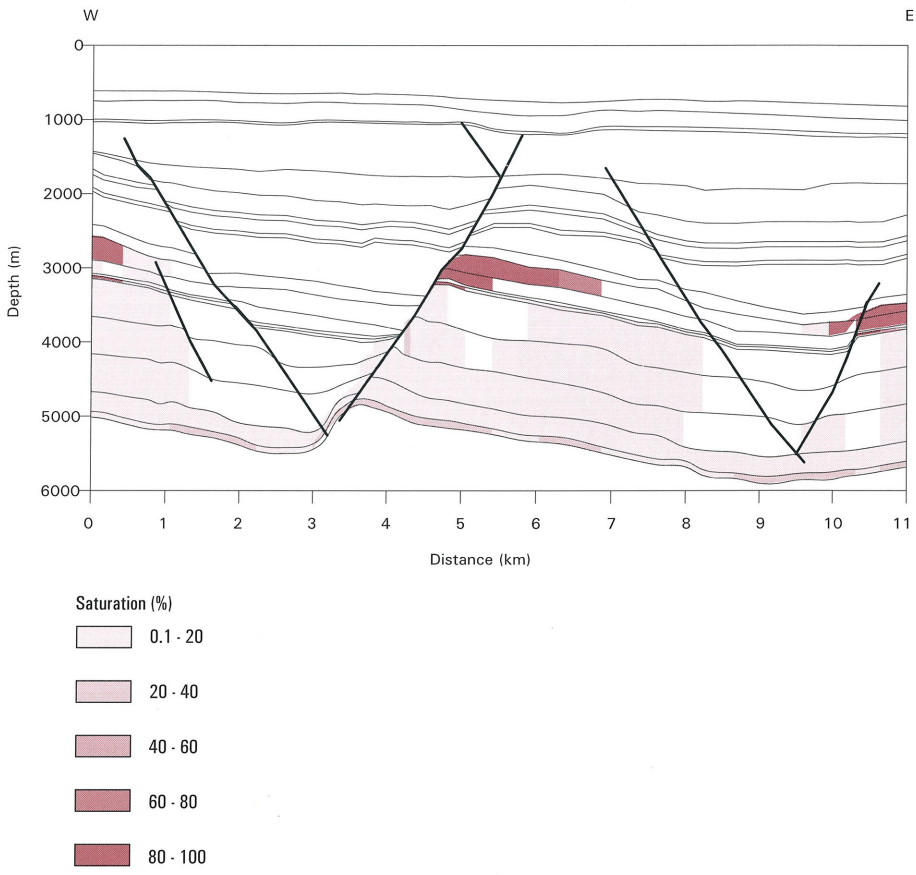


Figure 15.8 Modelled saturation for hydrocarbons generated from the gas-source rocks of the Epen Formation.

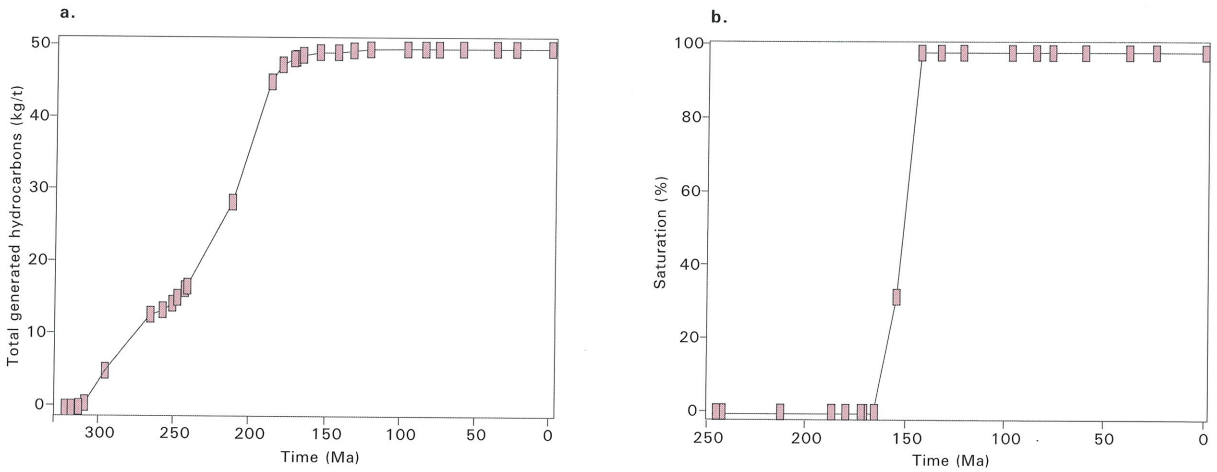
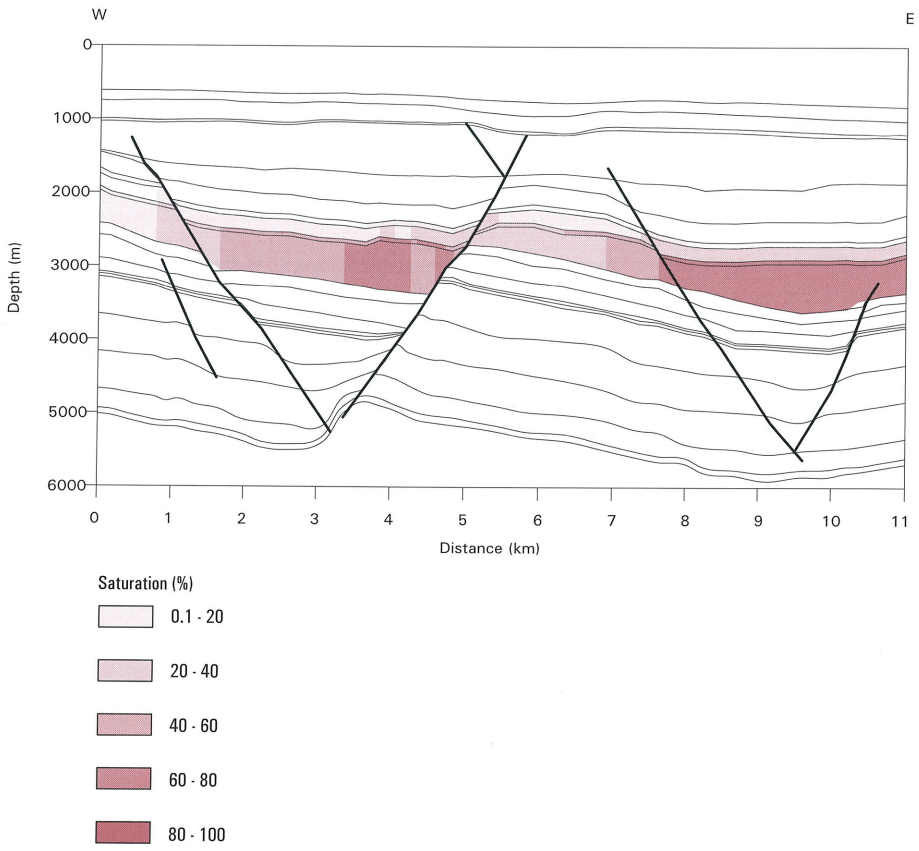


Figure 15.9 a) Generation history and *b)* accumulation history. The saturation history relates to the Triassic sandstone of the Waalwijk South-1 well, the generation history is of the deeply buried Namurian source rocks to the east of this well.

Figure 15.10 Present-day, calculated hydrocarbon saturation relating to the Altena Group oil-source rocks.



A modelling of the system with the base of the Altena Group as source rock also indicates this possibility as being improbable. The modelling results show that only the source rock in the most deeply buried parts of the basin become sufficiently saturated to initiate expulsion of oil (fig. 15.10). Expulsion of oil from the formation did not, however, begin until comparatively recently. Even above the most mature parts of the source rock, the principal transporting rock, the sandstone of the Middle Werkendam Member, has been insufficiently saturated to trigger transportation of oil to the reservoir. On a basis of these results, therefore, the oil in the Triassic reservoirs in the Loon op Zand field is highly unlikely to have originated from the deposits of the Altena Group, including the Sleen Formation.

The third alternative for the provenance of the oil is in the marine or lacustrine intervals of the Limburg Group or the marine deposits from the Namurian (Winstanley, 1993). Marine intervals in the Carboniferous have been well documented from the Peel Block, South Limburg and the Achterhoek (see NITG-TNO, 1999 & 1998 resp.). As mentioned above, Lower Namurian oil-source rocks have been encountered at several locations in the Netherlands and Belgium (Dusar et al., 1998). Although the correlation between oil occurrences and these oil-source rocks has never been demonstrated, this alternative would appear to be the most likely.

15.3 Hydrogeology of the Roer Valley Graben and environment

15.3.1 Groundwater in Tertiary deposits

Hydrogeological surveys of the subsurface of the Netherlands are often restricted to the groundwater in the shallow Quaternary and Upper Tertiary deposits, because the target for such studies is generally the fresh part of the groundwater intended for drinking water. Even at relatively shallow depths, the salt content of the groundwater in the Netherlands exceeds 150 mg/l (fig. 15.11), rendering it unsuitable for use as drinking water. In these studies, the flow velocity of the groundwater at greater depths, in the Tertiary sediments, is assumed to be negligible, and the prominently clay-bearing Breda Formation has been taken as the basis of the hydrological system.

However, several time-series studies on hydraulic heads (groundwater pressure) in the provinces of Limburg and Noord-Brabant performed in the nineties revealed that the hydraulic head was influenced by other (deeper) processes in addition to groundwater abstraction and surface agricultural interventions (Stuurman & Vermeulen, 1996). In recent decades, the relatively deep Tertiary aquifers in the Roer Valley Graben and in the Venlo Block experienced falls in hydraulic head values of 1 m/y and 0.5 m/y respectively which are virtually imperceptible in the shallow Pleistocene aquifers. The result of these falls was a decrease in deep effluent seepage (transportation of basicity water from deeper aquifers to the surface). The observed falls in hydraulic head point to a possible connection with large-scale drainage of brown coal quarries in Germany. These quarries are situated just over the border, both in the Roer Valley Graben and on the Erft and the Peel Blocks (fig. 3.1). As brown coal is excavated down to depths of several hundreds of metres, large quantities of groundwater are extracted, which results in considerable falls in hydraulic head locally. For example, around the Inden quarry in the Roer Valley Graben, over 100 million m^3 are extracted annually from the relatively shallow Upper Tertiary aquifers at that point. These horizons correspond to the deep aquifers in the Netherlands, where a fall in hydraulic head has been observed.

In order to counteract the effects of this intervention in the regional groundwater system in the Roer Valley Graben, part of the extracted water has for some years now been used to form an artificial lake in the former brown coal quarry of Zukunft, where approximately 65% of the water is reinfiltrated into shallow aquifers. The question is, however, whether this shallow reinfiltration of the groundwater

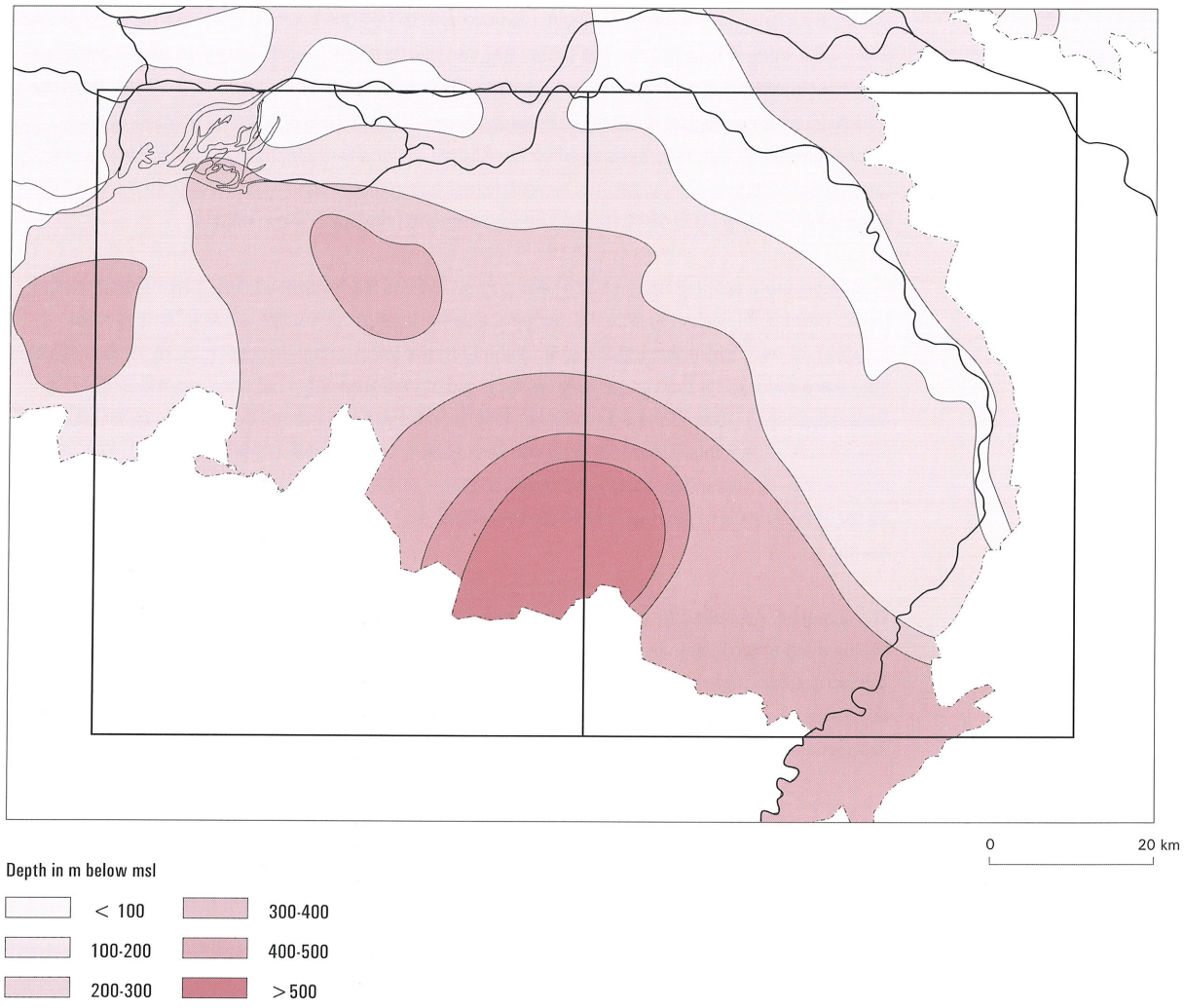


Figure 15.11 Depth of the fresh/brackish boundary (150 mg CL^- /l) of the groundwater in the southern part of the Netherlands (after Dufour, 1998).

wholly compensates for the fall in hydraulic head in the aquifers. German groundwater flow model studies indicate this indeed to be the case (Rouvé, 1986, 1991). In the model, however, the deeper Tertiary sequences were not included and the modelling of the Dutch part of the Roer Valley Graben was limited because the hydraulic head falls here were assumed to have ceased. However, a model study conducted by TNO, taking the deeper Lower Tertiary sequences into account, reveals that the large-scale extractions in the Netherlands did in fact result in a fall in hydraulic head in several of the aquifers (Stuurman & Vermeulen, 1996). This may have produced a decrease in the upward groundwater flow. The hydrogeological layer classification and parameter distribution (which largely dictates the range of influence of extraction) used in that study were not, however, based on the most recent data derived from wells and seismic logs.

Within the framework of the current mapping, an improved, cross-border hydrostratigraphic schematisation of the Cenozoic members has been compiled (NITG-TNO 2000), which forms the basis for a new flow model study (figure 15.12a). The schematisation into 32 layers is partly based on results obtained from the current mapping of the Tertiary deposits. This schematisation is combined with data from the TNO-NITG hydrogeological database of Pleistocene sediments in Noord-Brabant (REGIS-Brabant), the most recent model study performed by the Aachen University of Technology (RWTH Aachen) for the German section of the model area as well as hydrogeological maps of the groundwater plan for the province of Limburg (RGD 1985) for the Limburg section of the Roer Valley Graben.

In addition, more detailed research has been carried out into the hydrogeological parameters required for the flow model, including porosity and permeability. In previous studies, constant values were assumed for each hydrostratigraphic unit. Within the framework of the present study, depth-based relations were deduced for the various units with the aid of improved empirical formulas (Magara, 1978; Sclater & Christie, 1980; Mann & Mackenzie, 1990), which have been conditioned by the available well logs and measurements. Table 15.2 gives the permeability for a number of model units at two locations in the model. For the Inden locality, the model units are relatively shallow and consequently the permeability of the units is higher than below Eindhoven, where the majority of the units are situated more deeply.

The stationary groundwater study carried out reveals that the extraction in Germany causes a substantial lowering of the hydraulic head in the Dutch part of the Roer Valley Graben, particularly in the deep Tertiary aquifers (figure 15.12b). This indicates that the shallow, fresh hydrogeological system may also be affected, as shown in figure 15.13a and b. The reason for this is that the pressure decrease in the deep aquifers produces a slighter pressure gradient from deep to shallow, resulting in a decrease in the

Table 15.2 Permeabilities used in a few model units at the Inden and Eindhoven site from the flow model (aquitards grey, aquifers white)

Hydrological unit	*Permeability (metres/day)*	
	Inden (shallow layers)	*Eindhoven (deep layers)*
Tegelen gravel / Kedichem Formation	6.5×10^{1}	5.4×10^{1}
Topmost Brunssum clay	6.0×10^{-3}	2.5×10^{-3}
Waubach Sand	5.1×10^{1}	3.8×10^{1}
Inden brown coal	1×10^{-5}	N.A.
Neurath Sand	1.3×10^{1}	N.A.
Topmost Breda sequence	N.A.	2.6×10^{0}
Heksenberg brown coal	1×10^{-5}	N.A.
Veldhoven Clay	N.A	2.2×10^{-5}
Voort Sand	6.0×10^{0}	7.4×10^{-1}
Rupel Clay	1.1×10^{-3}	7.5×10^{-6}
Heers Sand	4.3×10^{0}	2.7×10^{-1}

Figure 15.12 a) Position of the model area in the Roer Valley Graben, including an illustration of the linear profile in fig. 15.13.

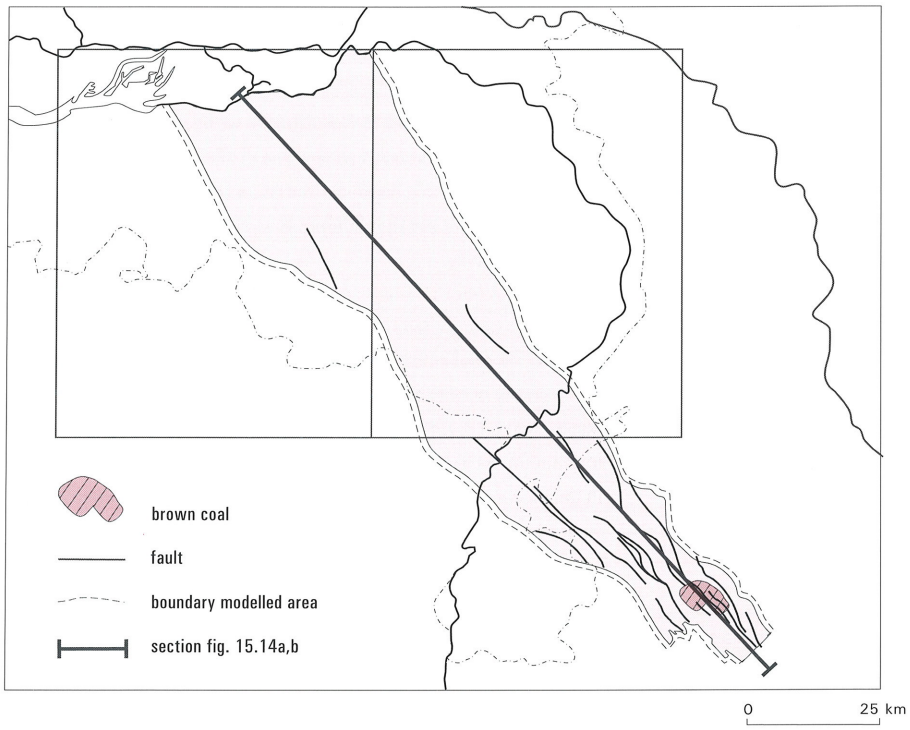
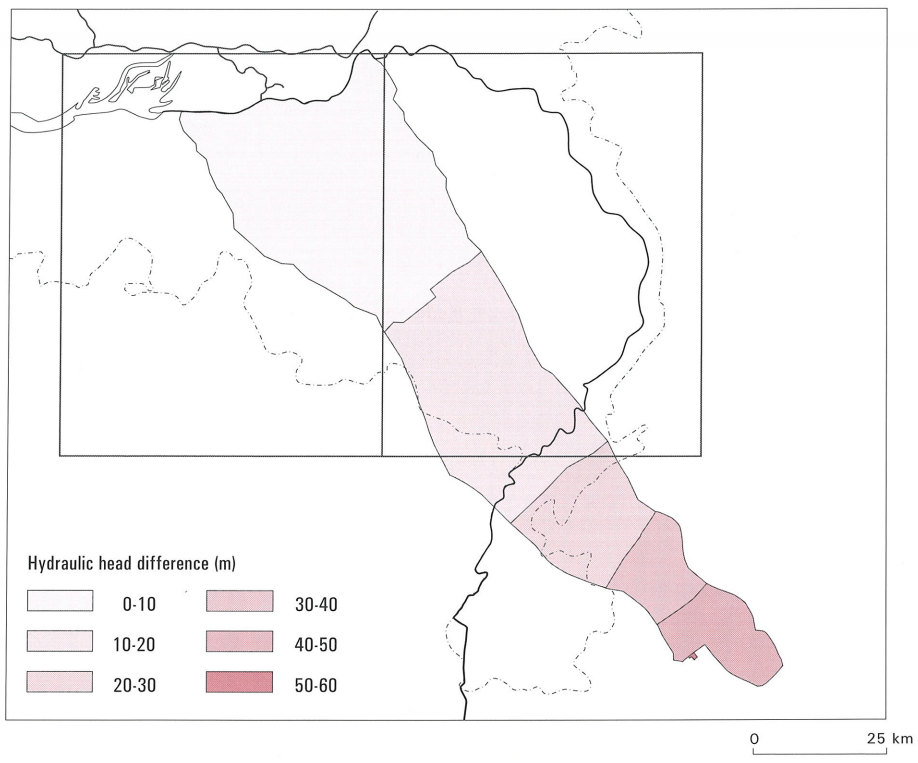


Figure 15.12 b) Calculated hydraulic head difference in Aquifer 5C (Voort Member; NMVFV) consequent to the large-scale groundwater extractions around the Inden brown coal quarry.



upward groundwater flow. This upward flow is very slow owing to the poor permeability of the frequent clay layers in the Roer Valley Graben. In order to accurately estimate the effect on the shallow groundwater, an instationary (time-dependent) model calculation is required. The decrease in upward flow may also account for the slow decrease in chloride content that has been observed at a depth of approximately 425 m beneath the Herten drinking water pumping station (Central Limburg). The decrease in upward flow causes an imbalance in the groundwater salinity. This would mean a gradual freshening of the groundwater at this depth. As the model study did not use variable densities and the flow may have been influenced by density differences in the groundwater, this correlation cannot be made with any degree of certainty.

The areal extent of the brown coal layers within the Heksenberg Member on Dutch territory has not been properly documented up to the present time and forms one of the uncertainties in the flow model. These poorly permeable brown coal layers in the German part of the Roer Valley Graben are generally assumed to be present, but deposition in a northwesterly direction was less thick and no longer continuous. (RGD 1993). Where the brown coal is absent, vertical groundwater flow is facilitated.
To gain a better understanding of the effect of the areal extent of the brown coal on the groundwater flow, a number of simulations were carried out in which the lateral extent of these layers was varied.

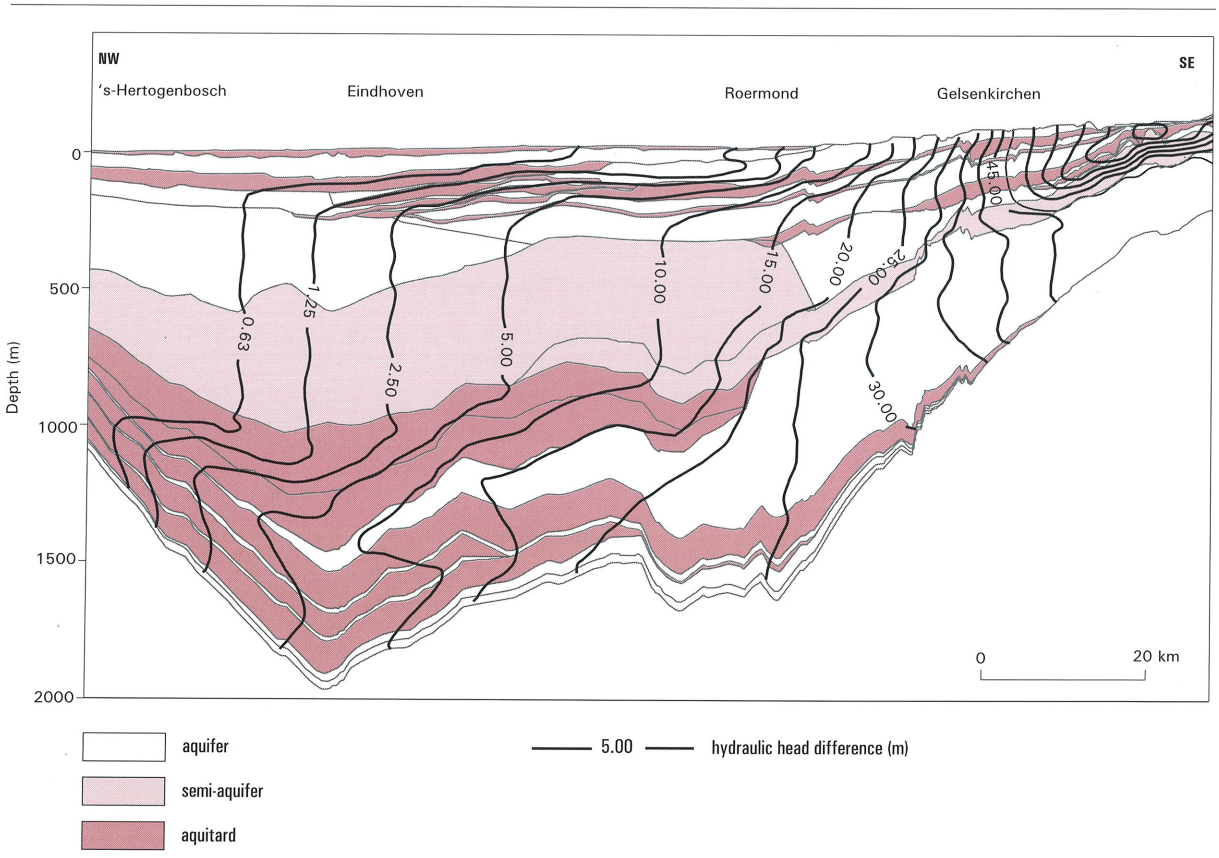


Figure 15.13 a) Calculated hydraulic head difference in the linear profile of fig. 15.12a, consequent to the large-scale groundwater extractions around the Inden brown coal quarry, for a maximum assumed areal extent of the brown coal within the Heksenberg Member.

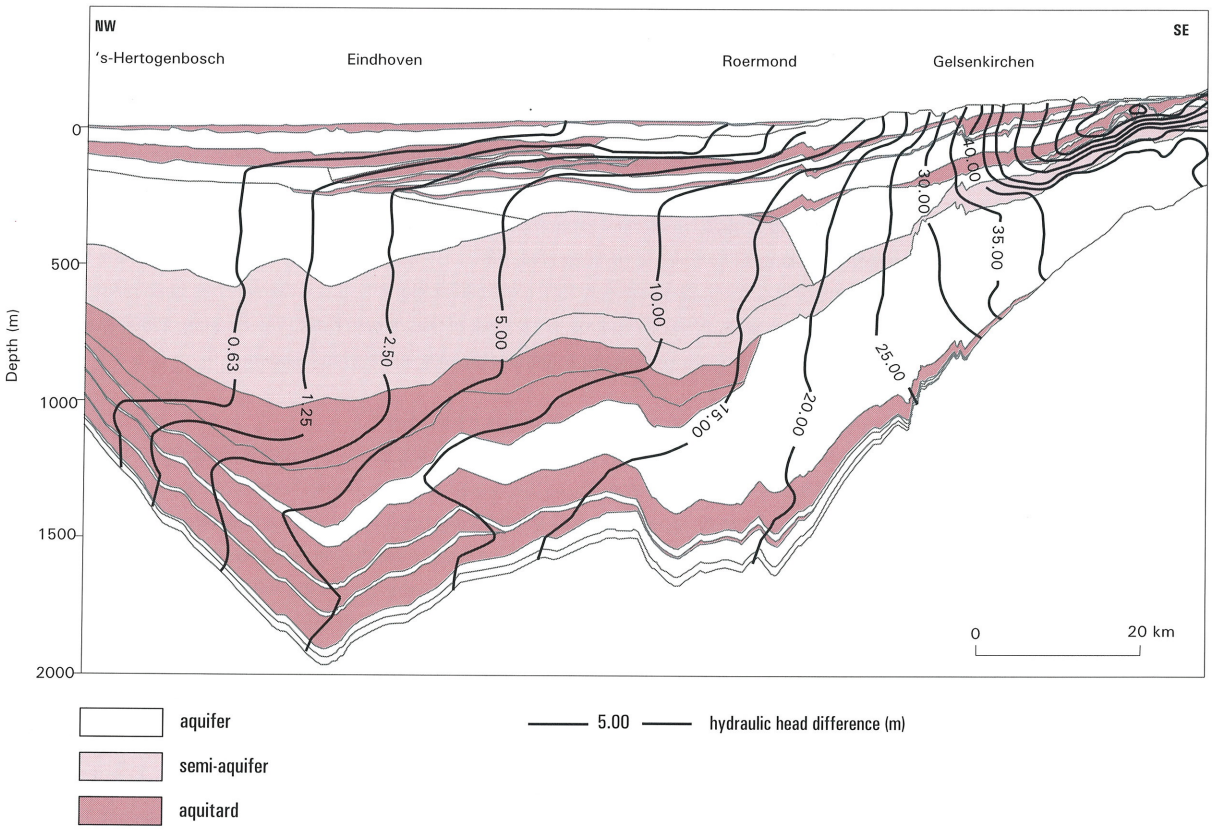


Figure 15.13 b) Ditto for a minimum assumed areal extent of the brown coal within the Heksenberg Member.

The outcomes indicated that where this was assumed to be comparatively large, the result was a greater, extraction-related fall in hydraulic head in the Lower Tertiary aquifers (figure 15.13a, b). The reason for this would appear to be that in this stationary model, the hydrological top system in the scenario with a relatively large areal extent of brown coal is not able to exert as much influence on the deep groundwater (less vertical groundwater movement). This deeper groundwater "system" is therefore dominated by the extraction activities around the brown coal quarries.

However, all the scenarios with a varying brown coal areal extent reveal substantial hydraulic head falls in the subsurface of the Netherlands. This confirms the supposition that large-scale extractions do have a significant influence on the hydrogeological system of the Tertiary and Pleistocene part of the Roer Valley Graben. Confirmation of these findings may be obtained by extending the monitoring of the hydraulic head in the deeper aquifers in the Roer Valley Graben.

15.3.2 Thermal water

At a number of places in the Roer Valley Graben and on the Peel Block, thermal mineral water meeting the requirements stipulated by the German norms for medicinal water (Heilwasser) has been encountered at various depths (Anonymous, 1979).

Arcen well, Klein Vink thermal bath: water from Zechstein aquifer

In the Arcen-1 well in the Venlo Graben, thermal mineral water is abstracted from the dolomitic limestone of the Zechstein Group at approximately 840 m below surface level (RGD 1987b). At abstraction depth, the water, designated type "Fluoride, Iodide and Iron-bearing thermal-mineral water, 3% *Sole* strength" (Zuurdeeg et al., 1987), is at a temperature of approximately 40°C. This is 15°C warmer than would be expected at a normal geothermal gradient (3°C/ 100 m). The implication is that the water originates from deeper layers. The chemical composition of the formation water, particularly the higher trace element content, indicates that a substantial proportion of the water originates from the Carboniferous Limestone Group (Dinantian) (Zuurdeeg et al., 1987). On this location the top of the Carboniferous Limestone Group is situated between 1500 and 2000 m (fig. 4.1). Since the well has been placed close to a (minor) fault system a few kilometres to the west of the Viersen Fault (Van Rooijen, 2000), it is likely that the mineral-bearing groundwater migrates upwards via this fault system.

Asten-2 well: water from the Vessem Member

The water in the Asten-2 well (Roer Valley Graben) that has been encountered at approximately 1500 m below surface level in sands belonging to the Vessem Member (Rupel Formation) is classified as medicinal, with the designation type: "(possibly Iron-bearing), Iodide and Fluoride-bearing *thermal Sole*, 5% strength" (TNO GG 1989). The temperature of the water from the Vessem Member, 59°C, is a few degrees above the temperature expected at this height, which, as in the Arcen well, implies that the water originates from deeper layers. The chemical composition of the water, with NaCl values higher than in seawater, indicates contact with evaporite-bearing carbonate rocks. This is comparable to the composition of the thermal mineral water from the Arcen well. The implication is that this water also originates from the Carboniferous Limestone Group (TNO GG 1989: Zuurdeeg et al., 1987). At this location, this unit is located at a depth of over 7 km.

The considerable depth of the Carboniferous Limestone Group in the Roer Valley Graben and the geographic position a few kilometres from the Peel Boundary Fault suggest that the water in this well migrates or has migrated upwards via the Peel Boundary Fault. An alternative supposition is that the water from the Peel Block, where the Carboniferous Limestone Group is less deep, flows laterally via the Peel Boundary Fault.

Oploo well: water from the Gulpen Formation

In the Oploo-16 well, which was drilled at the time of the coal exploration in 1912, artesian (NaCl content approx. 14000 mg/l), "salt" water was encountered in the sequence 500-570 m below surface level in limestone belonging to the Gulpen Formation. This water is characterised by a high temperature, approximately 6°C above the normal temperature (Van Waterschoot van der Gracht, 1913). The discharge of the outflowing water was 60 to 70 m^3/hour. The cause of this large water influx is probably the occurrence of a subvertical- or vertical joint zone of higher permeability, which enabled water to flow upwards from deeper sediments. The RGD (1984) considers it improbable that water ascended from a great depth along large faults to the southeast of the Gulpen Formation and subsequently flowed laterally via the jointed, topmost part of the Gulpen Formation in the direction of Oploo, in view of the heat loss that would result from lateral migration and also because the necessary pressure gradients have not been observed. In the Oploo-59 well, which was placed at the same location as the Oploo-16 in order to re-explore the potential for mineral water absorption, no artesian water has been encountered at the same depth. Neither has there been any temperature anomaly. The sediment here therefore appears to have "dual permeability" characteristics, on the one hand defined by the sediment matrix and on the other, determined by joints and/or faults in the sediment, giving rise to a variety of groundwater conditions.

This well was, however, found to contain water with a salinity of approximately 12000 mg/l, which indicates an exchange of minerals from the joints to the matrix through diffusion. The salt levels in both

wells display a similarity with the water in the Asten-2 and Arcen-1 wells and indicates that the water could very well originate from a greater depth. However, the absence of the exact composition of the water makes the origin impossible to determine.

15.4 Geothermal energy

15.4.1 Introduction

In the Netherlands, geothermal energy exploitation from ground water has for some time been regarded as being a potential source of energy. In the '80s, a number of inventory studies were carried out which did not, however, led to the actual exploitation of geothermal energy. In recent years, geothermal energy as a potential, renewable energy source has once again become the subject of attention, partly as a result of the 1997 Kyoto Protocol aimed at achieving a worldwide reduction in CO_2 emissions (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu, 1999).

Two geological preconditions determine geothermal energy exploitation: the temperature of the formation water must be high enough and production of a sufficient quantity of water must be feasible. With regard to the first-mentioned precondition, a distinction is made between deep and shallow aquifers. In the case of deep aquifers, the temperature of the formation water could be 70°C and higher, while in shallow aquifers, the temperature could be around 45°C. At a temperature gradient of 3°C/100m, this means that in the first-mentioned variant, aquifers deeper than 1800 m offer appropriate conditions, whereas for the second variant, depths of around 1200 m are suitable.

In order to meet the second criterion, the aquifers must have a sufficient degree of porosity and transmissivity (product of thickness and permeability) to achieve a production of over several thousand cubic metres a day. The latter tends to present the greatest risk factor and is often the reason why potentially appropriate aquifers and locations subsequently prove to be unsuitable for exploitation.

15.4.2 Temperature distribution in the subsurface

The first maps giving temperature data on the deep subsurface of the Roer Valley Graben area were published by Prins (1980) and Ramaekers (1991). These maps were based on data obtained from exploration wells for oil and gas (bottom hole temperatures and drill-stem test data; see fig. 3.1 for the location of the various wells). The maps show that the thermal contours of the subsurface correspond with the Late Jurassic – Early Cretaceous structural framework (fig. 15.15; NITG 1997b). The data on which these maps were based have been remodelled and supplemented by new data from hydrocarbon, coal and thermal energy exploration wells.

The data from the Asten-2 well, set in the context of a geothermal research project in the eastern part of the Roer Valley Graben, show an average temperature gradient of 32°C/km to a depth of around 1650 m (fig. 15.14; TNO GG 1989). Examined in detail, the geothermal gradient proves to vary in proportion to the depth. From 830 to 1093 m, the gradient is 33°C/km, increases to a value of 39°C/km between 1196 and 1415 m, and subsequently decreases to 23°C/km from 1494 to 1530 m (TNO GG 1989). The data derived from Asten-2 were compiled two weeks after completion of the well, which means that they may be regarded as being extremely reliable. During the exploration of coal in the southeastern part of the Peel Block, very precise temperature measurements were performed in six DSM wells (Neer-71, Beesel-72, Maasniel-74, Helden-75, Reuver-76 and Elmpt-77), to a depth of approximately 1350 m (Fig. 15.15; Peelcommissie, 1963). The temperatures in these wells displays a gradient of 21.4 to 29°C/km in the Quaternary and Tertiary sediments, and a higher gradient of 37.3 to 45.5°C/km in the underlying

Carboniferous layers (Peelcommissie, 1963). The average depth of the top of the Carboniferous in these wells is approximately 650 m.

New temperature data

New data have been collated from measurements in 23 exploration wells in the Roer Valley Graben, including the Peer well (KB-206) in Belgium and the Schwalmtal-1001 well in Germany. The temperature data derive from 4 drill-stem test (DST) measurements obtained in the Nederweert-1 well and 6 repeat formation test (RFT) measurements obtained in the Andel-6, Broekzijde-1, Brakel-1, Heeswijk-1 and Kerkwijk-1 wells. A series of bottom hole temperature (BHT) measurements from all 23 wells is also available. A proportion of the BHT data has been corrected with the aid of the Horner method to allow for temporal effects. For a description of this method, see e.g. Hermanrud et al., 1990.

In figure 15.15a, the DST, RFT and corrected BHT data have been plotted for each well, together with the temperature data for the geothermal Asten-2 exploration well and the coal exploration data derived

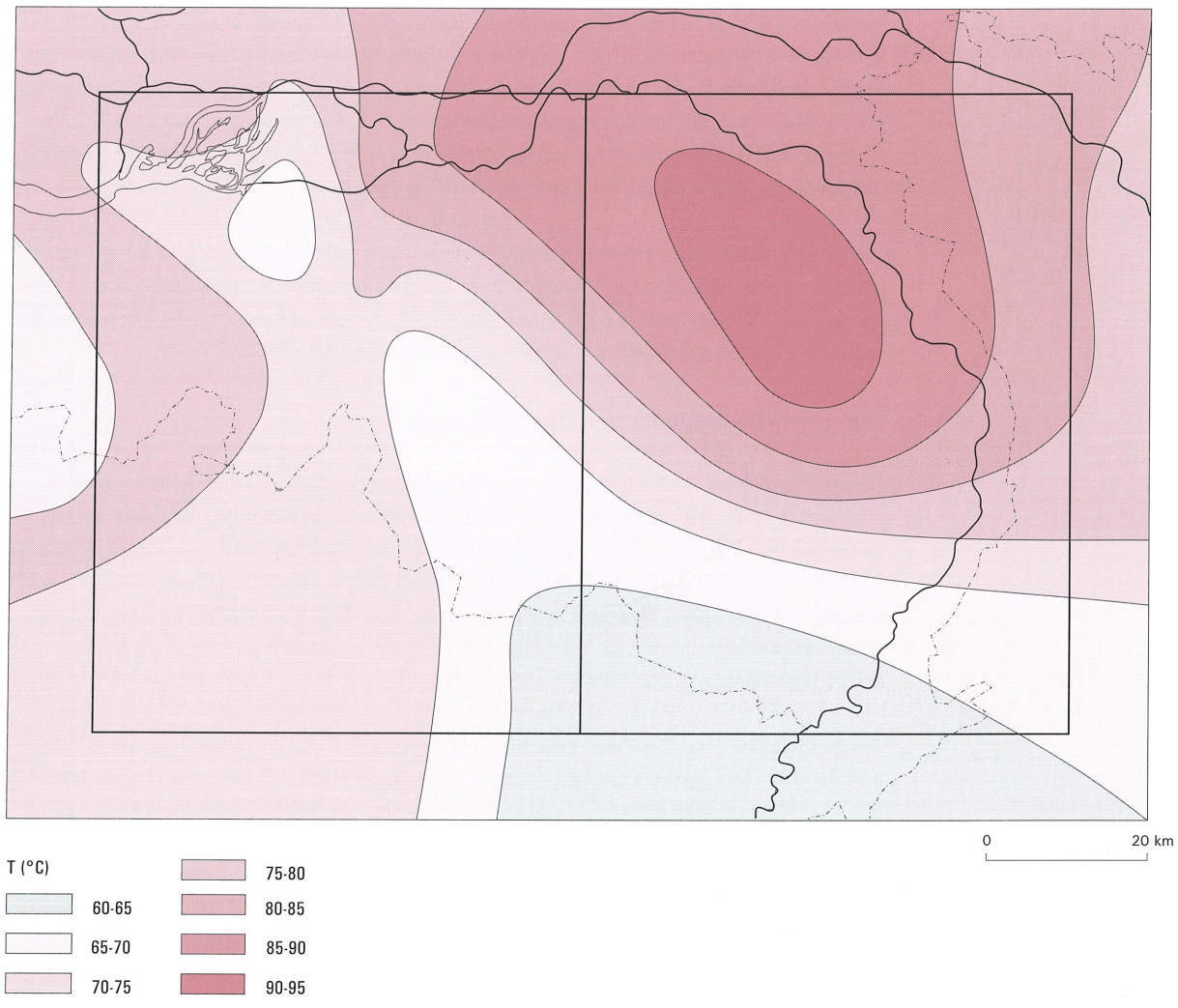


Figure 15.14 Spread of the temperature at 2000 m depth in the Netherlands (after NITG 1997b).

from the southeastern part of the Peel Block. The same data have been plotted for each measuring method in turn in figure 15.15b. The BHT measurements, which could not be corrected via the Horner method, have been given separately in figure 15.15c. The straight line in these figures represents the gradient obtained through linear regression of the Meer (KB-149) data (Vandenberghe et al., 1988) (fig. 15.15d). This reveals that the data from the Roer Valley Graben correspond to those from Meer-2,

Figure 15.15 a) DST, RFT, geothermal and Horner-corrected BHT data plotted for each well.

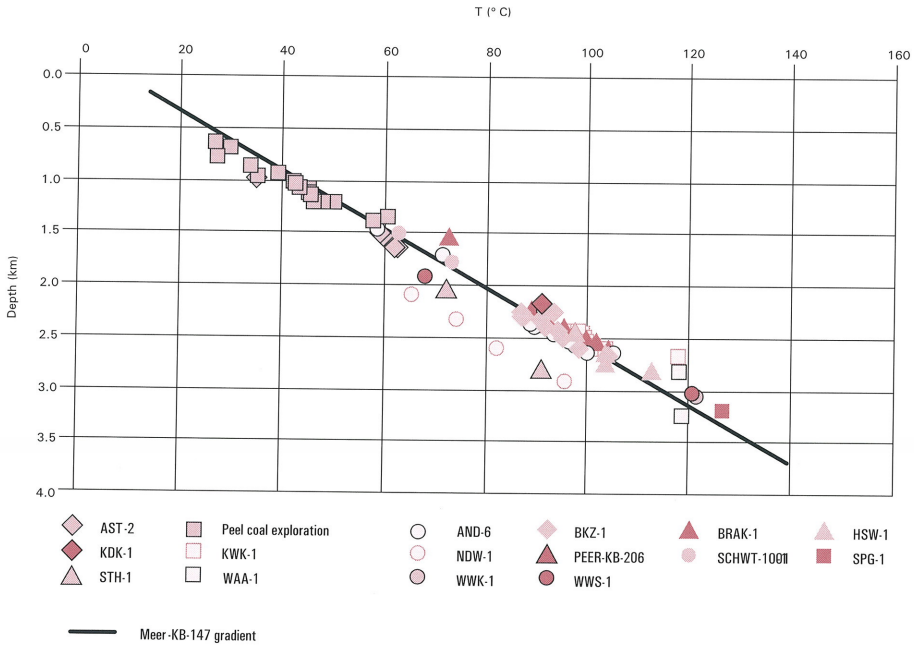
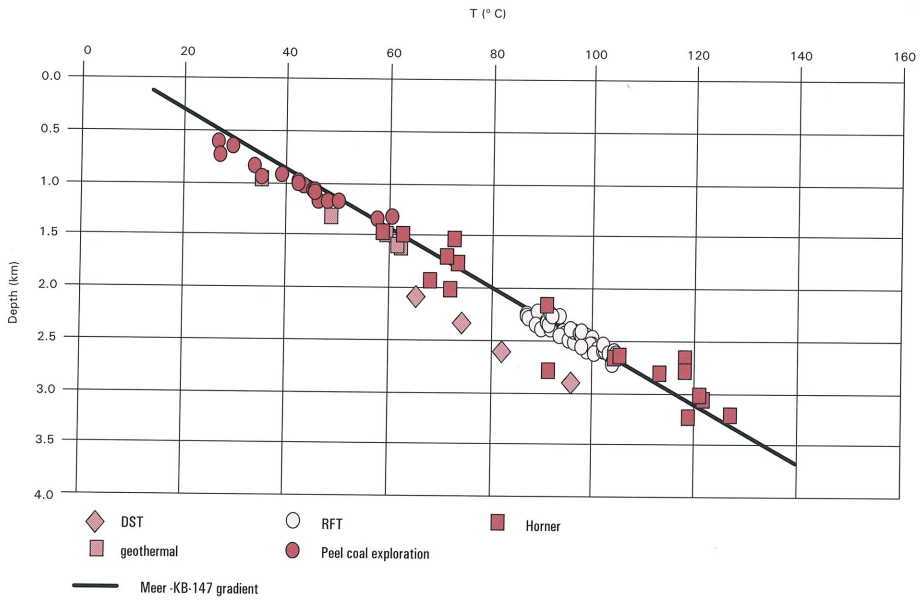


Figure 15.15 b) The same data as in fig. 15.15 a) plotted for each measuring method.



in particular those obtained from the RFT measurements. The DST temperature measurements from Nederweert-1 are approximately 15°C lower than average. Theoretically, these lower temperatures could be the result of very deep vertical groundwater infiltration; the chloride concentrations in the adjacent Asten-2 well provide evidence of deep (~1.5 km) groundwater infiltration of this nature in the past (TNO GG 1989). However, in the case of vertical flow towards the sandstones at 2.2 to 3 km, the groundwater would have to pass through several different clay layers as well as an evaporite. These temperature

Figure 15.15 c) Remaining, uncorrected BHT data.

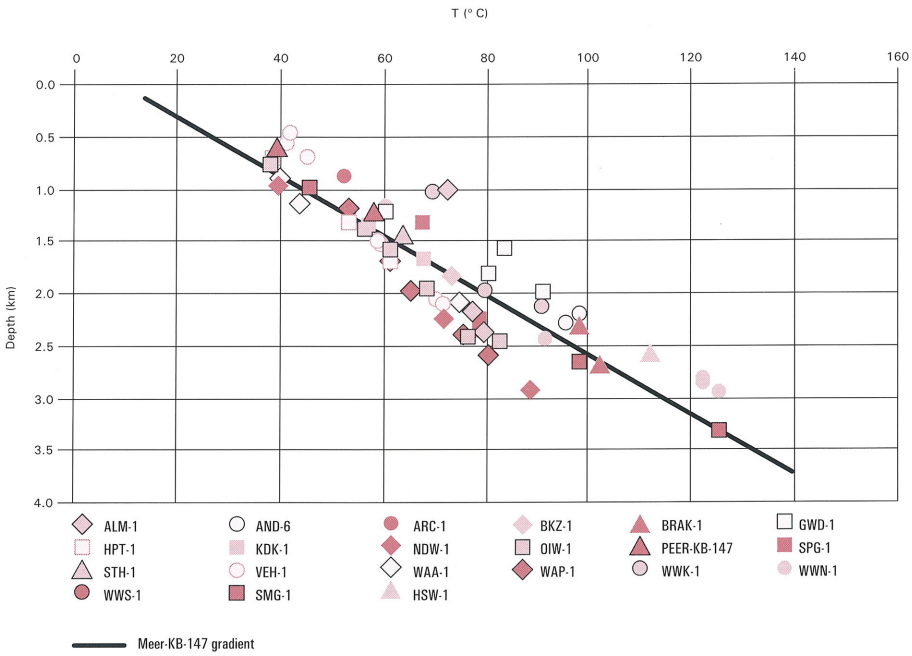
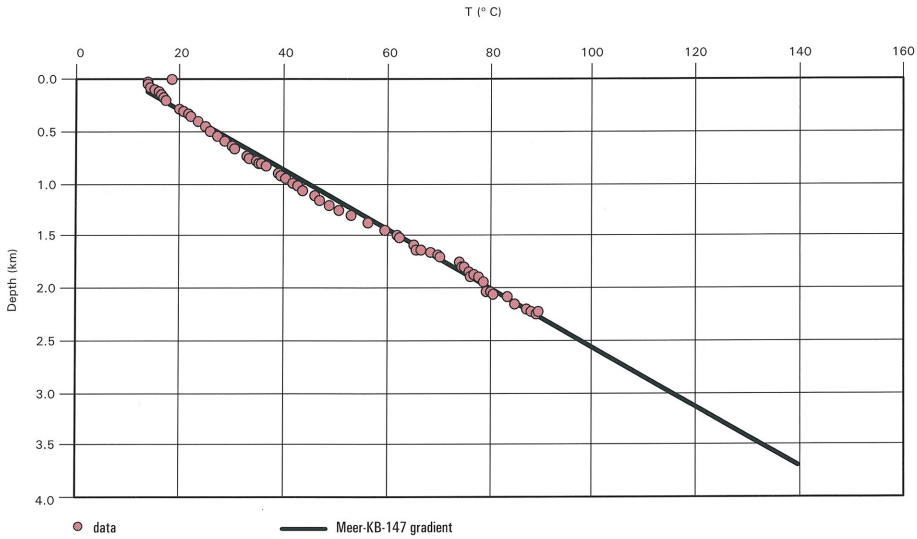


Figure 15.15 d) Temperature data of the geothermal Meer-KB-147 well (Vandenberghe et al., 1988).



measurements are therefore thought to be founded on a measurement error (Van Balen et al., in press). If the DST data from Nederweert-1 are discounted, the consequence is that the Roer Valley Graben is not a relatively cold area within the Netherlands, as has been suggested on the Ramaekers maps (1991) for example. The temperature-depth pattern in the Roer Valley Graben corresponds to the thermal gradient of the tectonically stable block to the southwest of the graben (Meer; KB-149). This means that the Cenozoic sedimentation and tectonic development of the Roer Valley Graben have virtually no effect on the present-day temperature field in the graben. This is presumably the consequence of relatively low tectonic subsidence and sedimentation rates.

15.4.3 Geothermal energy reserves

In the map sheet area, good potential deep geothermal conditions are thought to pertain in the Main Buntsandstein aquifers located in the Roer Valley Graben. In NITG (1997b), the total thermal energy reserve of the Main Buntsandstein Subgroup in de Roer Valley Graben and the West Netherlands Basin combined are estimated at 30 x 10^{18} J. The total reserve within the map sheet area is roughly half of this, approximately 15 x 10^{18} J. However, the calculations of the reserve in the Roer Valley Graben presupposed a relatively low temperature in the Roer Valley Graben, largely based on temperature measurements in the Nederweert-1 well. If the temperature is presumed in reality not to be lower than in the vicinity of the Roer Valley Graben, as postulated in section 15.4.2, the total geothermal energy reserve in the Main Buntsandstein Subgroup is then 15 to 30% higher, i.e. approximately 17-20 x 10^{18} J.

Good potential deep geothermal conditions pertain in the Breda Formation and the Vessem Member. In a geothermal study, for which specific purpose the Asten-2 well was placed (TNO GG, 1989), the total geothermal energy reserve in these Tertiary aquifers in the Roer Valley Graben was estimated at 0.2 x 10^{18} J.

Appendices

Seismic data used

Survey	*Year*	*Owner*	*2D/3D*
70*	1970	NAM	2D
7020*	1970	NAM	2D
7510*	1975	NAM	2D
7620*	1976	NAM	2D
80*	1980	BGD	2D
NBL80-*	1980	CHE	2D
81*	1981	BPE	2D
BR81-*	1981	ELF	2D
BW81-*	1981	ELF	2D
82*	1982	BPE	2D
B-82*	1982	BGD	2D
RGD82*	1982	RGD	2D
RGD83*	1983	RGD	2D
84*	1984	BPE	2D
8460*	1984	NAM	2D
8462*	1984	NAM	2D
B-84*	1984	BGD	2D
BR84-*	1984	ELF	2D
RM84*	1984	DGV-TNO	2D
8520*	1985	NAM	2D
MZ85-*	1985	Mobil	2D
86*	1986	DG	2D
8621*	1986	NAM	2D
8719*	1987	NAM	2D
8721*	1987	NAM	2D
N87-*	1987	BPE	2D
VN87-*	1987	Mobil	2D
MZ88-*	1988	Mobil	2D
8921*	1989	NAM	2D
8931*	1989	NAM	2D
N89-*	1989	BPE	2D
N90-*	1990	CLY	2D
99-*	1999	TNO-NITG	2D
Biesbosch	1986	NAM	3D
Dordrecht-1	1988	NAM	3D
Uitwijk	1989	NAM	3D
Dordrecht-2	1990	NAM	3D
Mookhoek	1991	NAM	3D
Waalwijk	1992	NAM	3D

BPE	British Petroleum Exploratie Maatschappij Nederland BV
BGD	Belgische Geologische Dienst
CHE	Chevron Oil Company of the Netherlands
CLY	Clyde Petroleum Exploratie B.V.
DG	Delft Geophysical B.V.
DGV-TNO	Dienst Grondwater Verkenning-TNO
ELF	Elf Petroland B.V.
NAM	Nederlands Aardolie Maatschappij B.V.
RGD	Rijks Geologische Dienst

Appendix B

Overview of wells used

Well nr.	*Name*	*Code*	*Owner*	*Final depth*	*Year*
1.	Alblasserdam-1	ALD-01	NAM	1650	1959
2.	Almkerk-1	ALM-01	NAM	2370	1970
3.	Altforst-1	ALT-01	BPM	654	1944
4.	America-11	ACA-11	ROvD	1201	1910
5.	Andel-1	AND-01	NAM	1981	1949
6.	Andel-2	AND-02	NAM	1719	1954
7.	Andel-4	AND-04	NAM	1927	1953
8.	Andel-5	AND-05	NAM	1554	1953
9.	Andel-6	AND-06	NAM	3136	1991
10.	Arcen-1	ARC-01	RGD	888	1987
11.	Asten-1	AST-01	NAM	2664	1953
12.	Asten-2	AST-02	TNO	1673	1987
13.	Baarlo-9	BRL-09	ROvD	1400	1909
14.	Barendrecht-1	BRT-01	NAM	3365	1984
15.	Barendrecht-Ziedewij-1	BRTZ-01	NAM	3259	1993
16.	Beeringen-15	BRN-15	ROD	1406	1915
17.	Beesel-12	BEE-12	ROD	1036	1910
18.	Beesel-52	BEE-52	DSM	1240	1921
19.	Beesel-72	BEE-72	DSM	1234	1954
20.	Belfeld-14	BFD-14	ROvD	1202	1911
21.	Bleskensgraaf-1	BLG-01	NAM	1517	1951
22.	Bleskensgraaf-2	BLG-02	NAM	1604	1958
23.	Brakel-1	BRAK-01	NAM	2689	1992
24.	Broekzijde-1	BKZ-01	BPE	2703	1989
25.	Cornelishof-4	CNH-04	ROvD	679	1905
26.	Dongen-1	DON-01	NAM	1542	1958
27.	Elmpt-77	EPT-77	DSM	1215	1958
28.	Elmpt-78	EPT-78	DSM	1127	1959
29.	Gewande-1	GWD-01	NAM	2355	1991
30.	Gewande	GWD-01-S1	NAM	2324	1991
31.	Giessendam-1	GSD-01	NAM	2575	1977
32.	Grashoek-1	GRH-01	NAM	450	1971
33.	Heeswijk-1	HSW-01	CLY	2544	1991
34.	Heinenoord-1	HEI-01	NAM	2316	1991
35.	Helden-20	HDN-20	ROvD	1252	1914
36.	Helden-75	HDN-75	DSM	1353	1955
37.	Helenaveen-5	HEL-05-A	ROvD	1233	1906
38.	Helenaveen-6	HEL-06	ROvD	1101	1907
39.	Helenaveen-7	HEL-07	ROvD	1155	1907
40.	Herpt-1	HPT-01	NAM	1758	1950
41.	Hilvarenbeek-1	HVB-01	CLY	2621	1995
42.	IJsselmonde-3	IJS-03	NAM	2132	1953
43.	Keldonk-1	KDK-01	CLY	2330	1992
44.	Kerkwijk-1	KWK-01	NAM	3281	1988
45.	Kessel-10	KES-10	ROvD	1127	1909

Overview of wells used

Well nr.	*Name*	*Code*	*Owner*	*Final depth*	*Year*
46.	Liessel-22	LIE-22	ROvD	1332	1915
47.	Loohorst-5	LHO-05	ROvD	142	1906
48.	Loon op Zand-1	LOZ-01	NAM	3062	1953
49.	Maasbommel-1	MSB-01	NAM	1714	1951
50.	Maasbommel-2	MSB-02	NAM	1278	1953
51.	Maasbree-13	MAB-13	ROvD	1131	1910
52.	Maasniel-74	MAN-74	DSM	1367	1955
53.	Maris-18	MRS-18	ROvD	1417	1914
54.	Meijel-8	MEL-08	ROvD	996	1908
55.	Melick-Herkenbosch-47	MHB-47	DSM	641	1922
56.	Melick-Herkenbosch-70	MHB-70	DSM	524	1955
57.	Molenaarsgraaf-1	MOL-01	NAM	1445	1959
58.	Molenaarsgraaf-2	MOL-02	NAM	3287	1986
59.	Nederweert-1	NDW-01	FIN	2943	1965
60.	Neer-71	NER-71	DSM	1293	1953
61.	Nijmegen-Valburg-1	NVG-01	NAM	1277	1968
62.	Oisterwijk-1	OIW-01	NAM	2496	1959
63.	Oploo-16	OPL-16	ROvD	1150	1913
64.	Oploo-59	OPL-59		550	
65.	Ottoland-1	OTL-01	NAM	3096	1988
66.	Oud-Alblas-1	OAS-01	NAM	2177	1958
67.	Raamsdonk-1	RSK-01	BPE	905	1987
68.	Reedijk-1	RDK-01	NAM	3053	1992
69.	Reuver-76	RVR-76	DSM	1105	1956
70.	Ridderkerk-32-S3	RKK-32-S3	NAM	3691	1990
71.	Rijsbergen-1	RSB-01	NAM	4645	1970
72.	Rotterdam Schulpweg-1	RTD-01	NAM	3305	1984
73.	Sanadome-1 (40C499)	SNM-499		759	1994
74.	Sevenum-19	SEV-19	ROvD	1005	1915
75.	Sint-Michielsgestel-1	SMG-01	FIN	3338	1969
76.	Sprang-Capelle-1	SPC-01	BPE	3180	1987
77.	Sprang-1	SPG-01	CLY	3077	1994
78.	Sprang-1-S1	SPG-01-S1	CLY	3214	1994
79.	Steelhoven-1	STH-01	PET	2798	1987
80.	Strijen-1	STR-01	AOP	2779	1964
81.	Strijen-West-1	STW-01	NAM	3101	1987
82.	Swalmen-21	SWM-21	ROvD	1112	1916
83.	Swalmen-73	SWM-73	DSM	1332	1954
84.	Veldhoven-1	VEH-01	NAM	2124	1959
85.	Vlodrop-1	VDP-01	ROvD	790	1906
86.	Vlodrop-2	VDP-02	ROvD	295	1906
87.	Vlodrop-3	VDP-03	ROvD	653	1908
88.	Vlodrop-48	VDP-48	DSM	950	1922
89.	Waalwijk-1	WWK-01	BPE	3802	1987
90.	Waalwijk-Noord-1 (v/h WWK-2)	WWN-01	BPE	3375	1989

Overview of wells used

Well nr.	Name	Code	Owner	Final depth	Year
91.	Waalwijk-Noord-2	WWN-02	CLY	3980	1991
92.	Waalwijk-South-1	WWS-01	CLY	3486	1991
93.	Waspik-1	WAP-01	NAM	2600	1959
94.	Werkendam-1	WED-01	NAM	2275	1958
95.	Werkendam-2	WED-02	NAM	3516	1965
96.	Werkendam-3	WED-03	NAM	3125	1991
97.	Wijk-Aalburg-1-S1	WAA-01	NAM	3330	1972

German wells

Well nr.	Name	Final depth	Source
98.	Brüggen-1	644	Wunstorf (1922)
99.	Brüggen-2	710	Wunstorf (1922)
100.	Brüggen-3	719	Wunstorf (1922)
101.	Dalheim-7	826	Wunstorf (1921a)
102.	Dalheim-8	761	Wunstorf (1921a)
103.	Dalheim-9	835	Wunstorf (1921a)
104.	Dorothea-1 (Wassenberg-1)	309	Krusch & Wunstorf (1907)
105.	Dorothea-2	566	Wunstorf (1921b)
106.	Dorothea-22	381	Wunstorf (1921b)
107.	Dorothea-25	506	Wunstorf (1921b)
108.	Elmpt-2	574	Wunstorf (1922)
109.	Elmpt-3	694	Krusch & Wunstorf (1907)
110.	Elmpt-4	662	Wunstorf (1922)
111.	Elmpt-15	763	Krusch & Wunstorf (1907)
112.	Emmerich-1	1449	Elberskirch & Wolburg (1962)
113.	Geldern-T-1	413	Klostermann (1984)
114.	Heidhausen	900	Wunstorf (1922)
115.	Hülm	1263	Klostermann (1997)
116.	Kreuzberg	801	Drozdzewski (pers. comm.)
117.	Niederrhein-4	620	Klostermann (1984)
118.	Niederrhein-5	807	Klostermann (1984)
119.	Niederrhein-29	1113	Drozdzewski (pers. comm.)
120.	Niederrhein-90	1062	Drozdzewski (pers. comm.)
121.	Niederrhein-100	650	Klostermann (1984)
122.	Schwalmtal-1001	1771	Zeller (1998)
123.	Tamen-1	500	Wunstorf (1921a)
124.	Tamen-4	633	Wunstorf (1921a)
125.	Tamen-5	448	Wunstorf (1921a)
126.	Tamen-6	453	Wunstorf (1921a)
127.	Twisteden-3	564	Klostermann (1984)
128.	Uedem-1	1506	Klostermann (1992)
129.	Viersen-1001	1573	Ribbert (1998a)

German wells

Well nr.	*Name*	*Final depth*	*Source*
130.	Vorst	702	Van Waterschoot van der Gracht (1909)
131.	Wachtendonk-1	1033	Elberskirch & Wolburg (1962)
132.	Walter-5	690	Klostermann (1984)
133.	Walter-8 (Wemb)	932	Klostermann (1984)
134.	Walter-10 (Klein Kevelaer)	593	Klostermann (1984)
135.	Walter-14	449	Klostermann (1984)
136.	Walter-37	559	Klostermann (1984)
137.	Watern	670	Wunstorf (1921a)

Belgian wells

Well nr.	*Name*	*Final depth*	*Source*
138.	Loenhout-Heibaart (KB129)	1638	Legrand (1968)
139.	Geel-35	1244	Legrand (1968)
140.	Kessel-bij-Lier-38	704	Legrand (1968)
141.	Zandhoven-39	851	Legrand (1968)
142.	Gruitrode-40	870	Legrand (1968)
143.	Balen-56	1116	Legrand (1968)
144.	Vlimmeren-57	1028	Legrand (1968)
145.	Geel-58	1014	Legrand (1968)
146.	Olen-59	936	Legrand (1968)
147.	Heppen-62	800	Legrand (1968)
148.	Rotem-64	1211	Legrand (1968)
149.	Neeroeteren-99	1020	Legrand (1968)
150.	Elen-100	977	Legrand (1968)
151.	Oostham-102	943	Legrand (1968)
152.	Korspel-106	1257	Legrand (1968)
153.	Mol-107	2034	Legrand (1968)
154.	Meerhout-108	1008	Legrand (1968)
155.	Leopoldsburg-118	1754	Legrand (1968)
156.	Turnhout-120	2706	Legrand (1968)
157.	Meeuwen-121	1321	Legrand (1968)
158.	Hechtel-124	977	Legrand (1968)
159.	Beverlo-125	945	Legrand (1968)
160.	Beersel-130	481	Legrand (1968)
161.	Booischot-132	1330	Legrand (1968)
162.	Neerglabbeek-146	1357	Dusar & Houlleberghs (1981)
163.	Meer-149	2517	Vandenberghe et al. (1988)
164.	Opglabbeek-161	1342	Boonen et al. (1985)
165.	Beerse-Merksplas-165	1761	Lie et al. (1987)
166.	Opoeteren-168	1371	Dusar et al. (1986)
167.	Gruitrode-169	1690	Dusar et al. (1987a)
168.	Poederlee-170 (DZP1)	1137	Langenaeker & Dusar (1992)

Belgian wells

Well nr.	*Name*	*Final depth*	*Source*
169.	Gruitrode-172	1599	Dusar et al. (1987b)
170.	Hechtel-Hoef-174	1500	Dusar et al. (1998)
171.	Peer-183	1498	Langenaeker (1992)
172.	Lommel-186	1504	Helsen & Langenaeker (1999)
173.	Molenbeersel-198	1773	Demyttenaere & Laga (1988)
174.	Bree-201	1340	De Craen & Swennen (1992)
175.	Peer-206	1348	

AOP American Overseas Petroleum Ltd.
BPE British Petroleum Exploratie Maatschappij Nederland BV
BPM Bataafsche Petroleum Maatschappij
CLY Clyde Petroleum Exploratie B.V.
DSM DSM Energie B.V.
FIN Fina
NAM Nederlands Aardolie Maatschappij B.V.
PET Petroland B.V.
ROvD Dienst der Rijksopsporing van Delfstoffen

Reservoir calculations Lower and Upper Germanic Trias Groups

The calculations in the tables below have been carried out for the Röt, Solling, Hardegsen, Detfurth and Volpriehausen Formations.
Cut-off values applied: clay content Vcl = 50%; effective porosity = 6%.
The 50% cut-off for the clay content is customary in industry. The 6% cut-off for the porosity derives from the crossplot of core permeability versus core porosity, where it is assumed that for permeabilities lower than 0.1 mD the producibility of the gas is zero.

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

Lower and Upper Germanic Trias Groups

Well	*Unit*	*Reservoir*			
		Gross	*Net*	*Øem*	*Vclm*
WWN-1	RNROY	16.7	0.9	6.8	38.1
	RNROF	55.8	34.4	9.9	27.8
	RNROL	31.6	8.3	7.6	31.4
	RNSOC	17.5	0.1	6.3	31.3
	RNSOB	5.3	3.8	8.7	6.8
	RBMH	18.9	15.0	10.0	19.8
	RBMDU	8.3	5.8	10.5	20.3
	RBMDL	12.7	12.7	14.6	8.5
	RBMVU	61.0	46.3	8.8	7.8
	RBMVL	59.7	26.7	7.6	11.9
	Total/Average for all units	287.5	154.1	9.4	16.1
WWS-1	RNROY	16.8	1.7	7.8	36.4
	RNROF	43.9	29.7	10.5	22.0
	RNROL	33.8	21.0	9.2	31.9
	RNSOC	21.0	0.0	–	–
	RNSOB	3.8	1.6	8.3	12.5
	RBMH	21.2	10.9	9.0	21.6
	RBMDU	8.5	5.2	10.7	16.7
	RBMDL	22.2	18.9	12.0	13.1
	RBMVU	75.8	59.9	8.1	8.1
	RBMVL	67.0	43.0	7.3	10.6
	Total/Average for all units	313.9	191.7	8.9	15.2

Legend appendices C and D

Status:

GAS = gas production

Test:

DST = drill stem test (quantity in litres)

Interval:

Interval in metres log depth

Yield:

G = gas
O = oil
C = condensate
W = water

Flow:

gas, Q50, in 1000 m^3/day
oil, water and condensate in m^3/day

Unit:

Unit = formation or member
RNROY = Upper Röt Fringe Claystone
RNROF = Röt Fringe Sandstone
RNROL = Lower Röt Fringe Claystone
RNSOC = Solling Claystone
RNSOB = Basal Solling Sandstone
RBMH = Hardegsen Formation
RBMDU = Upper Detfurth Sandstone
RBMDL = Lower Detfurth Sandstone
RBMVU = Upper Volpriehausen Sandstone
RBMVL = Lower Volpriehausen Sandstone

Show, status and test data Lower and Upper Germanic Trias Groups

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
WWN-1	gas	GAS	DST1A	3177.7-3262	G	382277	RBMH, RBMDU, RBMDL, RBMVU
					C	23	
			DST2	3044-3147	G	334138	RNROF, RNROL
					C	31	
					W	2.4	
			DST3A	3044-3262	G	501207	RNROF, RNROL, RBMH, RBMDU, RBMDL, RBMVU
					C	42	
					W	4.2	
WWS-1	oil/gas	GAS	DST1	3222-3270	G	17670	RNSOB, RBMH, RBMDU, RBMDL
					O	31	
					W	0.1	
			DST2	3115-3202	G	665445	RNROF, RNROL
					C	57	
					W	5.4	

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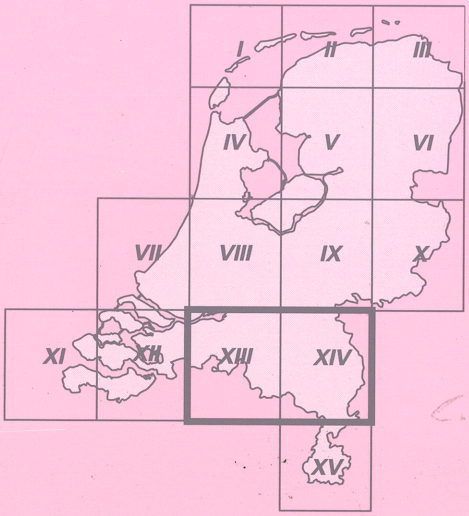
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