Netherlands Institute of
Applied Geoscience TNO

Explanation to Map Sheet XV
Sittard-Maastricht

Geological Atlas of the Subsurface of The Netherlands

TNO

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Sittard-Maastricht

Netherlands Institute of Applied Geoscience TNO - *National Geological Survey*, Utrecht 1999

Geological Atlas of the Subsurface of The Netherlands

Headframe of shaft II of the former coal mine Oranje-Nassau I at Heerlen, dating from the latter years of the 19th century.

Contents

Maps and sections

The publication of Map Sheet XV 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.

Reporting of NITG-TNO 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 largely acquired from seismic investigations and deep drilling which are nearly exclusively carried out by private companies. Because of the considerable commercial interests involved for the industry these data are classified, but are made available to the NITG-TNO 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 NITG-TNO to compile and publish this information, provided the data are older than 10 years. An exception is made for data from concession areas for hydrocarbons and coal, with a restriction of 5 years. This agreement enables the NITG-TNO to bring the geology subsurface of The Netherlands to wider attention.

The Sittard-Maastricht map sheet of the Geological Atlas of the Subsurface of The Netherlands is the seventh sheet 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 most recent Annual Report of the NITG-TNO gives an up-to-date overview of the progress of this mapping.

Each map sheet has its own features. This map sheet outlines the geology of the middle and southern part of the province of Limburg. Maps and explanation reveal that this province only encompasses a part of the geological succession that we recognise from the central and western part of this country. The older formations, particularly the Carboniferous and the Upper Cretaceous, are situated at or close to the surface. At the end of this era, the Cenozoic subsidence, so characteristic of the rest of The Netherlands, was followed by uplift, resulting in the distinctive South Limburg landscape. Young, synsedimentary fault tectonics initiated substantial differences in thickness in the formations, producing seismic disturbances right up to the present time. The afore-mentioned phenomena are well documented and the subject of many publications, on account of the presence of the near-surface, older geological deposits and the coal mining activities. Efforts to map Limburg geologically date from the first half of the previous century (Felder, W.M., 1981). While South Limburg was initially represented on a part of small-scale overview maps, from 1857 to 1869 three geological maps specifically devoted to this area were published by Labry (1857-1858), Binkhorst van den Binkhorst (1858) and Staring (1858-1869). Since then, around 100 maps relating to the geology of South Limburg have been published (Felder, W.M., op. cit.). In the present map sheet, existing viewpoints and new interpretations of old and new data have been incorporated in the framework of the series of map sheets constituting the Atlas.

The NITG-TNO anticipates that this map sheet, together with those already published or in progress, will contribute to a greater understanding of the structure and composition of the subsurface of The Netherlands. This is important not only to companies which are active in the fields of exploration and exploitation for mineral and natural resources, but also various governmental institutions and other interested parties.

As well as those people acknowledged in the credit column who are directly responsible for compiling this map sheet, many other employees of the NITG-TNO have been involved, whose efforts are all greatly appreciated. Regular discussions have been held with former RGD colleague Mr W.M. Felder,

acknowledged expert on the Limburg Cretaceous, were indispensable. The consultations with colleagues at the geological surveys in the adjacent countries, on the harmonisation of this map sheet with German maps and with German geological perceptions were extremely valuable. A special word of thanks is due to Dr P. Laga and Dr M. Dusar of the Belgian Geological Survey, and to Dr J. Prüfert of the Geologisches Landesamt Nordrhein-Westfalen. Many thanks are due to the companies which provided exploration data used in this map sheet.

Utrecht, June 1999

1 Introduction

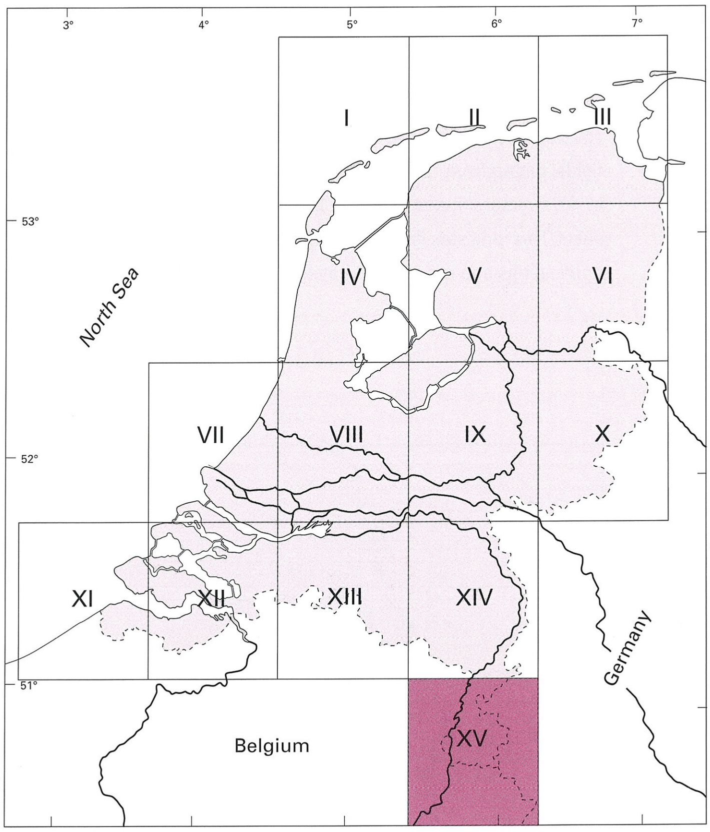
1.1 Extent of area studied

The Map Sheet XV (Sittard-Maastricht) is situated in the extreme southeast of The Netherlands (fig. 1.1). It covers the southern half of the province of Limburg. The area is bordered by the German federal state of Nordrhein-Westfalen and the Belgian regions of Vlaanderen and Wallonie.

1.2 Data base

The mapping of the map sheet area derives largely from data obtained during the exploration and production of coal. These activities were carried out predominantly by the Dutch Government (Rijksopsporing van Delfstoffen [Government Institute for the Geological Exploration of The Netherlands], Rijks Geologische Dienst [Geological Survey of The Netherlands]) and the coal mining industry. Of particular importance are the Kemperkoul-1, Limbricht-1 and Raath-1 boreholes, which were drilled in 1983 and 1984 by the Geological Survey of The Netherlands during the course of a programme

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



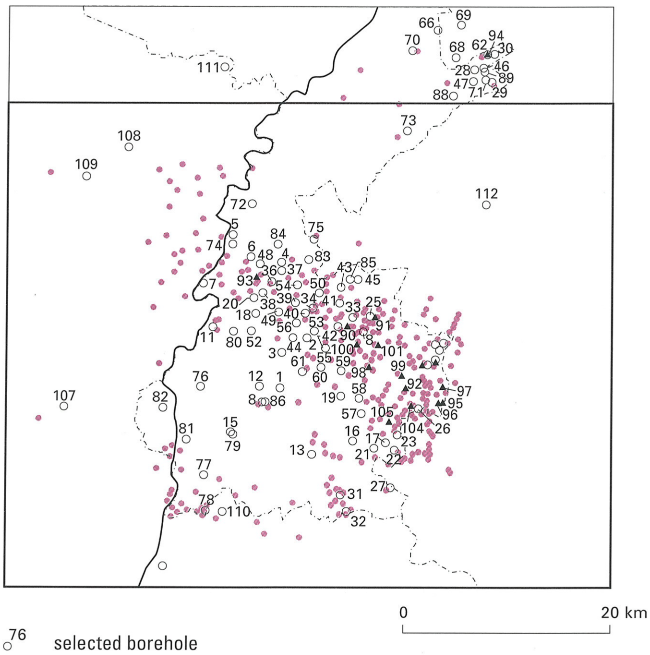
I	Vlieland-Terschelling	IX	Harderwijk-Nijmegen
II	Ameland-Leeuwarden	X	Almelo-Winterswijk
III	Rottumeroog-Groningen	XI	Middelburg-Breskens
IV	Texel-Purmerend	XII	Roosendaal-Terneuzen
V	Sneek-Zwolle	XIII	Breda-Valkenswaard
VI	Veendam-Hoogeveen	XIV	Oss-Roermond
VII	Noordwijk-Rotterdam	XV	Sittard-Maastricht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

for an inventory of coal occurrences in The Netherlands (Rijks Geologische Dienst, 1986). Substantial data were also used from boreholes drilled for the purposes of groundwater exploitation. A noteworthy category in this group is formed by the boreholes for mineral water and thermal water owned by Limburg provincial government and Thermae Onroerend Goed B.V. The NOVEM Geverik-1 well, which was placed to investigate the possibility of creating an underground water reservoir for a pumped-storage plant (OPAC), was also a major source of data (Price, 1987; RGD, 1986a).

Over 350 of the many hundreds of deeper exploration wells and shallower wells for mapping inventorisation in The Netherlands were selected on a basis of their position and stratigraphic range for use in the compilation of this map sheet. A further selection was made of 89 wells with the greatest relevance to deeper subsurface geology. In addition, use was made of the data obtained from 16 mine shafts. Their location is indicated in figure 1.2 and more detailed specifications are given in Appendix A. 80 wells in the adjacent areas of Belgium and Germany have been included in the mapping, seven of which are listed in Appendix A.

The seismic coverage of the map sheet area is sparse. For details, refer to the location map figure 1.3. For the mapping, use was also made of a number of seismic lines in Belgium, thanks to the Belgian Geological Survey. For the mapping of the area, an interpretation was made of a total of approximately 830 km of 2D-seismics, only 190 km of which were in the area covered by Map Sheet XV, 500 km in that covered by Map Sheet XIV and 149 km in Belgium. The older seismic data on the South Limburg coal fields, dating from 1958 and 1959, have not been used in the current mapping activities. The results used in the structural maps prepared by Patijn & Kimpe (1961) have, however, been incorporated in the map sheet. This indicates the considerable importance for the compilation of Map Sheet XV of the many publications and reports that have been published on the area in recent decades. Use has been made of

Figure 1.2 Location of the wells and mine shafts used for the mapping. A selection of these wells, giving number and specifications, can be found in Appendix A.



76 selected borehole

▲ mine shaft

• other borehole

a considerable number of geological interpretations (inter alia Jongmans & van Rummelen, 1942; Muller, 1945; NITG data base at the Geo-Mapping Department, South Netherlands division) as well as map data (see Appendix C), sometimes with a certain amount of revision, thus avoiding the necessity for reprocessing all the wells.

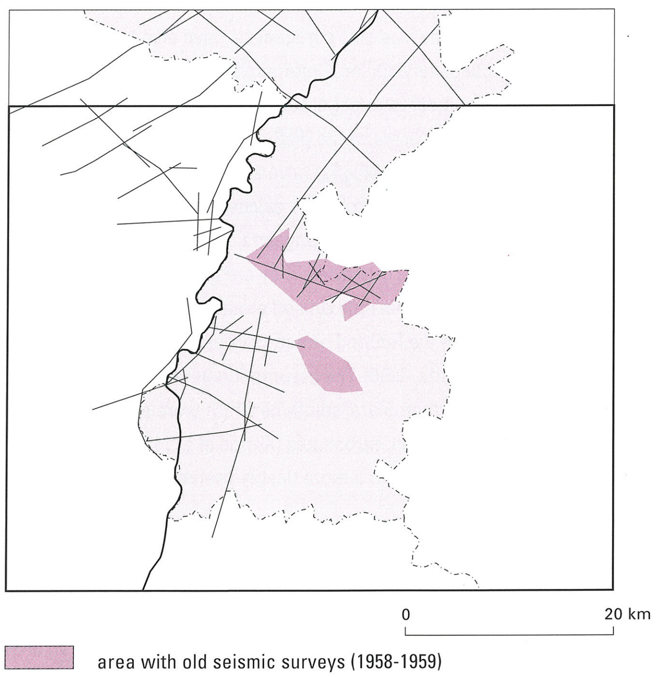
1.3 Mineral and natural resources

In South Limburg, one of the few areas in The Netherlands where pre-Quaternary formations crop out, the exploration of a variety of rock types has gone on from time immemorial. In the explanation to this map sheet, relating to the deeper subsurface geology, we have restricted ourselves primarily to discussing the exploration and production history of the mineral and natural resources in the subsurface.

1.3.1 Chert (Flint)

The subterranean exploitation of this mineral goes back to the Neolithic period (Bosch, 1976). In the Neolithic, around 4000 BC, a mining industry was in existence to the southeast of Maastricht (Rijckholt-Sint Geertruid), where flints were extracted from the Gulpen Formation (Lanaye Limestone). Archaeological excavations exposed a mine region of approximately 3000 m^2 with 67 vertical shafts (Engelen, 1989d). Flint mining was also carried out in the vicinity of Valkenburg, in small near-surface mines during the Neolithic, mainly from the Maastricht Formation (Emael Limestone) (Brounen & Ploegaert, 1996). Rademakers (1998) gives a detailed picture of the research activities in the prehistoric flint mines.

Figure 1.3 Location of the seismic lines used. Appendix B contains additional information on the various surveys.



all minerals and natural resources were the property of the State and providing for concession grants for their exploitation, there was initially only one mine in operation, the Domaniale Mine. This mine was expropriated from the abbey of Kloosterrade by the French occupier and when the Kingdom of The Netherlands was established it accrued to the State. Other concessions in existence were the Neuprick and Bleierheide concessions dating from1808, from which coal was mined from 1882-1904. During the course of the 19th century, following continuing exploration activities, several concessions were granted, a large majority of which were revoked as no actual exploitation took place. Only the concessions Willem, Sophia, Carl, Laura and Vereeniging were continued. In 1845, the Domaniale concession was contracted out to a private company. Not until the final decade of the same century, when the advent of a railway line improved access to the eastern part of South Limburg, did coal mining become properly established. During this period, the large Oranje-Nassau concession was granted, which led to the mine Oranje-Nassau I becoming operational in 1899. Other mines were soon to follow: the Willem-Sophia in 1902 and the Laura in 1905.

The Dutch State gradually began to display an interest in coal exploitation. Concerned about the considerable foreign influence on the Limburg mining industry, an Act which became effective in 1901 reserved for the State a substantial area of the South Limburg coal territory not yet covered by concessions. This area was later extended and the existing finders' rights were purchased from the mining concession applicants. In 1902, the "State Collieries" were established by Royal Decree, following which allocation of the Wilhelmina, Emma, Hendrik and Maurits concessions took place. These concessions were repeatedly extended in the first half of the 20th century. The Wilhelmina was the first state colliery to go into production in 1906.

After the financial anxiety of the early thirties following the global economic crisis, the depression, the Dutch coal mining industry experienced a boom during the pre- and post-war period. 12 surface facilities were in operation (fig. 1.4), with a combined annual production of around 12.6 million tons (Engelen, 1989c). In the post-war peak year of 1961, when 12 million tons of coal were produced, the mines provided work for 26 713 workers below ground and 22 515 on the surface (Westen, 1971; fig. 1.5). The energy content of this quantity of coal is approximately 16% of that of the 81.8 billion m^3 natural gas which was produced in The Netherlands and the Dutch part of the continental shelf in 1997. At the beginning of

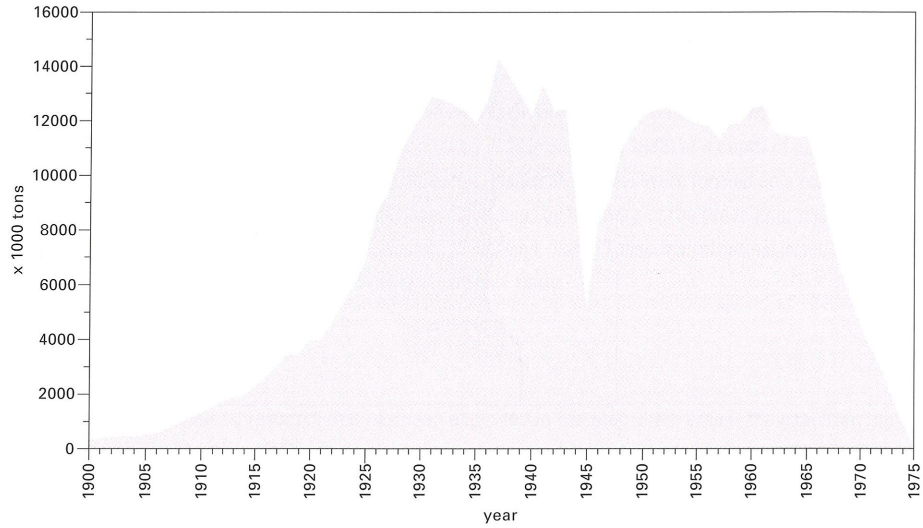


Figure 1.5 The annual production of the Limburg coal mines from 1900 to 1975 (sources: Westen, 1971 and the annual reports of the Staatstoezicht op de Mijnen [State Supervision of Mines].

the '50s, the 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). In the meantime, the construction of two shafts for the new State Colliery Beatrix was commenced here in 1952 (Kimpe, 1973).

The advent of natural gas to The Netherlands (the Groningen gas field having been discovered in 1959, with the granting of concessions 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 State Colliery Beatrix was suspended in 1962. Subsequently, the period 1967-1974 saw the gradual closure of the Dutch mines, commencing with the State Colliery Maurits and finishing with the Oranje Nassau I. This marked the end of a major, high-quality industrial activity in the region, during which 568 million tons of coal had been mined this century (Westen, 1971; fig. 1.5). The shaft house with engine room from shaft II of the last-mentioned mine has been preserved as a monument in the grounds of the Central Bureau of Statistics in Heerlen, together with the Nulland shaft of the Domaniale mine near Kerkrade and the slagheap of the State Colliery Wilhelmina between Schaesbergen and Spekholzerheide.

The subsurface of South Limburg still contains a large quantity of exploitable coal. To the north of the former area of mine workings, exploration took place within the framework of the coal inventory project conducted by the Dutch government at the beginning of the 80s (Pagnier et al., 1987; RGD 1986a). It has been calculated that the fault block between the North-South Fault and the Feldbiss contains a coal stock (geological reserve) of 591 million tons (Rijks Geologische Dienst, 1986). Further investigations need to be carried out to determine the reserves for the area situated further to the west.

1.3.4 Hydrocarbons

There are no occurrences of oil or gas fields in the map sheet area. Exploration of these hydrocarbons did, however, take place in the past, as evidenced by the "Eindhoven" drilling licence (1984-1994) held by BP Exploratie Maatschappij Nederland, which included the area to the north of the Feldbiss. This did not result in the drilling of any wells in this area. Previously, the Nederlandse Aardolie Maatschappij together with the State Collieries had drilled three exploration wells in 1949, located in the production area of the Emma. Finally, seismics were shot by that company in 1979 in South Limburg in the surroundings of the Visé-Puth anticline (Keulen & Ruyters, 1981).

The absence of oil and gas fields does not imply the non-generation of hydrocarbons in the area. Local traces of oil in the Caumer Subgroup have been reported by the coal mines. These relate to finds in internal fissures in syngenetic to early diagenetic, carbonate concretions, occurring in claystone beds within the reach of coalification of 30 to 10% volatile matter (Kimpe, 1958). Geochemical evaluation and burial history (Section 12.1) reveal that during the coalification of the coal seams in the Carboniferous which already occurred during the Late Carboniferous and Early Permian, large quantities of methane (CH_4) were released. However, where no gas traps had been formed, this gas was not able to accumulate into exploitable occurrences. Part of this gas nonetheless continued to be adsorbed onto the coal. During coal mining, "mine gas" may be given off, owing to pressure release. In areas characterised by gas-rich coals, such as fat coal (fig.12.6) containing 25% volatile matter, in the former Emma and Hendrik mines for example, the amount of mine gas per ton of coal might increase to 24 m^3 (Stuffken, 1958). Artificial ventilation at the coal front removed the mine gas. From 1952 onwards, specific suction took place from behind the extraction sits, in the State Collieries Emma, Hendrik and Maurits (Arets et al., 1962; Staatstoezicht op de Mijnen [State Supervision of Mines], 1962, 1968). The production of this mine gas increased to nearly 38 million m^3 in 1965, only to decrease again as a result of the mine closures. It was used to dry out the coal-slurry from the mines, for the Emma electric power station and the Maurits coke plant.

The subsurface of Limburg still contains a quantity of coalbed methane. Estimates as to the technically recoverable quantity of this gas in a study by GAPS (1994) range from 5 to 27 billion m^3, with a highest probability value in excess of 20 billion m^3. The feasibility of coalbed methane exploitation in South Limburg will not become apparent until after evaluation of all production-related, geological, planning, environmental and economic aspects.

1.3.5 Limestone

The South Limburg Upper Cretaceous limestones, which here form the calcareous part of the Chalk Group, are characterised by a low clay content, often less than 2%. Use of limestone goes back to prehistoric times. Underground exploitation appears to have taken place even before the Roman period, around the beginning of our era, (Engelen, 1989a). The Romans present in these parts systematically continued the exploitation. After a decline, exploitation was resumed in the Middle Ages. The stonemasons utilised the rocks containing specifically selected properties, such as purity, hardness and strength, derived almost exclusively from the Maastricht Formation (Felder, W.M., 1973). In the St. Pietersberg to the south of Maastricht, for example, the exploitation centred on the Nekum Limestone in the Maastricht Formation, resulting in an extensive system of galleries in that member. Underground exploitation nowadays is on a very limited scale, in the Sibbe Quarry to the southeast of Valkenburg. Here, the Emael Limestone was quarried for use as building stone and ornamental stone (Diederen, 1989) and amounts to several hundred m^3 a year.

Besides the underground exploitation, the limestones of the Maastricht Formation (Maastricht Limestone and the Kunrade Limestone) were also exploited in open quarries in numerous places (Felder, W.M., 1973). Nowadays, exploitation is restricted to four quarries, the largest of which is the ENCI to the south of Maastricht. At the peak of limestone exploitation, in 1974, combined production was over 3,750,000 tons, while in 1989, this was a mere 1,748,000 tons (Staatstoezicht op de Mijnen, 1990).

1.3.6 Brown Coal

Although not strictly speaking a subsurface natural resource, brown coal exploitation deserves a mention, being closely associated with the subsurface geology of the area. This mineral was exploited in opencast mining in the northeast of South Limburg between the Heerlerheide Fault and the 1st NE Mainfault (Bless, 1981a; Engelen, 1989b; Kuyl, 1980), see figure 1.6. The brown coal occurs in the Heksenberg Member of the Ville Formation, with the Morken Seam at the bottom and the Frimmersdorf Seam at the top. In the extraction areas in The Netherlands, these seams reach a thickness of a maximum of 10 m. Further to the east, in the Lower Rhine Bight in Germany, where large-scale strip-mining is still operational, these seams combine to form a single brown-coal seam, the Hauptflöz, over 100 m thick (Zagwijn & Hager, 1987).

Although brown coal in Limburg was documented shortly after the middle of the last century, exploitation was not initiated until 1917. Annual production soon reached around one and a half million tons. A drastic drop in economic value led to the collapse of brown coal exploitation in the early twenties, with only one quarry continuing to operate, the Carisborg I. The Second World War led to a recovery. During and shortly after the war, production was resumed in two existing quarries (the Energie and the Herman), and the Anna was opened. A further two quarries were started up. When the reserves became exhausted, they were closed again, with the result that by 1952, only the Anna quarry near Eygelshoven was still in operation, with an annual production of over 20,000 tons. In 1960, this quarry finally closed down as well.

1.3.7 Mineral Water

The mineral water derived from the Dinantian carbonates can be regarded as a noteworthy mineral in South Limburg (Bless, 1981a, b). Between 1931 and 1953, drinkable mineral water was produced by the Trega Spring in the Kastanjelaan in Maastricht, which had been discovered in 1927. Production was terminated because the supply pipe became corroded and became clogged with sinter. The exploitation of this mineral water was resumed in 1981 by the Limburg provincial government with the Kastanjelaan-2 and Heugem-1 wells (Bless et al., 1981). Analysis of the water from the springs tested at different depths demonstrated its potential use as table water as well as thermal bath water (Bless, 1981b). However, these findings were not pursued further.

Figure 1.6 Location of the former brown-coal concessions in South Limburg (after Kuyl, 1980).

Greater success was achieved by the Thermae 2000 and 2002 wells near Valkenburg, drilled in 1985 and 1986 (Bless, 1987; Krings et al., 1987), which also revealed the presence of mineral water at a depth of approximately 375 m and a temperature of just under 25^{o} C, suitable for balneological applications. The Thermae 2000 thermal bath complex was developed on a basis of this water from the Goeree Member of the Zeeland Formation.

1.4 Research set up

Seismic mapping

For the mapping of the map sheet area, an interpretation has been made of all the available seismic lines, recorded from 1969 onwards. Their position can be seen in figure 1.3, with more detailed specifications in Appendix B. A number of Belgian sections have also been included in the mapping. The coverage is sparse and very unevenly distributed over the area.

The reflectors traced are formed by the boundaries between the lithostratigraphic units (groups and formations). Calibration of the seismic data and well logging was carried out using the available data from acoustic logs and check-shot surveys.

The time-to-depth conversion of the seismic sections was carried out per layer (the so-called layer-cake method). The layers, corresponding to the lithostratigraphic units, each have a specific velocity distribution. For this a linear equation between the propagation velocity of sound in the layer and the depth of the layer was taken ($V_z = V_0 + kz$; see table 1.1.

To guarantee consistency between adjacent map sheets, the same velocity equations have been applied to all the map sheets of the Geological Atlas of the Subsurface. The parameters of these equations were determined from the acoustic data from 60 wells located throughout The Netherlands. In the determination of the parameters a maximum error of 5% in the seismically determined depth of a particular horizon was deemed acceptable. Table 1.1 gives an overview of the parameters used for the velocity distribution.

Table 1.1 Applied velocity distribution

The velocity distribution in the map sheet area is based on $V_z = V_0 + kz$:

Unit	V_o	*k*
North Sea Supergroup	1696	0.49
Chalk Group	2092	1.08
Altena Group	2297	0.62
Lower and Upper Germanic Trias Groups	3254	0.56

Geological research

The geological research focused on the lithostratigraphic composition of the rocks present in the map sheet area (fig. 1.7) and their geological history placed in a regional-geological context. The previously mentioned seismic sections and well-log data were used. 89 wells and 16 mine shafts were selected for use on the maps from a total of over 350 wells, based on the greatest relevance to the structure of the subsurface. Their location is shown in figure 1.2, with more detailed specifications in Appendix A. The lithostratigraphic units, which are indicated in figure 1.7, are discussed in greater detail in each chapter.

South Limburg is the subject of many publications on the subject of geology and mining activities, owing to its unique geographic position in The Netherlands. These publications were the source of a substantial amount of data which are of importance for the research for this map sheet. Appendix C gives the geological maps which were of particular importance in this research. Figure 1.8 shows the time periods as used in this explanation.

Biostratigraphic research

To clarify the geological research, specific biostratigraphic studies have been performed on sequences of the Chalk Group and the Middle and Upper North Sea Groups (Internal reports NITG-TNO, 1997-98). In addition, a substantial number of existing biostratigraphic reports were already available in the case of this map sheet area. The results of these studies have been incorporated in the explanation.

Geochemical research

Vitrinite analyses have been performed on the coal-bearing intervals of the Limburg Group in order to reconstruct the burial history of the map sheet area. The procedures, the results of the analyses and the utilised modelling are discussed in section 12.1.

Hydrogeological research

Special attention has been given to the hydrogeology of the map sheet area. The specific nature of the lithology and the topographical relief differentiate it from the rest of The Netherlands. This is discussed in further detail in section 12.2.

1.5 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 15). An overview of these units is given in figure 1.7. Depth maps have been plotted of the top of the pre-Permian, the base and the top of the Zechstein Group, and of the bases of the Lower Germanic Trias Group, the Altena Group, the Chalk Group, the North Sea Supergroup and the Upper North Sea Group. The Zechstein Group in the map sheet area is only thinly developed (0-50 m). The seismics are insufficient to map this interval separately. The depth map of this group has therefore been based on the base of the Lower Germanic Trias Group, to which the combined thickness of the Zechstein Group derived from sparse well logs has been added (Map 4). The Quaternary deposits have not been included on the maps of the North Sea Supergroup and the Upper North Sea Group (Maps 11 and 12).

Thickness maps were made of the Zechstein Group, the Lower and Upper Germanic Trias Groups, the Altena Group and the Chalk Group. The contours of the thickness map of the Chalk Group (Map 10) stop at the erosion boundary of the overlying Middle North Sea Group. A calculation of the thickness in the outcrop area, taking the local topography into account, falls outside the scope of the present map sheet. The thickness of the North Sea Supergroup and of the Upper North Sea Group can be roughly determined from the depth maps of this unit. The thickness may be obtained by adding the height of the topographic surface above Mean Sea Level (NAP) to the values found there.

The depth and thickness maps only depict wells of relevance to the contour pattern in question.

Subcrop maps have been made of the major unconformities at the bases of the Chalk Group and of the North Sea Supergroup, giving an impression of the degree of erosion preceding the deposition of these groups.

Finally, three structural sections, with a NW-SE and SW-NE orientation, are depicted on a separate map (Map 15).

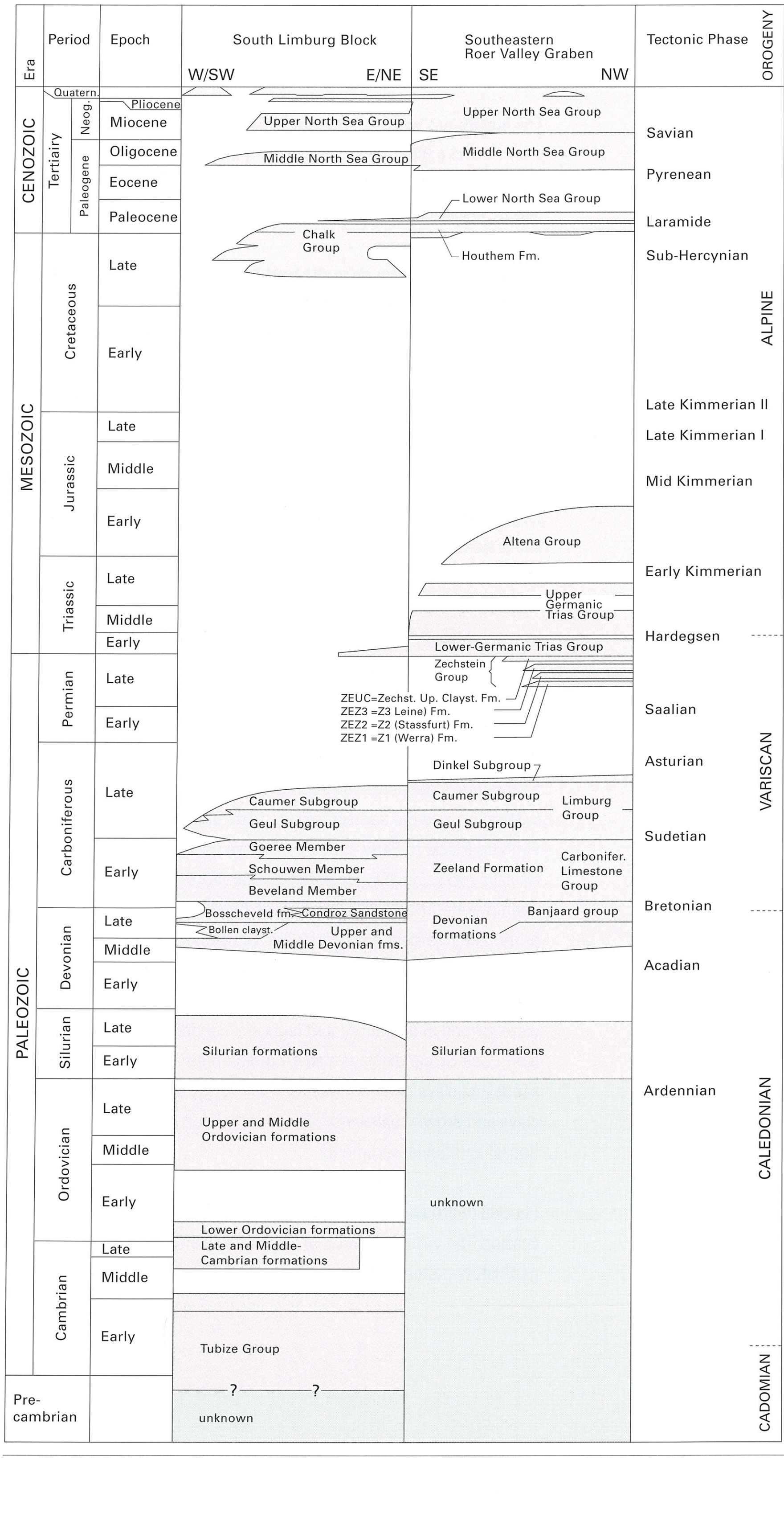
1.6 Explanation

The intention of the explanation is to supplement 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 the first part of the text, a description is given of the lithological successions, including an account of the lithostratigraphy and the sedimentary development. The second part of the text focuses on the geological history of the area. This relates to the basin development and the tectonic events in the context of the plate tectonics. Special attention is given to the geochemistry and the hydrogeology of the area.

Unless stated otherwise, the lithostratigraphy 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 section 1.7.2.

The Quaternary deposits are only referred to briefly in this explanation. A description with respect to the southeast of the area has been published in de Toelichtingen bij de Geologische kaart van Nederland 1:50 000, map sheet Heerlen (Kuyl, 1980). The geological surface map (Rijks Geologische Dienst, 1988) outlines the location of the Quaternary in South Limburg.

Figure 1.7 Diagram of the lithostratigraphic units in the map sheet area.



1.7 Summary

1.7.1 Stratigraphic succession

The lithostratigraphic succession in the map sheet area is schematically illustrated in figure 1.7. The diagram shows a bipartition of the area, reflecting the difference in development of the South Limburg Block and the Roer Valley Graben. The (present) extent of the rock formations has been largely determined by the structural development of the area.

The succession, as found in the map sheet area, begins with clastic and calcareous, shallow-marine and nearshore deposits of Late Devonian to earliest Carboniferous age. They are part of the Banjaard group. The Carboniferous Limestone Group (Dinantian) comprises marine carbonates, developed as dolomite at the bottom, deposited on an extensive carbonate platform. These are overlain by clastic deposits of the Limburg Group (Silesian), subdivided into three subgroups. The Geul Subgroup consists of claystones and sandstones, gradually grading from marine into predominantly continental deposits. During deposition of the Caumer Subgroup, paralic-deltaic conditions prevailed and numerous coal seams were formed. The Dinkel Subgroup consists largely of fluvial sandstones. Of the restricted-marine Zechstein Group (Late Permian), only the basin-margin development is found in the north of the map sheet area. This development consists of dolomitic and occasionally sandy claystones with a limestone intercalation. The Lower Germanic Trias Group is composed of fluvial sandstones and claystones, generally red in colour and deposited in an arid climate with pronounced fluctuations in water influx. The bottom of the Upper Germanic Trias Group comprises, in addition to comparable fluvial sediments, lagoonal deposits containing evaporites. These are followed by shallow-marine carbonates and claystones, also with an evaporite intercalation. The group ends with a continental, argillaceous and sandy rock sequence. The Altena Group (latest Triassic and Early Jurassic), only the bottommost part of which is present in the area studied, consists predominantly of argillaceous sediments, which were deposited in a moderately-deep, marine setting. Separated by a very large hiatus, the Chalk Group, from the Late Cretaceous and the earliest Tertiary, rests upon deposits varying in age from Late Carboniferous (South Limburg Block) to Early Jurassic (Roer Valley Graben). The oldest part of the Chalk Group consists of siliciclastic rocks, initially deposited in nearshore-marine and lagoonal conditions, later becoming more open-marine. The younger part of the Chalk Group comprises chalk and detritic limestone, partly with prominent interbedded chert layers. Deposition occurred in a shallow to moderately deep sea. The Lower North Sea Group consists of a thin succession of variegated, lacustrine clays, followed by marine marls, clays and sands. The Middle North Sea Group consists of sands and clays, which at the bottom, were formed in nearshore and lagoonal conditions, and at the top, in marine conditions. The Upper North Sea Group displays a striking bipartition in on the one hand marine, frequently glauconite-rich sands and clays and on the other hand sandy to conglomeratic coastal and river deposits, lacustrine clays and brown coal seams. The topmost part of this group comprises a thin sequence of aeolian (loess) and fluvial sediments.

Periods of erosion, related to the deformation phases, produced large hiatuses in the stratigraphic succession. The virtual duration of the hiatuses and their position in the stratigraphic column reflect the geohistory pattern in the map sheet area.

1.7.2 Structural units

The main structural units in and around Map Sheet XV are indicated in figure 1.9. These units have a strong influence on the geological history of the area. On the seismic section in figure 1.10 and the section sheet (Map 15) a number of these elements can be clearly identified. The post-Palaeozoic elements are defined by predominantly northwest-southeast striking faults.

The **Brabant Massif** is a major Caledonian structural element in the northwest of Belgium, defined on its east by the **Bordière Fault** (Faille Bordière). The northward course of this fault cannot be clearly determined in The Netherlands. In the northwest, the London Massif meets the Brabant Massif. The entire structure is referred to as the **London-Brabant Massif.** After the Brabant Massif had been partially covered by Upper Palaeozoic and Lower Mesozoic sediments, it again became uplifted at the end of the Jurassic, forming an incipient, distinct, topographically positive element.

To the north of the eastern part of the London-Brabant Massif is the **Campine Basin**, an area of subsidence during the Late Devonian and Carboniferous.

Variscan structural elements are characterised by folds and faults with a southwest-northeast to south-north trend, for example the **Visé Anticline**, the **Puth Anticline**, the **Waubach Anticline**, and the **Worm Syncline. The 70 m Fault, the Anticline Fault/Oranje Fault**, the **Willem Fault/Adolf Fault** and the **Aken Thrust** (known in Belgium as the **Moresnet Thrust**) are also part of the same system. No immediate indications have been found to suggest the continuation of the Visé Anticline in the Puth Anticline.

The **South Limburg Block** is in fact the eastern section of the **Eastern Campine Block**. During the Post-Variscan development, with the exception of the Late Cretaceous and the earlier Tertiary, this area was a high.

The **Feldbiss** separates the South Limburg Block from the Roer Valley Graben. Accompanying the Feldbiss are some subparallel faults (the most prominent of which are the **Benzenrade Fault**, the **Heerlerheide Fault** and the **Schin op Geul Fault** on the South Limburg Block and the **1st NE Mainfault** in the Roer Valley Graben), giving rise to a transitional area with a number of step faults. This is reflected in the overlying sedimentary Palaeozoic deposits.

The **Roer Valley Graben** is presumed to be Variscan in origin (part of the Late Palaeozoic **Campine Basin**). During the Triassic and the Jurassic, this area underwent subsidence and was distinctly fault-bounded from the Jurassic onwards. During the Late Cretaceous, it became uplifted (inverted), and returned to being an area of subsidence in the Cenozoic, with very active boundary faults from the Late-Oligocene onwards.

On its northern/northeastern margin, the Roer Valley Graben is defined by the **Peel Boundary** or **Peelrand Fault**, known in Germany as the **Rurrand Sprung.** The main antithetic faults in the graben are, in the south, the **Frelenberg Fault** (also interpreted as the Gangelt Fault; Rijks Geologische Dienst, 1985) and the **Maaseik Fault**, and in the north, the **Beegden Fault.** The latter has been mapped here as a single continuous fault, but may well comprise a number of offsetted fault segments (cf. Geluk et al., 1994 and Van den Berg, 1994).

To the north, the Peel Boundary Fault is defined by the **Peel Block**, which became strongly uplifted and profoundly eroded during the Late Jurassic and the Early Cretaceous.

The **Variscan front** represents the northern boundary of the overthrust tectonics of the Variscan orogeny during the Late Carboniferous to Early Permian. The front forms the boundary between the strongly folded and fractured rocks in the Variscan mountains and the much less intensely deformed rocks in the foreland. This front is generally set near the Aken Thrust and its extension in a southwesterly and westerly direction (Faille Eifélienne and Faille du Midi; and in its entirety is referred to as the Midi-Achen Thrust), while a substantial deformation still extends as far as the Willem Fault/Adolf Fault.

1.7.3 Geological history

The London-Brabant Massif, composed of Cambro-Silurian rocks, was formed during the Acadian phase of the Caledonian orogeny (fig. 1.8). Its eastern flank extended as far as the southern part of the map sheet area. Renewed, marine sedimentation in the geosynclinal Rhenohercynian Basin (fig. 3.1) reached this area from the south and southeast during the Middle Devonian. This transgression culminated in the Early Carboniferous, when the area formed part of a vast carbonate platform on the perimeter of a persisting low-relief landmass of the London-Brabant Massif, characterised by deposition of the Carboniferous Limestone Group.

Crustal movements of the Sudetic phase of the Variscan orogeny transformed the area into a foredeep (the Variscan Foreland Basin; fig. 5.4), with a supply of clastic sediments from the south and southeast (Limburg Group). The gradual land outbuilding gave way to delta areas with extensive coastal marshes, where peat formation took place on a large scale. During subsequent burial to a depth of several thousands of metres, the peat became transformed into coal. The Variscan deformation front moved steadily northwards. After the Asturian deformation, towards the end of the Carboniferous, fluvial conditions prevailed, with sandstones predominantly deposited.

During the youngest Carboniferous and the Early Permian, the area formed part of the Variscan mountains and was subject to erosion. The erosional products were transported to the more northerly Southern Permian Basin (fig. 11.4), in which the continental Upper Rotliegend Group was formed. During the Late Permian, the sea once again periodically invaded the basin. Here, five evaporite cycles (Zechstein Group) can be distinguished in The Netherlands, with distal prolongations extending to the extreme north of the map sheet area.

In the Early Triassic, the north of the map sheet area was again characterised by pronounced subsidence, particularly in the area where the Roer Valley Graben would later be sharply delineated. The frequently coarse-grained, clastic sediments of the Lower Germanic Trias Group were deposited in a fluvial facies. These were followed by fluvial and lacustrine deposits, with a major marine intercalation of carbonates and anhydrite, which are taken as belonging to the Upper Germanic Trias Group.

After an interruption in sedimentation as a consequence of the Early Kimmerian crustal movements marking the onset of the Alpine orogeny, towards the end of the Triassic the whole area was again submerged. This transgression persisted during the Early Jurassic. Possibly as early as the Middle Jurassic and in any case by the end of the Jurassic, the area was uplifted in response to the Mid and Late Kimmerian tectonic phases, triggering a pronounced NW-SE fault system. The strongly uplifted and eroded Peel and South Limburg Blocks were thus thrown sharply into relief against the still relatively low-lying Roer Valley Graben (fig. 1.9).

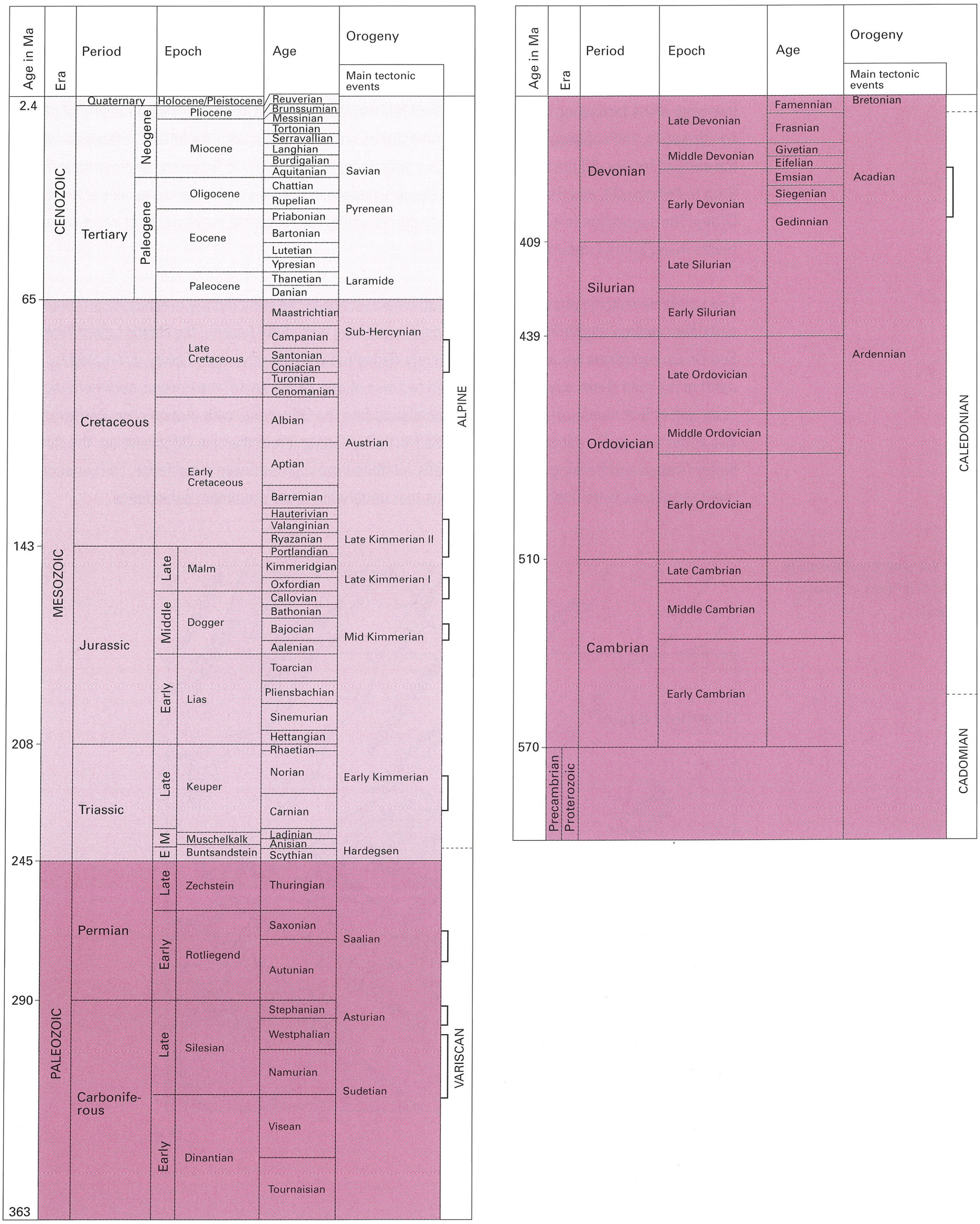
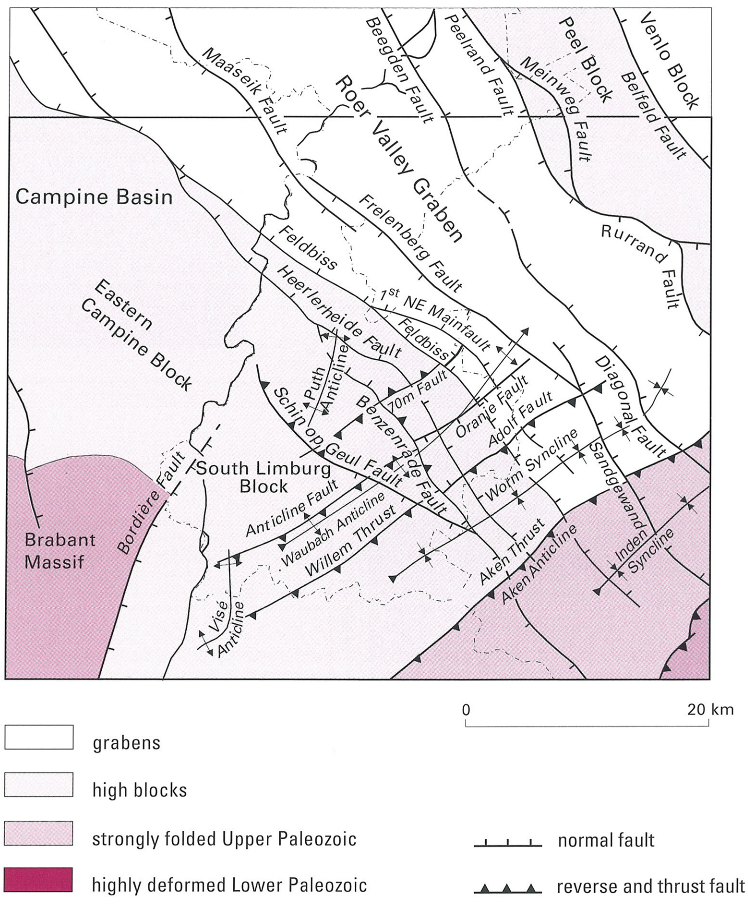


Figure 1.8 Geological timetable (after Harland et al., 1990). The orogenies and tectonic phases which are referred to in the text have been indicated in the right-hand column. The bar indicates the duration of a number of these phases.

After a long period of erosion and non-deposition, the sea again penetrated the map sheet area in the middle of the Late Cretaceous. Nearshore and lagoonal deposits were formed initially. The Roer Valley Graben, primarily still undergoing sedimentation, was uplifted by the Sub-Hercynian crustal movements. The flanking structural units, the Peel Block and the South Limburg Block, were now relatively low-lying areas facilitating the accumulation of full-marine sediments. These consisted initially of glauconitic sands, and subsequently of detritic limestones and chalks. Not until the latest Cretaceous and the earliest Tertiary did the Roer Valley Graben area become favourable to limestone sedimentation. Both the siliciclastic and the carbonaceous Upper Cretaceous deposits are reckoned as part of the Chalk Group. The succession is incomplete in many places owing to differential movements of various fault blocks in the South Limburg Block.

The Laramide tectonic phase during the Middle Palaeocene in the early Tertiary precluded continuing carbonate sedimentation in Northern Europe. Towards the end of the Eocene, the clastic Lower North Sea Group sediments which were subsequently deposited were largely eroded away, prompted by uplift of the map sheet area by the Pyrenean tectonic phase. At the end of the Eocene, sedimentation resumed, at first nearshore and lagoonal, persisting into the Oligocene, with marine clays and sands, this entire succession comprising the Middle North Sea Group. From the Late Oligocene on, the Roer Valley Graben and flanking fault blocks clearly exhibited more pronounced subsidence. Thicker sediment sequences were deposited in the areas that underwent more prominent subsidence.

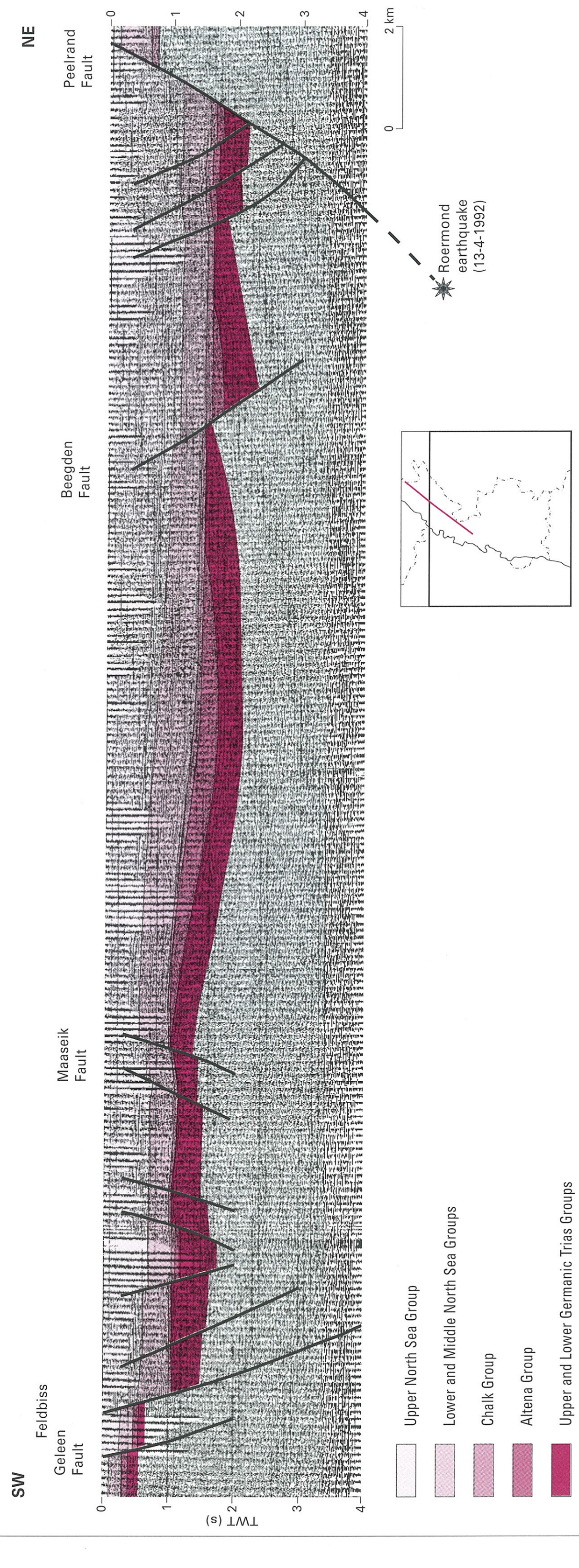
Figure 1.9 Location of the major structural elements in the map sheet area.



After an interruption, probably not represented in the central part of the Roer Valley Graben, deposition of the Upper North Sea Group commenced in the Miocene. In a south-easterly direction, marine clastic deposits interfingered with continental sands containing brown coal layers. At the end of the Miocene, the sea withdrew from the area definitively. Fluvial and lacustrine sediments were formed up to the end of the Pliocene.

The beginning of the Quaternary heralded a period of alternating glacials and interglacials and a contemporaneous rapid uplift of the South Limburg Block and the hinterland. This was accompanied by northward tilting of the South Limburg Block, triggering the formation of a landscape of fluvial terraces, partly covered by aeolian deposits (loess), during conditions inherent to climatic fluctuations. In the Roer Valley Graben, deposition of normal stratigraphic succession ensued.

Figure 1.10 Seismic section through the Roer Valley Graven (BPEMN line 8111). In addition to the large boundary faults, the section shows a number of antithetic faults. Besides a thick Tertiary and Quaternary sequence, the Triassic and a part of the Lower Jurassic have been preserved in the graben.



2 Cambro-Silurian

2.1 General

The old Palaeozoic Cambro-Silurian forms the basement of the geological structure of the map sheet area. However, these pre-Devonian deposits have, in this area, never been reached by drilling. Outside the map sheet area, in Belgium and in Germany, the Cambro-Silurian is well documented from wells and outcrops (Dusar & Langenaeker, 1992; Knapp, 1978).

In Belgium these deposits form the Brabant Massif (Legrand, 1968; De Vos et al., 1993). To the east of Maastricht, steeply inclined quartzites and schists of Cambrian age lying immediately below sandy Cretaceous deposits were revealed by a borehole (Dusar & Langenaeker, 1992). The Hermalle-sous-Argenteau well in the vicinity of Visé encountered upturned Silurian igneous rocks below Givetian limestones (Graulich, 1975). Elsewhere in the Brabant Massif, the Silurian consists predominantly of dark, graptolitic shales.

The old Palaeozoic in the Venn Anticline in Germany (Knapp, 1978) forms part of the Stavelot-Venn Massif. It is composed of Cambrian and Ordovician shales and turbiditic sandstones. The Silurian is not represented. In the vicinity of this massif, the Lower Devonian rests unconformably upon the older Upper Ordovicium. This development is consistent with that of the Dinant Synclinorium in Belgium.

The Lower Devonian is not thought to be present in South Limburg and that the Middle Devonian rests unconformably on the Silurian in a position consistent with the development in the Namen Synclinorium (Robardet et al., 1994).

2.2 Sedimentary development and palaeogeography

In the late Precambrian and the Early Cambrian, clastic rocks such as arkosic sands and quartz sands, as well as clays, were deposited in a shallow shelfsea extending from Southern England to Northern Germany. Fine-grained sedimentation prevailed later in the Middle and Late Cambrian. To the south of the shelfsea, a more intensively subsiding area formed, the Ardennes Basin (Walter, 1980).

In the Early and Middle Ordovician, to the north of the Ardennes Basin, the shelfsea became a deeper basin, the Brabant Depression, (Walter, 1980), in which dark graptolite shales and fine-grained sandstones formed. Along the southern margin, where the incipient uplift of the Ardennes Basin manifested itself, turbiditic sands were also deposited.

During the Late Ordovician, the Ardennian phases of the Caledonian orogeny marked the completion of the uplift of the Ardennes Basin (Robardet et al., 1994). This was accompanied by intense magmatic activity, both intrusively and extrusively (De Vos, 1998). The Brabant Depression became a foreland basin, in which predominantly graptolitic shales were deposited. Along its southern margin, shallow-water limestones and turbiditic sandstones were formed. Volcanic activity occurred locally.

3 Devonian

3.1 Stratigraphy

In the map sheet area, only the uppermost part of the Devonian has been encountered in a few boreholes. This sequence, part of the Banjaard group in this area, has only been adequately documented and dated in the Kastanjelaan-2 well. Immediately to the south of the study area, in Belgium, the Upper Devonian has been exposed in a number of places (Felder, P.J. & Bless, 1986; Rijks Geologische Dienst, 1984).

The composition of the older Devonian in the map sheet area may be deduced from stratigraphic data originating from the adjacent areas in Belgium and Germany. The succession would appear to be consistent with that pertaining in the Namen Synclinorium. In the west of the area studied, a development similar to that on the northern flank of this synclinorium may be expected, in the south and east, probably identical to the one on the southern flank (Robardet et al., 1994).

3.1.1 Middle and older Upper Devonian

In the west of the map sheet area, the Cambro-Silurian is overlain unconformably by the Givetian, which commences with a quantity of conglomerate and sandstone, with overlying limestones and calcareous sandstones. These are covered by some clastic deposits, followed by a thick, 100 to 150 m sequence of massive limestones of Frasnian age. On the culmination of the Visé Anticline, this sequence has disintegrated into a coarse collapsed breccia (Lustin Formation) (Poty, 1982). The Frasnian is overlain by a relatively thin sequence of claystones with a few limestone intercalations.

In the south and east of the map sheet area, the Devonian succession is presumed to begin as far back as in the Eifelian, in unconformable contact with the Silurian, with terrestrial conglomerates, followed by marine sandstones and claystones. The immediately overlying finer-clastic and calcareous deposits of Givetian and Frasnian age are presumably consistent with those in the west of the area. The Famennian, however, is thought to be more completely developed, with a few calcareous claystones at the bottom, followed by a thick sequence of sandstones, the Condroz Sandstone.

3.1.2 Banjaard group

The Banjaard group comprises marine claystones and sandstones intercalated with a small amount of carbonates (Van Adrichem Boogaert & Kouwe, 1993-1997). This unit has an informal status, having only been revealed by a small number of wells in The Netherlands, each of which has only reached a part of the group. The same applies to the Bosscheveld formation, that can be identified within the group. The Condroz Sandstone, not yet officially defined in The Netherlands and known in Germany as the "Condroz Sandstein" (Knapp, 1978) and in Belgium as the "Psammites du Condroz" (Thorez & Dreessen, 1986), is here taken as belonging to the Banjaard group.

3.1.2.1 Condroz Sandstone

The Condroz Sandstone consists of a sequence of shallow-marine, partly nearshore and lagoonal sandstones and claystones. In Germany and Belgium, to the south and southwest of the map sheet area, this lithological unit reaches a thickness of 400 to 500 m. This formation is not represented in the southwest of the study area.

The Condroz Sandstone has almost certainly only been encountered in the map sheet area in a borehole near Mesch (61H64), to the east of Eijsden. The formation has been exposed to the south of the study area, in the vicinity of Moresnet and Val-Dieu in Belgium (Rijks Geologische Dienst, 1984; Felder, P.J. & Bless, 1986).

3.1.2.2 Bosscheveld formation

The Bosscheveld formation is a condensed succession, comprising an alternation of dark-grey, partly calcareous claystones and siltstones, fine-grained sandstones and frequently nodule-like limestones. In the west of the area, this rock-unit ranges from Famennian to Early Tournaisian in age. In the east, the unit is likely to commence only in the latest Famennian. The Bosscheveld formation is presumed to occur in the subsurface throughout South Limburg, with the exception of the southwesternmost part, as the eastern flank of the Brabant Massif near Visé was intermittently uplifted at the end of the Devonian and the beginning of the Carboniferous. Consequently, the Famennian is not found in that area, and there are hiatuses in the Dinantian succession (Poty, 1982). The effect of this local development presumably continues across the border into The Netherlands.

In the west of the map sheet area, the Bosscheveld formation rests upon the last-mentioned Frasnian deposits, possibly slightly unconformably. The formation is conformably overlain by carbonates of the Zeeland Formation, Dinantian in age (fig. 4.1). The probable thickness of the Devonian succession situated to the west ranges from 300 to 500 m. In the south and east of the study area, the youngest part of the Bosscheveld formation rests conformably on the Condroz Sandstone, forming a transitional sequence to the overlying, conformable carbonates of the Zeeland Formation. The thickness of the Devonian succession in the south and east of the area is an estimated 700 to 1000 m.

3.2 Sedimentary development and palaeogeography

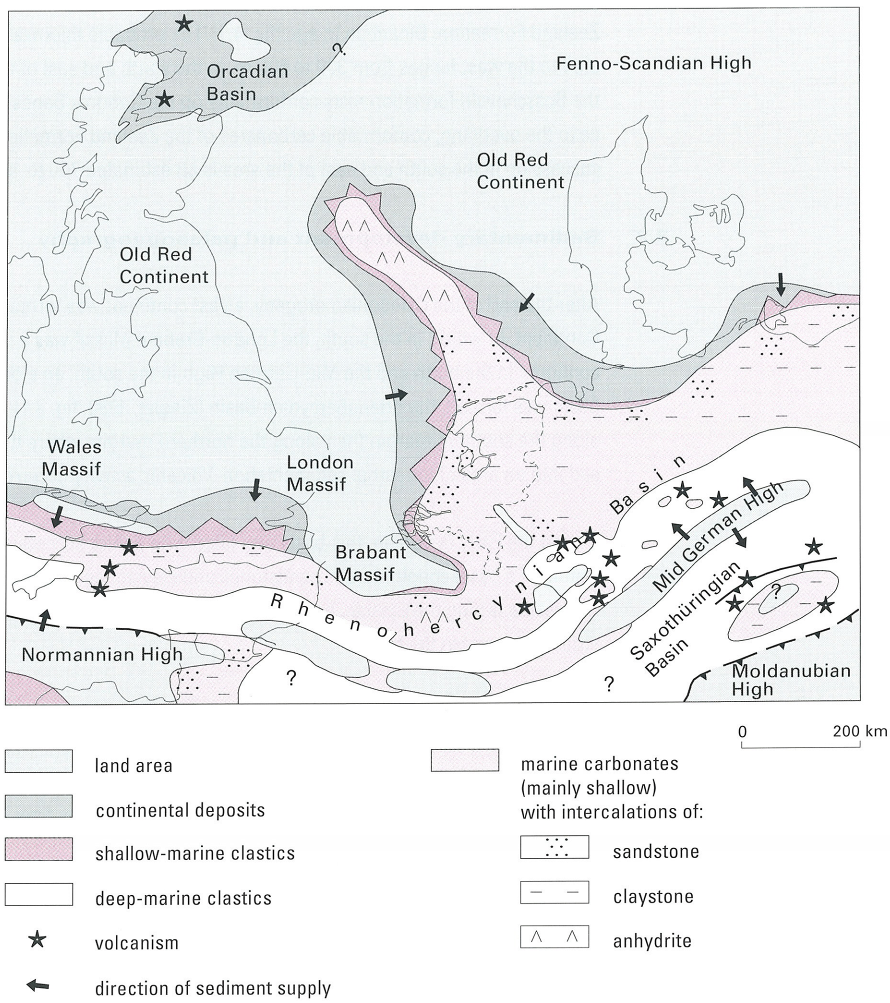
After the end of the Caledonian orogeny, a vast continent was formed in Northwest Europe, the Old Red Continent, of which, in the south, the London-Brabant Massif was a constituent element. Between this continent in the north and the Mid-German High in the south, an elongated, geosynclinal sedimentation basin was formed, the Rhenohercynian Basin (Ziegler, 1990; fig. 3.1). Greater water depths occurred along the southern margin than along the northern margin, where the area of deposition gradually passed into an area of terrestrial sedimentation. Volcanic activity occurred locally in this basin.

During the Early Devonian, this basis was filled with a thick succession of terrigeneous sediments, consisting of a basal conglomerate, sandstones and claystones, transported from the flanking highs. A regression during the Emsian, associated with the Acadian phase, caused a temporary increase in terrestrial sediments in the basin.

In the Middle Devonian, a transgression induced a considerable enlargement of the marine sedimentation area to the north, bringing the flanks of the London-Brabant Massif and a part of the older continent within reach of the sea (fig. 3.1). On the flank, situated in South Limburg, conglomerates (partly still terrestrial) were initially deposited, soon to be followed by finer clastics and finally carbonates.

The transgression persisted into the Late Devonian. The development of reefal limestones, which had commenced in the Givetian, continued in the Frasnian. The Famennian was characterised by a regression in response to a fall in sea level and tectonic activity in the Bretonian phase, the first manifestation of the Variscan Orogeny. In consequence, on the flank areas of the London-Brabant Massif, sedimentation was interrupted or incomplete or became condensed. Locally, clays and calcareous rocks (Bosscheveld formation) were deposited. More distally, thick sequences of sandstones and sandy claystones (Condroz Sandstone) with local calcareous intercalations developed, in a shallow coastal area with coastal barriers, tidal flats and lagoons (Thorez & Dreessen, 1986). The sandstones are in fact very fine-grained, micritic arkoses. A likely source area for these clastics is the Precambrian core of a high in the central Netherlands, where gneisses and crystalline schists underwent erosion (Paproth et al., 1986).

Figure 3.1 Palaeogeography of Northwest Europe at the time of the Middle Devonian (after Ziegler, 1990).



4 Carboniferous Limestone Group

4.1 Stratigraphy

The Carboniferous Limestone Group, of Dinantian (Tournaisian and Viséan) age, consists of grey, brown and black carbonate rocks, with possible intercalations of a varying quantity of intercalated claystones. Chert layers occur locally.

Only a small number of boreholes, in the southwest of the map sheet area have reached this group. In Belgium, immediately to the south of the study area, the unit has been exposed in the Geul Valley, near Visé (Rijks Geologische Dienst, 1984; Felder, P.J. & Bless, 1986).

Within the Carboniferous Limestone Group, only the Zeeland Formation can be distinguished in the map sheet area. The group is presumed to occur throughout the subsurface, with the exception of two small areas in the southwest, where it has been eroded away (fig. 4.2). The thickness may exceed 1000 m. The top lies approximately 30 m above Mean Sea Level to the south of Maastricht, increasing to a depth in excess of 5000 m to the north of the Feldbiss (see sections on Map 15; Bless et al., 1980).

The carbonates of the Carboniferous Limestone Group in South Limburg rest conformably upon the clastic-calcareous sediments of the Banjaard group. The claystones of the Limburg Group cover the Carboniferous Limestone conformably or separated by a hiatus, increasing in duration towards the Brabant Massif (Bless et al., 1976). In the southwest, where the Carboniferous Limestone Group subcrops against the Palaeozoic surface, it is overlain unconformably by the Chalk Group.

4.1.1 Zeeland Formation

The Zeeland Formation consists predominantly of light grey to brown and black limestones and grey to dark-brown dolomites. Chert layers generally occur. Claystone intercalations are found mainly in the bottommost and the uppermost part of the formation. In the weathered zone, where the formation is in contact with the Chalk Group, silicification of the carbonates is found. Based on their interpretation of geophysical data, Bless et al. (1986) suspect the probable presence of a thick succession of Devono-Dinantian in the strip of land between Visé and Maastricht and the area eastwards, where evaporites with rock salt may have developed in depressions in the Dinantian and even in the underlying Devonian.

From bottom to top, the Zeeland Formation consists of the Beveland, Schouwen and Goeree Members (fig 1.7 and fig. 4.1).

The *Beveland Member*, Tournaisian to Early-Viséan in age, is composed of grey, brownish grey and dark-brown, coarse-crystalline dolomites. In general these are secondary dolomites. A few dark-brown to black siltstone and claystone intercalations occur in places.

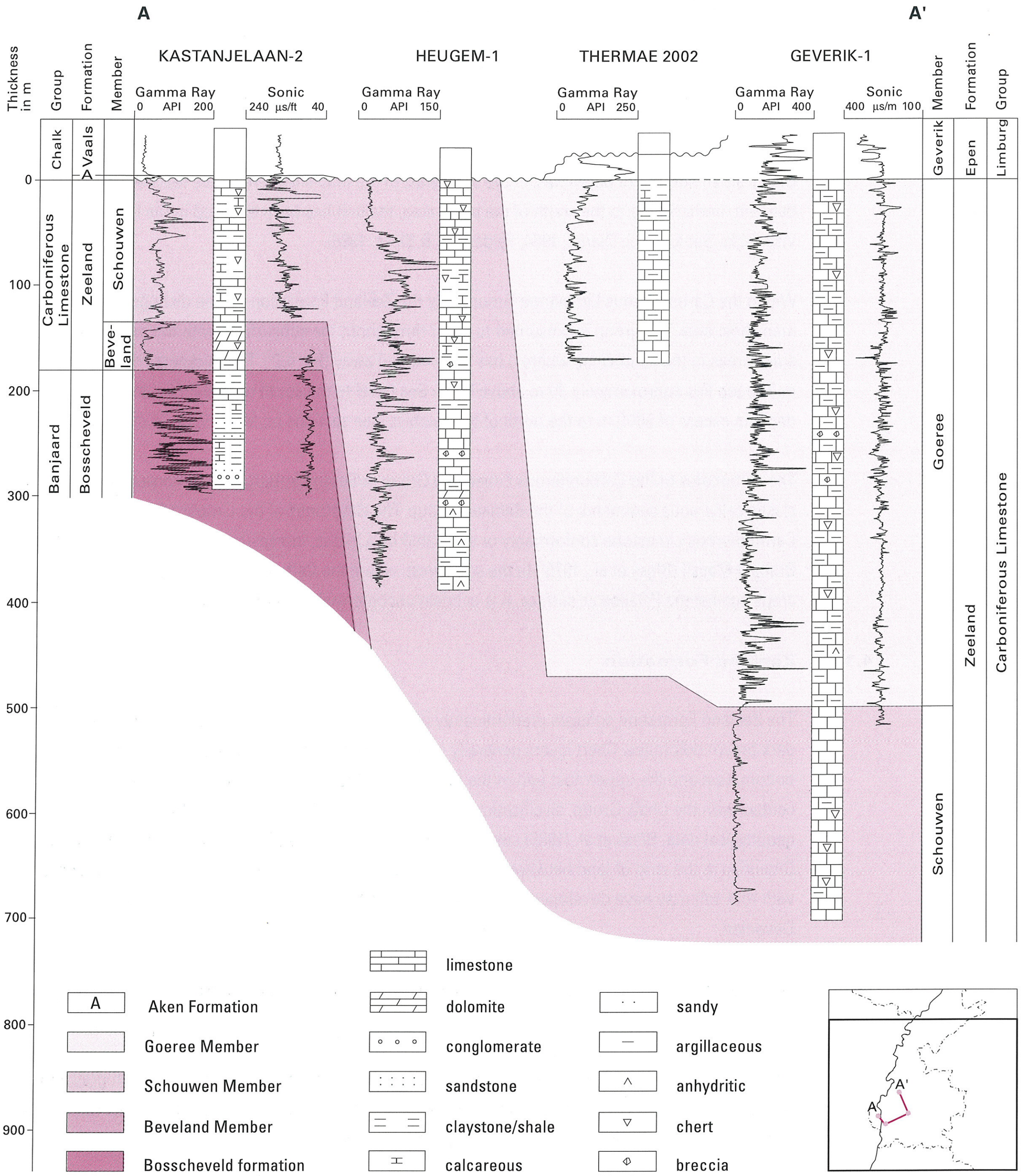


Figure 4.1 Stratigraphic section A-A' of the Upper Devonian and the Zeeland Formation between the Kastanjelaan-2, Heugem-1, Thermae 2002 and Geverik-1 wells. The reference-level is the top of the Carboniferous Limestone Group.

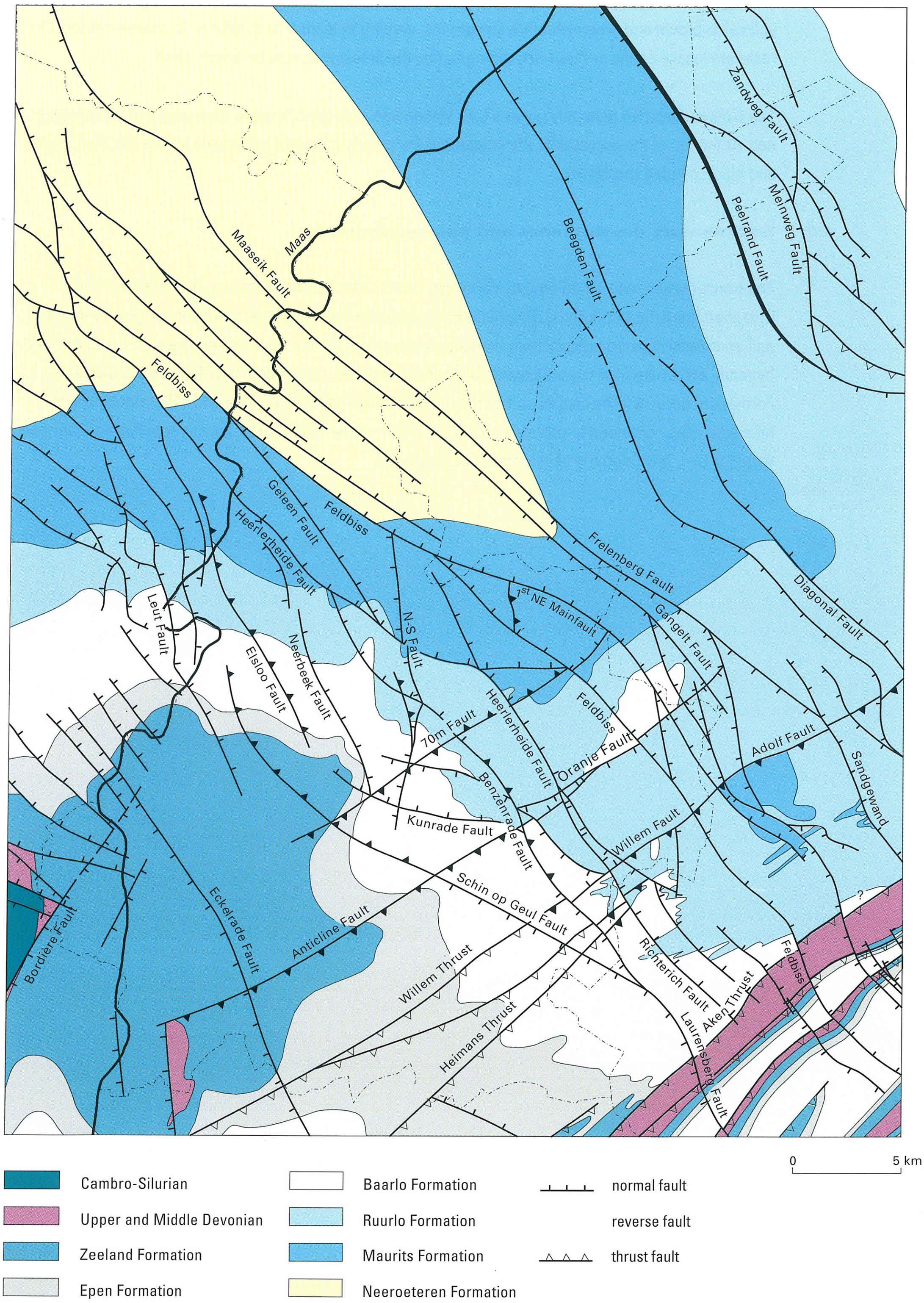


Figure 4.2 Subcrop geological map of the top of the pre-Permian, prepared with the use of data derived from Langenaeker (1998), Wrede (1985) and Rijks Geologische Dienst (1995).

The *Schouwen Member*, Middle to Late Viséan in age, comprises a thick sequence of light to dark-grey, yellowish-brown and brownish-black limestones, varying in texture from micritic to coarse-detritic. The rocks are locally oolitic or fossil-rich. Along faults, the limestones may be dolomitised.

The *Goeree Member*, generally given a Late Viséan age, is formed by grey, dark-grey and black limestones. At the top of the succession, the limestones frequently pass into calcareous and/or silicified shales and black, bedded chert layers.

4.2 Sedimentary development and palaeogeography

The transgression, which had already commenced at the end of the Devonian, persisted into the Dinantian (Early Carboniferous). The flanks of the London-Brabant Massif were submerged by the sea and an extensive carbonate platform developed around its perimeter. In places, the high was inhabited by many carbonate-forming organisms. Deposition of a thick succession of carbonates (Zeeland Formation) occurred. The central part of the massif, smoothened by erosion and still producing very little sediment, continued to protrude above the water. In the coastal area, locally, sabkhas and lagoons were formed, favouring the development of evaporites.

5 Limburg Group

5.1 General

The Limburg Group forms part of the Silesian (Late Carboniferous). In Limburg, these deposits were customarily subdivided into the chronostratigraphic units widely referred to in Western Europe, the Namurian and the Westphalian (inter alia Rijks Geologische Dienst, 1995). A further subdivision was applied with the use of marine bands, characteristic lithologies and fossil content. This specified detail correlation enabled a nomenclature of the coal seams and the marine bands to be introduced for the mining district (Jongmans, 1928; Jongmans & van Rummelen, 1940; Van Amerom, 1975). The "coal groups", which were identified in the Silesian, are subdivided by marine bands and are in fact chronostratigraphic units (fig. 5.1), confirmed by intercalated, kaolinised volcanic ash layers (Kimpe, 1969; Burger et al., 1984).

The Limburg Group is composed of an alternation of claystones, siltstones and sandstones with, especially in the middle part, a large number of intercalated coal seams. During the deposition, the prevailing conditions were initially marine and later continental. In the area of study, three subgroups can be distinguished, from bottom to top the Geul, the Caumer and the Dinkel Subgroups.

The Limburg Group is found in the subsurface throughout the map sheet area with the exception of the southwest of South Limburg, where it has been eroded away. The thickness of the group increases in a northerly to northeasterly direction to over 3500 m. In the southwest the base lies a few hundred metres below the surface and in a northerly direction plunges stepwise to a depth of more than 5000 m (Bless et al., 1980).

The Limburg Group rests on the Carboniferous Limestone Group conformably or separated by a small hiatus. Owing to its predominantly north to northeast inclined strata, increasingly younger deposits crop out on the Carboniferous surface in this direction (Map 15 and fig. 4.2). This is also reflected in the well correlation in figure 5.2. The unconformable younger overlying deposits extend from the Zechstein Group in the north (in the Roer Valley Graben), via the Lower Germanic Trias, the Chalk and the Middle North Sea Groups, to the Upper North Sea Group in the south and southeast (on the South Limburg Block), as shown in figure 5.3.

5.2 Geul Subgroup

This subgroup is composed of marine and continental claystones and siltstones without coal seams, with a few sandstones intercalated at the top. In Limburg the subgroup is composed entirely of the Epen Formation. The formation has been exposed in the Geul Valley (Rijks Geologische Dienst, 1984; Felder, P.J. & Bless, 1986).

5.2.1 Epen Formation

The Epen Formation, Namurian A to Namurian C in age, consists of a succession of dark dark-grey to black claystones and siltstones with a number of fine to medium-grained sandstone intercalations. At the bottom, the succession consists predominantly of marine sediments; towards the top, more deltaic deposits are gradually intercalated. The formation exhibits a cyclicity of coarsening-upward sequences. The formation occurs throughout the map sheet area, with the exception of the southwest, where it has been eroded away. In the area not affected by erosion, the thickness is between 300 and 400 m.

The formation rests on the carbonates of the Zeeland Formation, conformably or separated by a small hiatus increasing in size towards the Brabant Massif (Bless et al., 1976),. The upper boundary lies below the first distinct coal seam marking the beginning of the Baarlo Formation, part of the Caumer Subgroup. This boundary is facies-determined and may be strongly diachronous.

Two members can be distinguished within the Epen Formation. The Geverik Member at the base, and the Ubachsberg Member at the top.

The *Geverik Member*, a condensed deposit of Namurian A age, consists of dark-grey to black, strongly bituminous, cleavable slate with limestone and siltstone laminae. It has a high natural radio-activity, as can be seen on the Gamma-Ray log (fig. 5.2). The 66 m thickness found in the Geverik-1 well is likely to be close to the maximum.

The *Ubachsberg Member*, of late Namurian B to early Namurian C age, is characterised by the occurrence of prominent sandstones and has a thickness of around 20 m.

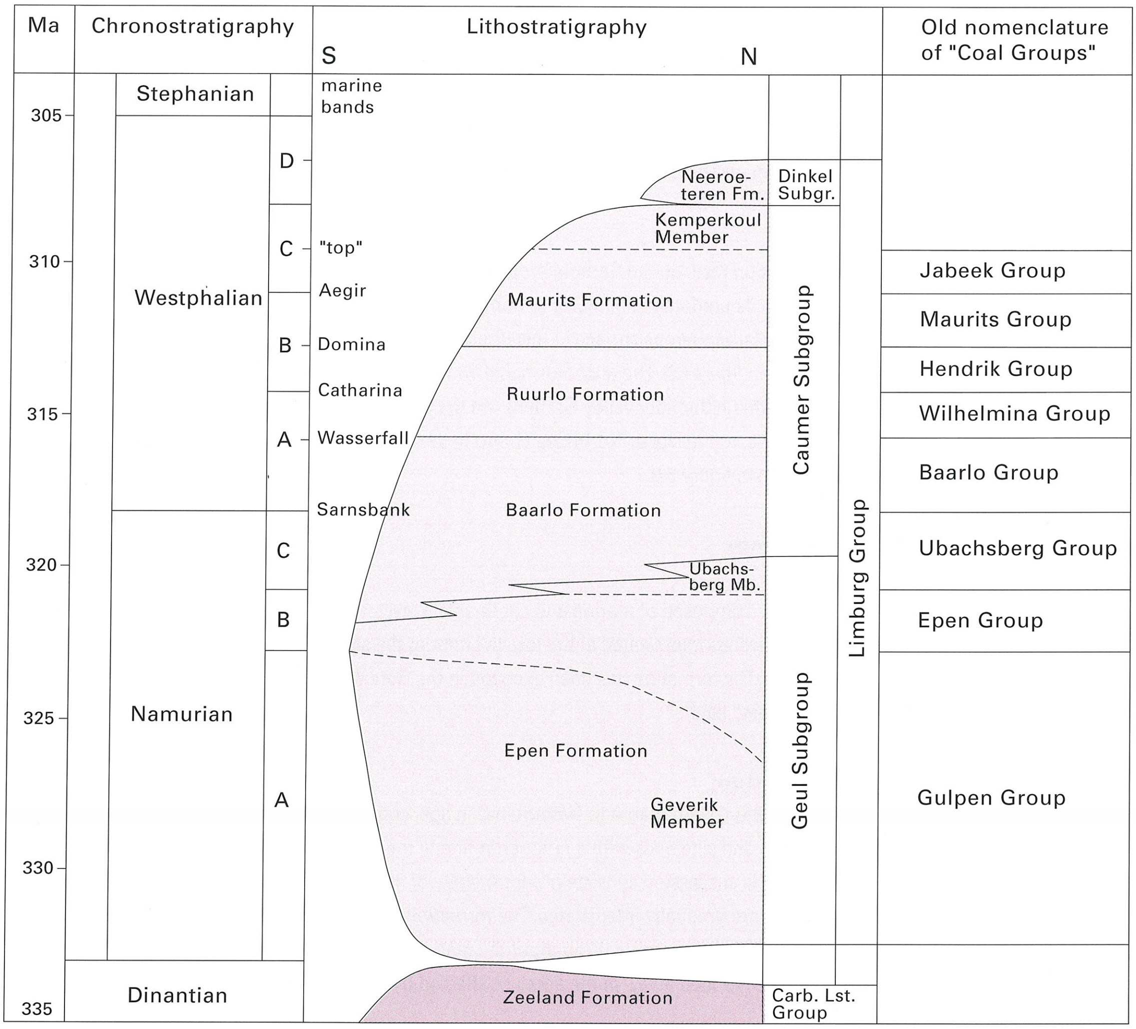


Figure 5.1 Litho-chronostratigraphic diagram of the Limburg Group.

5.3 Caumer Subgroup

The Caumer Subgroup consists predominantly of continental claystones, siltstones and sandstones with coal seams intercalated. In the Caumer Subgroup in the map sheet area, the Baarlo, the Ruurlo and the Maurits Formations can be distinguished (fig. 5.1). Just across the German border, in the valley of the Worm, a few outcrops occur (Carboniferous route of the Mining Museum in Rolduc; Rijks Geologische Dienst, 1984).

5.3.1 Baarlo Formation

The Baarlo Formation, ranging from Late Namurian B to Early Westphalian A age, is composed of a succession of claystones, siltstones, sandstones and coal seams with a distinctive coarsening-upward cycles. The formation occurs in the north and northeast of the map sheet area. In the southwest, it was subsequently eroded away. The thickness in the area not affected by erosion is approximately 1000 m.

The Baarlo Formation rests conformably upon the Epen Formation. The lower boundary lies at the first distinct coal seam. The boundary with the overlying Ruurlo Formation coincides with a change in the cyclical composition of thick coarsening-upward cycles, to an alternation of thinner, alternating fining and coarsening-upward cycles.

5.3.2 Ruurlo Formation

The Ruurlo Formation, Late Westphalian A and Early Westphalian B in age, comprises a succession of claystones, siltstones, sandstones and coal seams with both fining-upward and coarsening-upward cycles. The formation is found in the north and northeast of the map sheet area. In the southwest it was subsequently eroded away. The thickness in the uneroded area is approximately 1000 m.

The Ruurlo Formation rests conformably upon the Baarlo Formation. On the boundary, the pattern of the cyclical composition of the succession changes. The uppermost boundary is characterised by the transition to the sandstone-poor and coal-rich Maurits Formation.

5.3.3 Maurits Formation

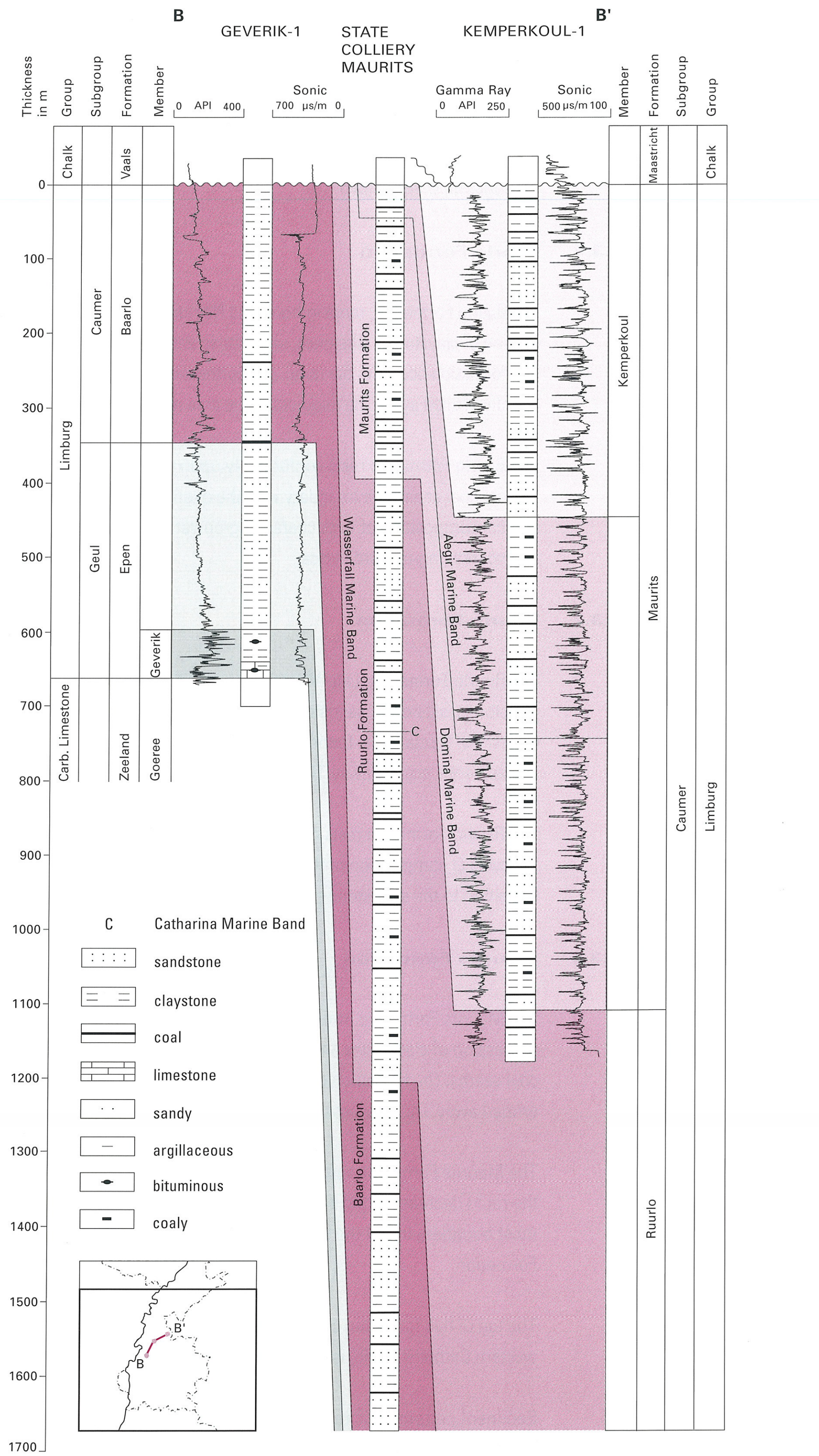
The Maurits Formation, ranging from Late Westphalian B to Early Westphalian C in age, comprises a succession of claystones and siltstones with only a few sandstones and a relatively large number of coal seams. The formation occurs in the north of the map sheet area. In the south, it was subsequently eroded away. The thickness in the uneroded area may exceed 1100 m.

The Maurits Formation rests conformably upon the Ruurlo Formation. The lower boundary is marked by the rapid decrease in the sandstones and the increase in the coal seams in the succession. The uppermost boundary lies at the base of the prominent sandstone development of the overlying Neeroeteren Formation.

The top of this formation contains the *Kemperkoul Member.* This member, which can be identified in the western Campine Basin, is characterised by sandstone intercalations with sandstones from 5 to 15 m thick.

Sediment petrographic research in the sandstones of the Maurits Formation in the Kemperkoul-1 well has demonstrated these to be predominantly lithic sandstones with an varying clay content, mainly cemented with Fe-dolomite, locally with siderite, and to a smaller degree with quartz (RGD, 1986b).

Figure 5.2 Stratigraphic section B-B' of the Limburg Group, with the Geverik-1 well, a compiled section of the State Colliery Maurits and the Kemperkoul-1 well. The reference-level is the top of the Limburg Group.



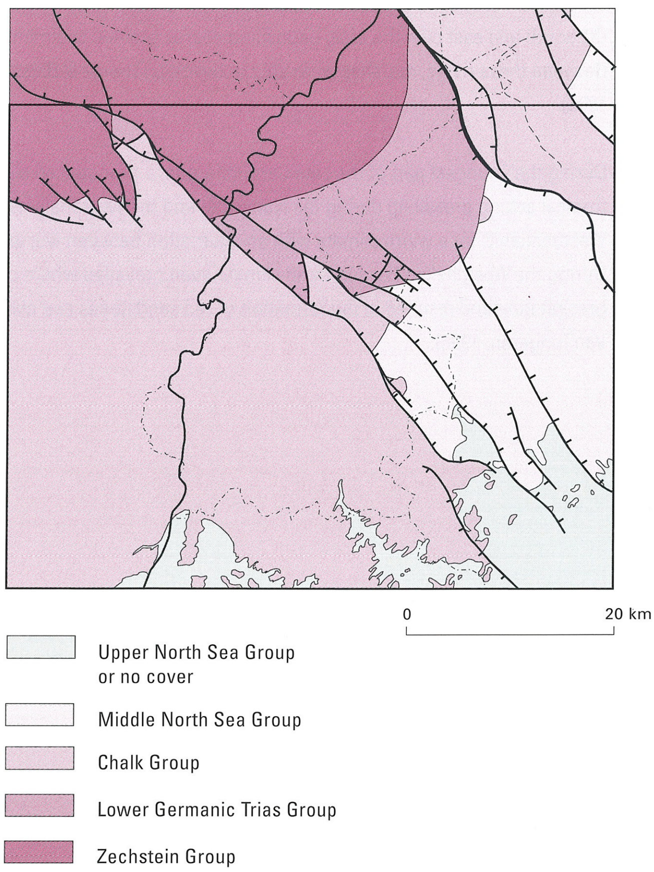
5.4 Dinkel Subgroup

The Dinkel Subgroup is composed predominantly of sandstones with numerous claystone and siltstone intercalations and a few coal seams. In the map sheet area, the subgroup is represented by the Neeroeteren Formation.

5.4.1 Neeroeteren Formation

The Neeroeteren Formation, of Westphalian D age, consists of massive, white, coarse-grained to gravel-bearing, arkosic sandstones, some claystones and siltstones and an occasional coal seam. This unit is only present to the north of the Feldbiss, where the estimated thickness is 200 to 400 m. The Neeroeteren Formation is well documented from Belgian wells in the Campine Basin (Dusar & Houlleberghs, 1981; Dusar et al., 1987). In The Netherlands, this formation has not been reached by drilling.

Figure 5.3 Supercrop map of the Palaeozoic surface. The map shows which formations lie directly on this surface. With data derived from Klostermann et al. (1990), Langenaeker (1998) and Rijks Geologische Dienst (1984).



The Neeroeteren Formation rests conformably or separated by a minor angular unconformity upon the Kemperkoul Member of the Maurits Formation. The lower boundary is determined by the sudden advance of prominent sandstones. The formation is unconformably overlain by the Zechstein Group and the Lower Germanic Trias Group.

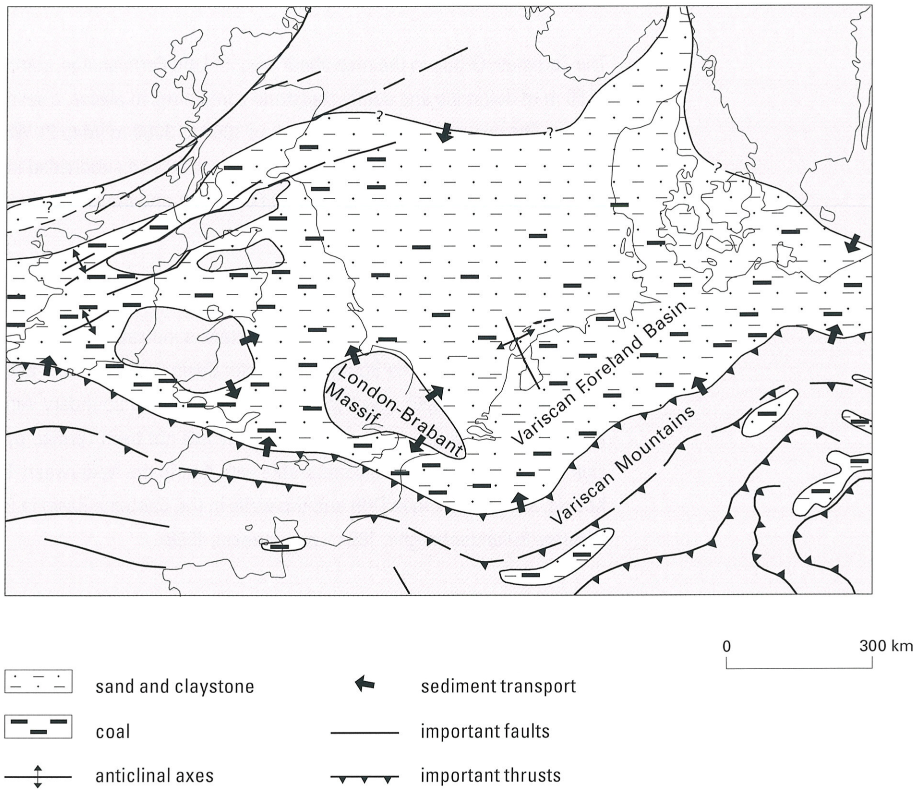
5.5 Sedimentary development and palaeogeography

The deposits of the Limburg Group reflect the regressive deltaic accumulation of an east-west oriented foreland basin (fig. 5.4). 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 and, what is of even greater significance, was extremely flat; 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 shifted northwards during the Late Carboniferous. There, to the north of the Brabant Massif, the Campine Basin was thrown into relief.

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). The top part of the succession, the Dinkel Subgroup, demonstrates here that 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 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). During the Westphalian D a semi-arid climate even prevailed where on occasion evaporation exceeded precipitation and resulted in the formation of red sandstones and claystones with caliches (Pagnier & Van Tongeren, 1996).

Figure 5.4 Palaeogeographic map of Northwest Europe at the time of the Late Carboniferous (after Ziegler, 1990).



6 Zechstein Group

6.1 Stratigraphy

The Zechstein Group in the map sheet area, of Late Permian age, comprises a succession of a maximum of 50 m of dolomitic and sandy claystone containing, in places, a several metre-thick limestone bed at the top. The group is present at a depth of 1000 to 3000 m (Map 2). Where most completely developed and well logged, the group may, from bottom to top, be subdivided into the Z1 (Werra) Formation, the Z2 (Stassfurt) Formation, the Z3 (Leine) Formation and the Zechstein Upper Claystone Formation (see fig. 1.7).

The Zechstein Group is only found in the north of the map sheet area, in the Roer Valley Graben and in the east of the Campine Basin. The areal extent is indicated on Map 2. The group was deposited here close to the margin of the Southern Permian Basin (Van Adrichem Boogaert & Burgers, 1983; Ziegler, 1990; Geluk et al., 1996), revealing in fact a depositional boundary. Although the occurrence of the Zechstein Group in the area of Map Sheet XV has not been verified by wells, the stratigraphic succession may be assumed to be comparable with that in the Nederweert-1 well (Van Adrichem Boogaert & Kouwe, 1993-1997, Annex D-9) and the wells in the Campine Basin in Belgium (including KB 172; Wouters & Vandenberghe, 1994; Langenaeker, 1998).

The Zechstein Group rests unconformably on the sandstones of the Carboniferous Neeroeteren and Maurits Formations of the Limburg Group and is covered, possibly via a small hiatus, by the sandstones of the Lower Buntsandstein Formation.

6.1.1 Z1 (Werra) Formation

The Z1 (Werra) Formation consists of grey dolomitic claystones or sandstones. They belong to the *Z1 Middle Claystone Member*. Separated by a small hiatus, this is followed by the Z2 (Stassfurt) Formation.

6.1.2 Z2 (Stassfurt) Formation

The Z2 (Stassfurt) Formation also consists of dolomitic claystones, which are part of the *Z2 Middle Claystone Member*, and, at the bottom, may contain some anhydrite. Where no clear distinction can be made between this member and the preceding one, they are taken as belonging the informal Zechstein Middle claystone. Separated by a small hiatus, this is overlain by the Z3 (Leine) Formation.

6.1.3 Z3 (Leine) Formation

The Z3 (Leine) Formation is composed of the *Grey Salt Clay Member* at the base, followed by the *Z3 Carbonate Member*, consisting of grey, argillaceous limestone. Along the southern margin of the Southern Permian Basin, this limestone is present locally. Deposits of the younger Zechstein cycles are not represented here, with the result that there is a hiatus between the Z3 (Leine) Formation and the Zechstein Upper Claystone Formation.

6.1.4 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation consists of red and brownish-red claystones, which are partly sandy, with a few thin sandstone intercalations. These are overlain conformably or via a small hiatus by the sandy Nederweert Member of the Lower Buntsandstein Formation.

6.2 Sedimentary development and palaeogeography

The Early Permian marked the commencement of a period of long-lasting erosion of the Variscan Mountain Chain in response to the uplifted Variscan foreland in the Saalian phase. Not until towards the end of the Late Permian, when the sea periodically gained access to the North European Permian basins, did the north of the map sheet area come within reach of the sedimentation, on the southern margin of the Southern Permian Basin (fig. 11.4). In the central part of this basin, 4 to 5 evaporation cycles in the Zechstein developed, resulting in hundreds of metres of anhydrite and rock salt (Van Adrichem Boogaert & Burgers, 1983). In the area being studied the first two cycles initiated deposition of lagoonal claystones (Zechstein Middle claystone), and the third cycle – under the influence of a transgression which had reached the map sheet area – gave rise to a marine limestone (Z3 Carbonate Member). The development ended with a continental claystone (Zechstein Upper Claystone Formation) which covers the older Zechstein unconformably (Geluk et al., 1996).

7 Lower and Upper Germanic Groups

7.1 General

The Triassic deposits consist predominantly of red and green coloured, clastic sediments, with intercalations of grey limestones, marls and evaporites. They are subdivided into the Lower Germanic Trias Group and the Upper Germanic Trias Group. The succession rests conformably or separated by a small hiatus on the Zechstein Group or, unconformably on the Neeroeteren or the Maurits Formation of the Limburg Group. It is covered unconformably by the Altena Group or, in those areas where it has been seriously affected by subsequent erosion, unconformably by the Chalk Group or the Middle North Sea Group. Only the bottommost part of the Lower Germanic Trias Group has been encountered, from boreholes in the north of South Limburg.

The development of the Triassic is expected to be largely comparable with that encountered in the Nederweert-1 well (Van Adrichem Boogaert & Kouwe, 1993-1997, Annex E-2) and in a number of wells in the Belgian part of the Campine Basin (Wouters & Vandenberghe, 1994; Langenaeker, 1998). This has largely formed the basis of the description of the Triassic formations. Figure 7.1 exhibits the chrono/lithostratigraphic division of the Germanic Trias.

The Germanic Trias groups are only encountered in the middle and north of the map sheet area. The depth of the base ranges from 350 m on the northern part of the South Limburg Block to over 3100 m in the middle of the Roer Valley Graben (Map 5). The thickness of the succession increases to over 1100 m in this graben (Map 6). The age extends from the latest Permian into the Late Triassic.

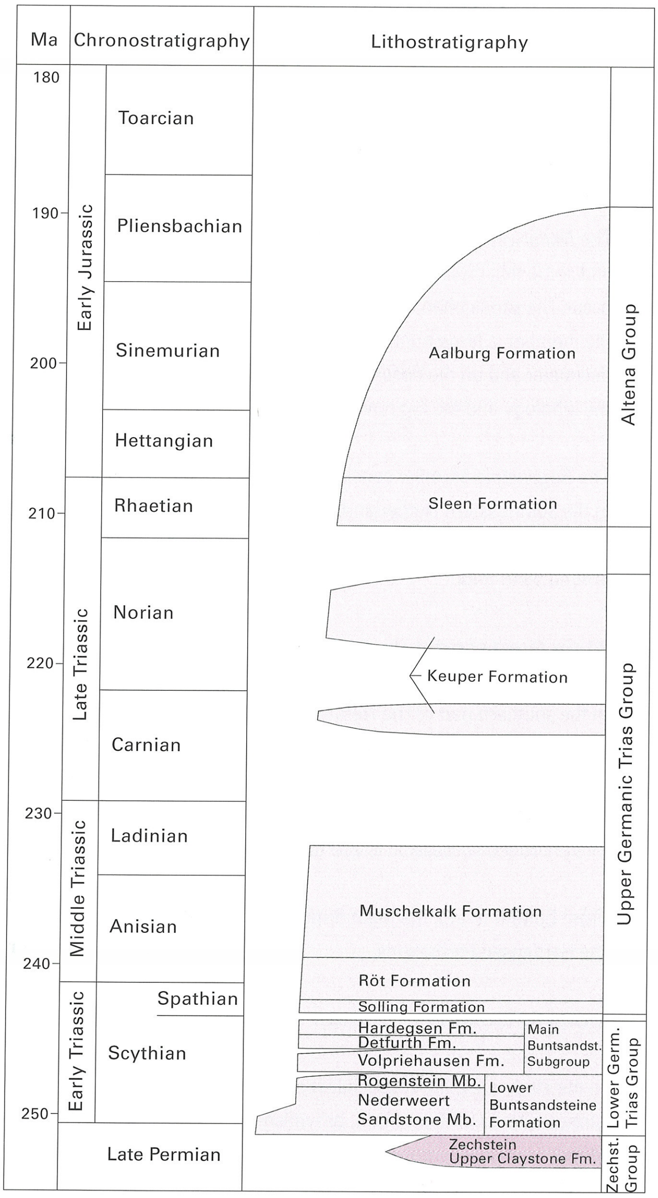
7.2 Lower Germanic Trias Group

7.2.1 Stratigraphy

The Lower Germanic Trias Group, of latest Permian to Scythian age, comprises terrestrial, clastic redbed deposits. In this alternation of conglomerates, sandstones and claystones, four formations can be distinguished, from bottom to top the Lower Buntsandstein, the Volpriehausen, the Detfurth and the Hardegsen Formations. The last-mentioned three formations in combination form the Main Buntsandstein Subgroup. Within the group, minor unconformities occur at the base of the Volpriehausen and Detfurth Formation, which, locally, may facilitate the erosion of tens of metres (Geluk & Röhling, 1997).

The Lower Germanic Trias Group rests conformably upon the Zechstein Group or unconformably upon the Limburg Group, and is unconformably overlain by the Upper Germanic Trias or the Chalk Group. The group is a maximum of 650 m thick.

Figure 7.1 Litho-chronostratigraphic diagram of the Lower and Upper-Germanic Trias Groups and the Altena Group.



7.2.2 Lower Buntsandstein Formation

In the study area, this formation consists of pink and white conglomerates, sandstones and dark brick-red siltstones and claystones. The coarse-clastic development, the Nederweert Sandstone Member, only occurs in the Roer Valley Graben and the adjacent area in Belgium and Germany. This is succeeded by the predominantly argillaceous/silty Rogenstein Member.

The *Nederweert Sandstone Member* comprises cross-bedded, occasionally conglomeratic sandstones and some thin claystone layers. Mainly at the bottom of the member, a few conglomerate intercalations occur. The sands often contain rounded clay pebbles, and the clays display dessication cracks. Within the member, a large number of fining-upward sedimentary cycles can be distinguished, both on the decimeter and on the decameter scale. The thickness reaches a maximum of 340 m. Figure 7.2 shows the lithology and the log reading of the Nederweert Sandstone Member in the Limbricht-1 well.

The *Rogenstein Member* consists of red and green, fine-sandy, fine-laminated claystones and siltstones. In the southeastern Netherlands, only the topmost part of this member is developed. The characteristic calcareous oolite beds, to which it owes its name, are absent there. The sequence is assumed to be around 50 m thick.

7.2.3 Main Buntsandstein Subgroup

In the southern part of The Netherlands, the Main Buntsandstein Subgroup consists mainly of sandstones. The subgroup rests upon the Lower Buntsandstein Formation separated by a small hiatus and is unconformably overlain by the Solling Formation of the Upper Germanic Trias Group. The Main Buntsandstein Subgroup is only found in the north of the map sheet area, in the Roer Valley Graben. The uneroded succession is 200 to 240 m thick in the study area and is of Scythian age.

From bottom to top, the Main Buntsandstein Group is composed of the Volpriehausen, the Detfurth and the Hardegsen Formations.

7.2.3.1 Volpriehausen Formation

In the study area, the Volpriehausen Formation consists of massive, pink, light-brown and white sandstones with a number of thin, brownish-red and green claystone intercalations. The cement of the sandstones is mainly carbonate. In the Roer Valley Graben, where this unit has not been affected by erosion, the thickness is 100 to 135 m.

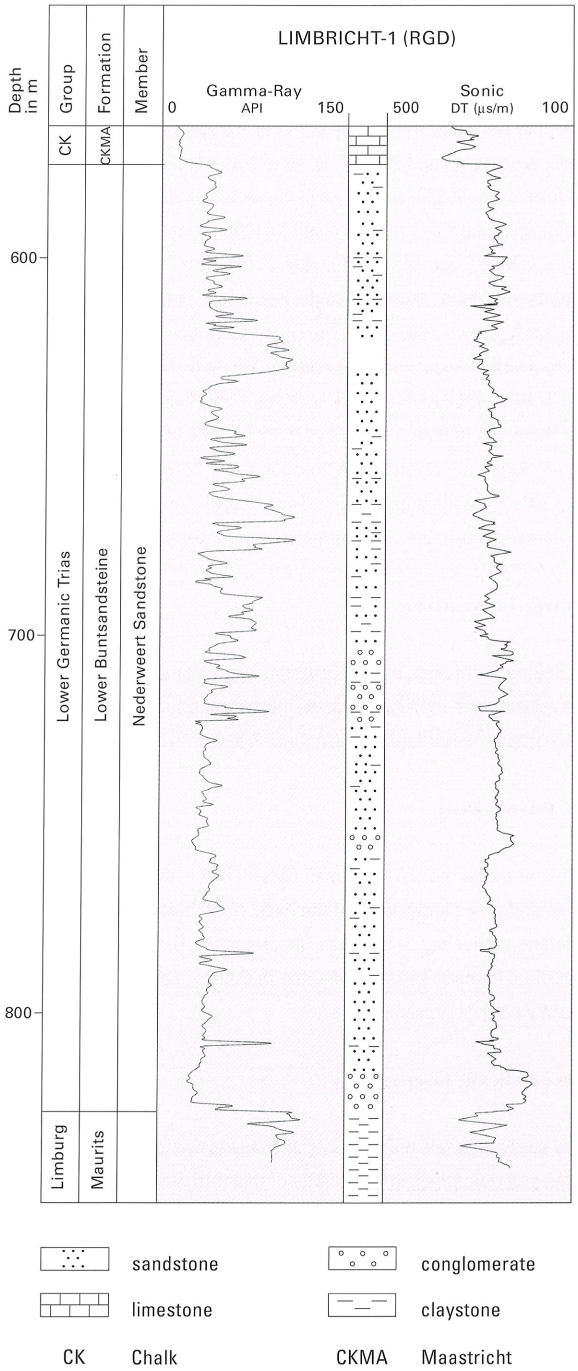
7.2.3.2 Detfurth Formation

The Detfurth Formation is formed by light coloured sandstones with a reddish-brown claystone/siltstone intercalation. The largest, uneroded thickness is approximately 30 m.

7.2.3.3 Hardegsen Formation

This formation is composed of a pile-up of sandstone-claystone alternations, in which the sandstone component gradually decreases towards the top. The sandstone is pink or white and the claystone red to brownish-red. The thickness ranges from 60 to 70 m in the uneroded area.

Figure 7.2 Well-log of the Nederweert Sandstone Member in the Limbricht-1 well. Various conglomeratic intercalations can be identified from the well-logs.



7.3 Upper Germanic Trias Group

7.3.1 Stratigraphy

The Upper Germanic Trias Group comprises a great variety of rocks: continental, red, green and grey claystones, sandstones and evaporites, as well as marine limestones, dolomites and evaporites. Combined, they form a single unit, as they were deposited in the same palaeogeographic setting. At the base there is a major unconformity, with the result that the group rests upon different formations of the Lower Germanic Trias Group via a hiatus that varies in size regionally. This unconformity is the Basal Solling Unconformity (also referred to as the Hardegsen Unconformity or Spathian Unconformity; Van Adrichem Boogaert & Kouwe, 1993-1997). The Upper Germanic Trias Group is unconformably overlain by the Altena Group, which only occurs in the north of the map sheet area in the central part of the Roer Valley Graben (Map 7). Where the Altena Group is present, the succession has not been affected by pre-Cretaceous erosion. There, the thickness is 400 to 475 m. The age of the group is Late Scythian up to Norian (Van der Zwan & Spaak, 1992; Van Adrichem Boogaert & Kouwe, 1993-1997). The group is subdivided, from bottom to top, into the Solling, the Röt, the Muschelkalk and the Keuper Formations. The Muschelkalk Formation is a marine deposit; the other formations are mostly continental or lagoonal in origin.

7.3.2 Solling Formation

The Solling Formation, of Late Scythian age, consists of grey, basal sandstone, succeeded by red and green claystones. In the study area, the formation rests unconformably, separated by a relatively small hiatus, upon the Hardegsen Formation. Where it is completely present, its thickness is 20 to 25 m

7.3.3 Röt Formation

At the margin of the NW-European Triassic Basin, the formation consists of red, often anhydritic, claystones and grey sandstones. At the base, there is an anhydritic sequence several metres thick, forming the lateral equivalent of the Main Röt Evaporite. The Röt Formation rests conformably on the Solling Formation. In the map sheet area, the thickness is a maximum of 150 to 175 m. The formation is predominantly earliest Anisian in age.

7.3.4 Muschelkalk Formation

In the study area this unit consists of a succession of grey, and in places red, marls, argillaceous limestones and dolomites. In the middle of this formation, a sequence of anhydrite is found, probably over 10 m thick, which is taken as belonging to the *Muschelkalk Evaporite Member.*

The Muschelkalk Formation rests conformably upon the Röt Formation and is unconformably overlain by the Keuper Formation. In the Roer Valley Graben, where the unit has not been reduced by subsequent erosion, the thickness is 200 to 225 m. The formation is Anisian to Early Ladinian in age.

7.3.5 Keuper Formation

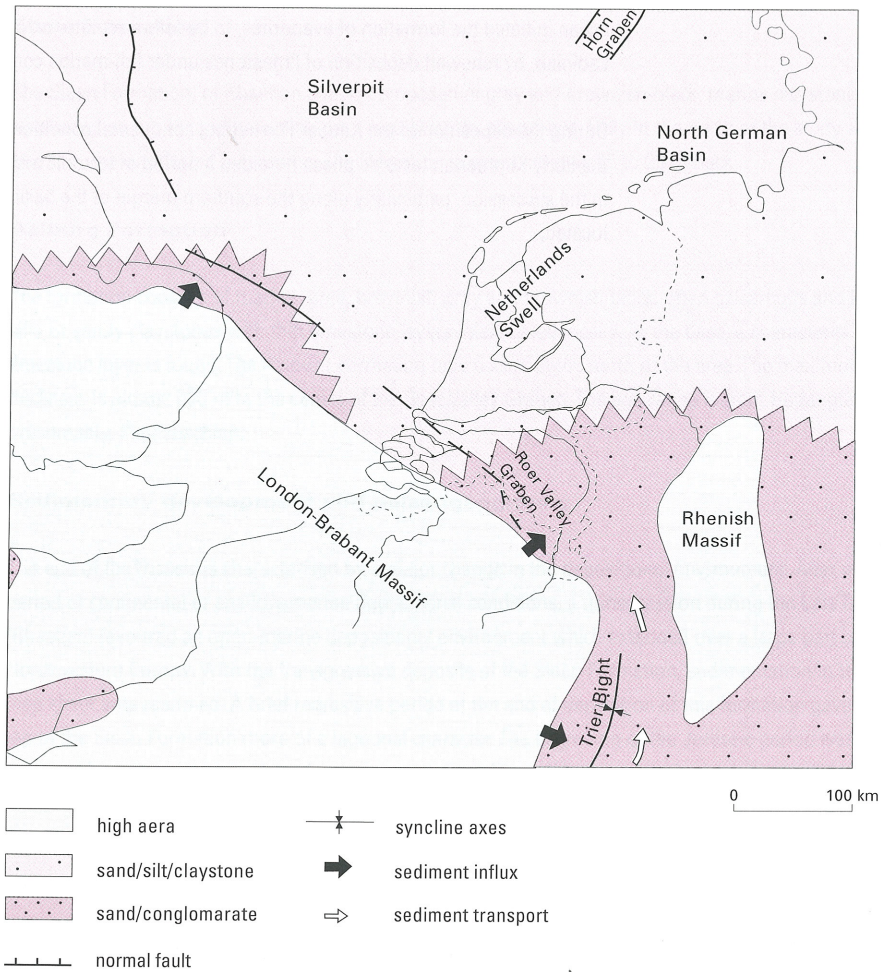
In the southeastern Netherlands, the Keuper exhibits an incomplete development (Geluk et al., 1996). The succession in the map sheet area cannot be verified from wells, but from the general distribution pattern it may be inferred that only the topmost part of the Keuper is present here, resting on the Muschelkalk via a large hiatus. A further large hiatus occurs within the formation. The Keuper Formation is covered unconformably by the marine claystones of the Sleen Formation.

The Keuper Formation in the study area, of Carnian and Norian age, is composed of continental, reddish-brown, green, silty claystones, which are often anhydritic and dolomitic. A few red and grey sandstones are found locally. In the uneroded area, the thickness is thought to be between 30 and 50 m.

7.4 Sedimentary development and palaeogeography

In the very latest Permian, the sea had finally withdrawn from Northern Europe. The incipient influx of clastics at the end of the Zechstein was prolonged into the Triassic. The deposits of the Lower Germanic Trias Group were laid down in a large continental basin, which was in essence the same as during deposition of the Zechstein. 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 (fig. 1.8): the Hardegsen phase, which led to the formation of a hiatus between the Lower and the Upper Germanic Trias, and the Early Kimmerian phase, which resulted in a large hiatus between the Upper Germanic Trias Group.

Figure 7.3 Palaeogeographic map of Northwest Europe at the time of the Early Triassic (after Ziegler, 1990 and Geluk, in press.).



9.1.3 Gulpen Formation

This formation consists of light coloured to white, very fine-grained limestones. At the base, the formation frequently contains a large amount of glauconite; at the top, chert nodules and layers are common. The Gulpen Formation rests unconformably upon the siliciclastic Vaals Formation or, where this is absent in the extreme southwest of Limburg, upon the Palaeozoic surface. A distinct unconformity is present within the formation, with the result that the bottommost part of this unit (Zeven Wegen and Beutenaken Limestones) has been removed partly or entirely by erosion. In the southeast of the area, this unconformity may in places extend as far as the Palaeozoic surface (Felder, W.M., 1980, 1996). At the base of the unconformable succession lies the Vijlen Limestone, which is glauconitic at the base. The Maastricht Formation rests unconformably upon the Gulpen Formation, via a small hiatus.

The thickness of the Gulpen Formation varies considerably and is a maximum of circa 100 m in the southwest of Limburg. The age extends from Late Campanian to Late Maastrichtian.

The subdivision into members is displayed in figure 9.1. These members are bounded by characteristic horizons, of which the two bottommost ones (at the bases of the Beutenaken Limestone and the Vijlen Limestone) developed as true unconformities. Consequently, the Zeven Wegen Limestone is only found in the south of the line Bunde-Drielandenpunt and the Beutenaken Limestone is restricted to an area to the south of Gulpen. The Zeven Wegen Limestone is mostly white and developed in a pelagic chalk-facies. The Lixhe and Lanaye Limestones contain characteristic, blackish-grey chert layers and nodules.

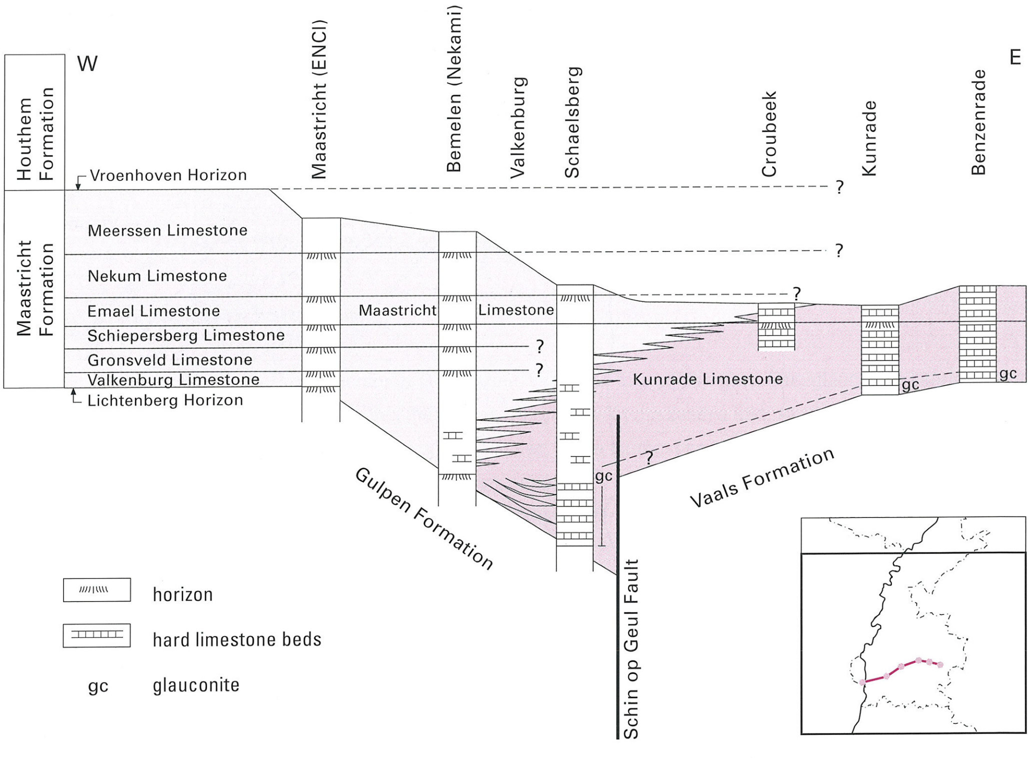


Figure 9.5 Correspondence between the Maastricht Limestone and the Kunrade Limestone, two different facial developments in the Maastricht Formation (after Felder, W.M., 1975). See also *Figure 9.2.*

The Gulpen Formation, particularly on the eastern Campine Block, developed as a glauconitic marl, containing some sand and silt. The sediments exhibiting this facies, which occur along the more elevated area of the Roer Valley Graben in the Late Cretaceous, were termed the pre-Valkenburg Strata by P.J. Felder et al. (1985). P.J. Felder & Bless (1989), place the calcareous Benzenrade Sand referred to in 9.1.2 in this lithological unit.

9.1.4 Maastricht Formation

The Maastricht Formation comprises light-yellow to light-greyish-yellow, limestones. At the base lies a glauconitic layer containing fossil hash. At the base of the formation predominantly fine-grained, and at the top, coarse-grained rocks occur ("Maastricht tufkrijt"). In western South Limburg, the bottom part of the succession contains many chert nodules and layers. In the part higher up, many hardgrounds and fossil hash is in layers and lenses occur. Here, too, is the Maastricht Limestone, which developed during the Maastrichtian facies of the Maastricht Formation. In eastern and central South Limburg (Felder, W.M., 1975), where the highest part of the formation is not represented, this unit is composed of alternating layers of hard and soft limestone, with chert either absent or occurring only sporadically. This is the Kunrade Limestone, which developed during the Kunrade facies of the Maastricht Formation. Figure 9.5 illustrates the correspondence between these two facies in section.

The Maastricht Formation rests unconformably on the Gulpen Formation, separated by a small hiatus (Felder, W.M., 1996). Where the last-mentioned unit is not represented, to the north of the Schin op Geul Fault, the Maastricht Formation rests upon the Vaals Formation or on pre-Cretaceous deposits. In the northwest of the study area, the Houthem Formation overlies the Maastricht Formation, separated by a small hiatus. Elsewhere, it is unconformably overlain by siliciclastic deposits of the Middle North Sea Group and, where these are absent, locally by thin Quaternary sediments of the Upper North Sea Group.

The thickness of the Maastricht Formation ranges from, at the most, some tens of metres in the Roer Valley Graben to 90 m in South Limburg. The formation is mainly of Late Maastrichtian age. In the topmost part of the formation, which has only been encountered locally (Geulhemmerberg and Groeve Curfs), the formation extends as far as the Danian (Smit and Brinkhuis, 1996; Jagt et al., 1996; Herngreen et al., 1998). The Cretaceous/Tertiary boundary has been encountered here, at the Berg and Terblijt Horizon, a few metres below the upper side of the formation boundary formed by the Vroenhoven Horizon.

In the Maastrichtian Limestone, the six members referred to in figure 9.1 can be distinguished. They are again bounded by distinctive horizons.

9.1.5 Houthem Formation

This formation 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. As a consequence of subsequent erosion, the Houthem Formation is only represented in the north and northwest of the study area.

The Houthem Formation rests upon the Maastricht Formation, separated by a small hiatus. In the middle and north of the area, the Landen Formation rests disconformably on the Houthem Formation. To the south of the areal extent of the Landen Formation, the Houthem Formation is unconformably overlain by sands of the Tongeren Formation, which are part of the Middle North Sea Group or, where these are absent, in the southern extent, by local Quaternary deposits of the Upper North Sea Group.

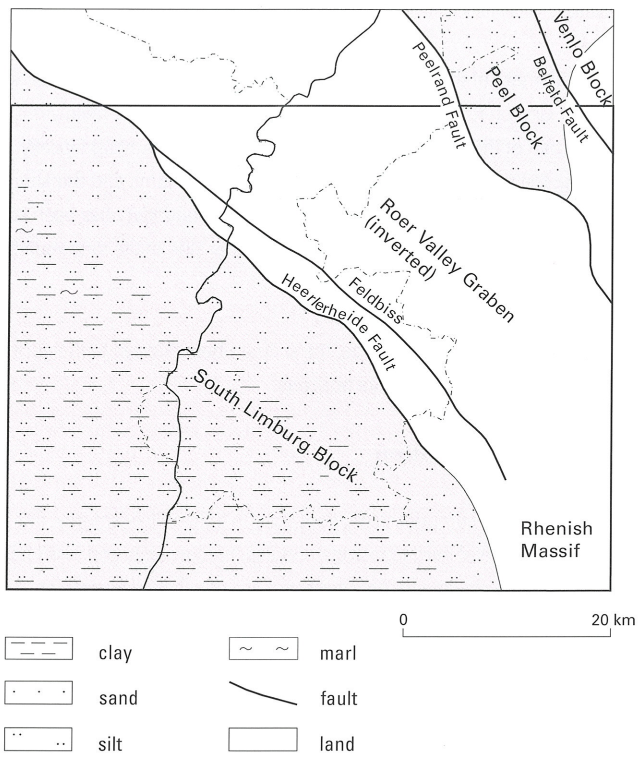
The succession is several tens of metres thick and is of Danian age.

The subdivision of Houthem Formation into members can be seen on figure 9.1. The members are bounded by discontinuity planes, with the Vroenhoven Horizon at the base of the formation.

9.2 Sedimentary development and palaeogeography

The beginning of the Cretaceous heralded the commencement of a transgression, during which the sea, from a northerly direction, encroached over the previously uplifted areas. By the beginning of the Late Cretaceous, the sea had reached the central part of the Netherlands. The land areas surrounding the northern Chalk Sea were partly submerged, causing the supply of clastic material to decrease significantly, as a result of which limestone accumulation prevailed. Along the margins of the highs, deposition of sand continued.

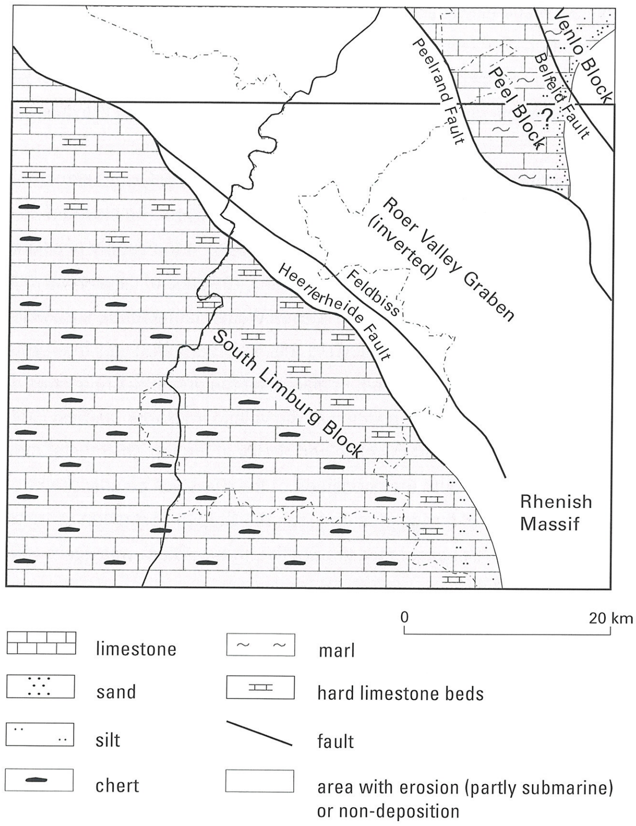
The progressively transgressing sea reached Limburg during the Santonian. Initially, a coastal environment, with rivers and lagoons, developed. Here, the Aken Formation was formed. Tectonic inversion during the Santonian and Early Campanian initiated uplift of the Roer Valley Graben and the northern part of the South Limburg Block (a tectonic high between the Feldbiss and the Heerlerheide Fault; see



a.

Figure 9.6 Palaeogeographic maps of the map sheet area during the Late Cretaceous (with data derived from Bless et al., 1987).
a. Early-Campanian
b. middle Late-Maastrichtian
c. late Late-Maastrichtian

b.


Venlo Block
Belfeld Fault
Peel Block
Peelrand Fault
Roer Valley Graben
(inverted)
Feldbiss
Heerlerheide Fault
South Limburg Block
Rhenish
Massif
0
20 km
limestone
sand
silt
chert
marl
hard limestone beds
fault
area with erosion (partly submarine)
or non-deposition

c.

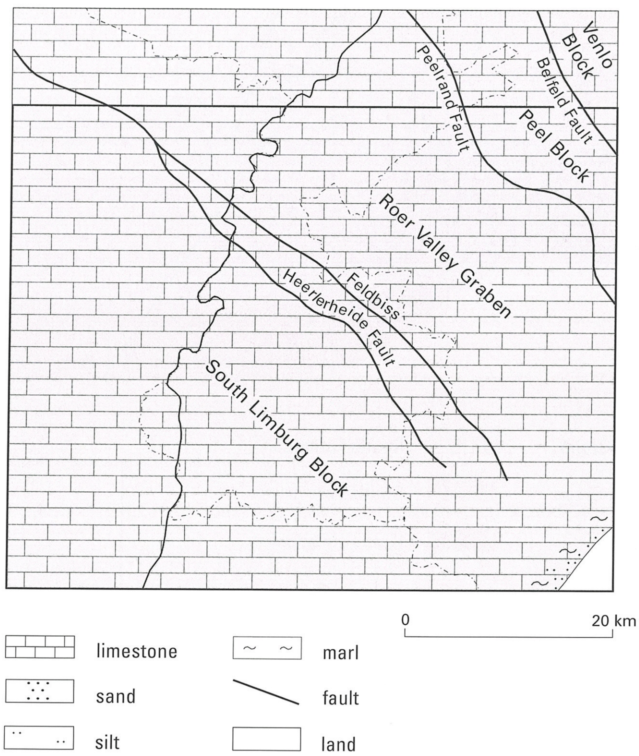

Venlo
Block
Belfeld Fault
Peel Block
Peelrand Fault
Roer Valley Graben
Feldbiss
Heerlerheide Fault
South Limburg Block
0
20 km
limestone
sand
silt
marl
fault
land

fig. 9.6a) and at first also to the southwest of this, inducing the virtual complete removal of the Aken Formation by erosion. In the shallow sea contemporaneously covering South Limburg, the Vaals Formation formed, consisting of sandy and argillaceous sediments with a high proportion of glauconite. A comparable development took place to the northeast of the inverted graben, on the Peel Block.

During the deposition of the Gulpen Formation (Late Campanian) the sea had migrated further southwards and limestone accumulation began to prevail. The elevated area of the Roer Valley Graben had gradually levelled, with a consequent decrease in the supply of clastic material. The initial deposition was chalk, largely composed of coccoliths, residues of calcareous algae consisting of minute calcareous plates, 0.5 to 20 mm in diameter (Zeven Wegen Limestone), succeeded by glauconitic, marly limestone (Beutenaken Limestone). Following this, sedimentation was interrupted. Crustal movements occurred in the South Limburg Block and, in places, all the previous Cretaceous deposits were eroded away (Felder, W.M., 1996). After the deposition of the Vijlen Limestone (earliest Late Maastrichtian), exhibiting a glauconitic development at the base and chalky at the top, the crustal movements in the southwest of South Limburg ceased. With the deposition of the chert-rich pelagic chalks of Lixhe and Lanaye, in a sea with a minimal influx of terrigenous material, the Gulpen Formation came to an end in the first half of the Late Maastrichtian. Subsequently, the South Limburg Block was again affected by sea-floor movements,

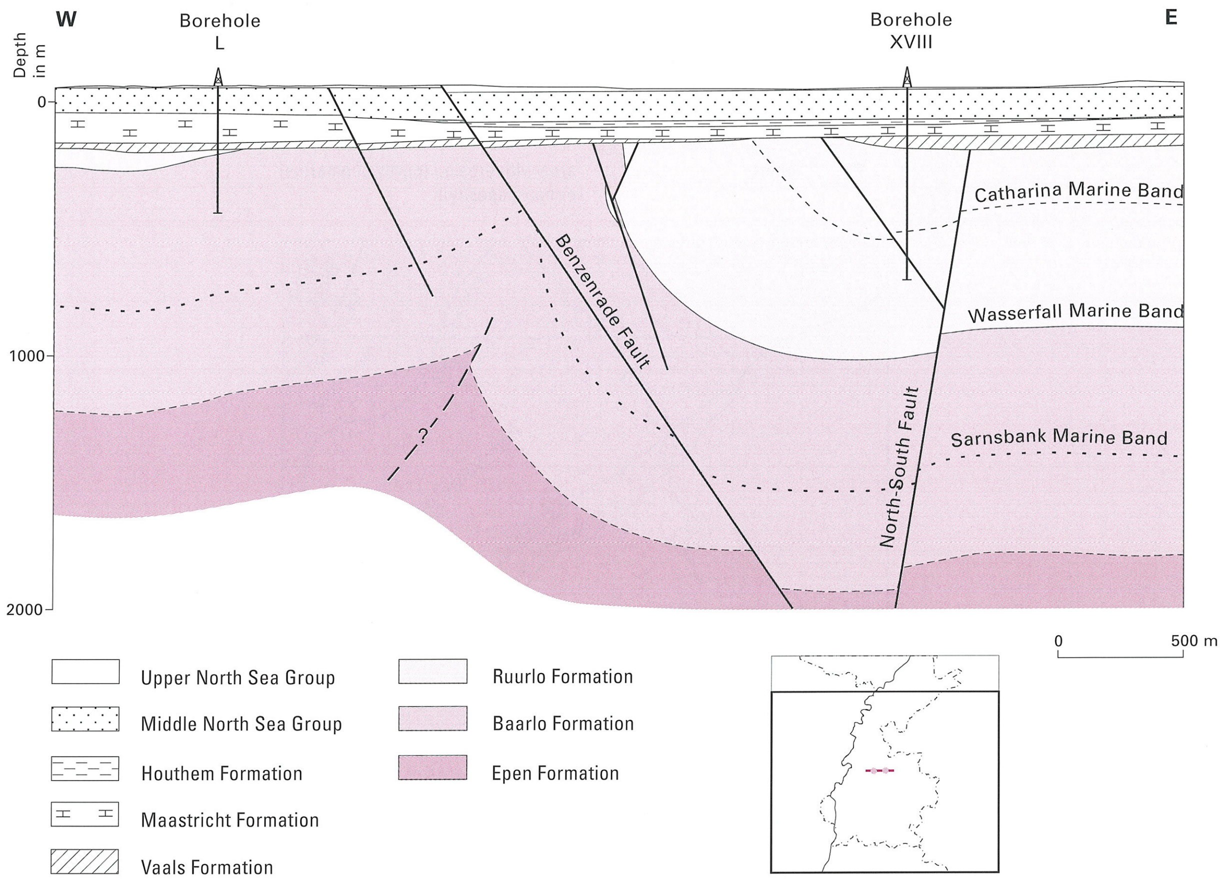


Figure 9.7 Structural section across the Puth Anticline (modified after Patijn, 1963).

accompanied by tilting of the fault-bounded blocks to the northeast. In the early Late Maastrichtian, the sea temporarily invaded the area of the Roer Valley Graben (Bless et al., 1993).

After a brief interruption, the limestone sedimentation continued, with the Maastricht Formation. Initially along, and later also within the contemporaneously, again subsiding Roer Valley Graben area (fig. 9.6c), an alternation of hard and soft limestones was deposited (Kunrade Limestone) in relatively shallow conditions. On the higher parts of the block-faulted area, submarine erosion took place, locally as far down as the Carboniferous (W.M. Felder, pers. com.). Further to the southwest, presumably in somewhat deeper water, large quantities of chert were formed, in a soft limestone (Maastricht Limestone) (Bless et al., 1987). During the last part of the Late Maastrichtian, the crustal movements again ceased and the Nekum and Meerssen Limestones were deposited in more or less uniform conditions.

Higher up in the succession, in particular, coarser-grained limestones formed, with bioclastic grains of silt and sand grain size. This type of limestone is also termed tuffaceous chalk (Zijlstra, 1995). The palaeowater depth was certainly not very great. Bless (1991) estimates this at 45 to 65 m. Hardgrounds and fossil hash layers indicate fluctuating periods of a very shallow sea.

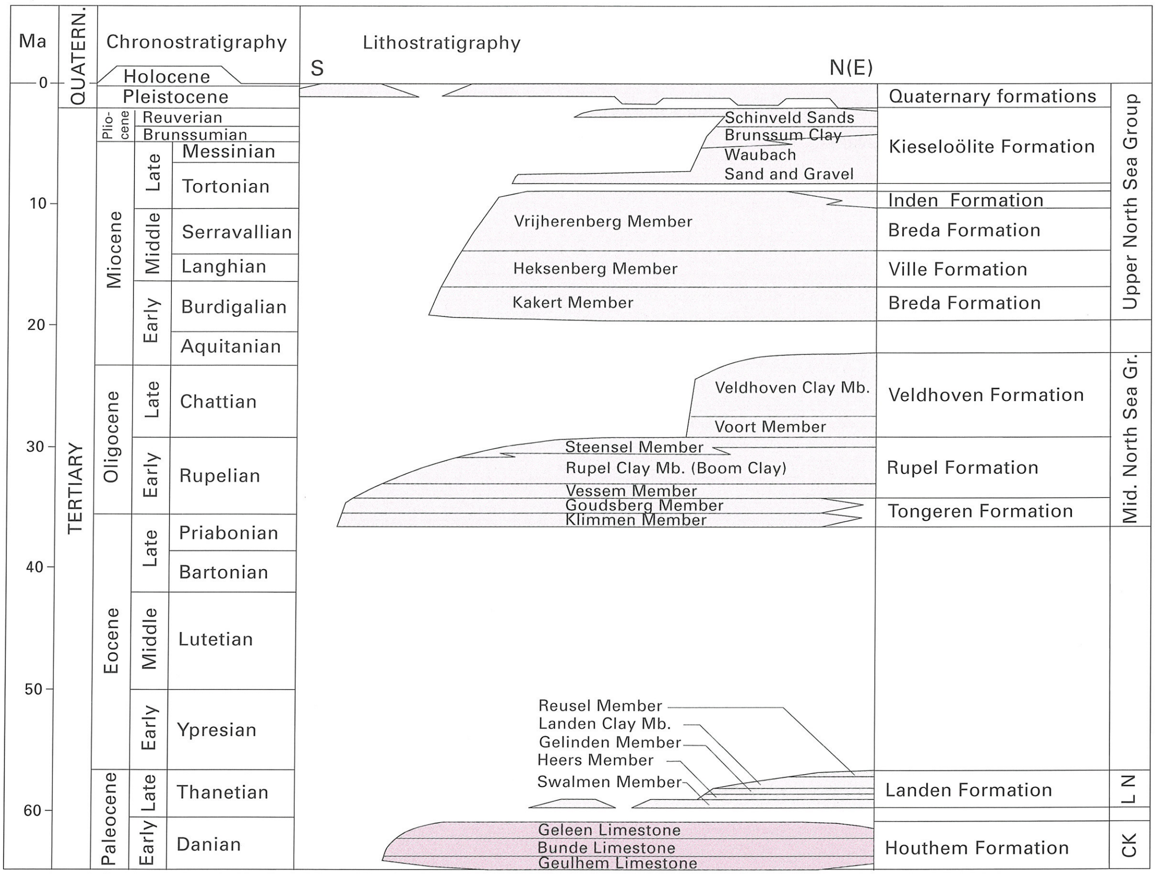
A brief interruption to the sedimentation at the end of the Cretaceous was superseded by the deposition of the Houthem Formation, in a comparable, shallow-marine limestone facies in the earliest Tertiary (Danian).

10 North Sea Supergroup

10.1 Stratigraphy

The North Sea Supergroup, ranging in age from Late Paleocene to Holocene (fig. 10.1). consists predominantly of sandstones (often unconsolidated), sands, silts and clays. The deposits are partly marine in origin and partly continental. The supergroup is subdivided into the Lower North Sea, the Middle North Sea and the Upper North Sea Groups, separated from each other by unconformities (Van Adrichem Boogaert & Kouwe, 1993-1997). The contact with the underlying Chalk Group, or, locally, with the Limburg Group in the extreme south of the area studied, is unconformable.

The North Sea Supergroup is found throughout the area. To the south of the Maastricht-Kerkrade line, there are almost exclusively thin, fluvial and aeolian Quaternary deposits belonging to the Upper North Sea Group. These are beyond the scope of Maps 11 and 12. Towards the north, an increasingly more complete succession of the Middle and Upper North Sea Groups is encountered, which, increases strongly in thickness step-wise in the northwest-southeast trending fault-blocks, commencing with the Heerlerheide Fault (fig. 10.2 and fig. 10.4).



L N Lower North Sea Group
CK Chalk Group

Figure 10.1 Litho-chronostratigraphic diagram of the North Sea Super Group.

The map sheet area is situated on the southern margin of the Cenozoic North Sea Basin. Consequently, the deposits from that epoch often display large hiatuses (see fig. 10.1). Uplift occurred during the Pliocene and Quaternary of the Ardennes and the Rhenish Massif, resulting in young erosion, which made a conspicuous impact on the landscape in South Limburg. The subsidence of the Roer Valley Graben also played a significant role in the deposition of the North Sea Supergroup.

The thickness of the North Sea Supergroup is zero to a few metres in the south of the map sheet area and increases to over 1500 m in the Roer Valley Graben. The depth to the base of the supergroup provides an indication of the thickness of the deposits. In southern Limburg, when ascertaining the true thickness, allowance should be made for the height of the surface level, which may increase to over 300 m above NAP. An impression can be obtained from the sections (Map 15). The base of the North Sea Supergroup lies between + 200 m Mean Sea Level in the extreme south to - 1550 m in the Roer Valley Graben in the north of the area.

North Sea Supergroup occurrences at or near the surface are discussed in detail in the "Toelichting bij de Geologische Kaart van Nederland 1:50.000" (Kuyl, 1980). Outcrops are described by, inter alia, Bosch (1980) and Felder, P.J. & Bless (1986).

10.2 Lower North Sea Group

Only the bottommost part of this group, the Landen Formation, is present in the middle and north of the area studied.

10.2.1 Landen Formation

The bottommost part of this formation, the *Swalmen Member*, is a sandy and argillaceous succession, frequently containing small brown coal seams at the top and deposited in a brackish-water, lagoonal to fresh-water environment. Locally, red and green colours occur in the clays. In South Limburg, this succession is called the Lutterade Clay (Rijks Geologische Dienst, 1984).

The higher part of the Landen Formation is composed of marine deposits: at the bottom, fine-grained, glauconitic sands (*Heers Member*), succeeded by light coloured marls (*Gelinden Member*) and dark-grey clays (*Landen Clay Member*). The formation is covered by a sandy succession (*Reusel Member*).

In the map sheet area, only the Swalmen Member in South Limburg has been identified from wells. This occurrence is an erosional relic of the Landen Formation, intermittent between the Houthem and Tongeren Formations. A more complete succession has been encountered on the Peel Block. The thickness ranges from a few metres to a maximum of 15 m. Seismic data indicate the presence of a similar succession in the Roer Valley Graben with a thickness of 50 to 100 m.

10.3 Middle North Sea Group

This group is found in the middle and the north of the map sheet area. The southern extent is determined by post-depositional erosion. South of the continuous Tertiary cover, there are scattered occurrences of fine sands and sandstone blocks ("blokbestrooiing"), which are classified as belonging to the Holset Sands (Kuyl, 1980). Their exact age is not known, but they are thought to be erosional relic of the Upper Oligocene Veldhoven Formation (Rijks Geologische Dienst 1984; W.M. Felder, pers. com.). Where the Lower North Sea Group is absent, the Middle North Sea Group lies at the base of the North Sea Supergroup. Deposits of the Upper North Sea Group cover the Middle North Sea Group unconformably.

The thickness of the Middle North Sea Group ranges from 0 to approximately 500 m, which is the maximum thickness achieved in the Roer Valley Graben. The group ranges from latest Eocene to Late Oligocene in age. The uppermost part of the group quite possibly still reaches the earliest Miocene in the Roer Valley Graben. The group has outcrops at various localities in the map sheet area, (Bosch, 1980; Rijks Geologische Dienst, 1984).

The Middle North Sea Group is composed of the Tongeren, the Rupel and the Veldhoven Formations.

10.3.1 Tongeren Formation

This unit comprises sandstones and clays with thin intercalations of sand and brown coal. The formation is found in the middle and north of South Limburg (Kuyl, 1975). The northern boundary is situated in the Roer Valley Graben but cannot be precisely localised because too few well-log data are available. The thickness, a maximum of 50 m, decreases in a northerly direction. The age ranges from latest Eocene to Early Oligocene.

At the base of the Tongeren Formation, the *Klimmen Member* can be distinguished. This member comprises marine, argillaceous sandstones, passing into very fine, micaceous, sandstones. These are overlain by the *Goudsberg Member*, which is composed of clays where thin layers of brown coal and argillaceous sand are found. This succession, which frequently contains gastropod shells (including abundant *Cerithium* shells), is a lagoonal to continental deposit.

10.3.2 Rupel Formation

The Rupel Formation consists of, marine, dark brownish-grey clays with intercalations of argillaceous, glauconitic sands. At the bottom, sands are encountered. The topmost part of the formation also displays a sandy development. The Rupel Formation rests conformably, or separated by a small hiatus, upon the Tongeren Formation and is conformably overlain by the Veldhoven Formation or, where this has suffered erosion, by the Breda Formation or young, Quaternary deposits. The formation is found throughout the map sheet area with the exception of the south of South Limburg. The thickness of the formation in South Limburg is 40 to 80 m thick, gradually increasing to over 100 m towards the north. The formation is of Early Oligocene age.

The succession containing sands at the base of the Rupel Formation is attributed to the *Vessem Member* (Van Adrichem Boogaert & Kouwe, 1993-1997). In South Limburg, a tripartition has been made in this sequence (Kuyl, 1975; Rijks Geologische Dienst, 1984), from bottom to top the Berg Sand Member (grey, fine to coarse sands), the Kleine Spouwen Member (argillaceous sands and sandy clays, formerly the Nucula Clay Member) and the Waterval Member (glauconitic, fine-grained sands). Overlying this is the *Rupel Clay Member.* This is chiefly an argillaceous succession with intercalations of sandy clays and argillaceous, glauconitic sands. The quantity of sand in this sequence decreases in a northerly direction. It contains layers with characteristic calcareous concretions (septaria). In the specific South Limburg stratigraphy, this unit is known as the Boom Clay. The sandy development at the top of the Rupel Formation forms the *Steensel Member.* It consists of sandy clays which upwardly pass into fine, glauconitic sands. This succession is only found where the uppermost part of the Rupel Formation has been preserved from subsequent erosion.

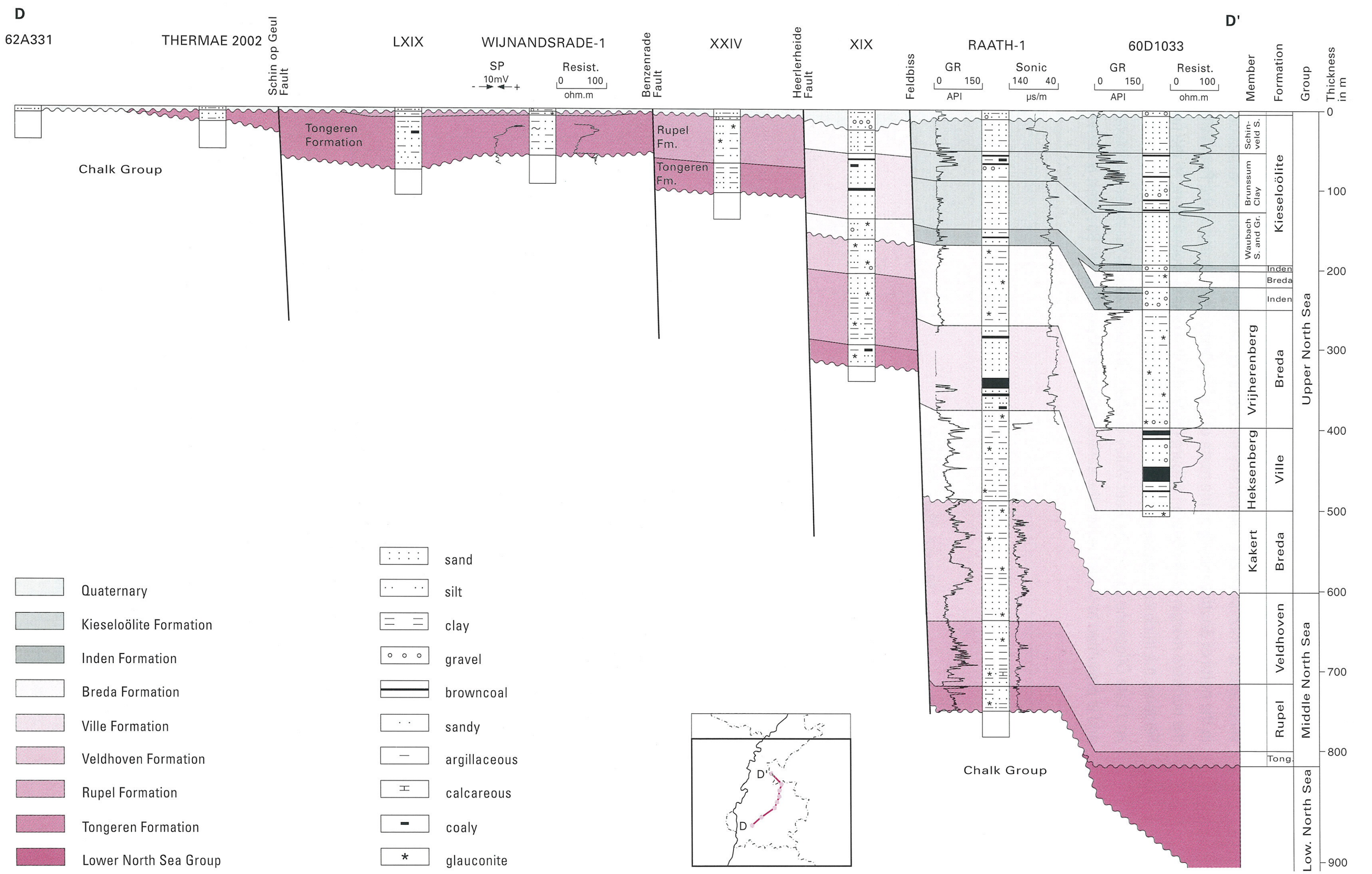


Figure 10.2 Stratigraphic section D-D' of the North Sea Super Group between the 62A331, Thermae 2002, LXIX, Wijnandsrade-1, XXIV, XIX, Raath-1 and 60D1033 wells. The reference-level is the top of the Upper North Sea Group.

10.3.3 Veldhoven Formation

The Veldhoven Formation consists of an alternation of marine, often shell-rich sands and clays. The bottommost part is the sandiest. The formation conformably succeeds the Rupel Formation and in the map sheet area is unconformably overlain by the Breda Formation. The Veldhoven Formation is encountered in the north of South Limburg to the north of the Heerlerheide Fault and in the Roer Valley Graben. On the northern margin of the South Limburg Block, the thickness is around 50 m. To the north of the Feldbiss, the thickness increases step-wise and exceeds 150 m in the Roer Valley Graben. The formation is of Late Oligocene age. In the Roer Valley Graben, the unit exhibits the most complete development and is presumed to continue into the earliest Miocene (Van Adrichem Boogaert & Kouwe, 1993-1997).

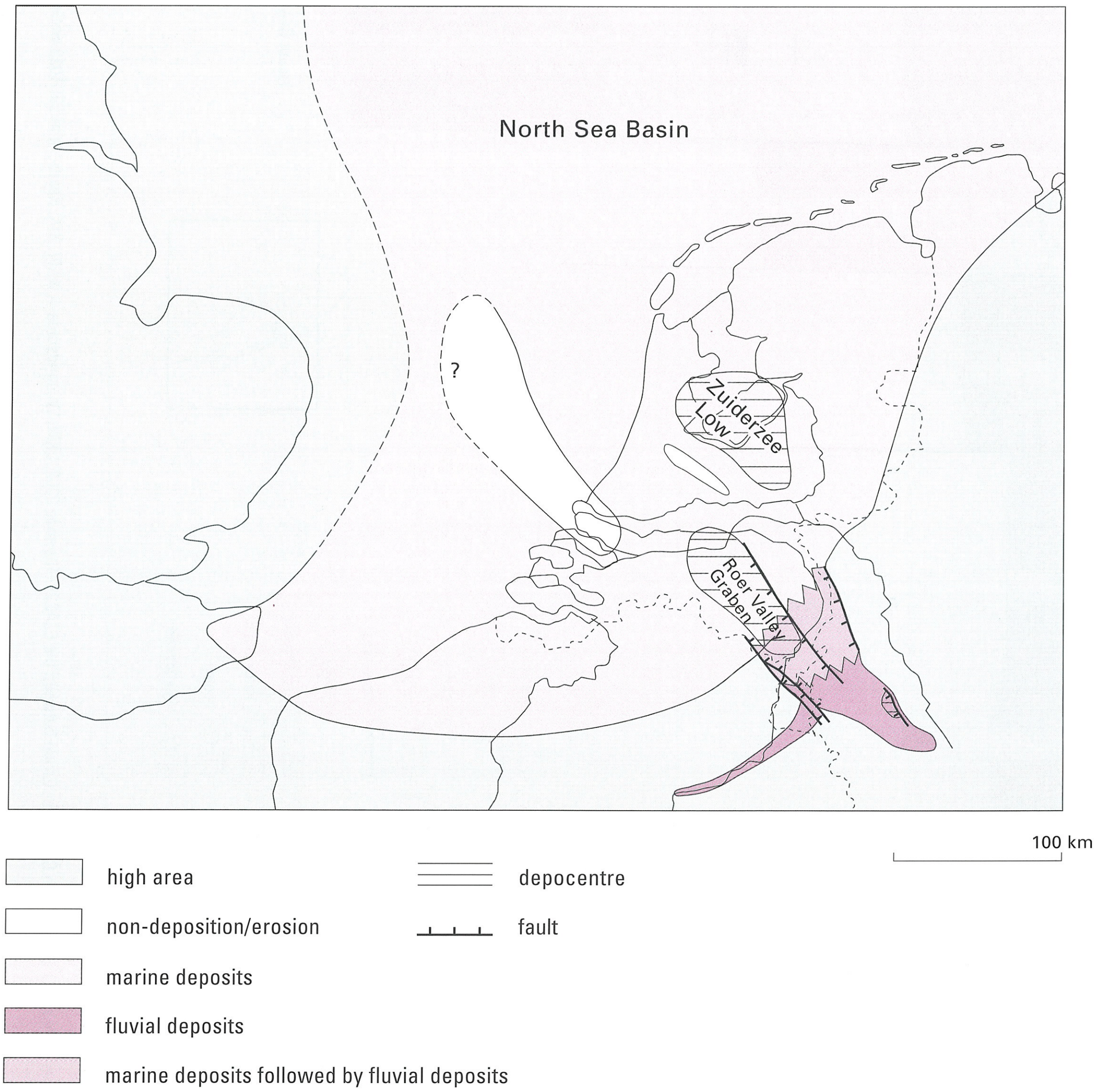


Figure 10.3 Palaeogeographic map of The Netherlands and surroundings during the Late Miocene (with data derived from Zagwijn & Doppert, 1978, Zagwijn, 1989 and Van den Berg, 1996). The southeast of The Netherlands is characterised by a fluvial system of the old Maas and the old Rhine with a northwesterly prograding delta.

At the base of the Veldhoven Formation in the study area, the *Voort Member* can be distinguished. This member consists predominantly of sands with a few argillaceous layers. The immediately overlying part of the formation comprises an alternation of argillaceous and sandy sequences, each with a thickness ranging from ten to several tens of metres. A full subdivision of the part higher up in the Veldhoven Formation into the *Veldhoven Clay Member* and the sandy *Someren Member*, as identified further to the northwest in the Roer Valley Graben (Van Adrichem Boogaert & Kouwe, 1993-1997), is not clearly distinguishable in this area.

10.4 Upper North Sea Group

Deposits of the Upper North Sea Group occur throughout the map sheet area. In the south of South Limburg, however, they are restricted to a thin, interrupted covering layer of Quaternary, fluvial and aeolian sediments, as well as to erosional products of the Cretaceous (clay with flints) and other eluvial deposits (Kuyl, 1980). Further to the north, these cover the older part (Miocene and Pliocene) of the Upper North Sea Group. The shallow subsurface geology of South Limburg has been delineated in the geological overview maps (Rijks Geologische Dienst, 1984, 1988, 1989) and is also discussed extensively in the "Toelichting bij de Gologische Kaart van Nederland 1:50 000" (inter alia, Kuyl, 1980). Outcrops of this subgroup are discussed in these maps.

The older part of the Upper North Sea Group, with the exception of the young Quaternary (cover sand, loess, brook and river deposits), which rests unconformably upon the Middle North Sea Group, is illustrated in Map 12, which shows the depth to the base (base of the Breda Formation). The southern extent has here, too, been determined by erosion. The thickness of the group in the map sheet area ranges from zero to 900 m. The age is from Early Miocene to the present time.

In the Upper North Sea Group, the marine Breda Formation and the continental Ville, Inden and Kieseloölite Formations can be distinguished, succeeded by five Quaternary formations (Kuyl, 1980) which are beyond the scope of the explanation to this map sheet.

10.4.1 Breda Formation

The formation comprises marine, glauconitic, greenish-grey to greenish-black sands (shell-rich in places), sandy clays and clays. In the study area, they rest unconformably upon the Rupel Formation or, to the north of the Heerlerheide Fault in the west of the area and to the north of the Feldbiss, upon the Veldhoven Formation. In Limburg, the Breda Formation interfingers with the continental Ville and Inden Formations, which display their maximum development further to the east in the Lower Rhine Bight (Fabian, 1958; Hager & Prüfert, 1988; Van Adrichem Boogaert & Kouwe, 1993-1997).

The position of occurrences of the Breda Formation can be seen on Map 12. The thickness (including the Heksenberg Member) ranges from 0 to over 200 in the south of the area of distribution. To the south of the Feldbiss and the 1st NE Mainfault, in the Roer Valley Graben, the thickness increases very sharply step-wise to approximately 700 m. The Breda Formation is of Miocene age.

In South Limburg, a tongue of continental deposits (Heksenberg Member) divides the Breda Formation into two parts. The bottommost part is the *Kakert Member*, the uppermost part, the *Vrijherenberg Member*.

10.4.2 Ville Formation

The Ville Formation in the map sheet area is composed of littoral and continental sands with two intercalations of brown coal with a thickness that may reach several tens of metres. The thickness of the brown coals increases in a northerly direction.

In the map sheet area, the formation occurs as a tongue in the Breda Formation and is called the *Heksenberg Member*. In South Limburg, the thickness is a maximum of 90 m (Kuyl, 1975). The brown-coal occurrences of the Morken Seam can be distinguished at the bottom of the member and the Frimmersdorf Seam at the top. The sands beneath the Morken brown coal have developed locally as pure quartz sand (silver sand, with < 0.01% Fe_2O_3 and < 0.025% Al_2O_3) (Kuyl, 1973; Collaris, 1989). They have been mined in two quarries on the Heksenberg in the vicinity of Heerlerheide. The Heksenberg Member can be found as far as the east of Noord-Brabant and the north of Limburg (Peel Block). The age is Early to Middle Miocene.

10.4.3 Inden Formation

In the study area, the Inden Formation consists of littoral and continental sands and a few clays, and contains two brown-coal intercalations. Further to the east, in Germany, the formation may consist entirely of brown coal (Zagwijn & Hager, 1987). The formation is only encountered in the Roer Valley Graben, where it forms a wedge in the marine Breda Formation, extending much less further to the westnorthwest than the Heksenberg tongue. The western boundary has not been precisely identified.

In the map sheet area, the Inden Formation attains a thickness of several tens of metres. Within the formation, the brown coals of the Friesheim Seam and the Schophoven Seam can be identified. The formation is of Late Miocene age.

10.4.4 Kieseloolite Formation

This formation is a continental deposit, whose bottommost part comprises fluvial, coarse sands and gravels, and the uppermost part clays and sands. The Kieseloolite Formation is found mainly to the north of the Feldbiss. The thickness increases rapidly from some tens of metres in a northerly direction step-wise in the vicinity of the large northwest faults, to over 200 m in the Roer Valley Graben. To the south of the Feldbiss, erosional relics of this formation, consisting entirely of gravels, are found locally, particularly in the vicinity of Nieuwenhagen and to the southeast of Sittard and Ubachsberg.

To the north of the Feldbiss, the Kieseloolite Formation rests unconformably upon the Breda Formation or the Inden Formation. The erosional relics to their south rest upon the Ville Formation (Heksenberg Member), Tongeren Formation or Gulpen Formation, separated by a hiatus increasing in a southerly direction. The Kieseloolite may be covered, partly conformably by Early Pleistocene and partly unconformably by Late Pleistocene deposits.

The age of the Kieseloolite Formation is Late Miocene to Late Pliocene (Van Adrichem Boogaert & Kouwe, 1993-1997).

In the map sheet area, the *Waubach Sand and Gravel Member* is distinguished at the bottom of the Kieseloolite Formation. In places, clays are still encountered in this member. The gravel contains a small quantity of oolitic chert concretions. The Waubach Member is succeeded by the *Brunssum Clay Member*, composed of heavy clays with numerous brown-coal intercalations and a sand tongue (*Pey*

Sand), and the *Schinveld Sand Member*, that mainly comprise fine sands with a few clay intercalations (Doppert et al., 1975).

10.4.5 Quaternary formations

The Quaternary formations in southern Limburg are thin, clastic deposits of variable grain size, reflecting a complex fluvial and peri-glacial geology (Kuyl, 1980; Rijks Geologische Dienst 1988, 1989). In the tectonically uplifted area to the south of the Feldbiss, river terraces were formed. To the north of this fault, along which a terrace intersection occurred, subsidence of the surface prevailed. Here, in the Roer Valley Graben, the thickness of the Quaternary formations may increase to over 150 m.

10.5 Sedimentary development and palaeogeography

During deposition of the North Sea Supergroup, the map sheet area lay on the southeast margin of the North Sea Basin. Deposition of the supergroup was to a considerable extent controlled by eustatic sea-level changes (Haq et al., 1987) and local tectonics.

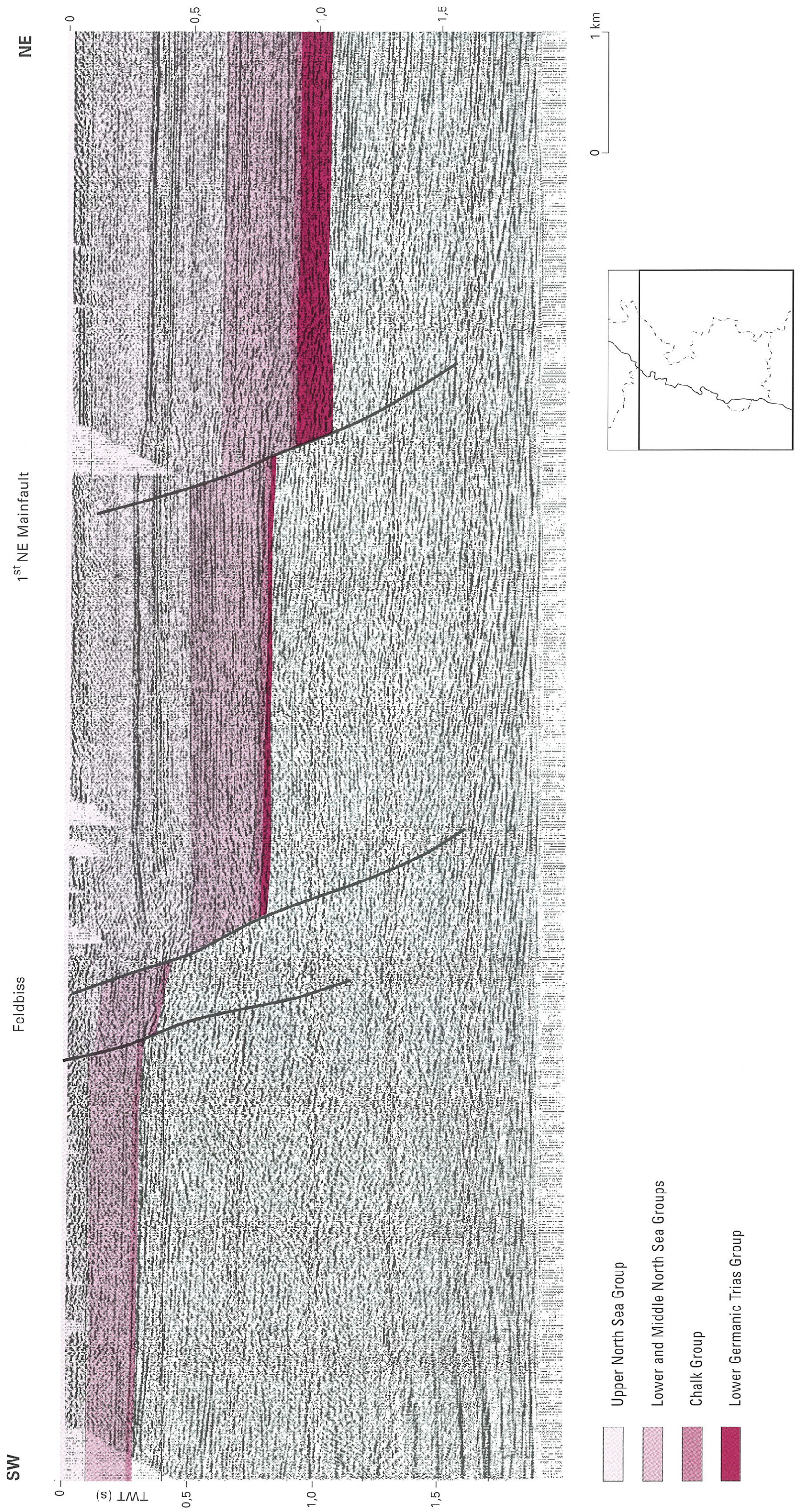
In the southeast of The Netherlands and surroundings, lacustrine and lagoonal deposits were formed initially, preceding marine sedimentation (Swalmen Member). The deposition of marine sands and clays (Landen and Dongen Formations) continued into the Late Eocene, with a few interruptions mainly perceptible along the basin margins in response to sea-level fluctuations.

After a period of uplift and erosion resulting from the Pyrenean phase, the sea reached the area once again at the end of the Eocene, during which shallow-marine sands were initially deposited (Klimmen Member). During the earliest Oligocene, the sea level fell favouring lagoonal conditions in the map sheet area (Goudsberg Member), and subsequently rose again, to achieve a full-marine depositional environment during the deposition of the Rupel Formation. During the maximum high stand, the Rupel Clay was deposited, displaying a partly bituminous development. Finally, at the end of the Early Oligocene, the sea level dropped once more, favouring the deposition of sandy sediments in the study area (Steensel Member).

Deposition of the Veldhoven Formation (Late Oligocene) was again characterised by a succession of sea-level rises and falls. The margin of the sedimentation basin lay close to southern Limburg, with the result that a considerable amount of sand was able to reach the map sheet area (Voort Member). After the clay sedimentation finally predominated (Veldhoven Clay Member), sands were once again deposited during the regressive phase (Someren Member).

Deposits of the Breda Formation, which marked the resumed sedimentation during the Miocene, comprised marine, glauconitic sands and clays. They were initially confined to the Roer Valley Graben, but rapidly extended to the more elevated, flanking blocks (Zagwijn, 1989). Further to the southeast, in the Lower Rhine Bight in Germany, fluvial sedimentation, which had commenced in the Oligocene (Köln Formation), occurred in the Miocene (Ville and Inden Formations). In the deltaic transitional area towards the marine realm lying further to the west, marine marshes with mangroves developed, where widespread peat formation took place (Zagwijn & Hager, 1987). A palaeogeographic map of that time is given in figure 10.3. The combination of relative surface subsidence and plant growth in a warm and humid climate favoured the formation of very thick sequences of brown coal (for example the Morken and Frimmersdorf Seams which are tongues of a massive brown-coal sequence exceeding 100 m, the Hauptflöz of the Ville Formation, and the Friesheim and Schophoven Seams in the Inden Formation). During low stands, the continental deposits migrated into the marine depositional area much further to the west (for example the Heksenberg Member of the Ville Formation).

Figure 10.4 Seismic section in the north of South Limburg across the Feldbiss and the 1st NE Mainfault (RGD line 81-04).



The Late Miocene and the Pliocene were marked by a vigorous regression in the Lower Rhine Bight. The Kieseloolite Formation resulted. Sand and gravel deposits in a protruding delta of the old Rhine, with braided and meandering streams, penetrated far into the Roer Valley Graben, also reaching the Venlo Block (Waubach Sands and Gravels and Schinveld Sands). Mainly in the Pliocene, this fluvial area was characterised by lakes, where clay and, from time to time, peat accumulated (Venlo Clay, Brunssum Clay and Reuver Clay). The eastern part of the South Limburg Block was flooded by the old Maas, accompanied by gravel deposition.

Not till the beginning of the Quaternary did the Maas reach southern Limburg. At first, the river followed a more easterly course (to the south and east of the Ubachsberg Massif (the East Maas). Later in the Early Pleistocene (from the Eburonian onwards) the course of the Maas diverted to the west of this massif (West Maas: Kuyl, 1980; Rijks Geologische Dienst 1989) consequent to a structural tilting of the area.

The uplift of the hinterland, which resulted in the Late Miocene and Pliocene regression, increased sharply at the beginning of the Pleistocene. For the South Limburg Block, Van den Berg (1994) calculated a rate of uplift 20 times as great as that in the preceding period. In the interaction between uplift, sedimentation and erosion in a climate of alternating glacial and interglacial periods, 20 terraces were formed by the river Maas in South Limburg (Rijks Geologische Dienst 1989), when river gravel was deposited during the cold periods and erosion and incision took place during the warm periods (Van den Berg, 1996). The oldest terraces are topographically the most elevated. In the vicinity of the Feldbiss, an intersection of terraces occurred. To the north of this major fault, surface subsidence prevailed and a normal, fluvial succession was deposited. Peri-glacial conditions in the middle and Late Pleistocene favoured the deposition of aeolian sediments (loess and cover sand) over a wide area.

11 Geological history

11.1 Introduction

This chapter describes the geological history of the map sheet area, from the Cambro-Silurian to the Quaternary. The data on the Cambro-Slilurian and the Devonian in the map sheet area are scarce. For these periods, the description is based entirely on publications on the surrounding areas. For details of the Quaternary of Limburg, reference should be made to the publication by Zagwijn (1989), the geological map, map sheet Heerlen (Kuyl,1980) and the shallow surface map of South Limburg (Rijks Geologische Dienst, 1988).

The geological history of each subsequent period is illustrated by the different tectonic phases that were active in the map sheet area (fig. 1.8). During the Early Palaeozoic, these phases were the Ardennian and Acadian phases, characterised by compressive forces. In the Devonian up to the earliest Carboniferous, this was the pre-Variscan Bretonian phase, with only a slight effect on the area in the vicinity of the Brabant Massif. During the Late Carboniferous and earliest Permian, the following compressive phases, in succession, can be identified: the Sudetic, Asturian and Saalian phases of the Variscan orogeny, related to the forming of the Variscan Mountains in Western and Central Europe. The Late Triassic to earliest Cretaceous period was marked by the Kimmerian extensional tectonic phases, which were responsible for the formation of major structural units in the Mesozoic. The Sub-Hercynian and Laramide phases of the Alpine orogeny, during the Late Cretaceous and earliest Tertiary, displayed a compressive stress field, causing a brief change (inversion) in the direction of movement of the major structural elements. Later compressive episodes during the Tertiary are associated with the Pyrenean and Savian phases of the Alpine orogeny. The compressive deformation reflects the collision between Africa and Europe. The resulting uplift of the Alps had a pronounced effect on the supply of sediment. Besides the tectonic phases, climate changes and consequent sea level fluctuations (Haq et al., 1987) were the determining factors in the development of the area.

The position of the map sheet area in a regional context is depicted in figure 11.1. The major tectonic structures discussed in this chapter are illustrated in figure 1.9.

11.2 Basin development, sedimentation and tectonics

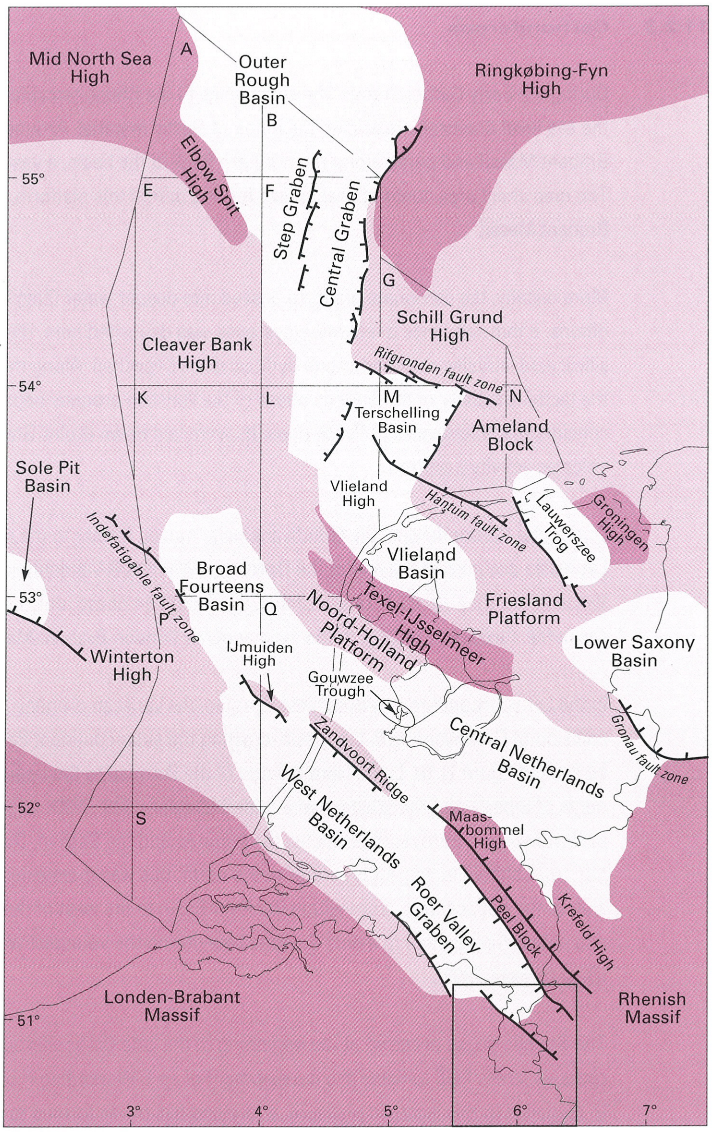
11.2.1 Cambro-Silurian

After the Cadomian orogeny, at the end of the Precambrian, the palaeogeography of the area where later Northwestern Europe would be situated, was determined by the continents of Laurentia-Greenland in the west, separated by the Iapetus Ocean from Baltica in the southeast, and Gondwana, a large continent situated in the south, comprising subsequent South America, Africa, Antarctica and Australia (Scotese & McKerrow, 1990). There are many interpretations of the complex movement of the lithosphere plates over the globe during the early Palaeozoic (Wouters & Vandenberghe, 1994), owing to the lack of outcrops and the considerable depth of rocks involved. The rough pattern of likely development is outlined below.

During the course of the Early Palaeozoic, the Gondwana plate moved gradually to the north. Parts of this lithospheric plate broke off and formed microcontinents, including Avalonia. The Rheic Ocean opened between these plate sections and Gondwana, and between Avalonia and Baltica lay the Tornquist Sea. Figure 11.2a depicts the position of the continents and oceans during the Ordovician. On eastern Avalonia lay the area comprising present-day southern England to northern Germany (Robardet et al., 1994), in other words the area of which this map sheet forms a part. The small lithospheric plates (microcontinents) moved relatively more rapidly towards the north, in the direction of Baltica.

Simultaneously, the oceanic Iapetus plate gradually subducted beneath the flanking continents, causing a narrowing of the Iapetus Ocean. The collision of Avalonia and possibly other microcontinents with Baltica at the end of the Ordovician, after closure of the Tornquist Sea, is demonstrated by the Ardennes phase of the Caledonian orogeny, initiating folding and uplift of the Cambro-Ordovician Ardennes Basin (Wouters & Vandenberghe, 1994; the 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. Ultimately 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), London High connected itself 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 map sheet area.

Figure 11.1 Overview map of the main structural elements in The Netherlands during the Mesozoic (after van Adrichem Boogaert & Kouwe, 1993-1997). The position of the map sheet area has been outlined.



11.2.2 Devonian

During the Caledonian orogeny (Cambrian-Silurian) 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). This basin, in virtually the same form, continued to be a pronounced region of subsidence until the Late Carboniferous. Owing to an increase in surface subsidence and a cyclical rise in sea level, the area of sedimentation extended significantly during the Middle and early Late Devonian (fig. 3.1). The Late Devonian was marked by a global sea-level fall. Particularly during the Late Devonian, continental sedimentation occurred on the Old Red Continent over a large area.

During the Devonian, the map sheet area was situated on the northern margin of the Rhenohercynian Basin in a position to the east of the London-Brabant Massif. From the Middle Devonian on, sedimentation here occurred in a shallow-marine environment.

11.2.3 Carboniferous

During the Early Carboniferous, the subsidence of the Rhenohercynian Basin persisted. A further rise in the sea level drastically restricted the influx of clastic material. Around the perimeter of the London-Brabant Massif and partly along the northern flank of the basin, a vast carbonate platform was created. The map sheet area contemporaneously formed part of this platform, just to the east of the London-Brabant Massif.

More distally, the carbonate platform passed into deeper water (Ziegler, 1990). Under starved basin conditions, a thin sequence of euxinic claystones was deposited here, often containing some carbonate or silicic acid. Initially, stratified cherts (lydites) were deposited. Along the southern margin of this basin, the tectonic activity of the Sudetic phase of the Variscan orogeny began to become delineated. Here, considerable thicknesses of flysch deposits were laid down (Kulm-Grauwacke), and, locally, submarine volcanic activity occurred.

During the Carboniferous, the Gondwana plate moved further to the north. The first contact with Laurussia occurred at the end of the Devonian (Wouters & Vandenberghe, 1994), and preluded the Variscan orogeny. An early phase of this, the Bretonian phase, only produced limited uplifts and hiatuses in the succession locally, in the vicinity of the London-Brabant Massif.

In the Late Carboniferous and earliest Permian, the Variscan orogeny proceeded with the subsequent collision of Gondwana with Laurussia, creating the supercontinent Pangaea, the contours of which can be seen in figure 11.1b. Later, from the end of the Permian to the beginning of the Triassic, the continents of Siberia and Kazakhstan were added (Ziegler, 1989, 1990), triggering three deformation phases in Northwestern Europe: the Sudetic, the Asturian and the Saalian. During these phases, the deformation front shifted increasingly further to the north; this was manifested in the successively northward shift of the depocentres, from within the Ruhr Basin to the west of the map sheet area in the Namurian and oldest Westphalian to inside the Ems Low during the youngest Westphalian and Stephanian (Drozdzewski, 1992).

The Sudetic phase occurred at the beginning of the Late Carboniferous. The north-south oriented compressive stress field initiated the development of an E-W trending mountain chain transecting Europe. In response to this isostatic pressure, a foreland basin was formed to the north of this fold belt (fig. 5.4) following drastic subsidence at the beginning of the Late Carboniferous. This basin became the depocentre of erosion products from the fold belt, deposited as a thick sediment succession. Initially, during the Namurian, this consisted of deep-marine clays, sometimes rich in organic material. The basin gradually became shallower and the marine environment passed into a continental environment. 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, were 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 prevailed during the Westphalian D, when the Asturian deformation phase began to manifest itself. This resulted in the deposition of sandstones predominantly, 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. This is reflected in the red colour of the youngest Westphalian and the Stephanian deposits.

The Asturian and Saalian deformation phases initiated the northward migration of the Variscan orogenic front, at the end of the Westphalian, causing the deposits in the foreland basin to become strongly folded and to move northwards, along low-angle overthrust planes, including the prominent Aken Thrust directly to the southeast of the area studied (fig. 11.3). To the north of this, strong folding with over-

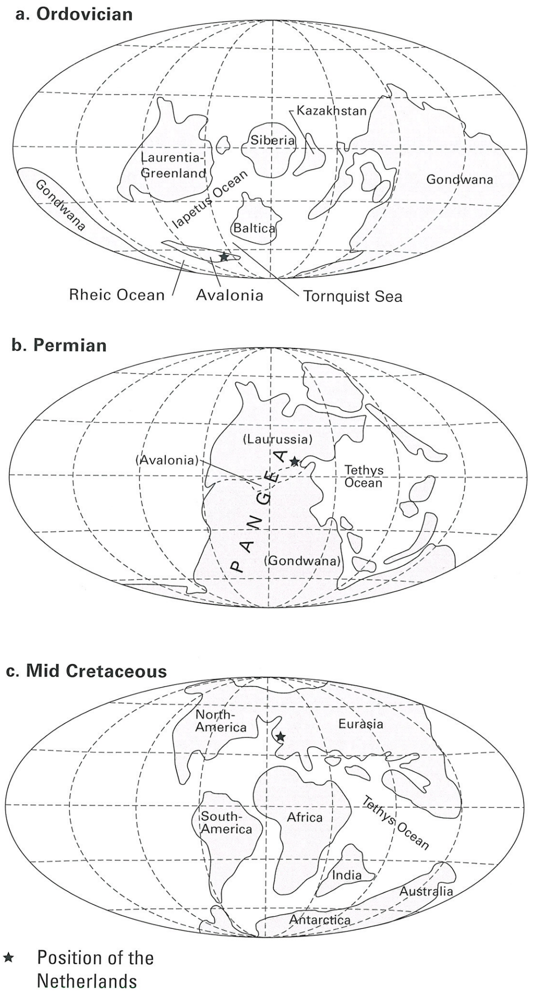


Figure 11.2 Position of the continents and oceans during the Ordovician, Permian and Middle Cretaceous. After Scotese & McKerrow (1990) and Scotese (1991). In the middle figure, the elements of which Pangaea is composed are given in brackets.

thrusts occurred right up to the Willem-Adolf Fault (fig. 4.2). The northern boundary of the Variscan front could therefore be set at this fault. Further to the north, the pattern is tectonically less disturbed, and is characterised by fault tectonics with upward and downward moving blocks. As a result of the northwardly migrating deformation front, no sedimentation occurred in the Campine Basin during the Stephanian.

The Variscan tectonic structures are mainly SW-NE oriented. The folds are asymmetric, with long, gentle southeast-flanks and short, steep, sometimes overturned, northwest-flanks, and the main faults, often with a wide deformation zone and pronounced differences in throw, are largely developed as reverse faults (Patijn, 1963; Kuyl, 1980; Rijks Geologische Dienst 1995). All these structures were not manifested at the level of the present pre-Permian abrasion surface. In addition, a few fold structures are found: the SW-NE oriented Waubach Anticline and the almost north-south oriented anticlines of Ham, Puth and Visé. Wrede (1987) attributes this divergence in direction of strike to a deflection in the southeast-originating pressure to a westerly direction along the rigid austere eastern edge of the Brabant Massif. As post-Palaeozoic movements in these structures have also been established, partly on geophysical grounds, arguments have been put forward to suggest the influence of halokinesis in their formation (Bless et al., 1986).

The Saalian deformation phase during the Stephanian and the earliest Permian is the last phase of the Variscan orogeny. During this phase, the compressive stress-field was succeeded by E-W trending extensional changes. To the north of the Variscan Mountains, NW-SE and WE oriented fault systems developed with dextral transverse movements (Ziegler, 1990).

The Asturian phase made a considerable impact on the map sheet area. The effect of the Saalian phase cannot be separately determined. The subcrop map of the pre-Permian surface (fig. 4.2) shows that profound erosion in the southwest of the map sheet area even reached the Devonian. This pattern is, however, the cumulative effect of all the erosion that has occurred since the Asturian phase, during which a succession thousands of metres thick was removed (Veld et al., 1996; section 12.1).

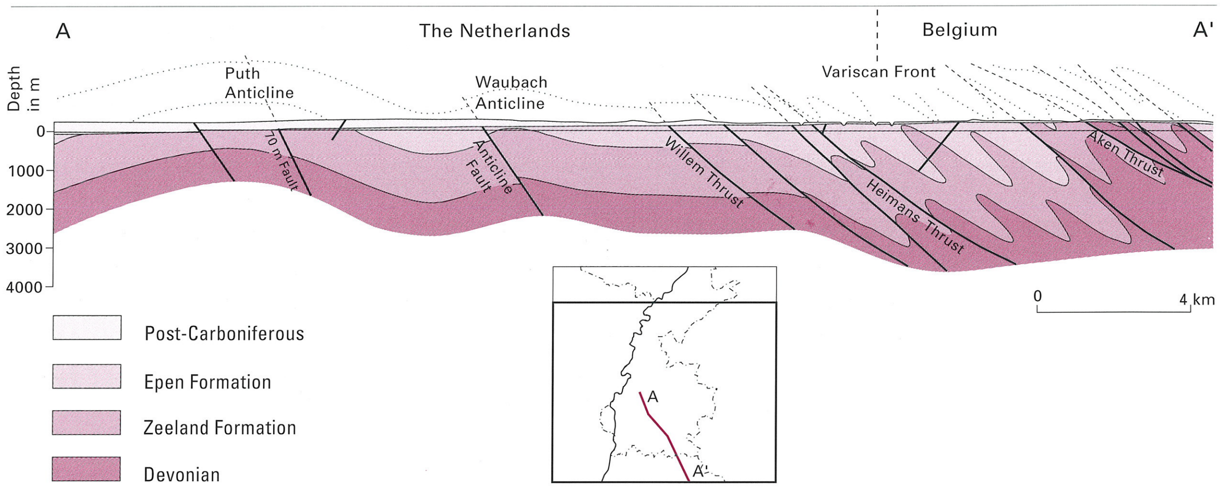


Figure 11.3 Structural section across the Variscan front, from Valkenburg to Moresnet (after Rijks Geologische Dienst, 1995).

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.

11.2.4 Permian

At the end of the Saalian tectonic phase in the Early Permian, a vast landmass was formed. Intensive wrench-deformation of this area during the Early Permian induced extensive volcanic activity in Germany and further deformation of other areas in the Variscan hinterland (Ziegler, 1990). 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 Southern Permian Basins (fig. 11.4). In the 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). In the central and westerly North Sea area, the sedimentation did not resume until late in the Late Permian, with the deposition of the Upper Rotliegend Group.

During the Early Permian and a large part of the Late Permian, the map sheet area lay to the south of the Southern Permian Basin. This long period was marked by severe erosion of the Carboniferous deposits, which produced the present subcrop pattern (fig. 4.2). As a result of the Asturian and Saalian phases together, in the middle and south of the map sheet area erosion removed a sediment succession 2900 m thick (in the vicinity of Sittard) to 5400 m thick (in the southeastern part of South Limburg) (Veld et al., 1996; see section 12.1.).

Graben formation in the North Atlantic/Arctic area combined with a eustatic sea-level rise as a consequence of the melting of the Gondwana ice cap initiated the forming of an open connection between the Arctic 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, five of which have been identified in the Netherlands. Major transgressions mark the bases of the different cycles. To some extent, these transgressions reached the extreme north of the map sheet area, where a thin facies margin developed with clastic rocks and shallow-marine carbonates.

The transgressions characterising the Zechstein formations favoured normal marine conditions during the first three cycles, but during the Z4 (Aller) Formation a transition to continental sedimentary conditions occurred. At the end of the Permian, a changeover in sedimentary environment took place; evaporites were superseded by lacustrine claystones and siltstones. These clastics originated from a southerly direction. The Zechstein Upper Claystone Formation, which forms the transition to exclusively clastic conditions, rests on older deposits of the Zechstein Group, separated by a hiatus.

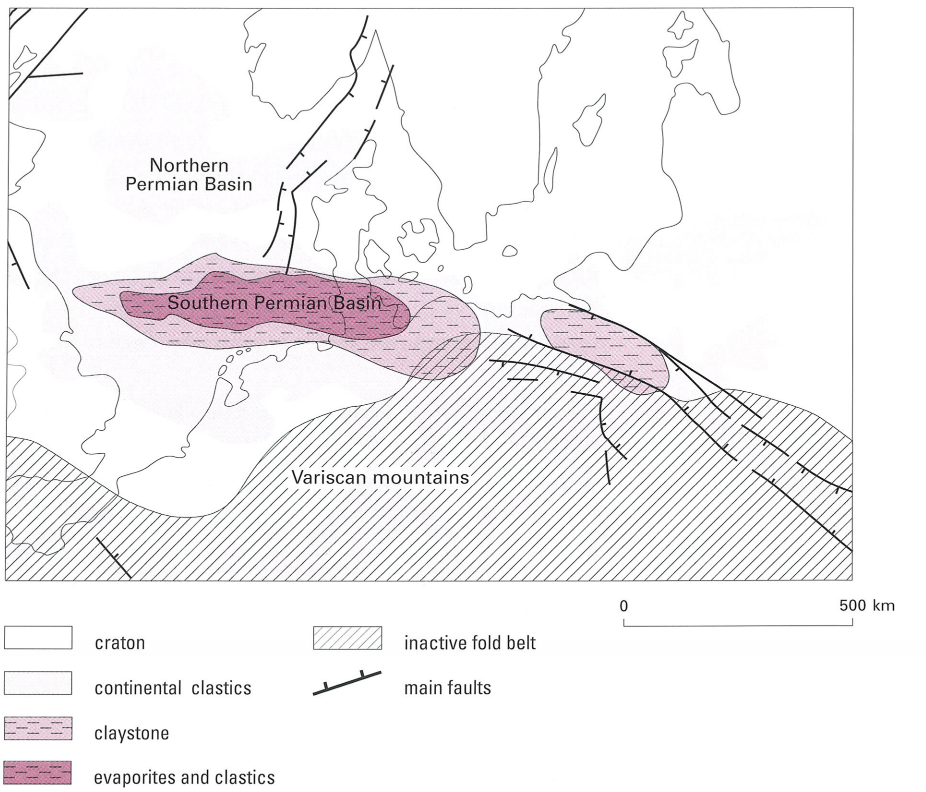
11.2.5 Triassic

The Triassic was characterised initially by extremely uniform basin subsidence. The Southern Permian Basin continued to exist in essence and is therefore often referred to as the Permo-Triassic Basin. The sedimentation area extended southwards, as a result of which the map sheet area became positioned on the southern margin zone of the basin. The Triassic is characterised by two phases of extensional tectonics (Ziegler, 1990). The clastics transported during the Triassic largely originated from the Variscan Mountains.

Sedimentation in a large part of the North European depositional area initially occurred in a lacustrine to playa environment. Along the southern boundary, however, more proximal, fluvial sands and conglomerates developed (see fig. 7.4). 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). During the Early Triassic, several Variscan tectonic elements were reactivated during the Hardegsen phase. This induced intensive erosion of the Netherlands Swell and minor erosion of the areas of subsidence such as the Ems Low and the Off-Holland Low.

The Hardegsen phase was followed by a long period of incipient thermal subsidence, which was to persist until the Middle Keuper (Carnian). During the latest Scythian, fluvial and lacustrine deposits of the Solling Formation covered the basin area like a blanket. The Early Triassic structures, such as the Ems Low and the Netherlands Swell, subsided uniformly. During the Middle Triassic, the Permo-Triassic Basin achieved a connection with the open ocean. A net sea-level rise facilitated a slow transgression in

Figure 11.4 Palaeogeographic map of Northwestern Europe at the beginning of the Late Permian, showing the position of the Southern Permian Basin (after Ziegler, 1990).



the basin from the east (Haq et al., 1987). During this transgression, the influx of sea water stagnated a number of times, culminating in wide-scale deposition of evaporites throughout the Permo-Triassic Basin.

During the Middle Anisian, a normal marine environment was established in the east and centre of the basin. From the Tethys Ocean, situated to the east of Pangaea (fig. 11.2b), the sea invaded this basin via an opening rift system (Ziegler, 1990). The highs were flooded by the sea and the decrease in supply of clastic material favoured the deposition of carbonates, marls and evaporites from the Late Anisian to Ladinian (Muschelkalk Formation). It is supposed that deposition of these marine deposits also occurred in the map sheet area, partly in a marginal facies. A regression during the Late Triassic (Late Ladinian/Norian) brought a return to continental conditions (Keuper Formation). In the study area, Muschelkalk and Keuper deposits have been preserved in the Roer Valley Graben.

During the Norian (Late Triassic), a tectonically highly active period commenced which was to continue until the earliest Cretaceous. This period was characterised by the disintegration of Pangaea, when the Tethys Ocean opened further and the opening of the northern Atlantic Ocean commenced (Ziegler, 1990). A number of large-scale extensional phases can be identified. These "Kimmerian" phases dominated the Mesozoic tectonic development of Northwestern Europe. They are reflected by major hiatuses in the stratigraphic succession.

The first of these phases, the Early Kimmerian tectonic phase, initiated pronounced differentiation in surface movements in the area. Regionally, uplift induced substantial erosion (Geluk et al., 1996). The effect on the study area is not known. At the end the Triassic (Rhaetian) a distinctive transgression occurred. Marine sediments covered the virtually entirely eroded, continental surface.

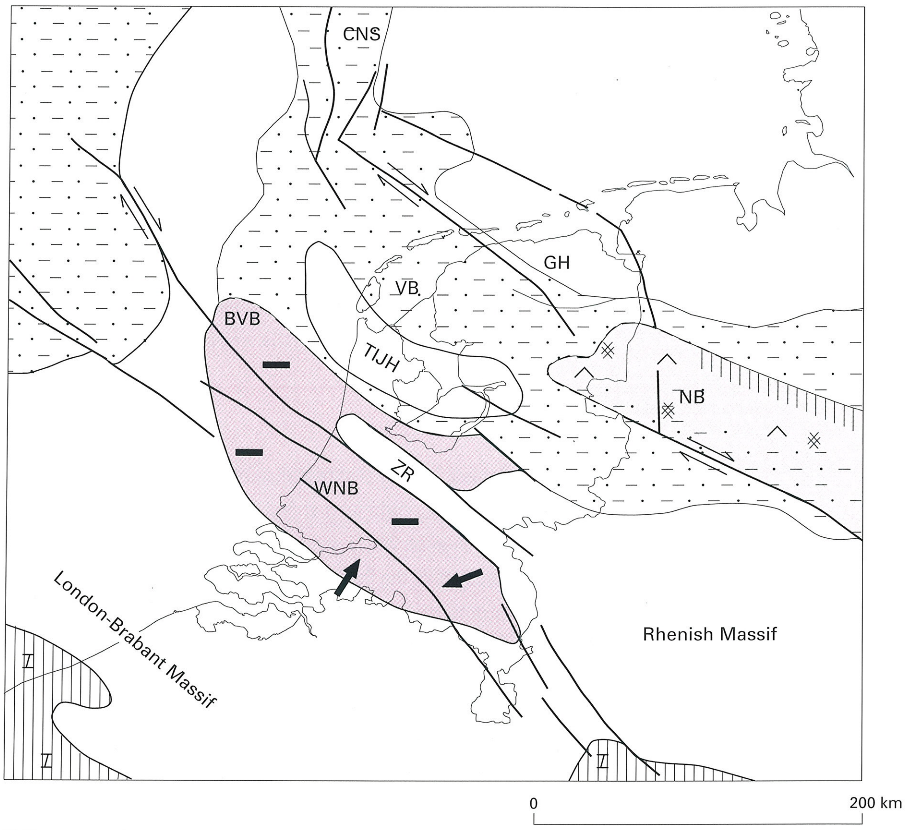
11.2.6 Jurassic

During the Jurassic, regional subsidence of a large part of northern Europe, which had commenced at the end of the Triassic, continued at first. Via a rift system, a connection with the Arctic Sea was established. In combination with a sea-level rise, this 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, which can be inferred from the uniform composition and the fine-grained character of the deposits. To the east and the west of the map sheet area, highs were present in this marine basin - the Rhenish and Brabant Massifs. Their influence on the sedimentation was, however, minimal. At the end of the Early Jurassic, 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 sediments in large parts of Northwestern Europe during the Toarcian.

Little is known about the Middle Jurassic owing to a large hiatus in the sedimentary succession. In response to the Mid Kimmerian tectonic phase during the Middle Jurassic (Aalenian-Bathonian), several areas were uplifted. The effect of the uplift was intensified by a contemporaneous sea-level fall (Haq et al., 1987). The marine basin area became smaller, with the result that the map sheet area, which was still governed by marine conditions during the Early Jurassic, became terrestrial during the course of the Middle Jurassic.

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 at the southern end was accommodated by transtensional dextral strike-slip movements along a system of reactivated NW-SE-trending fault systems. This was partly caused by the rigid Late Kimmerian Brabant Massif (Vercoutere & van den Haute, 1993), which impeded southwards progradation. It was also a consequence of the presence of a zone of relative weakness, an originally Variscan (possibly even Caledonian) fault system, to the north of this massif. The result was the formation of a number of NW-SE-trending basins and highs, parallel to the London-Brabant Massif (fig. 11.5; Ziegler, 1990). Of these, the Roer Valley Graben in particular, with its flanking high blocks, is of significance for the geological structure of the map sheet area (Geluk et al., 1994). In the Late Jurassic, continental sediments were formed in this graben, to the northwest of the area studied. Erosion took place on the more elevated blocks, which, in the south of the area studied, was added to the erosion which had previously occurred subsequent to the Sudetic phase, the result of which can be seen in the subcrop pattern in Map 13 and figure 4.2.

Figure 11.5 Palaeogeographic map of The Netherlands and surrounding area during the Late Jurassic (after Ziegler, 1990).



BVB	Broad Fourteens Basin		
CNS	Central North Sea Graben		continental deposits
GH	Groningen High		coastal, shallow marine clay- and sandstones
NB	Lower Saxony Basin		evaporites
TIJH	Texel-IJsselmeer High		shallow marine claystones and carbonates
VB	Vlieland Basin		main faults
WNB	West Netherlands Basin		wrench faults
ZR	Zandvoort Ridge		clastic influx

11.2.7 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 probably a response to the increased rates in spreading of the ocean floors 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 favoured an accentuation of the relief around the basins and other regional uplifts in NW Europe. In the map sheet area, the flanks of the Roer Valley Graben were upheaved. Subsequently, the differential surface movements decreased. The Late Kimmerian erosional surface was covered with marine sediments by the sea transgressing southwards during the course of the Early Cretaceous, and in the aforementioned basin areas, continental sedimentation was succeeded by marine sedimentation.

During the Aptian, a brief regression took place, associated with the Austrian tectonic phase (Ziegler, 1990). This was followed by a continuation of the Cretaceous transgression, the effect of which, together with regional subsidence, was that by the beginning of the Late Cretaceous, the coastline had migrated to the centre of The Netherlands. This Albian transgression is identified throughout Western Europe and attributed to a pronounced sea-level rise.

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. The subsequent proportional decrease of terrigenous clastic material was the reason for the predominantly marine bioclastic components in the Upper Cretaceous deposits, favouring the formation of limestones. The sedimentary succession exhibits a number of unconformities and hiatuses, partly caused by salt movement and partly associated with tectonism and sea-level fluctuations.

This period of regional subsidence came to an end during the Coniacian. Europe underwent major plate reorganisation (fig. 11.2c) induced by an extensional stress regime and graben formation preceding 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 inversion affected the Roer Valley Graben in the Santonian and Early Campanian (Kuyl, 1983; Bless et al., 1987; Gras & Geluk, in press). The flanking areas encountered in the map sheet area were, however, invaded by the sea in the Late Santonian. Initially, lagoonal/nearshore conditions predominated, followed by full-marine conditions, accompanied by deposition of glauconitic sands in the Early Campanian. Not until the Late Campanian did carbonate deposition prevail in this area (fig. 9.6a, b).

In the area studied, a few Palaeozoic anticlines were slightly reactivated, in particular the Anticlines of Puth (fig. 9.7), Waubach and Visé. On or in the vicinity of these structures, the Santonian and Early Campanian (Formations of Aken and Vaals) are absent, as revealed by the isopach pattern of the clastic Upper Cretaceous in South Limburg (fig. 9.4). A notable presence in the map sheet is the WNW-ESEoriented Eys-Wittem High, which appears to be an independent development, unrelated to the fault system of the Roer Valley Graben (Kimpe et al., 1978).

The end of the Cretaceous was characterised by a relaxation of the compressive stresses. The positive relief of the Roer Valley Graben area disappeared. In the Late Maastrichtian and the Danian, this area was again submerged by the sea (fig. 9.6c). Faults, which had previously functioned as a reverse fault, again became normal faults. This structural pattern continued in the Cenozoic. In a number of large faults, such as the Benzenrade Fault, the Kunrade Fault and the Schin op Geul Fault, the resultant of the movements along these faults on the base of the Chalk is, completely or partially, the reverse of that on the base of North Sea Supergroup (Maps 9 and 11).

11.2.8 Cenozoic

After the Laramide tectonic phase, at the beginning of the Cenozoic, which was accompanied by a pronounced sea-level fall, the North Sea Basin was formed. The extensive calcareous sedimentation still present during the Cretaceous and earliest Tertiary, came to an abrupt end. During the Tertiary and the Quaternary, a rising sea level combined with continuing regional subsidence in the centre of the North Sea resulted in the deposition of over 3500 m of sediment in the centre. In the map sheet area, situated on the southeast margin of this basin, the subsidence was considerably less. This is reflected in the thickness pattern and the location of the various extensional limits of the North Sea Supergroup (Maps 11 and 12). 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)

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, which was reflected in the primary activity of the Alpine orogeny.

At the end of the Eocene, the Pyrenean tectonic phase caused an uplift of a NW-SE-oriented zone in the centre and southeast of The Netherlands, termed the Southern Early Tertiary High by Van Adrichem Boogaert & Kouwe (1993-1997). The ensuing erosion incised the most profoundly in the southeast. The Eocene is therefore absent in the map sheet area. In the Roer Valley Graben and the Peel Block, the Palaeocene Landen Formation has largely been preserved from erosion. In the earliest Oligocene, sedimentation resumed in the map sheet area, initially shallow-marine and lagoonal, and later full-marine.

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 illustrated in the well-log correlation in figure 10.2 and in the sections in Map 15. This is also indicated by the pattern of the depth of the base of the Upper North Sea Group (Map 12). 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 surroundings (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. 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 (fig. 10.3). 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 that can now be seen in the south of the map sheet area. The faults in the Roer Valley Graben system have a right-lateral component within generally extensional forces (Van den Berg, 1994).

In South Limburg, the large NW-SE-trending faults of the Roer Valley Graben system have a dip of 50 to 60 ° in the Carboniferous (Sax, 1946). The throw of the faults increases sharply from SE to NW.

12 Applied geology

12.1 Geochemistry and burial history

12.1.1 Introduction

Through the exploration and exploitation of coal in Limburg, a considerable amount of knowledge was gained on this mineral resource. Even after productive mining had ceased in the seventies, research into the characteristics of coal continued. The resumption of research in the eighties within the framework of the "Inventarisatie-onderzoek Nederlandse kolenvoorkomens" [Inventory Investigation of coal occurrences in The Netherlands] (RGD, 1986) once again resulted in a substantial amount of geological, geochemical and coal petrographic data, derived predominantly from three fully cored boreholes in the area to the north of the mine concessions in South Limburg. However, despite the long history of exploitation and the large quantity of available data, no overview of the patterns of coalification and burial history of the area as a whole has ever been made. The following is a compilation of the relevant data necessary for a reconstruction of the burial history and hydrocarbon generation.

12.1.2 Coal-bearing

With regard to the coal-bearing of the Carboniferous in the Netherlands, Limburg is particularly well documented. Above all, ancient mining activities and large-scale coal exploration in this district contributed a large amount of reliable data. In the greater part of The Netherlands, the largest coal-bearing is found in the bottommost part of the Ruurlo Formation and the Maurits Formation. With respect to South Limburg, however, the topmost part of the Ruurlo Formation has also been found to contain reasonable to good coal-bearing, as also has the Kemperkoul Member of the Maurits Formation. Table 12.1 provides an overview of the coal-bearing in a number of wells in the map sheet area.

12.1.3 Coalification and classification

Optical as well as chemical analyses have been used to characterise the coal. In the microscopic analyses, the maceral and mineral content and the degree of coalification have been determined. A Rock-Eval analysis provides bulk-chemical information on the coal rank (Tmax) and the type of organic material is determined by means of the Hydrogen and Oxygen indices.

Figure 12.1 provides a compilation of several of the coalification trends. The figure gives a clear picture of increasing coal rank along with the increase in depth. The increase in depth of the coalification gradients together with increasing stratigraphic depth can also be extrapolated. Table 12.2 gives the coalification range and coalification gradients (both in vitrinite-reflection values and in Tmax values) for a number of individual wells.

Table 12.1 Overview of the coal-bearing in the Carboniferous in a number of wells in South Limburg.

Well code	*Well*	*Interval*	*Thickness (m)*	*Coal-bearing (%)*
KPK-01	Kemperkoul-1	Maurits Formation		
		(Kemperkoul Member)	446	4.0
		(main Maurits member)	663	4.0
		Ruurlo Formation	67	1.5
RAA-01	Raath-1	Maurits Formation	339	4.9
LBR-01	Limbricht-1	Maurits Formation	247	5.4
XIV	Geleen	Maurits Formation	437	7.3
XIX	Douvergenhout	Maurits Formation	340	2.7
		Ruurlo Formation	693	6.9
XL	Wiggelraderhof	Maurits Formation	615	7.9
		Ruurlo Formation	39	4.3
XLV	Jabeek	Maurits Formation	566	1.4
LI	Oirsbeek	Maurits Formation	217	5.6
LV	Munstergeleen	Maurits Formation	181	3.4
		Ruurlo Formation	164	1.4

Table 12.2 Overview of the measured coalification parameters in the map sheet area.

	%Rr(oil)		*Tmax (°C)*	
Well	*Range*	*Gradient (/km)*	*Range*	*Gradient (/km)*
KPK-1	0.67 – 1.26	0.40	428 – 469	31.6
XLV	0.79 – 0.95	0.35	431 – 440	11.0
LBR-1	0.71 – 0.84	0.45	426 – 440	27.1
XL	0.82 – 1.19	0.50	433 – 464	40.8
LI	0.82 – 0.95	0.16	433 – 443	60.2
XIX	0.91 – 1.68	0.75	439 – 491	51.4
XIV	0.88 – 1.04	0.24	433 – 444	23.9

Two generalised extremes in coalification trends in the area can be identified. Both coalification trends are however comparable in terms of steepness, but the absolute values for each stratigraphic level are higher in the wells and measuring points lying further to the southeast. The lateral picture of the coalification trends in the area, as illustrated in figure 12.2, is complex. There is no link between the present-day depth of the Carboniferous and the degree of coalification. The coalification is mainly associated with the geology of the pre-Permian surface in the map sheet area (fig. 4.2). The Zeeland Formation is encountered around Maastricht, the relatively shallow Epen and Baarlo Formations are found further to the east, while to the north, the Ruurlo and Maurits Formations rest upon the pre-Permian surface. Had the whole area undergone a uniform burial and/or geothermal history, the vertical coalification trends

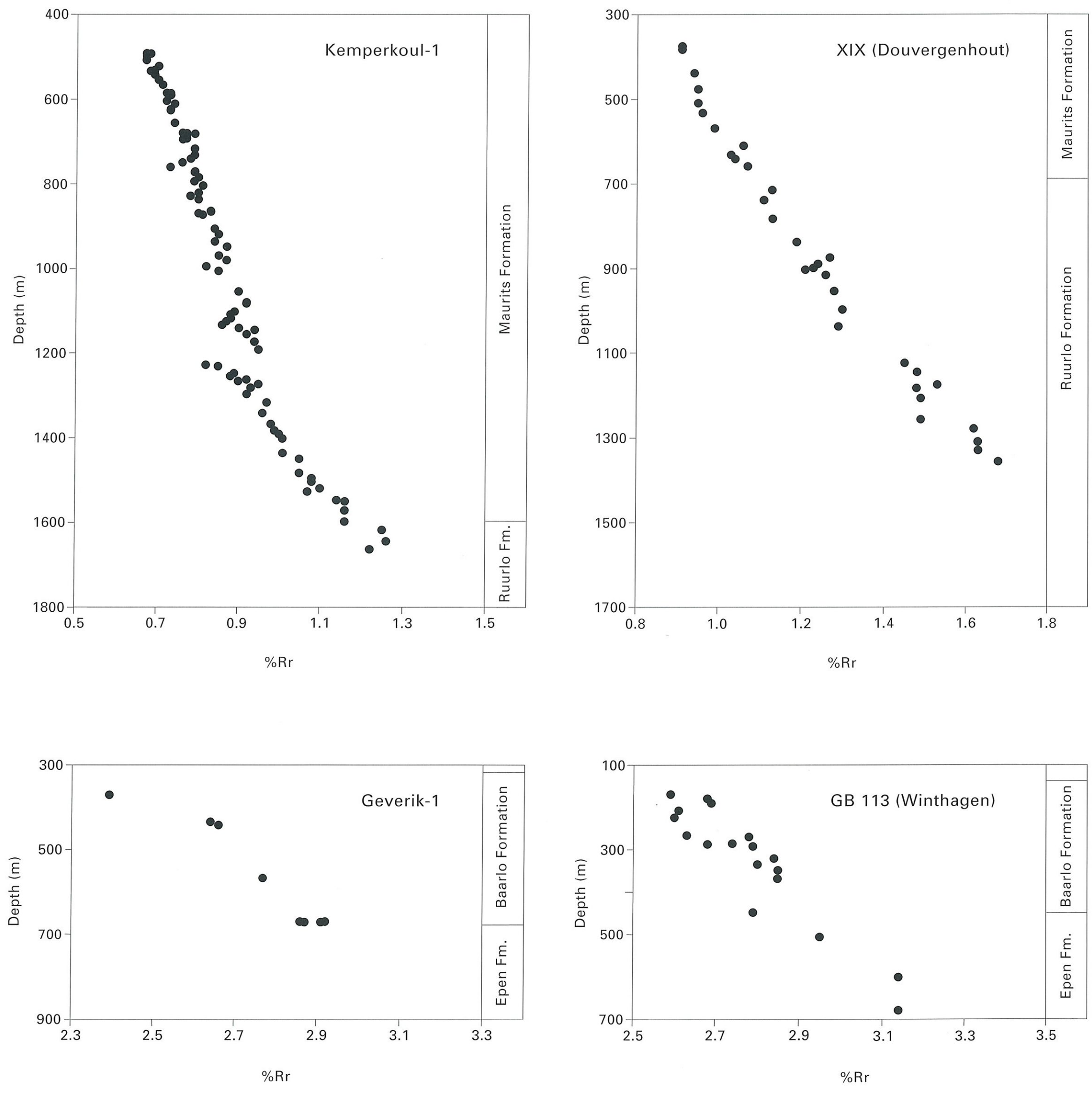
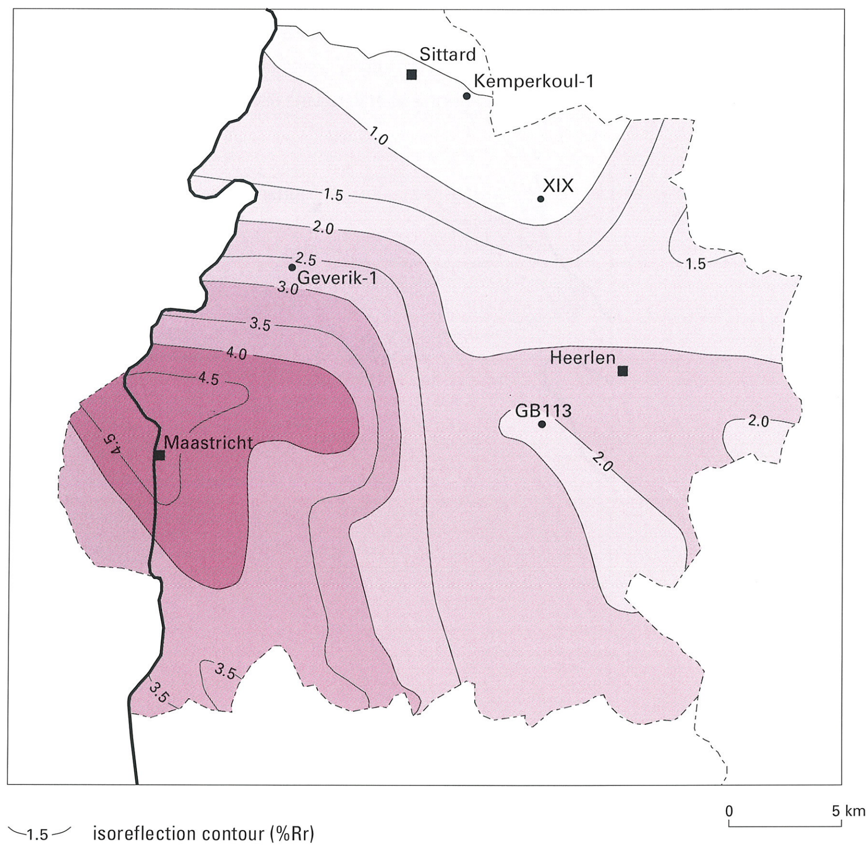


Figure 12.1 Vertical coalification trends given as vitrinite reflection values (%Rr) against the depth from four wells in Map Sheet XV.

would also be reflected in lateral coalification, with higher reflection values for the stratigraphically older units. However, the two different vertical coalification trends suggest that this is not the case. Based on old mining data, a coalification map has been made of coal seam GB 23 (Furth Seam, located in the uppermost part of the Ruurlo Formation). The lateral coalification range of this stratigraphical horizon is illustrated in figure 12.3. From the southeast to the northwest, a very clear decrease in the coal rank can be perceived. This trend can be traced as far as the Campine Basin in Belgium. The extreme north of South Limburg, however, exhibits the reverse trend, one of increasing coal ranks. In the area of the State Colliery Beatrix on the Peel Block, a similar trend can be perceived in coal seam GB 23, where the coal rank decreases towards the south. This trend may be linked to the presence of a coalification anomaly in the vicinity of Erkelenz (Erren & Bredewout, 1991; Veld et al., 1996). A coalification high in the Meeuwen-Bree area in the north of the Campine Basin is also associated with the Erkelenz-intrusive (Dusar, 1982).

On a basis of the coal rank, the coal types in the area range from long-flame coal to steam coal (fig. 12.6). The maceral analyses and the Rock-Eval data clearly indicate that the organic material is gas-generative. The average vitrinite content of the coal is 77%, the inertinite contents are around 11% and the liptinite content, approximately 12%. These values show a remarkable analogy with those of coal occurrences elsewhere in Northwest Europe.

Figure 12.2 Coalification map of the top of the Carboniferous in South Limburg. The coalification pattern shows a clear correlation with the stratigraphy (older units have a higher coalification than younger units).



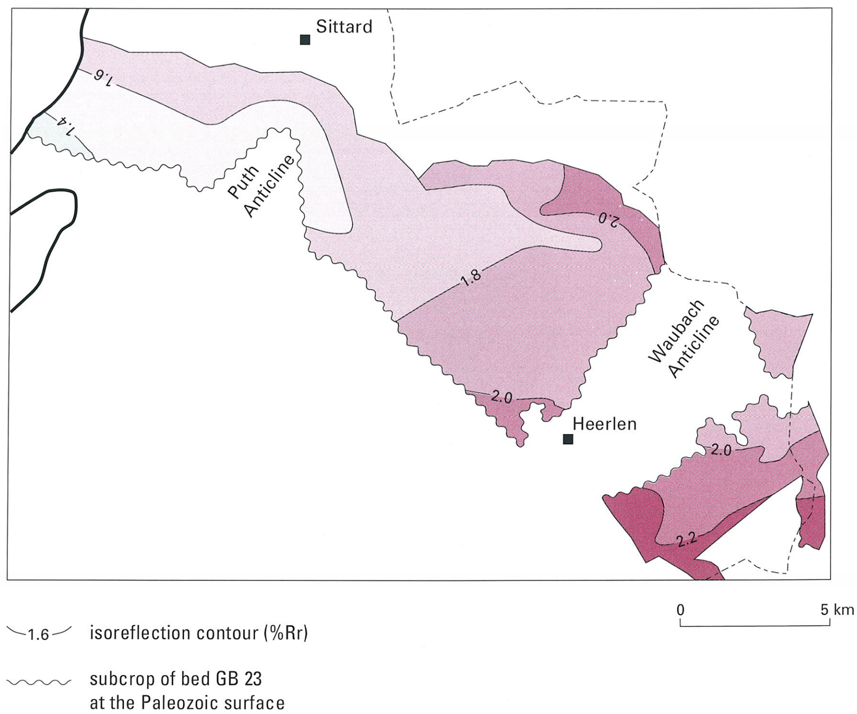
12.1.4 Burial history and hydrocarbon generation

A clear reconstruction of the burial history of an area requires detailed data, such as stratigraphy, lithology and (palaeo)geothermy. The stratigraphic column of the map sheet area, however, displays large hiatuses. During the Variscan orogeny, the area was subjected to folding, faulting and overthrusting, accompanied by intense erosion. This resulted in a Westphalian C to Early-Triassic hiatus. On the high blocks, the sandstones and conglomerates of Triassic age were removed during subsequent erosive phases of the Alpine orogeny. The oldest sediments to be deposited on the Buntsandstein or on the Carboniferous are of Late Cretaceous age. These predominantly marine sediments were often subjected to renewed erosion during the Late Cretaceous/Early Tertiary inversions. For the modelling of the burial history, these periods of erosion mean that a substantial amount of information on the Late Palaeozoic and the greater part of the Mesozoic is missing.

The present-day overburden is not sufficient to account for the coalification values of the Carboniferous. Vitrinite reflection measurements performed on sediments immediately overlying the Carboniferous give substantially lower readings than the underlying Carboniferous.

Wolf & Bless (1987) give vitrinite reflection values of 0.32 to 0.46 % in Upper Cretaceous sediments resting upon highly coalified Dinantian sediments. These data indicate a pre-Cretaceous coalification of the Carboniferous. From regional geology and published data, it may be deduced that a maximum thickness of the Permian, Triassic and Jurassic strata in the map sheet area is approximately 1200 m, whereas the maximum thickness of Upper Cretaceous and Tertiary rocks is unlikely to have exceeded 800 m. Owing to the slight burial depth, the thickness is insufficient to achieve the coalification pattern of the Carboniferous. From the above it may be concluded that the coalification of the Carboniferous in the map sheet area during Middle to Late Jurassic is improbable. For the modelling of the burial history of

Figure 12.3 Lateral variation in coalification (%Rr) of coal seam, GB 23 (Furth seam, upper Westphalian A).

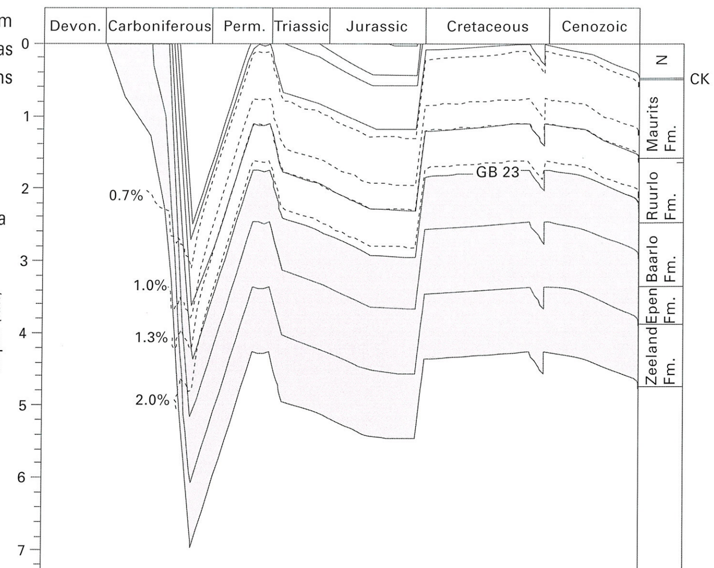


Map Sheet XV, the generally accepted hypothesis of a pre-Permian (Zechstein)-determined coalification pattern of Carboniferous has therefore been adhered to (Teichmüller,1987; Robert, 1989).

Kemperkoul-1 well has been selected as reference well for the modelling of the burial history in the map sheet area. The result of the modelling is illustrated in figure 12.4. By means of this model, the time-temperature history of the coal has been established, enabling the theoretical degree of coalification to be calculated. For an accurate analogy between the present (measured) coalification trend and the theoretical coalification values, an additional sediment succession must be assumed at the top of the Carboniferous of approximately 2700 m, which was again removed by erosion during the Late Carboniferous/Early Permian. With respect to whole area, modelling suggests that this post-Westphalian C succession varies in thickness from 1500 to 3000 m. Allowing for the present-day differences in the stratigraphic age at the top of the Carboniferous, this means that in the entire map sheet area, the total thickness of the eroded Upper Carboniferous ranges from circa 2900 m in the vicinity of Sittard to 5400 m in the southern part of the map sheet area. These thicknesses imply a very thick succession of Upper Carboniferous, difficult to harmonise with the stratigraphic development of the area.

The observed trend of decrease in coalification values in coal seam GB 23 from the Variscan front towards the northwest persists into the Campine Basin (Langenaeker, 1992). This implies that the coalification of both areas have the same cause, possibly a decrease in the (vertical) heat flow or a decrease in the quantity of (eroded) sediment towards the northwest. However the coalification pattern in the map sheet area is so complex that it cannot be accounted for by simple assumptions of equal heat flows and/or thicknesses of eroded sediment throughout the area. Such assumptions produce very large differences in modelled values of the above-mentioned parameters over very short distances.

Figure 12.4 Burial history diagram of the Kemperkoul-1 well. Gas was generated mainly from coal seams with a coalification higher than 1.3% Rr. The final depth of Kemperkoul-1 is 1665 m. The modelling below this depth is based on regional-geological data of the area.

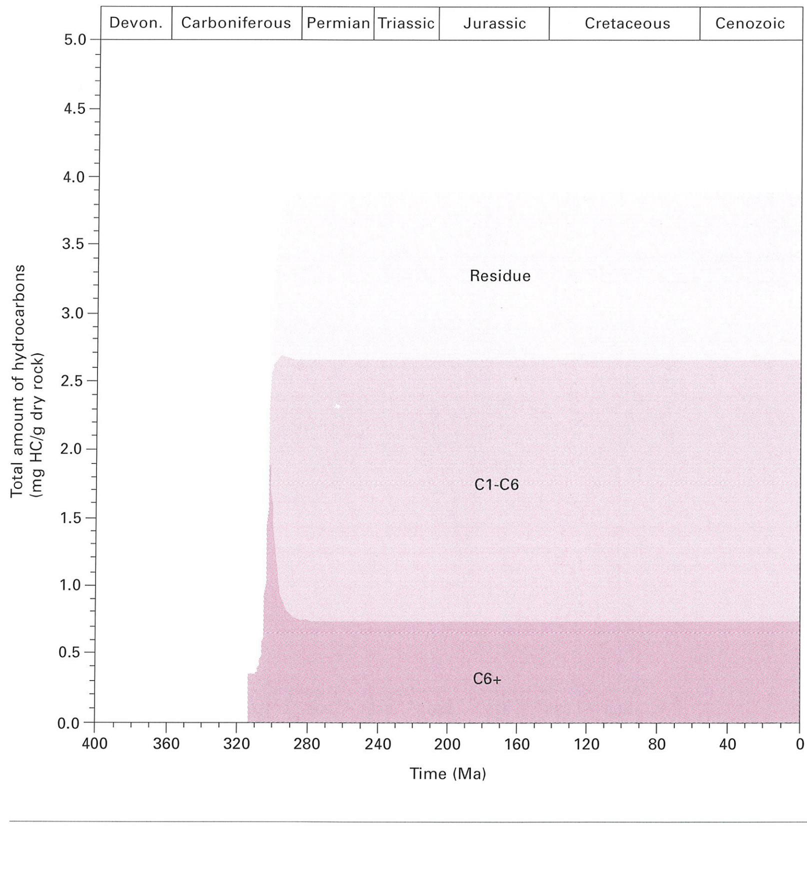


N North Sea Supergroup
CK Chalk Group

A possible explanation of the relatively high coalification value in the southern part of the study area is given by the hypothesis of lateral fluid flow of a high temperature (Von Winterfeld, 1994; Lünenschloss et al., 1997). This fluid flow was supposedly caused by the tectonic activity during the Variscan orogeny, which induced a liquid flow from the overthrust front in the direction of the foreland. In this perception, the thickness of the succession of eroded Upper Carboniferous sediments may transpire to be significantly lower than in the above-mentioned modelling. An alternative modelling study for the Kemperkoul-1 well has been carried out, in which an augmented heat flow during the Late Carboniferous/Early Permian was introduced and a thickness of 700 m (2000 m less than in the previously mentioned model) of the additional and subsequently again eroded succession at the top of the Carboniferous was assumed. The associated coalification values prove to correspond with the values measured in the pit.

No oil or gas occurrences have been demonstrated in the map sheet area. This does not, however, mean that no hydrocarbon generation took place. The burial history determined the time-temperature history of the gas-source rock. Figure 12.5 gives the hydrocarbon generation of the bottommost part of the Ruurlo Formation (Upper Westphalian A) as a function of time in the Kemperhoul-1 well. Modelling has revealed that approximately 2 mg of gas per gram was generated from this interval at the location of Kemperkoul-1 well. Part of this gas remained behind as so-called coalbed methane (see 1.3.4), while the other part was expelled.

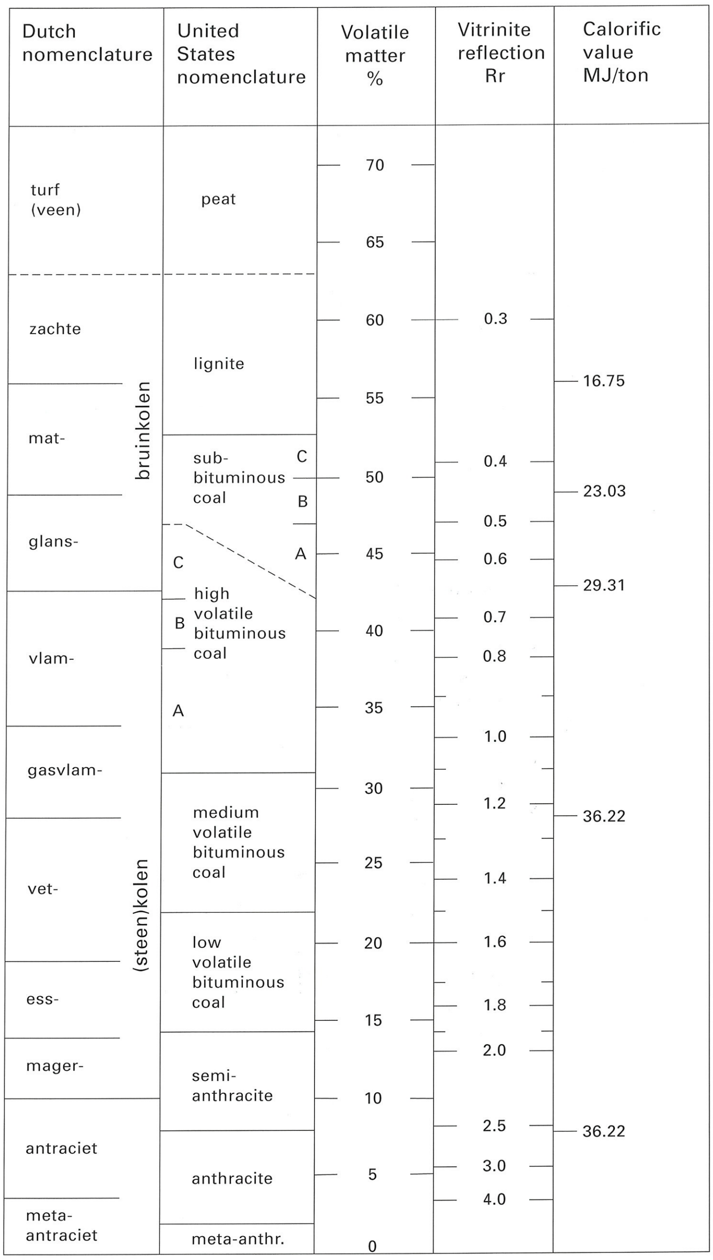
Figure 12.5 Hydrocarbon generation as a function of time in the Kemperkoul-1 well.



12.2 Hydrogeology

The presence of Palaeozoic, Mesozoic and Cenozoic sediments on or relatively close to surface level, combined with the varied morphological appearance of the present land surface, promotes an account of the hydrogeology of this map sheet. First, a schematic overview will be given of the relatively shallow hydrogeological parameters of, in particular, the Cretaceous and Tertiary deposits within this map sheet. Following this, the exploitation of groundwater from the Tertiary and Cretaceous aquifers will be discussed. The chapter concludes with a section on the occurrence of groundwater in Palaeozoic deposits.

Figure 12.6 Classification of brown coal and coal (after Stach et al., 1982). The Dutch nomenclature has been derived from the German.

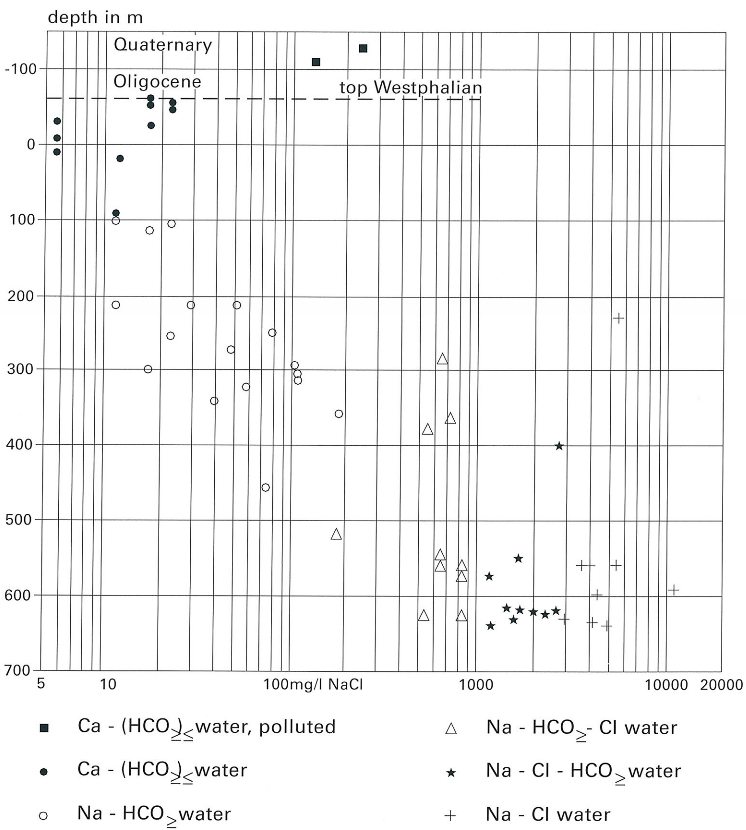


tion of the sources and the hydrostatic pressure. The ultimate level of the mine water cannot be predicted with any degree of certainty. Some experts are of the opinion that the salt water, which is of poor quality, will penetrate the overlying Cretaceous aquifers, forming a potential threat to the drinking water supply (Kimpe, 1980). Others consider that the original state of equilibrium will be re-established, with the warm, salt water occurring beneath the fresh water in the upper layers (Van Rooijen, 1989).

The tectonic structure and lithology of the Palaeozoic rocks relatively close to the surface account for the frequent divergence in the chemical composition and the geothermal characteristics of the water that is present, in comparison with the 'shallow' groundwater in the rest of The Netherlands. Regular chemical research into the mine water during the mining era presented a picture of hydrochemical evolution of the water in the Caumer Subgroup (Westphalian) (Kimpe, 1963). At greater depths, the mineralisation is higher, which is demonstrated by an increase in Na^+ and Cl^- concentrations (fig. 12.9). In order of descent, Ca-$(HCO_3)_2$ water types from the Cretaceous and Na-HCO_3 water can be recognised as transitional types, and at depths greater than 500 m below Mean Sea Level (NAP), the water is of Na-Cl type.

Thermal (mineral) water is found at a number of places in Limburg. In the case of thermal water, the temperature of the groundwater clearly exceeds the level that would be expected on a basis of the normal geothermal gradient (approx. 3° C per 100 m). Groundwater may be termed mineral water when the NaCl content is higher than 1000 mg/l or when a particular norm for iron, iodine, hydrogen sulphide, fluorine or other minerals is exceeded.

Figure 12.9 Increase in the salt content with increasing depth in the Caumer subgroup in the State Colliery Wilhelmina (after Kimpe, 1980).



To the south of Heerlen in the Grondgalerij Laag VI Fault, a spring was formed with a temperature of 50° C, 35° C higher than that commensurate with the depth in geothermal terms (Kimpe, 1980).
The mineral-rich water that was exploited for Thermae 2000 in Valkenburg derives from the Zeeland Formation (Dinantian limestone) at a depth slightly less than 400 m below surface level and has a temperature of 24.5° C (Krings & Langguth, 1987).

The Heugem-1a and Kastanjelaan-2 wells in Maastricht have revealed the occurrence of mineral water and thermal mineral water in the Dinantian and Upper Devonian (Bless, 1981b). To the northwest of the fault zone that runs between these wells, thermal mineral water of 23° C is probable at depths between 450 and 600 m. Again, various water-bearing sequences, separated by shales, supply water varying in composition. To the southeast of the fault zone, mineral water with 450 mg/l Cl^- is found at a shallow depth (approx. 250 m), while at a depth of between 750 and 1000 m, thermal mineral water may be expected, with a composition comparable to the thermal mineral water from the Kastanjelaan-2 (Bless, 1981b).

The origin of the salt, thermal water in the Carboniferous sediments should be sought in the deeper subsurface. The fracture and joint system allows the water to flow upwards from a great depth as ascending water. Saline deposits from the Devonian are thought likely to be a contributory factor (Kimpe et al., 1978).

Appendices

Appendix A

Overview of wells used (selection)

Dutch wells Numerical order	Well nr.	Name	Code	Commissioned/ Owned by	Final depth in m	Year completed
1	24	Heek			280	1874
2	43	Kamp Nuth			473	1897
3	67	Aalbeek			735	1899
4	75	Sittard			520	1902
5	80	Obbicht		Ned. Mij. t.h. Verr. v. Mijnbk. Werken	905	1905
6	81	Waubach			736	
7	83	Maasland			621	
8	92	Varebeuker		Oranje Nassau	804	
9	102	Ubach over Worms		Laura en Vereeniging	815	1919
10	103	Eygelshoven		Laura en Vereeniging	930	1921
11	104	Geulle		ROVD	598	1921
12	105	Houthem		ROVD	323	1921
13	106	Gulpen		ROVD	688	1921
14	107	Eygelshoven		Laura en Vereeniging	1189	1922
15	109	Cadier en Keer		ROVD	258	1921
16	110	Overeijs		ROVD	541	1922
17	111	Bocholtz		ROVD	594	1922
18	112	Neerbeek		ROVD	683	1922
19	113	Winthagen		ROVD	700	1922
20	114	Krawinkel		ROVD	800	1922
21	115	Banerheide		ROVD	509	1923
22	116	Bocholtz		Willem Sophia	800	1924
23	117	Prickart			686	1924
24	119	Ubach over Worms		Laura en Vereniging	933	1925
25	120	Ubach over Worms		Laura en Vereniging	1103	
26	121	Spekholzerheide		Willem Sophia	683	1926
27	126				306	1937
28	131			Cons. Biermans-Banque d'Outremer	800	1926
29	132			ROVD	1008	1926
30	133			Cons. Biermans-Banque d'Outremer	1052	1927
31	139			Mij. Cavando Acquiro	400	1936
32	143			Mij. Cavando Acquiro	353	1938
33	II	Amstenrade		Staatsmijnen	1157	
34	VII	Wolfshagen		Staatsmijnen	626	1909
35	VIII	Brunssum		Staatsmijnen	601	
36	XIII	Rijksweg Geleen		Staatsmijnen	831	
37	XIV	Geleen		Staatsmijnen	1044	1913
38	XV	Rijksweg Geleen		Staatsmijnen	622	1913
39	XVII	Puth		Staatsmijnen	717	1914
40	XVIII	Heisterbrug		Staatsmijnen	742	1914
41	XIX	Douvergenhout		Staatsmijnen	1383	
42	XXIV	Hoensbroek		Staatsmijnen	240	1916

Overview of wells used (selection)

Dutch wells Numerical order	*Well nr.*	*Name*	*Code*	*Commissioned/ Owned by*	*Final depth in m*	*Year completed*
43	XL	Wiggelraderhof		Staatsmijnen	1002	1920
44	XLIII	Nuth		Staatsmijnen	638	1920
45	XLV	Jabeek		Staatsmijnen	1355	1922
46	XLVII			Staatsmijnen	1194	1922
47	XLVIII			Staatsmijnen	1091	1922
48	XLIX	Rosengarten		Staatsmijnen	553	1920
49	L	Spaubeek		Staatsmijnen	505	1921
50	LI	Oirsbeek		Staatsmijnen	566	1921
51	LII			Staatsmijnen	1263	1921
52	LIII	Grijze Grubben		Staatsmijnen	583	1921
53	LIV	Nuth		Staatsmijnen	496	1921
54	LV	Munstergeleen		Staatsmijnen	775	1922
55	LVI	Hellebroek		Staatsmijnen	699	1922
56	LVII	Nagelbeek		Staatsmijnen	900	1922
57	LIX			Staatsmijnen	510	1922
58	LXIII			Staatsmijnen	501	1937
59	LXVI	Voerendaal-1	VRD-1	NAM/Staatsmijnen	720	1949
60	LXVII	Wijnandsrade-1	WNR-1	NAM/Staatsmijnen	554	1949
61	LXIX	Hulsberg		Staatsmijnen	303	1953
62	LXX	Melick/H.	MHB-70	Staatsmijnen	524	1954
63	LXXI	Neer	NER-71	Staatsmijnen	1293	1954
64	LXXII	Beesel	BEE-72	Staatsmijnen	1234	1954
65	LXXIII	Swalmen	SWM-73	Staatsmijnen	1332	1954
66	LXXIV	Maasniel	MAN-74	Staatsmijnen	1367	1955
67	LXXVI	Reuver	RVR-76	Staatsmijnen	1105	1956
68	LXXVII	Elmpt-77	EPT-77	Staatsmijnen	1215	1958
69	LXXVIII	Elmpt-78	EPT-78	Staatsmijnen	1127	1959
70	58G191	Straat		Provincie Limburg	773	1991
71	58G192	Meinweg		Provincie Limburg	360	1992
72	60A412	Buchten		Provincie Limburg	255	1992
73	60B123	Posterholt		Provincie Limburg	427	1991
74	60C1131	Berg aan de Maas		Provincie Limburg	221	1993
75	60D1033	Broeksittard		Gemeente Sittard	507	1992
76	61F341			RGD	252	1985
77	61H18			Waterleidingmij. Limburg	97	1971
78	61H64			RGD	57	1984
79	62A331			RGD	152	1982
80		Geverik-1	GVK-1	NEOM	1687	1986
81		Heugem-1A	HEU-1A	Provincie Limburg	503	1981
82		Kastanjelaan-2	KSL-2	Provincie Limburg	501	1981
83		Kemperkoul-1	KPK-1	RGD	1665	1983
84		Limbricht-1	LBR-1	RGD	1059	1984
85		Raath-1	RAA-1	RGD	1203	1984
86		Thermae 2000	TH2000	Thermae Onroerend Goed	381	1986
87		Thermae 2002	TH2002	Thermae Onroerend Goed	382	1986

Overview of wells used (selection)

Dutch wells Numerical order	Well nr.	Name	Code	Commissioned/ Owned by	Final depth in m	Year completed
88		Vlodrop-1	VDP-1	ROVD	790	1906
89		Vlodrop-3	VDP-3	ROVD	654	1908

Mines. Numerical order.	Name	Exploitation company.	Maximum shaft depth in m
90	Emma	Staatsmijnen in Limburg	822
91	Hendrik	Staatsmijnen in Limburg	1057
92	Wilhelmina	Staatsmijnen in Limburg	825
93	Maurits	Staatsmijnen in Limburg	895
94	Beatrix	Staatsmijnen in Limburg	717
95	Willem	Domaniale Mijn Maatschappij	802
96	Nulland	Domaniale Mijn Maatschappij	347
97	Beerenbosch	Domaniale Mijn Maatschappij	502
98	Oranje Nassau I	"Oranje Nassau Mijnen"	470
99	Oranje Nassau II	"Oranje Nassau Mijnen"	474
100	Oranje Nassau III	"Oranje Nassau Mijnen"	844
101	Oranje Nassau IV	"Oranje Nassau Mijnen"	740
102	Julia	Charb. réunies "Laura en Vereniging"	568
103	Laura	Charb. réunies "Laura en Vereniging"	730
104	Willem	Charbonnages "Willem-Sophia"	651
105	Sophia	Charbonnages "Willem-Sophia"	328

Foreign wells Numerical order.	Well nr.	Well name	Commissioned by	Final depth in m	Year completed
106	Dal. 122W/258	Hermalle-sous-Argenteau	Belgische Geol. Dienst	353	1975
107	KB 134	Martinslinde	Belgische Geol. Dienst	301	1967
108	KB 146	Neerglabbeek	Belgische Geol. Dienst	1357	1980
109	KB 172	Gruitrode Ophovenderheide	Belgische Geol. Dienst	1599	1984
110	KB 192	's Gravenvoeren	Belgische Geol. Dienst	866	1986
111	KB 198	Molenbeersel	Belgische Geol. Dienst	1773	1987
112	STRN-01	Straeten 1	DEA-Wintershall	1451	1957

NAM = Nederlandse Aardolie Maatschappij B.V.
NEOM = Nederlandse Energie Ontwikkelings Maatschappij
RGD = Rijks Geologische Dienst
ROVD = Dienst der Rijksopsporing van Delfstoffen

Appendix B

Seismic data used (2D)

Survey	*Year*	*Commissioned by*
70*	1969	NAM
7915*	1979	NAM
NBL80*	1980	Chevron
80*	1980-81	BGD
81*	1981	BP
81*	1981	RGD
82*	1982	BP
82*	1982	RGD
82*	1982	BGD
83*	1983	RGD
84*	1984	BP
84*	1984	BGD
85*	1985	NEOM
LSC-89*	1989	BGD
N90*	1990	Clyde

* = random figure

BGD = Belgische Geologische Dienst
BP = BP Exploratie Maatschappij Nederland BV
Clyde = Clyde Petroleum Exploratie B.V.
NAM = Nederlandse Aardolie Maatschappij B.V.
NEOM = Nederlandse Energie Ontwikkelings Maatschappij
RGD = Rijks Geologische Dienst

Geological maps referred to

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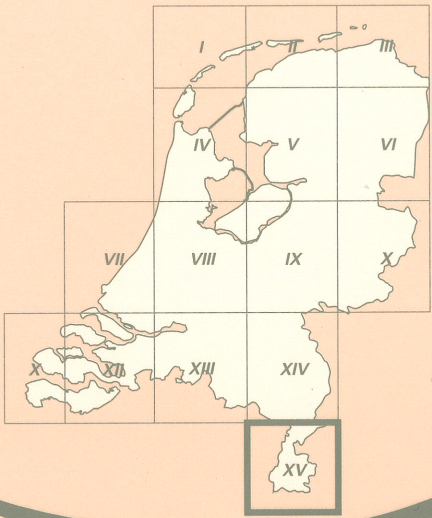
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