Netherlands Institute for Applied Geosciene TNO
- National Geological Survey

Map sheet X
Almelo-Winterswijk

Geological Atlas of the Subsurface of The Netherlands

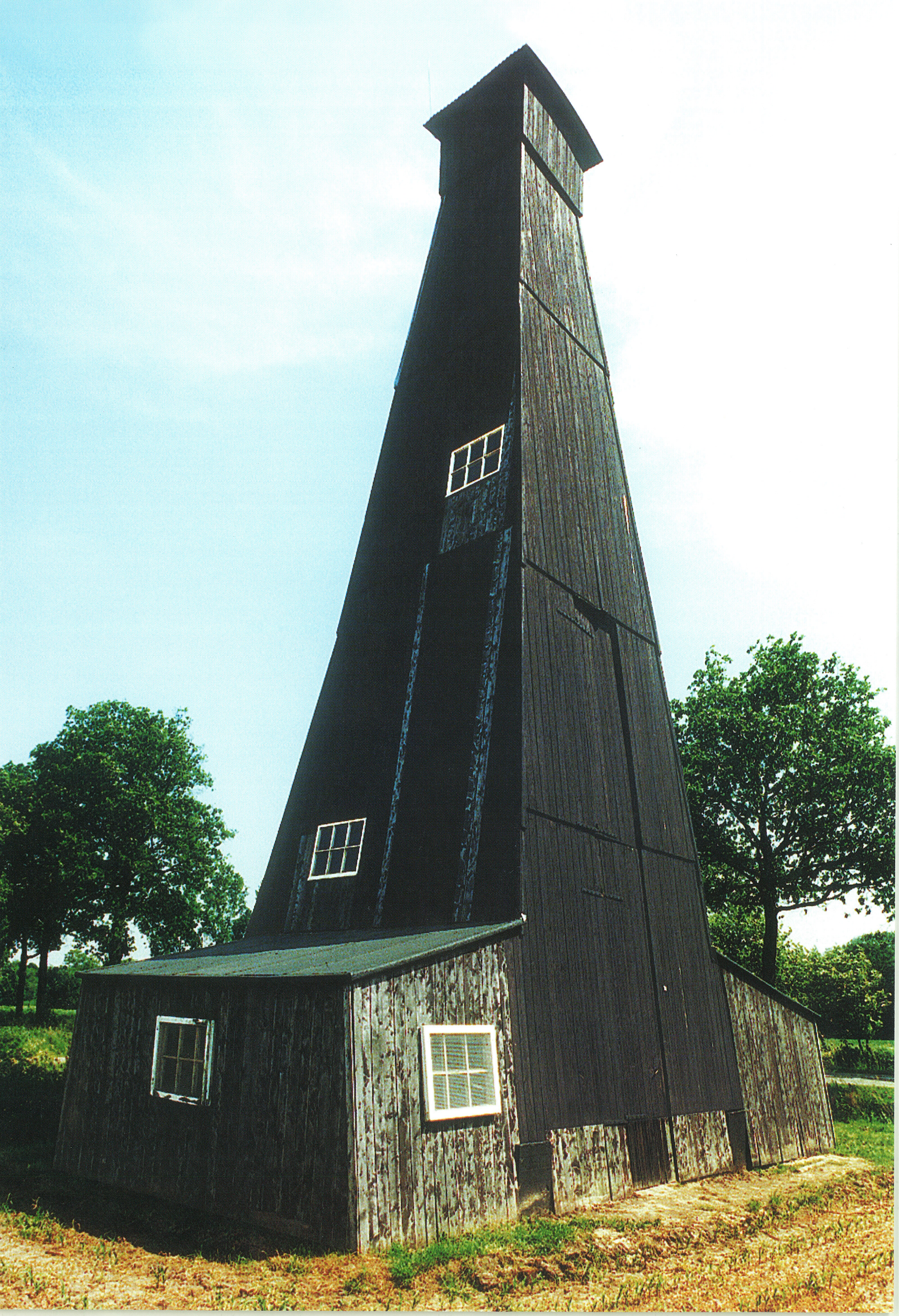
TNO

Explanation to map sheet X
Almelo-Winterswijk

Netherlands Institute of Applied Geoscience TNO, Haarlem 1998

Geological Atlas of the Subsurface of The Netherlands

Historical saltderrick in the concession Twenthe-Rijn.
Courtesy Akzo Nobel Chemicals B.V.



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

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

The existing mining legislation that applies to The Netherlands Onshore and Continental Shelf, 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, with a restriction of 5 years. This agreement enables the NITG-TNO to bring the geology subsurface of The Netherlands to wider attention.

The Almelo-Winterswijk map sheet of the Geological Atlas of the Subsurface of The Netherlands is the sixth 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).

Each map sheet has its own features. The map sheet in question outlines the geology of an important part of the provinces of Overijssel and Gelderland. Maps and sections reveal a highly eventful history in these provinces. For a great part of the geological history, the area underwent continuous subsidence, resulting in a thick depositional build-up of marine and terrestrial sediments. An inversion of tectonic movement at the end of the Cretaceous caused strong uplift and erosion within the original areas of subsidence and led to deposition of thick chalk successions on the formerly stable highs. Gas-bearing reservoirs have been discovered in Permian carbonates and in Upper Carboniferous fluvial sandstone layers.

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 who are active in the fields of exploration and exploitation for mineral and natural resources, but also various governmental institutions and other interested parties.

As 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 consultations have been held with Dr F. Kockel and R. Baldschuhn of the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and Dr H.-G. Röhling of the Niedersächsisches Landesamt für Bodenforschung in Hannover, Dr D. Juch and Dr G. Drozdzewski of the Geologisches Landesamt of Krefeld on the harmonisation of this map sheet with German maps and with geological perceptions. Special thanks are due to the companies which provided data used in this map sheet.

Haarlem, April 1998

1 Introduction

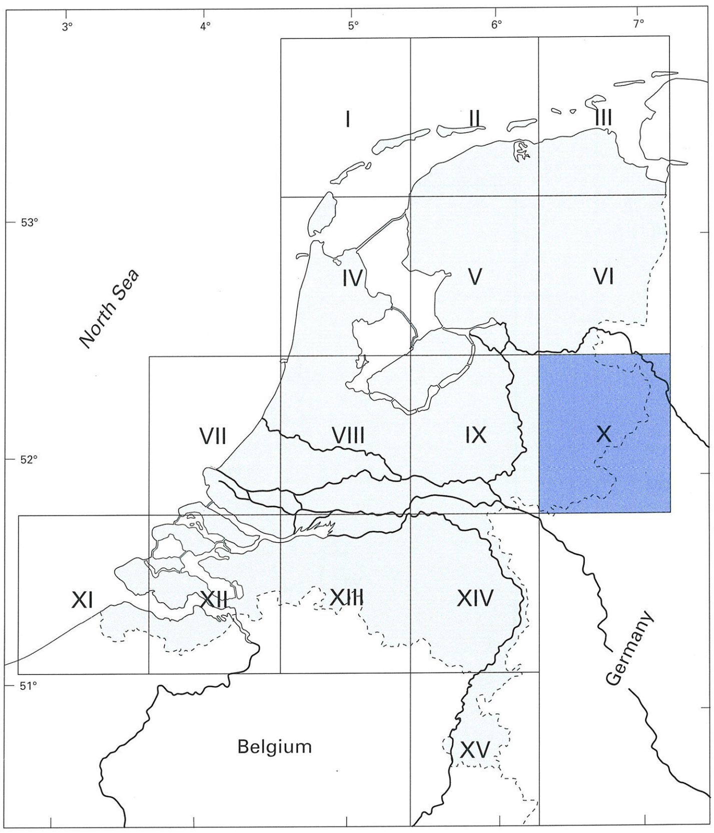
1.1 Extent of area studied

The map sheet area is situated in the eastern part of the provinces of Overijssel and Gelderland, and is bordered by the German federal states of Niedersachsen and Nordrhein-Westfalen (fig. 1.1).

1.2 Data base

The mapping of this map sheet area is based on seismic data and well data compiled by industry and government within the framework of the exploration and exploitation of mineral and natural resources. For mapping purposes, predominant use was made of 2D seismics and only in the extreme north were 3D seismics used (fig. 1.3; appendix A). Deep drilling was carried out in a total of 540 wells in the map sheet area. Data from 140 of these, selected primarily on a basis of their geographic distribution, were used in this map sheet (fig. 1.4; appendix B).

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



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

1.3 History of the exploration

The exploration of mineral and natural resources in this map sheet area commenced at a relatively early date - half way through the last century. Since that time, exploration of various mineral and natural resources has been performed in the map sheet area. Limestone, ores, coal, rock salt and hydrocarbons will be dealt with in turn in the following subsections. The area has three concessions for natural gas exploitation, three concessions for rock salt exploitation and one concession for the exploitation of both rock salt and coal (fig. 1.2).

1.3.1 Limestone

The presence of limestone close to the surface to the east of Winterswijk had been documented since 1850. For a long time this was thought to be the *Wealden limestone* (Lower Cretaceous); it was not until 1902 that it was established to be a much older limestone of the Muschelkalk (Middle Triassic) (Müller, 1902). This made the area interesting for mining purposes as the top of the Carboniferous and the Zechstein was now thought to be much closer to the surface than was originally assumed, and exploration for coal and salt was initiated (see below 1.3.3).

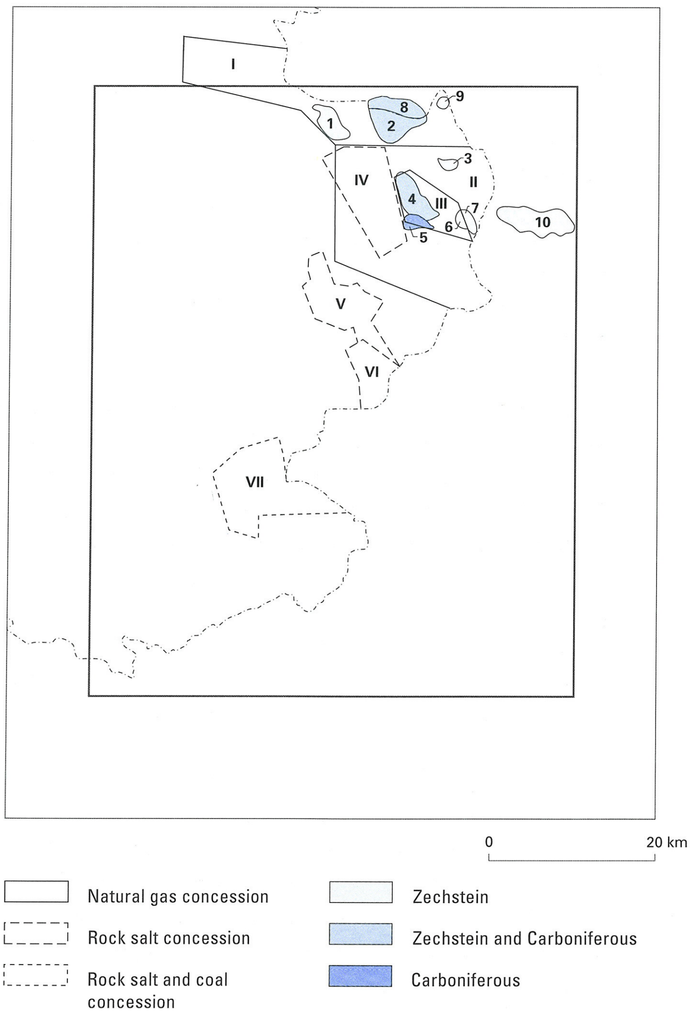


Figure 1.2 Overview map of the concessions granted and gas fields within the map sheet area. The concession areas situated in the map sheet area are: I: Tubbergen Concession (NAM), II: Twenthe Concession (NAM), III: Rossum-De Lutte Concession (NAM), IV: Weerselo Concession (Akzo-Nobel), V: Twenthe-Rijn and Extension Twenthe-Rijn Concessions (Akzo-Nobel), VI: Buurse Concession (Akzo-Nobel), VII: Gelria Concession (Hope & Co.). The gas fields situated in the map sheet area and some of the relevant German fields are: 1: Tubbergen-Mander, 2: Tubbergen, 3: Rammelbeek, 4: Rossum-Weerselo, 5: Oldenzaal, 6: De Lutte West, 7: De Lutte Oost, 8: Itterbeck-Halle, 9: Denekamp, 10: Bentheim. For each gas field, the productive horizon has also been indicated.

Limestone mining commenced in 1853, with a test pit where rock is extracted for road metalling. This application did not prove to be a success and production was terminated shortly afterwards. A few years later, slightly further to the west, a small quarry went into operation for a number of years, which is now absorbed by the present area of the Winterswijkse Steengroeve (Harsveldt, 1979).

The exploitation of limestone near Winterswijk became effective in 1932 when a local haulier, a certain Mr Hannink, who was familiar with the Upper Cretaceous limestone quarries in adjacent Münsterland, conceived the idea of starting up a similar quarry to the east of Winterswijk. Although in fact the Upper Cretaceous proved to be absent in the Winterswijk area, the quarry has been successfully exploited ever since. The principal application of this limestone is as agricultural fertiliser and as aggregate in road construction.

Limestone of the Muschelkalk situated close to the surface, as in the Winterswijk area, is also encountered in a vast area to the south of Enschede (RGD, 1988a).

Limestone of the Upper Cretaceous is found at the surface in a small area in the Achterhoek. In 1920 a feasibility study was carried out by the ENCI into the potential for exploitation and 20 tons of limestone was extracted. Owing to the anticipated high initial expenses involved, it was decided not to proceed with exploitation (RGD, 1988a).

1.3.2 Ore

Following speculations concerning high ore resources in this particular area, several concessions for the exploitation of mineral and natural resources (including sulphur, silver and copper) were allocated for the Winterswijk area in 1906. Exploration of the top 100 m was permitted for one year but failed to reveal the desired mineral and natural resources (Harsveldt, 1979). The Winterswijk Silvermines proved to be an illusion.

1.3.3 Coal

The discovery that not the Lower Cretaceous but the Muschelkalk lay close to the surface in the Winterswijk area (Müller, 1902) at once gave the area potential for exploration purposes. The overburden of the Carboniferous was considerably thinner than was at first thought, and the top of the Carboniferous coal measures could be presumed to lie within reach for mining purposes. In 1903 parts of Twente and the Achterhoek were designated by the government as areas not eligible for public exploration; exploration was restricted to the Dienst der Rijksopsporing van Delfstoffen (ROvD) *[Government Institute for the Geological Exploration of The Netherlands]*, which carried out a large number of reconnaissance wells between 1901 and 1923 based on the prospect of coal and salt occurrences (section 1.3.4). The presence of exploitable amounts of rock salt and coal in the area was indeed demonstrated. At the same time the first oil find was made, entirely unintentionally (section 1.3.5).

After parts of the Achterhoek had been reopened for exploration in 1923, the "Nederlandse Maatschappij voor Mijnbouwkundige Werken", in cooperation with the Bankers Hope & Co., commenced exploration of the area to the north of Winterswijk. Between 1924 and 1927 six shallow reconnaissance boreholes and five deep boreholes were drilled. On a basis of the data derived from these wells, the Gelria Concession for the exploitation of coal and rock salt was allocatcd in 1930 (fig. 1.2). The terms and conditions stipulated in the concession contained the provision that the exploitation of rock salt must be carried out by dry mining. Up to now, no exploitation of mineral and natural resources has taken place in this concession area.

In the eighties, renewed investigations were carried out by the Geological Survey of The Netherlands in the map sheet area for an inventory of coal occurrences in The Netherlands. Seismic surveys were carried out and three boreholes were drilled (Hengevelde-1, Joppe-1 and Ruurlo-1 wells). This research revealed that exploitable coal reserves in Gelderland are also present outside the Gelria Concession.

1.3.4 Rock salt

Between 1901 and 1923, the presence of exploitable rock salt was demonstrated by exploration of the Achterhoek and Twente by the ROvD. The rock salt in the vicinity of Winterswijk was also found to contain potassium-magnesium levels.

In order to reduce the dependence on German salt importation (German salt export being heavily taxed during the First World War), the Buurse concession was allocated to "N.V. Koninklijke Nederlandse Zoutindustrie" (KNZ: now Akzo-Nobel Chemicals B.V.) for the exploitation of rock salt by means of solution mining in this area. Rock salt had been documented in Twente since 1886, when during drinking-water drilling activity on the Twickel country estate, rock salt was unexpectedly encountered. Rock salt was exploited in the Buurse concession between 1919 and 1952. With the construction of the Twente canal to extend transportation by inland waterways, the attention of KNZ turned to the area to the south of Hengelo. As a consequence of successful exploration by drilling, the Twenthe-Rijn concession was allocated to the KNZ in 1933. An application submitted simultaneously for virtually the same area by the "Nederlandse Maatschappij voor Mijnbouwkundige Werken" was not granted (Visser, 1987). Rock salt mining was transferred to this area near the Twente canal. Up to the present time, over 420 boreholes have been drilled. By the end of 1994 the Twenthe-Rijn concession had been expanded as far as the Buurse concession (fig. 1.2).

In the Gelria concession (fig. 1.2), allocated in 1930 for the combined exploitation of rock salt and coal, no mining activities have been conducted up to the present time.

During the Second World War, the Deurningen and Weerselo salt-structures in Twente were encountered. Further seismic research and a drill hole by the KNZ indicated the likelihood that they were part of a single large salt plug (Harsveldt, 1980). In 1967 the Weerselo concession for this area was allocated to the KNZ but up to now no mining has been carried out. This volume, however, demonstrates the presence of a local salt structure, combined with salt intrusion along the Gronau Fault Zone (Maps 3 & 4; see also section 1.4 and 12.3).

1.3.5 Hydrocarbons

The first indication of the presence of hydrocarbons in the area was provided by oil traces in Carboniferous sandstone and Zechstein anhydrite in the Ratum-1 and Plantengaarde-1 wells. The Corle-1 well in 1923 revealed the first oil find in The Netherlands, with a total yield of only 240 l, which was of no economic importance. Subsequently, further oil traces were reported in a number of the Gelria wells.

In the adjacent area in Germany the history of hydrocarbon exploitation goes back to the previous century; immediately to the east of the map sheet area in the vicinity of Sieringshoek, native asphalt exploitation has gone on since the 18th century (Kemper, 1976). The discovery in 1938 of the gas field near Bentheim directly to the east of the Dutch border (Hinze, 1988; fig. 1.2) is significant for exploration in The Netherlands. To the north of the area, various oil and gas fields have been discovered in the Carboniferous, Zechstein, Upper Jurassic and Lower Cretaceous deposits. During the Second World War actual hydrocarbon exploration within the map sheet area was undertaken by the BPM/Elwerath consortium. Up to 1945 a number of boreholes were drilled, all without success.

In the post-war period, several gas finds were made in Twente by the "Nederlandse Aardolie Maatschappij" (NAM), including the Dutch/German Tubbergen/Itterbeck-Halle field (1951), and the fields Denekamp (1952), Rossum-Weerselo (1955), De Lutte (1956), Tubbergen-Mander (1968), Rammelbeek (1970) and Oldenzaal (1976). As a result, concessions were obtained by the NAM, encompassing parts of the map sheet area, these being the concessions Tubbergen (1953), Rossum-De Lutte (1961) and Twenthe (1977) (fig. 1.2).

Despite the promising results obtained from the Corle-1 well and oil traces in other wells, oil and gas exploration continue to remain unsuccessful in the Achterhoek.

1.4 Research set up

The mapping of the subsurface of The Netherlands is predominantly based on the data collected by the companies referred to in the preceding section.

Seismic mapping

For regional mapping purposes it was decided to adopt a seismic line-grid of a maximum of 4 by 4 kilometres. Predominant use was made of 2D seismics, with occasional use of 3D seismics. The seismic data were collated during the period 1970 to 1990 (see appendix A). The position of the seismic lines is illustrated in figure 1.3.

The selected reflectors form the boundaries between the large lithostratigraphic units (groups and formations). Calibration of the seismic data and well logging was carried out by means of 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). For this a linear equation between the velocity and the depth of the layer was taken ($Vz = Vo + kz$).

An exception to the linear equation is the Zechstein Group. In view of the specific lithostratigraphic composition of this group, a hyperbolic equation between the interval velocity and the time interval was selected ($Vint = a + [d/(\Delta t\text{-}b)]^c$; see table 1.1, c).

To guarantee consistency between depth maps of adjacent map sheets, the same velocity equations have been applied to all the map sheets in principle. The parameters of this regional velocity distribution were determined from the acoustic data obtained from 65 wells located throughout The Netherlands. In the determination of the parameters a maximum error of 5% between the depth values of the well and the seismic interpretation is considered acceptable. Two different velocity distributions were used (table 1.1a and 1.1b); one for the strongly inverted Central Netherlands Basin and the Lower Saxony Basin and one for the non-inverted Tubbergen and Dalfsen High (fig. 1.8). In the inverted areas, the deposits were located at deeper levels in geological history that they are at present. As a result, the deposits have a greater seismic velocity than may be assumed on a basis of their present depth.

To establish consistency of the geological maps with German maps (Baldschuhn et al., 1996) regular contacts have been maintained with the BGR in Hannover. In the case of the southern part of the map sheet area, a depth map of the top of the Carboniferous was used (Juch, 1994). In East Twente the maximum error between the depth in the borehole and the value calculated from seismic data was greater than 5%. The occurrence of high interval velocities in the Triassic deposits (Jaritz et al., 1991) is thought to be the cause of this large discrepancy. In the area lying adjacent to Germany a correction of 100 to 300 m increasing in an easterly direction had to be applied to the whole pattern of the depth contours to ensure consistency with German maps.

In part of the map sheet area, particularly the east and southeast, the Mesozoic deposits lie close beneath or sometimes actually at the surface. Seismic data provide insufficient resolution to map the layers at the shallowest depth, and shallow wells were therefore used in these areas (fig. 1.4).

In the mapping of the Gronau Fault Zone, problems were encountered in seismic interpretation, particularly in the central part. Both the quality and the line density of the seismics were not optimal. The area has now been shot by a 3D survey, the data of which were not available at the time of mapping. The interpretation of the seismics relating to the area around the fault zone (Triassic), proved impossible to correlate with the results from the Weerselo-1 and Deurningen-Weerselo-3 wells (Zechstein). Intrusion of Zechstein salt in the fault zone is thought to be the explanation. Indicating a fault zone on the map solved the apparent problem. An interpretation based on 3D seismic is expected to drastically reduce these uncertainties.

Figure 1.3 Location of the seismic lines used. Appendix A gives additional information on the owner and the age of the various 2D and 3D surveys.

Table 1.1. Applied velocity distribution

a. The applied velocity distribution outside the inverted areas is based on $Vz = Vo + kz$.

Vz: average velocity at depth z (m/s);

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

k: specific constant (1/s)

z: depth (m).

Unit	*Vo*	*k*
North Sea Supergroup	1696	0.49
Chalk Group	2092	1.08
Holland Formation	2020	0.63
Vlieland subgroup	2051	0.41
Niedersachsen Group	1507	0.82
Lower and Upper Germanic Trias Groups	2293	0.69
Upper Rotliegend Group	3535	0.18

b. As in a, the velocity distribution applied in the inverted areas is based on $Vz = Vo + kz$:

Unit	*Vo*	*k*
North Sea Supergroup	1696	0.49
Chalk Group	2092	1.08
Holland Formation	2020	0.63
Vlieland subgroup	2051	0.41
Niedersachsen Group	2297	0.62
Altena Group	2297	0.62
Lower and Upper Germanic Trias Groups	3254	0.56
Upper Rotliegend Group	3535	0.18

c. The velocity distribution for the Zechstein Group throughout the area is based on $Vint = a + [d/(\Delta t-b)]^c$:

Vint= average interval velocity (m/s)

Δt = time interval Zechstein (s)

a = asymptote interval velocity (m/s)

b = asymptote Δt (s)

c = constant

d = constant (m)

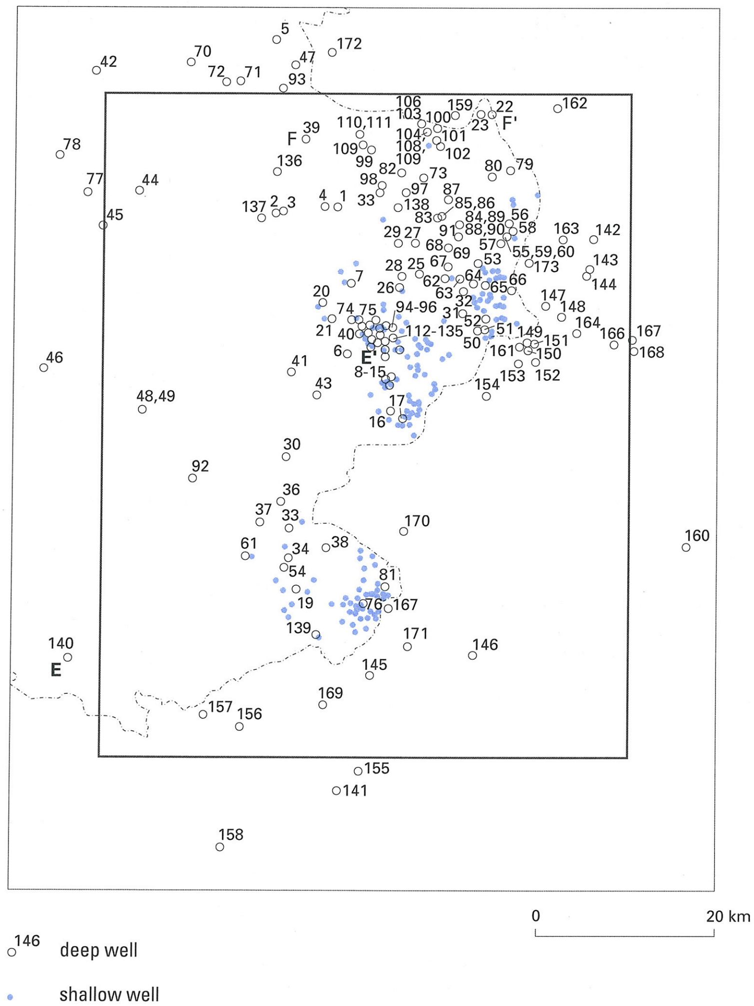
Unit:	a	b	c	d
Zechstein Group:	4410	-0.018	1	47.36

Geological research

The geological research focused on the lithostratigraphic composition of the rocks present in the map sheet area (fig. 1.5) and their geological history with respect to the regional developments. The previously mentioned seismic data and well-log data were used, supplemented with data from lithostratigraphic, palynostratigraphic and biostratigraphic data obtained from wells. In order to acquire a better understanding of the geological structure, a detailed study has been made of the area across the German border.

The map sheet area also contains a large number of non-confidential shallow wells with publicly accessible data files. These well data provide an important addition to seismic data in areas where old rocks lie close to the surface, as is the case in East Twente and the Achterhoek. The data derived from these wells have been obtained from the NITG-TNO geological data base and have also been utilised for the maps and explanation. These shallow wells include observation boreholes, drilling for water extraction and for scientific research. Figure 1.4 shows the location of these wells and gives an idea of the data coverage. The total number of non-confidential wells concerned in the mapping is over 150.

Figure 1.4 Location of the wells used for the geophysical and geological mapping. For the numbering of the deep wells, reference should be made to appendix B where the name, owner, final depth and date of the well is given. The non-classified wells used have also been included in this figure; this information has been obtained from the NITG-TNO geological data base.



Well-log data was also derived from German literature (including the Deutscher Planungsatlas, 1976). These wells are frequently described in detail, sometimes being documented with well-log data records. Two deep wells penetrating the Devonian, the Münsterland-1 and Isselburg-3 wells, are of particular importance. An overview of the German wells used is given in appendix B, together with references to the literature source.

Two geological studies have been specifically carried out in relation to this mapping. The geology of the Mesozoic in the Achterhoek (Dirven, 1995) comprised a compilation of all the lithostratigraphic and chronostratigraphic data from wells in the Achterhoek, involving the preparation of stratigraphic sections applied to the Mesozoic era. This information was stored in a Geographical Information System. In the structural analysis of the Gronau Fault Zone (Grönloh, 1995) a number of seismic sections were balanced and reconstructed, and structural maps prepared for six major tectonic phases. A palaeo-stress field orientation was prepared for each tectonic phase. Section 12.3, that deals with the Gronau Fault Zone, is therefore based on the results from this study.

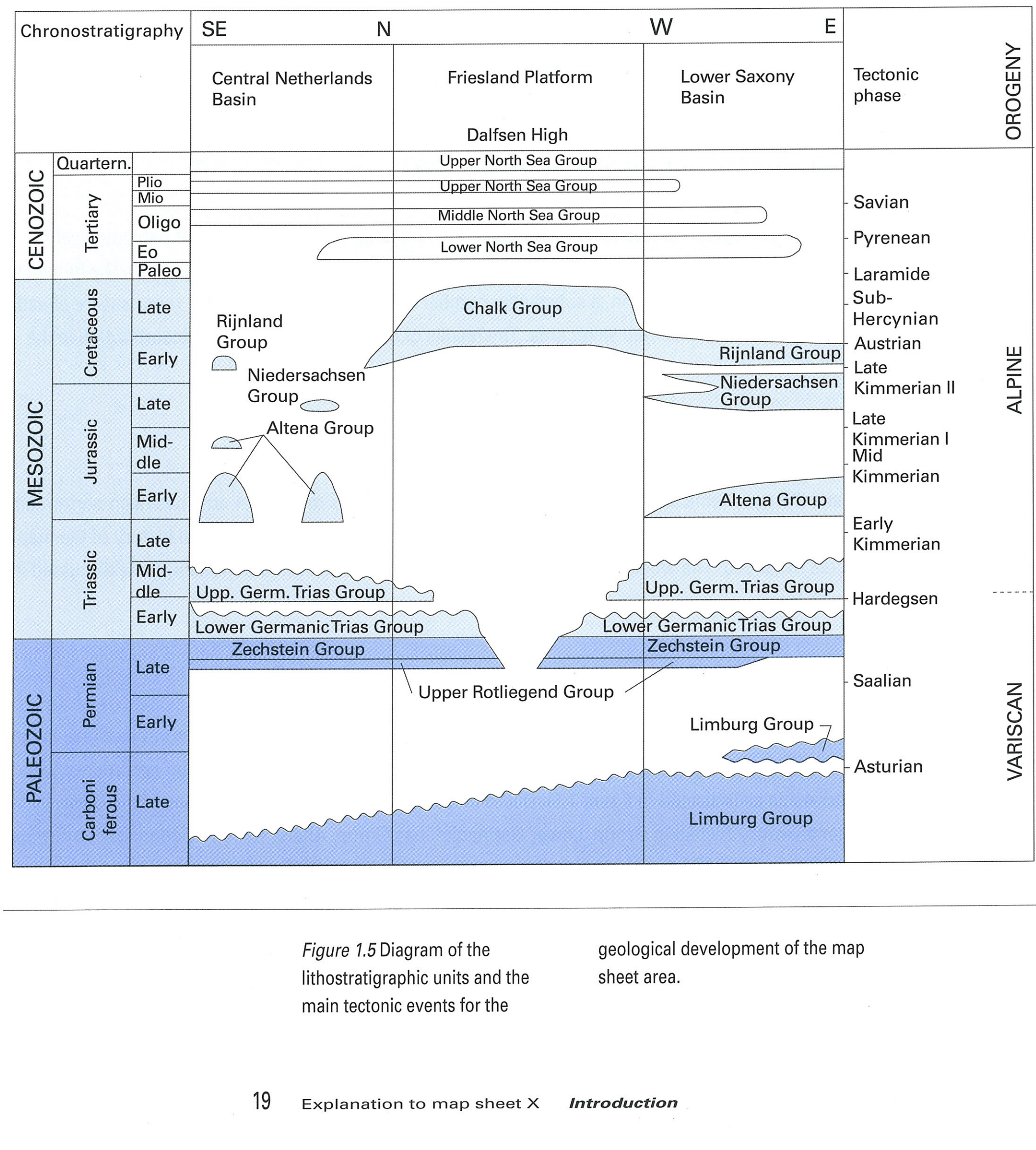


Figure 1.5 Diagram of the lithostratigraphic units and the main tectonic events for the geological development of the map sheet area.

Petrophysical research

In addition to the geological research, the petrophysical characteristics of the reservoir rocks have also been determined. Well-log data have been processed for the calculation of porosity, water saturation and hydrocarbon content. The calculations were calibrated on a basis of core analyses.
The Limburg Group has been petrophysically evaluated by means of nine wells. These wells are situated in the northern part of the map sheet area. In three of them, the sandstones of the Limburg Group have proved to be gas-bearing (appendix D). For the petrophysical evaluation use was made of the 'single porosity model' with the density log as porosity log. The gamma-ray log serves as clay indicator.

The Zechstein Group (e.c. Z2 and Z3 Carbonate members) has been illustrated by eight selected wells. Seven wells are situated in the northern part of the map sheet area, and the other one in the southern part, Winterswijk-1 well. The Z2 Carbonate from six wells in the map sheet area has been evaluated, two of which have proved to be gas-bearing. The Z3 Carbonate has also been evaluated on a basis of six wells in the map sheet area, one of which is gas-bearing (appendix F).

This evaluation has been carried out with the aid of an in-house complex-lithology-model specially developed for the petrophysical evaluation of (argillaceous, anhydritical) limestone/dolomite reservoirs. The porosity and the dolomite, carbonate and anhydrite content are equated by means of tool comparisons (density, sonic and neutron). First, the clay content is calculated from the gamma-ray log. Next, the effective porosity is calculated, followed by the dolomite content, and finally the remaining contents are calculated.

Biostratigraphic and palynological research

To clarify the geological research and the geophysical mapping, biostratigraphic and palynological studies have been performed on sequences of the Limburg, the Altena, the Niedersachsen, the Rijnland and the Chalk Groups. 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

To pursue the geochemical research, an analysis of 24 wells in this map sheet area has been performed. The coalification (vitrinite content) of the samples has been measured and the burial history of the map sheet area modelled. The working method, the measurement results and the modelling are discussed in section 12.4.

1.5 Maps and sections

The results of the seismic mapping are shown in a series of maps and in three structural sections. In the case of each lithostratigraphic group, depth and thickness maps have been plotted (in accordance with the subdivision as indicated in figure 1.5). Depth maps have been plotted of the bases of the Upper Rotliegend Group, Zechstein Group, Lower Germanic Trias Group, Altena Group, Niedersachsen Group, Rijnland Group, Chalk Group, North Sea Supergroup and Upper North Sea Group. Moreover, a depth map has been plotted of the top of the Zechstein Group. The depth maps of the bases of the Upper Rotliegend Group, Zechstein Group and Lower Germanic Trias Group in particular give an impression of the structural trend of the area - NW-SE oriented - superimposed on a WNW-ESE-oriented trend dating from the Carboniferous. Subcrop maps have been made of the major unconformities, which are on the base of the Niedersachsen Group, Rijnland Group and North Sea Supergroup. The depth maps only show faults with an offset of more than 50 m.

Thickness maps have been plotted of all the above-mentioned stratigraphic units, with the exception of the Lower Germanic Trias Group and the North Sea Supergroup. The Lower Germanic Trias Group and the Upper Germanic Trias Group together are presented as one single map. A thickness map of the North Sea Supergroup may be obtained by adding the present-day altitude to the depth map.

In general the seismic lines used for the mapping of the map sheet area are of a reasonable quality. However, as they were insufficient to determine the base of the Upper Rotliegend Group, the depth map of this group is based on the seismic depth map of the base of the Zechstein Group, to which a thickness map of the Upper Rotliegend Group based on well logs has been added (fig. 4.1).

The depth and thickness maps do not show wells containing a fault in the particular group or where the final depth of this group is located.

The subcrop geological maps of the base of the Niedersachsen Group, Rijnland Group and North Sea Supergroup (Maps 17, 18 & 19) illustrate the stratigraphic units situated below the unconformities and give an impression of the degree of erosion preceding the deposition of these groups.

Finally, three structural sections are depicted on a separate map (Map 20). These sections, with a NW-SE and SW-NE orientation, have been selected in such a way as to link up with sections of the adjacent map sheets.

1.6 Explanation

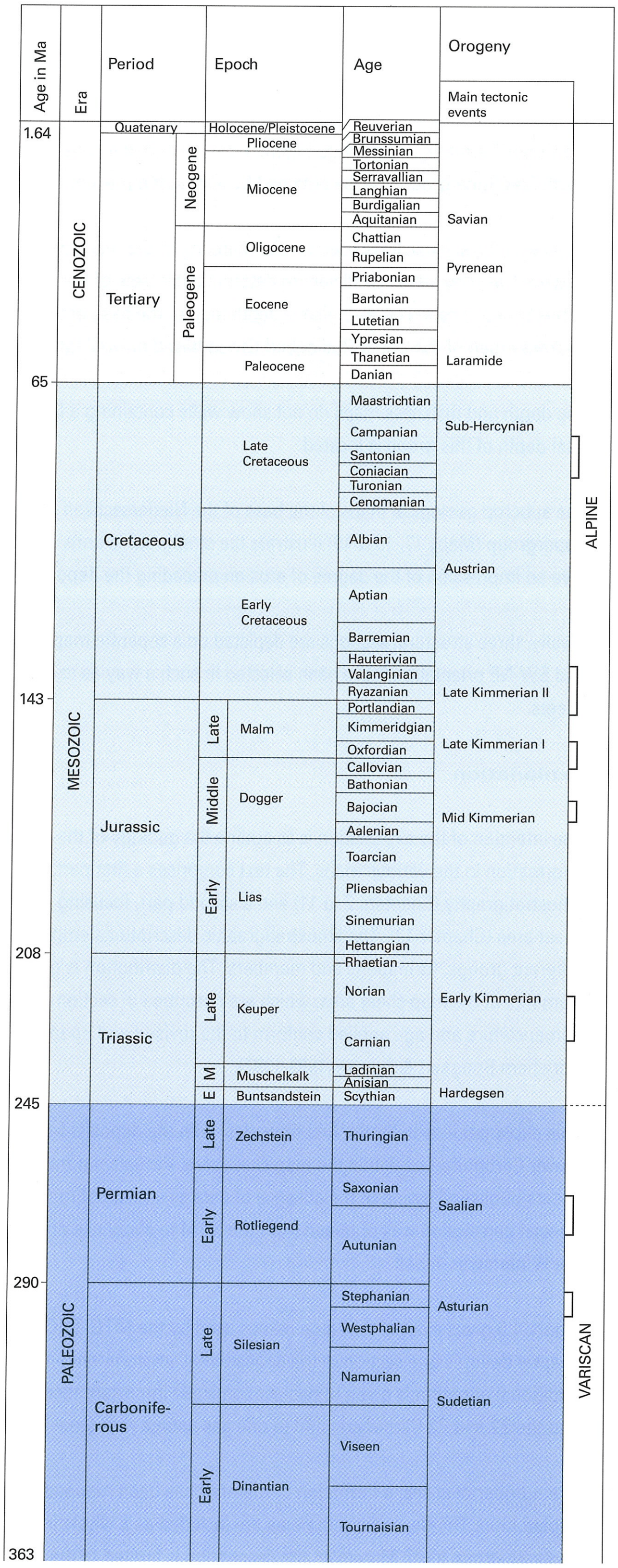
The intention of the explanation is to outline the geology of the map sheet area as illustrated by the information in the various maps. The text comprises a first part, giving a description of the lithostratigraphy (Chapters 2 to 11) and a second part, focusing on the geological history of the map sheet area (Chapter 12). 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 1.6.2. Unless stated otherwise, the nomenclature and age applied conform to the revised and updated stratigraphic nomenclature (Van Adrichem Boogaert & Kouwe, 1993-1997).

This explanation will, for the first time, deal with the deposits from the pre-Devonian, Devonian and Lower Carboniferous within the map sheet area. Virtually no mention was made of these in the map sheets published owing to the absence of data as a result of the prohibitive depth of the deposits. Special permission was obtained from the NAM to allow use of the data from the pre-Westphalian from the Winterswijk-1 well.

Figure 1.6 gives a list of the stage names used by the NITG-TNO occurring in this explanation. Each chapter devotes one section to the depositional environment and the palaeogeography. Finally, additional attention is given to two economically important reservoir rocks (the Tubbergen Sandstone and the Z2 and Z3 Carbonate) and to one gas-source rock (coal in the Limburg Group).

In a number of cases, a formation or member has been mapped and included as a text figure in the explanation. The Cenozoic sediments are included as a whole in the North Sea Supergroup and not at a separate group level. Moreover, the description is limited to the Tertiary sediments. For the description of

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



the Quaternary deposits reference should be made to the Rijks Geologische Dienst (1975), de Toelichting bij de Geologische Kaart van Nederland 1:50.000, map sheet Almelo/Denekamp (Rijks Geologische Dienst, 1993a) and the recently published map Top marien Tertiair (Rijks Geologische Dienst, 1996).

Finally, chapter 12 contains a description of the geological history illustrated by the sedimentary setting and structural development.

1.7 Summary

1.7.1 Stratigraphic succession

The stratigraphic column of the map sheet area is shown in figure 1.5. The (present) extent of the sediments has been largely determined by the structural development of the area. Sediments from the Late Carboniferous exhibit a clastic composition, are predominantly lacustrine to fluvial in origin and contain many coal beds. Separated by a large hiatus, the Limburg Group is overlain by the Upper Rotliegend Group - mainly comprising dune and wadi deposits - characteristic of a desert area. The Zechstein Group, Late Permian in age, spans a number of evaporite cycles. The succession of clay, carbonate, sulphate and rock salt was formed under marine conditions. The Lower Germanic Trias Group again exhibits a clastic composition and is continental (fluvial and lacustrine) in origin. In the Upper Germanic Trias Group the carbonates and evaporites reflect marine episodes in the basin. The Altena Group (Early and Middle Jurassic) consists of fine-grained marine sediments. The Niedersachsen Group (Late Jurassic to earliest Cretaceous) represents predominantly evaporitic, lacustrine, and lagoonal deposits. Marine sediments were deposited during the entire remaining part of the Cretaceous, subdivided into the clastic sediments of the Rijnland Group (Early Cretaceous) and the carbonates of the Chalk Group (Late Cretaceous). The North Sea Supergroup (Tertiary and Quaternary) is composed of clastic sediments. The sediments were originally deposited under marine conditions, but during the Quaternary a transition to continental conditions occurred.

Periods of erosion, related to the deformation phases, produced several 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. (fig. 1.5).

1.7.2 Structural units

The geological history is illustrated by the structural elements differentiated in the map sheet are (fig. 1.7). These units comprise, to a greater or lesser degree, Variscan elements which were reactivated and modified during later tectonic phases.

The *Achterhoek High* is a broad anticlinal structure to the southwest of the Gronau Fault Zone. The high is characterised by the presence of sediments, Westphalian A to Early Westphalian C in age, at the top of the Carboniferous (fig. 3.3).

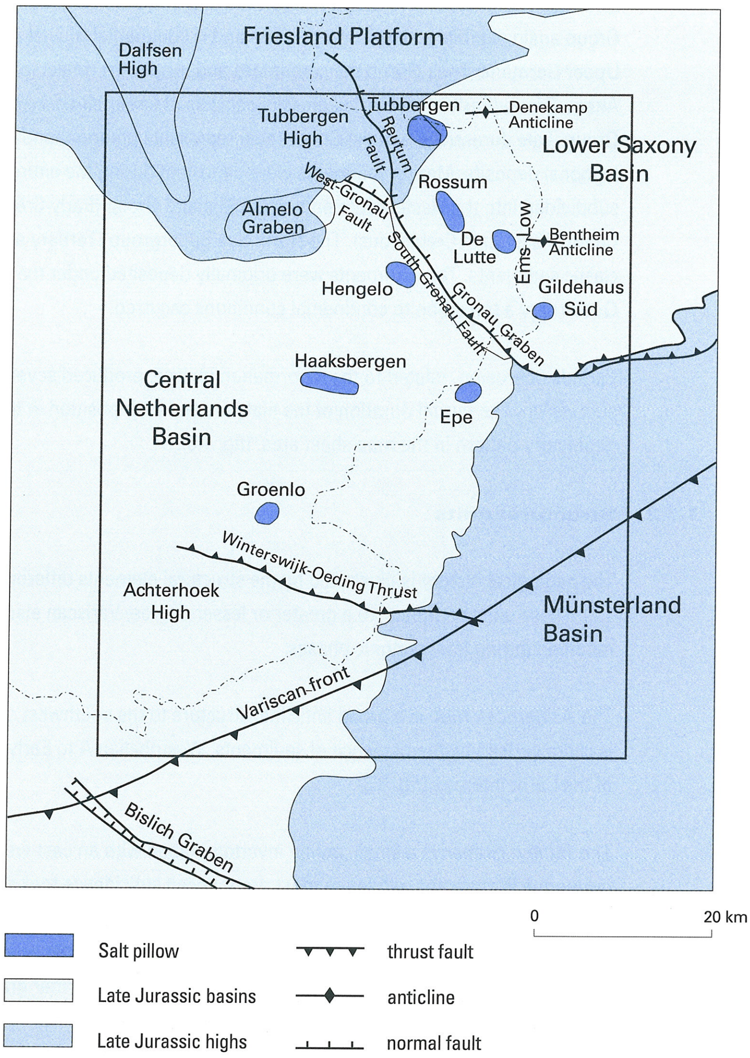
The *Almelo Graben* is a small, gently inverted graben with an east-west orientation. The graben initiated during the Portlandian, while the most pronounced subsidence took place during the Hauterivian to Early Albian. During the Sub-Hercynian phase, inversion of the graben occurred, with the major uplift encompassing the area exhibiting the most pronounced subsidence in its eastern part. As a result of the inversion at the level of the base of the Rijnland Group, the former graben appears as a clear positive relief (Map 12).

The *Bentheim Anticline* is an eastwest oriented, strongly inverted part of the Lower Saxony Basin. The most extreme subsidence occurred here during the Valanginian to Albian period, succeeded by inversion occurring during the Coniacian to Santonian.

In the southern part of the map sheet area, the formation during the Late Jurassic and Early Cretaceous of differentially subsiding WNW-ESE half grabens in which sediment sequences were deposited, took place in the eastern part of the *Central Netherlands Basin*. During the Late Cretaceous the basin was uplifted (inverted) and profound erosion occurred. Virtually throughout the area, the North Sea Supergroup rests directly on the Triassic or Lower Jurassic (Map 19). On the north and northeast margin, the Central Netherlands Basin is separated from the Tubbergen High and the Lower Saxony Basin partly by prominent fault zones.

Two of the prominent fault zones occurring within the Central Netherlands Basin are the *Winterswijk-Oeding Thrust* and the *Bislich Graben*, both situated in the south of the map sheet area. The Bislich Graben is a WNW-ESE oriented graben only 800 m wide. In this area, salt intrusion occurred during the

Figure 1.7 Location and overview of the structural units, fault zones and salt structures of importance in the geological development of map sheet X.



Early Kimmerian phase, initiating a period of profound erosion. This was followed by subsidence and the development of the graben, which again levelled up with Lower and Middle Jurassic deposits.

During the Early Triassic, the eastern part of the map sheet area was situated on the western margin of the *Ems Low*. This structure, NNE-SSW in orientation, was manifested by thick deposition of the Main Buntsandstein Subgroup (fig. 6.4). The western part of the map sheet area was part of the *Netherlands Swell*, where a Triassic succession attenuated by erosion is present.

The *Dalfsen High* in the northwest of the map sheet area is characterised by deep erosion during the Late Kimmerian phases. On the high, the Carboniferous crops out under the Rijnland Group (Map 18). The Dalfsen High is a part of the Friesland Platform (fig. 1.8).

The NW-SE oriented *Gronau Fault Zone* lies in the northeastern part of the map sheet area and forms the boundary between the Central Netherlands Basin and the Lower Saxony Basin. The fault zone is composed of three elements, namely the South Gronau Fault, West Gronau Fault and Reutum Fault. From the Late Carboniferous until recently, the fault zone had a great effect on the geological development of this map sheet area. This fault zone is dealt with in great detail in section 12.3. Zechstein Salt intruded locally along the fault zone. (Weerselo salt-structure).

The *Gronau Graben* is a half graben filled with a thick sequence of Upper Jurassic sediments, formed as a consequence of the extensional stress along the South Gronau Fault.

The *Lower Saxony Basin* is situated to the northeast of the Gronau Fault Zone. The basin is characterised by intensive subsidence during the Late Jurassic which presumably continued into the

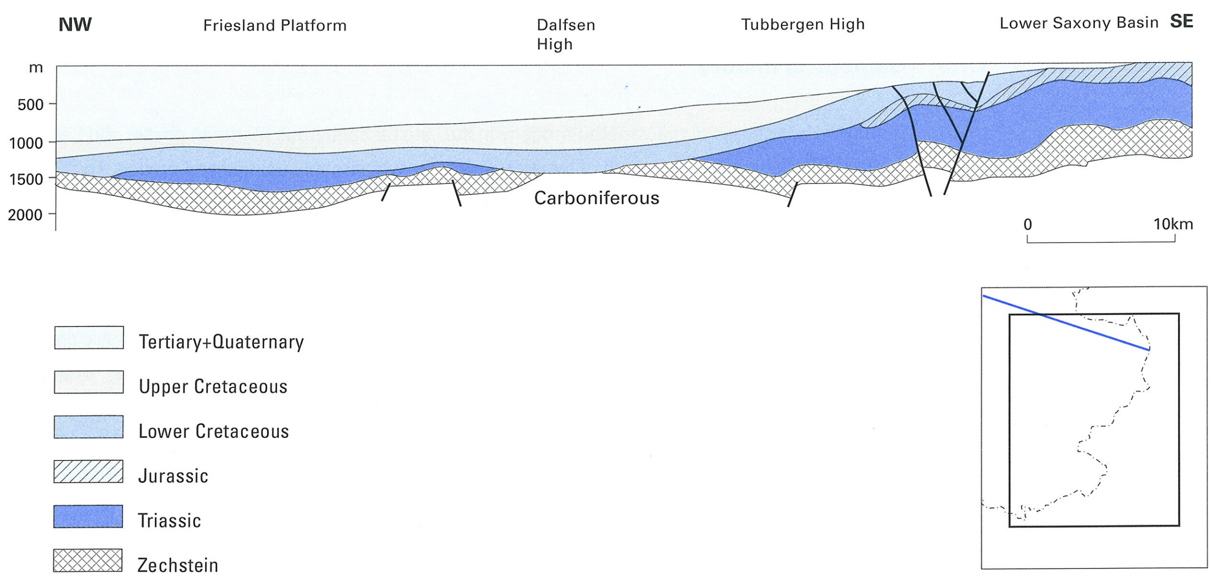


Figure 1.8 Section through the northern part of the map sheet area. This section indicates the Friesland Platform, the Dalfsen High, the Tubbergen High and the Lower Saxony Basin. The tectonic elements are characterised by great differences in geological structure: thick Cretaceous deposits cover the Friesland Platform, the Dalfsen High and the Tubbergen High, while they are absent in the Lower Saxony Basin owing to tectonic inversion.

Late Cretaceous. Inversion occurred during the Sub-Hercynian phase (Coniacian-Campanian), the areas undergoing the strongest subsidence being the most intensively uplifted and eroded.

Salt structures occur at various places in the area. In comparison with the northern part of The Netherlands the salt pillows are smaller in size and sometimes fault-bounded. This difference is attributed to the slighter depositional thickness of the salt. The salt structures of *Itterbeck-Denekamp, Rossum* and *De Lutte* were formed during the Late Jurassic and influenced the extent of the Lower Saxony Group. Other salt pillows within the area are *Groenlo, Haaksbergen, Gildehaus-Süd* and *Epe.*

The *Tubbergen High*, to the east of the Dalfsen High, is the most southeasterly part of the Friesland Platform (fig. 1.8). The high is characterised by profound erosion during the Late Kimmerian phases, cutting down into the deposits of the Upper Rotliegend Group, Zechstein Group and Lower or Upper Germanic Trias Group. The high constituted a major source area for sediments during the Valanginian and Hauterivian. During the Hauterivian to Aptian the high was subsequently covered by sediment and major subsidence coincided with the Sub-Hercynian phase (Coniacian-Campanian).

The *Münsterland Basin*, to the southeast of the map sheet area, encompasses the area containing Upper Cretaceous deposits. The area became exposed as a high during the Late Kimmerian phases, when pronounced erosion cut down to the Carboniferous. The area constituted a major source area for sediments during the Valanginian to Aptian period. In this period it was also known as the northern part of the Rhenish Massif. During the Albian, the high was flooded and covered with sediments; the Münsterland Basin proper originated during the Sub-Hercynian phase (Coniacian-Campanian).

The *Variscan front* represents the zone displaying the most northerly overthrust tectonics during the Variscan orogeny in the Late Carboniferous to Early Permian. The front forms the boundary between the strongly folded and broken rocks in the Variscan mountain chain and the considerably less highly deformed rocks in the foreland basin.

1.7.3 Geological history

During the last phases of the Variscan orogeny in the Late Carboniferous (Asturian phase) and Early Permian (Saalian phase), the south of the map sheet area was strongly uplifted and eroded. To the east of the Gronau Fault Zone, however, the sedimentation persisted into the youngest Carboniferous. During the Late Permian to the Middle Jurassic, there followed a period of predominant subsidence and sedimentation. The basin configuration was clearly influenced by the structures formed during the Saalian phase. This subsidence was interrupted by two tectonic phases: the Hardegsen phase in the Early Triassic and the Early Kimmerian phase during the Late Triassic. During the Late Jurassic and earliest Cretaceous, major phases of uplift occurred (Late Kimmerian phases; Maps 17 & 18), when much of the post-Carboniferous sediments present on the highs was eroded. During the Late Jurassic and Early Cretaceous, differentiated subsidence took place (Maps 10 & 12) in the Central Netherlands Basin and Lower Saxony Basin, followed by two phases of uplift and erosion (inversion) during the Late Cretaceous (Sub-Hercynian phase). In the greater part of the map sheet area this inversion gave rise to deeply incising erosion with, as a result, the absence of virtually the entire Jurassic and Cretaceous succession (Maps 7 - 14). The Mesozoic tectonic phases were, together, the cause of a dominant NW-SE structural trend in the area. Finally, the depth map of the base of the North Sea Supergroup (Map 15) reveals that the Tertiary was marked by the most pronounced subsidence in the western part of the map sheet area. In the Late Tertiary (Map 16) until recent times, uplift in the east of the map sheet area resulted in erosion of the Tertiary deposits.

2 Pre-Devonian, Devonian and Lower Carboniferous

2.1 Introduction

Sediments of the pre-Devonian, Devonian and Lower Carboniferous are the oldest deposits discussed in this explanation. This map sheet area, together with the southern part of The Netherlands, is one of the few areas where rocks older than Westphalian have been reached by drilling (Winterswijk-1 well). This is also the case in six wells in western Germany (Wachtendonk-1, Münsterland-1, Isselburg-3, Versmold-1, Vingerhoets-93, Soest-Erwitte-1/1A; Deutscher Planungsatlas, 1976). The deposits comprise claystones and siltstones of Ordovician to Silurian age, clastics of the Banjaard group and limestone and dolomite of the Carboniferous Limestone Group. The stratigraphic succession of these sediments ranges from Ordovician to Early Carboniferous in age.

The top of the Carboniferous Limestone Group within the map sheet area ranges in depth from 4300 m in the vicinity of Winterswijk to nearly 7000 m in the northeast. The depth to the base of the Banjaard group is not known. The minimum combined thickness of the Carboniferous Limestone Group and Banjaard group is 700 m.

2.2 Pre-Devonian

The pre-Devonian deposits have only been encountered at some distance from the map sheet area. The Soest-Erwitte-1/1a well (approximately 120 km to the southeast of the map sheet area; Clausen & Leuteritz, 1982) and wells in Belgium and the southern North Sea (Van Adrichem Boogaert & Kouwe, 1993-1997) suggest the occurrence of a thick sequence of dark-coloured clay/siltstone Ordovician to Silurian in age under the Banjaard group in the south of the map sheet area. The contact with the overlying Banjaard group is unconformable.

2.3 Banjaard group

The Banjaard group and the constituent units all have an informal status in The Netherlands (Van Adrichem Boogaert & Kouwe, 1993-1997). Deposits of the Banjaard group have been demonstrated in the southern part of the map sheet area (the Winterswijk-1, Münsterland-1 and Isselburg-3 wells). None of the individual wells penetrated the entire group fully. The deposits of the group are composed of sandstone, claystone and limestone. The Banjaard group is thought to rest unconformably on deposits of the Silurian or Ordovician age. The greatest penetration, 550 m, is present in de Winterswijk-1 well; this is followed by the Münsterland-1 with a penetration of 449 m and Isselburg-3, with 190 m. The group is subdivided into the Banjaard clastics, Bollen claystone and Bosscheveld formation (fig. 2.1). The deposits are Middle to Late Devonian in age, while in the deepest part of the succession Early Devonian deposits may also occur. Within the map sheet area the top of the deposits lies at approximately 4500 m in the SE, increasing to a depth to probably well over 7000 m in the NE.

The *Banjaard clastics* is an informally defined unit composed of thin layers of light coloured sandstones, claystones and limestones and has only been recovered in the Winterswijk-1 well. The upper boundary of the unit is determined by the claystones of the overlying Bollen claystone; the base of the formation has not been reached. The unit is limited in its areal extent and, in an easterly direction, partly passes laterally into massive limestone. Two thick coarsening-upward sequences can be differentiated within the unit. A core from the basal part of the formation displayed an arkose with a 25% plagioclase content (RGD, 1978a). The minimum thickness of the unit is 360 m.

The topmost part of the Banjaard clastics is regarded as being the lateral equivalent of the Frasnian and Givetian limestones which have been found further to the east in the Münsterland-1 and Versmold-1 wells. While no supportive biostratigraphic research has been carried out, the abundant occurrences of thin carbonate and dolomite beds make this probable. It is even possible that the basal part of the formation is of Eifelian or Early Devonian (Gedinnian - Emsian) age.

The *Bollen claystone*, of Frasnian - Famennian age, lies with a sharp boundary on the Banjaard clastics and consists predominantly of dark coloured claystone, with intercalations of thin layers of sandstone and limestone. The unit has a vast lateral extent and a comparatively uniform thickness of approximately 125 m. The boundary with the overlying Bosscheveld formation is gradual.

The *Bosscheveld formation*, of Famennian to possibly Early Tournaisian age, contains an alternation of claystone, limestone and sandstone. The deposits in the Winterswijk-1 well achieve a thickness of nearly 50 m and in the Münsterland-1 well are over 80 m. Further towards the south the unit becomes sandier and grades into the Condroz Sandstone, as has been found in the Wachtendonk-1 well (Wolburg, 1963, 1970b).

2.4 Carboniferous Limestone Group

The deposits of the Carboniferous Limestone Group, of Dinantian age (Early Carboniferous), are presumed to occur throughout the map sheet area. The group in the map sheet area is represented by a succession consisting of dark-grey, marly to argillaceous, dolomitic limestone. The deposits are part of the Zeeland Formation. The group rests conformably on the Banjaard group and is covered unconformably, including by a hiatus, by the Limburg Group.

2.4.1 Zeeland Formation

The Zeeland Formation in the Winterswijk-1 well is 185 m thick. In this well, the succession consists of a massive, fossil-bearing limestone, with a few shale intercalations. Towards the south and east, the thickness reduces drastically to between 20 and 30 m and the massive carbonates pass into dark coloured dolomite and limestone, with layers of marl and shale (fig. 2.1). Despite the decreasing thickness, the stratigraphic succession appears more complete. The lithological development is no longer commensurate with the Zeeland Formation; an adequate stratigraphic nomenclature is not yet available. The dark limestones have been found to contain beds of tuffaceous rocks and silicified limestone (Kelch, 1963); fossils present include crinoides, trilobites and corals (Wolburg, 1963). The deposits are of Early Tournaisian to Viséan age.

2.5 Sedimentary development and palaeogeography

Deposition of the Silurian and Ordovician rocks within the map sheet area is presumed to have taken place under deep-marine conditions. Lying unconformably above these rocks are the (Lower and) Middle Devonian sands of the Banjaard clastics, which were deposited under shallow-marine conditions (fig. 2.2a). The source area of these sands must be sought in the west or northwest; towards the east, outside the map sheet area, these sands grade into carbonates, indicating clear water conditions, with a small influx of clastic components present. The Bollen claystone and the Bosscheveld formation were deposited during a major transgression, during which the source areas of clastics in the vicinity of the map sheet area were covered by the sea (fig. 2.2b). The proportion of clastics continued to decrease, and clay sedimentation made way for the deposition of carbonates of the Zeeland Formation. Deposition of these carbonates took place in a relatively shallow sea, to the north of a deep basin, in which only a thin, highly condensed succession (the so-called Kulm-facies condensed sequence) is present (fig. 2.2c). A major transgression at the beginning of the Namurian initiated the deposition of clays and sands of the Limburg Group.

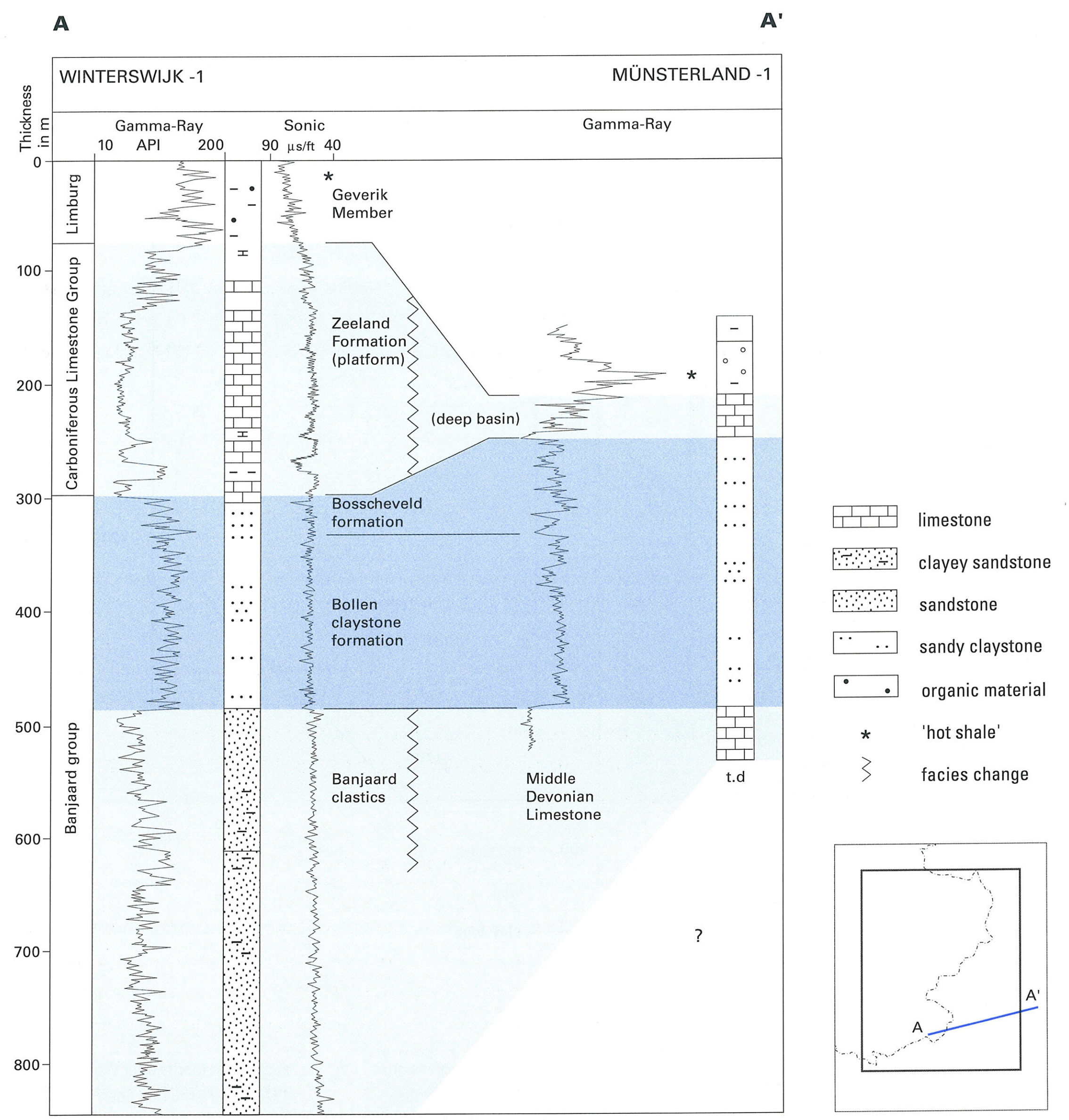


Figure 2.1 Stratigraphic section A-A' of the Banjaard group and the Carboniferous Limestone Group in the Winterswijk-1 and Münsterland-1 wells.

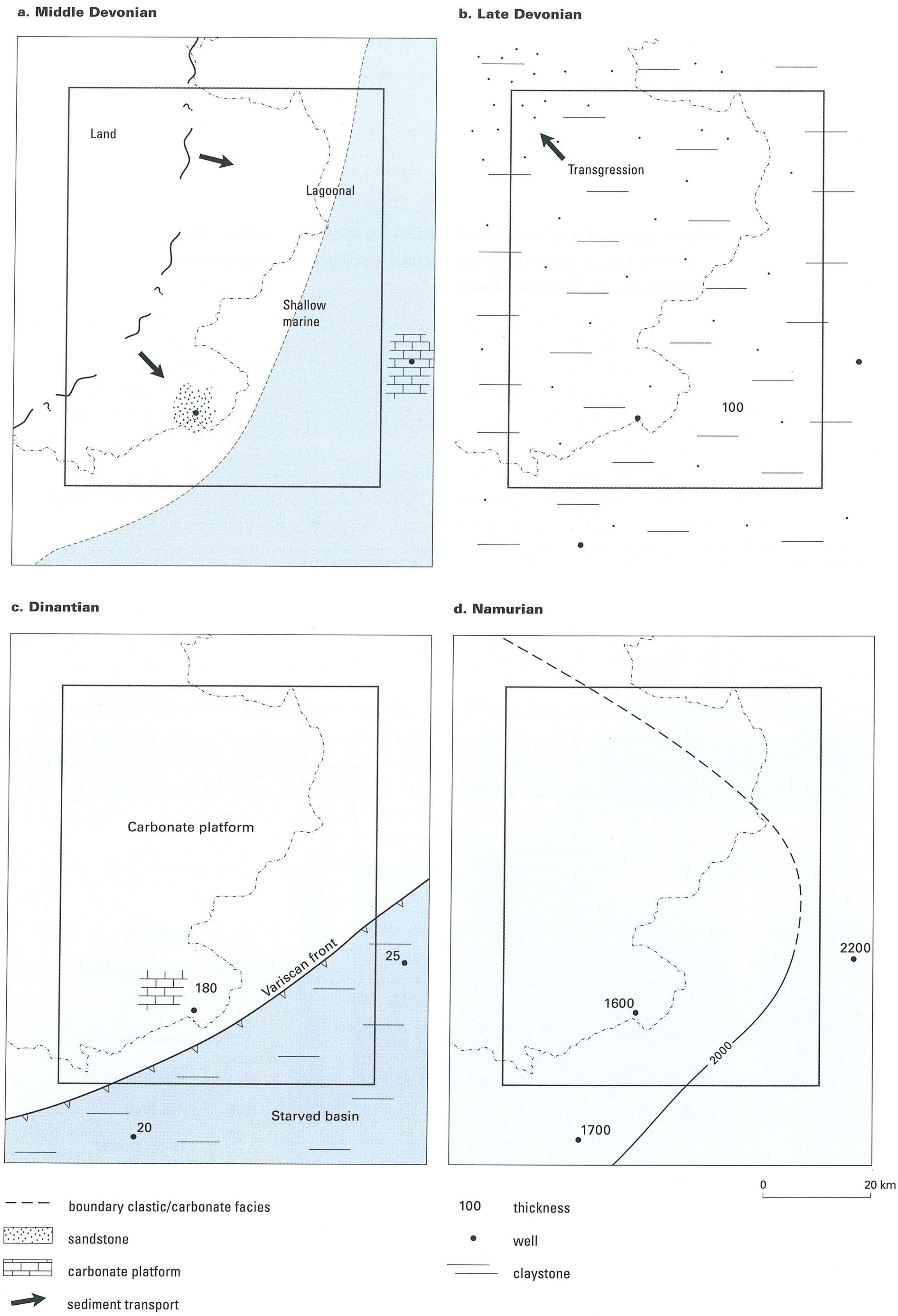


Figure 2.2 Palaeogeography at the time of deposition of the Banjaard clastics and the Lower Carboniferous.
a. Middle Devonian; Banjaard clastics. Clastics were deposited in a shallow-marine setting along the periphery of a positive area, while further to the east, thick carbonaceous successions were formed. b. Late Devonian: The Bollen claystone and Bosscheveld formation were deposited throughout the area during a pronounced transgression. c. Dinantian; Carboniferous Limestone Group. The map sheet area was the location of a carbonate platform, which was bounded on the south side by a deep basin with a thin, condensed succession (partly after Wolburg, 1970b). d. Namurian; Epen Formation. A thick sequence of marine sediments was deposited throughout the area.

3 Limburg Group

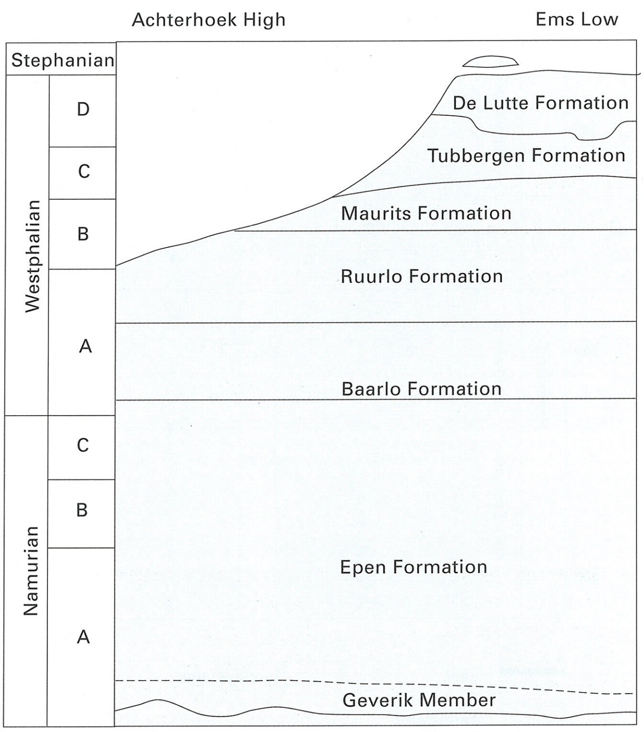
3.1 Stratigraphy

The Limburg Group, of Namurian to Stephanian age, consists of a thick succession of predominantly grey to black, fine-grained siliciclastic sediments, which are also red coloured in the youngest part. The Limburg Group represents virtually the entire Upper Carboniferous and is subdivided into four subgroups, each representing a particular phase of the Late Carboniferous regressive megasequence. The basal part, the Geul Subgroup, is characterised by several fossil-bearing marine bands in a claystone succession. The characteristic lithologies of the Caumer Subgroup are claystone beds and coal seams. The Dinkel Subgroup consists largely of sandstone and is also virtually devoid of coal seams and red colouring. Lastly, the Hunze Subgroup is composed mainly of a red coloured claystone succession. To illustrate the lithostratigraphy more clearly, marine bands and coal seams have also been correlated to give a better understanding of the chronostratigraphic relations pertaining.

The Limburg Group in the map sheet area rests unconformably, including a hiatus, on the Carboniferous Limestone Group and in the major part of the map sheet area is unconformably overlain by the Upper Rotliegend Group (Map 1). In the east and northwest, the Zechstein and the Rijnland Group respectively (Map 18) rest unconformably on the Limburg Group.

Deposits of the Limburg Group are found throughout the map sheet area. The thickness of the entire Limburg Group in the map sheet area increases to approximately 3000 m in the extreme south to well over of 6000 m in the extreme northeast. The reduced thickness in the southern part of the area is the consequence of severe erosion during the Late Carboniferous and Early Permian. This erosion is illustrated by the age of the top of the Limburg Group (fig. 3.1, 3.3 & 3.4).

Figure 3.1 Lithostratigraphic diagram of the subdivision of the Limburg Group in the map sheet area. The Achterhoek High was subjected to profound erosion. The most complete succession has been preserved in the Ems Low.



The depth of the top of the Limburg Group in the major part of the area is less than 1500 m (Map 1). Only in a small area in the extreme north are depths exceeding 1500 m encountered (Maps 1 & 2). The accessibility of the upper surface of this group at less than 1000 m in the southeast of the area even permits conventional mining. For this purpose, the group has been explored by reconnaissance wells, about which much more is now known than in other parts of the northern Netherlands. A few of the wells have even reached the base of the group. The depth of the base of the group ranges from 4300 m in the extreme south to a probable 7000 m in the north of the map sheet area. The fault pattern is predominantly northwest-southeast oriented and gives an indication of the structural pattern within the area.

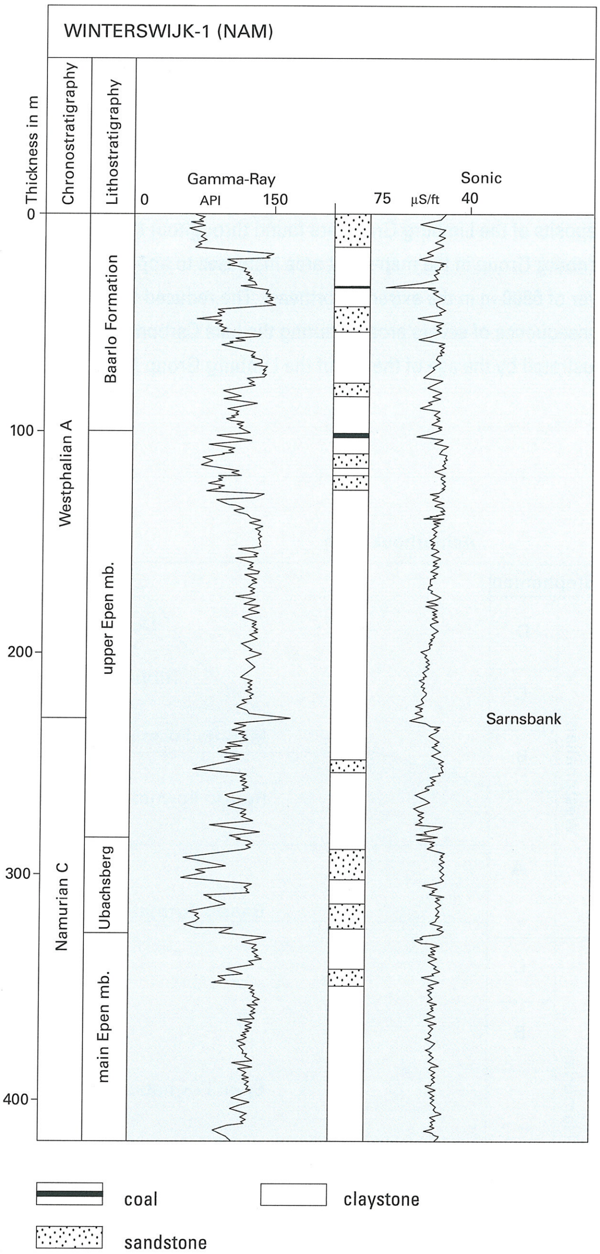


Figure 3.2 Stratigraphic division and log pattern of the top part of the Geul Subgroup (Epen Formation) and the transition to the Caumer Subgroup (Baarlo Formation) in the Winterswijk-1 well. The top part of the Epen Formation is of Westphalian A age.

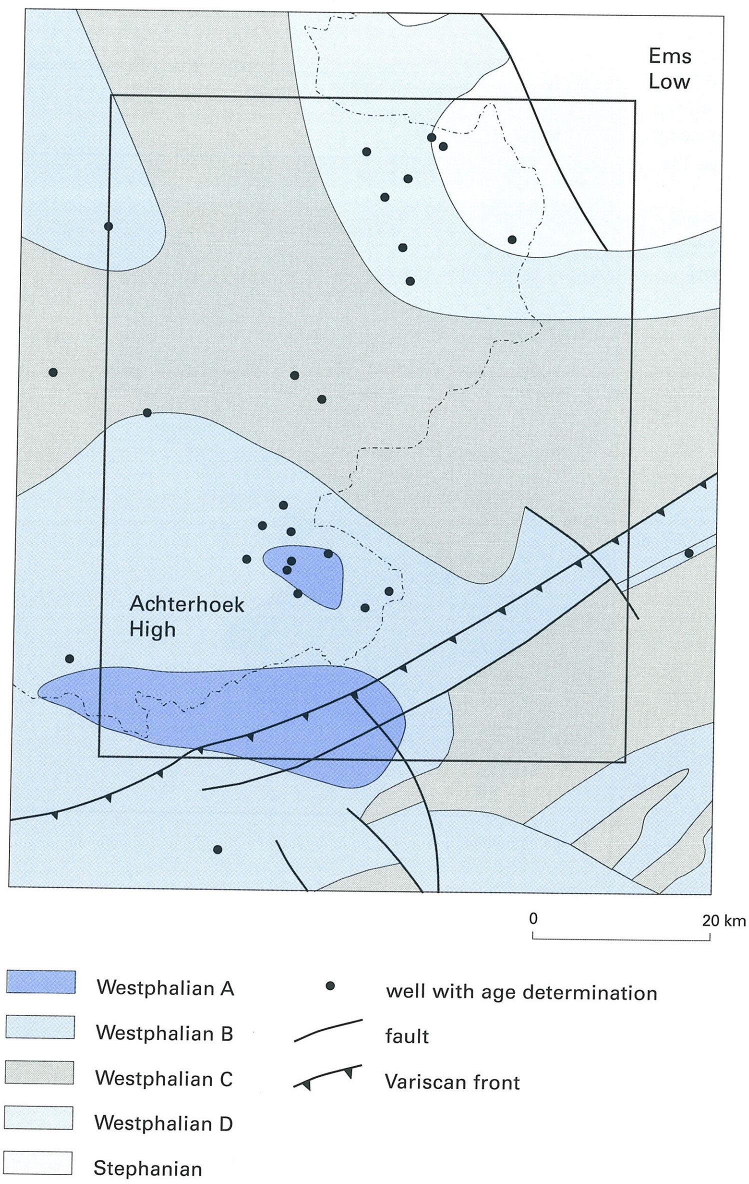
3.2 Geul Subgroup

The Geul Subgroup exhibits predominantly dark coloured claystone. Coal seams do not occur in this subgroup. The subgroup comprises the Epen Formation, Namurian to Westphalian A in age (fig. 3.1).

3.2.1 Epen Formation

The Epen Formation, of Namurian A to earliest Westphalian A age, is present throughout the map sheet area. The formation has been fully penetrated in the Winterswijk-1, Münsterland-1 and Isselburg-3 wells. The formation rests disconformably on the Carboniferous Limestone Group, separated by a hiatus, and is conformably overlain by the Baarlo Formation. The formation is subdivided into the Geverik, the main

Figure 3.3 Geological map of the top of the Limburg Group. Variations in the age of the Limburg Group give an indication of the palaeo-structures. The difference in structure pattern on both sides of the Variscan front is striking; very pronounced, closely-spaced folding of the sediments to the southeast of the front and a more moderate deformation pattern to the northwest. The map has been based on seismic interpretation, interpretation of well logs and palynological research (RGD, 1995c). The data for the German part of the map have been derived from Teichmüller et al. (1984).

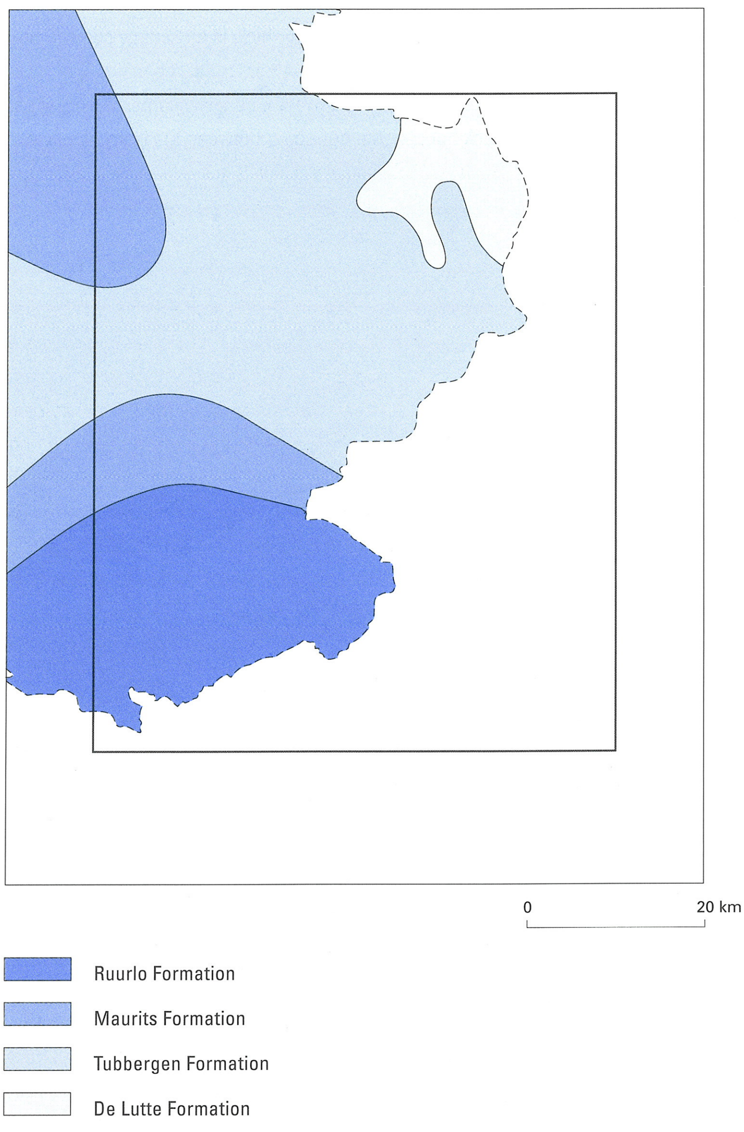


Epen, the Ubachsberg and the Upper Epen members (fig. 3.2). The main Epen and the upper Epen members have an informal status. The thickness of the formation ranges from 1600 to a probable 2000 m or more (fig. 2.2d). Detailed log correlation has revealed that the top 150 to 180 m of the formation to be of Westphalian A age (fig. 3.2).

The *Geverik Member*, at the base of the Epen Formation and of earliest Namurian A age, consists of claystones with a high organic material content, so-called hot shales. The member displays a uniform development in the area and is 50 to 80 m thick. In Germany this member is known as the *Posidonienschiefer* and *Hangende Alaunschiefer*. The percentage of organic components is approximately 5% (Richwien et al., 1963).

The *main Epen member*, of Namurian A to C age, consists predominantly of dark coloured claystone and siltstone and only a very small percentage of sandstones. The member is characterised by the multiple occurrences of marine beds containing goniatites and bivalves. The sequence comprises a

Figure 3.4 Geological map of the top of the Limburg Group, showing the lithostratigraphic unit located at the top of the Limburg Group. The map has been based on the interpretation from well logs and data from literature (Van Adrichem Boogaert & Kouwe 1993-1997).



cyclical succession of coarsening-upward sequences, 50 to 100 m thick (fig. 3.2). Such sequences can be identified over wide areas, from the southern part of The Netherlands right across to the North Sea. The characteristic marine beds are found at the base of these sequences. A sandstone sequence, ranging from a few metres to over 10 m thick, caps the sequences. Within the map sheet area the member has been encountered in the Winterswijk-1 well, where it is 1450 m thick. The thickness in the Isselburg-3 well is slightly greater (1600 m), whereas in the Münsterland-1 well 2200 m was penetrated (Drozdzewski, 1992; Richwien et al., 1963; Wolburg, 1963, 1970a). Regionally, the sequence thickens in a southeasterly direction (Wolburg, 1970a), but apparent thickening is found in the Münsterland-1 well, induced by faults and highly inclined bedding (Richwien et al. 1963). Sparse data (Ziegler, 1990) suggest a gradual increase in thickness to the north to reach approximately 1900 m.

The *main Epen member* is overlain by two thicker sandstone beds, together forming the *Ubachsberg Member*, of youngest Namurian C age (fig. 3.2). The sequence is also known as Grenzsandstein (Germany) or *Passage sandstone* (England). The sandstones, with a combined thickness of 25 to 35 m, have a large lateral extent. The sandstones are found immediately under the marine Sarnsbank horizon.

The *upper Epen member*, 150 to 180 m thick, is one single coarsening-upwards succession consisting predominantly of claystone, ending with an argillaceous top. The member may also contain dispersed carbonaceous intervals but, by definition, no coal seams. The basal part of the member reveals the marine Sarnsbank horizon, the boundary between the Namurian and Westphalian. The member, therefore, is almost entirely of earliest Westphalian A age (fig. 3.2).

3.3 Caumer Subgroup

The Caumer Subgroup, ranging from Westphalian A to Early Westphalian C in age, is composed of a thick succession of predominantly fine-grained siliciclastic sediments and frequent occurrences of coal seams. In the map sheet area the Caumer Subgroup comprises three formations, the Baarlo, Ruurlo and Maurits Formations. In the centre and northeast of the map sheet area the subgroup is conformably or unconformably overlain by the Tubbergen Formation. In the south and northwest of the map sheet area the subgroup is unconformably overlain by deposits of the Upper Rotliegend, the Zechstein or the Rijnland Group. The subgroup here achieves a thickness of 1400 m. The subgroup has not been completely penetrated in any of the wells. From German literature sources it can be inferred that the Caumer Subgroup in the northern part is 2000 m thick (Drozdzewski, 1992, 1993; Stancu-Kristoff & Stehn, 1984).

3.3.1 Baarlo Formation

The Baarlo Formation, Westphalian A in age, consists of dark coloured claystone, with frequent occurrences of coal seams and sandstones. The formation is present throughout the map sheet area, but has only been encountered in wells in the southern part of the area. Sandstones occur in coarsening-upward sequences (fig. 3.5). The lower boundary of the formation is set at the base of the deepest coal seam in the Upper Carboniferous. The topmost boundary is at the transition from coarsening-upward to fining-upward sequences. The formation was fully penetrated in the Winterswijk-1 well with a thickness of nearly 670 m.

The sandstones in this formation occur predominantly in coarsening-upward sequences. These sequences achieve a thickness ranging from some tens of metres to 300 m on occasion. The base of such sequences, contain claystones with marine to brackish-water fossils (goniatites, *Lingula*). Particularly in the middle part of the formation, a thick complex of coarse-grain sandstones occurs. Log

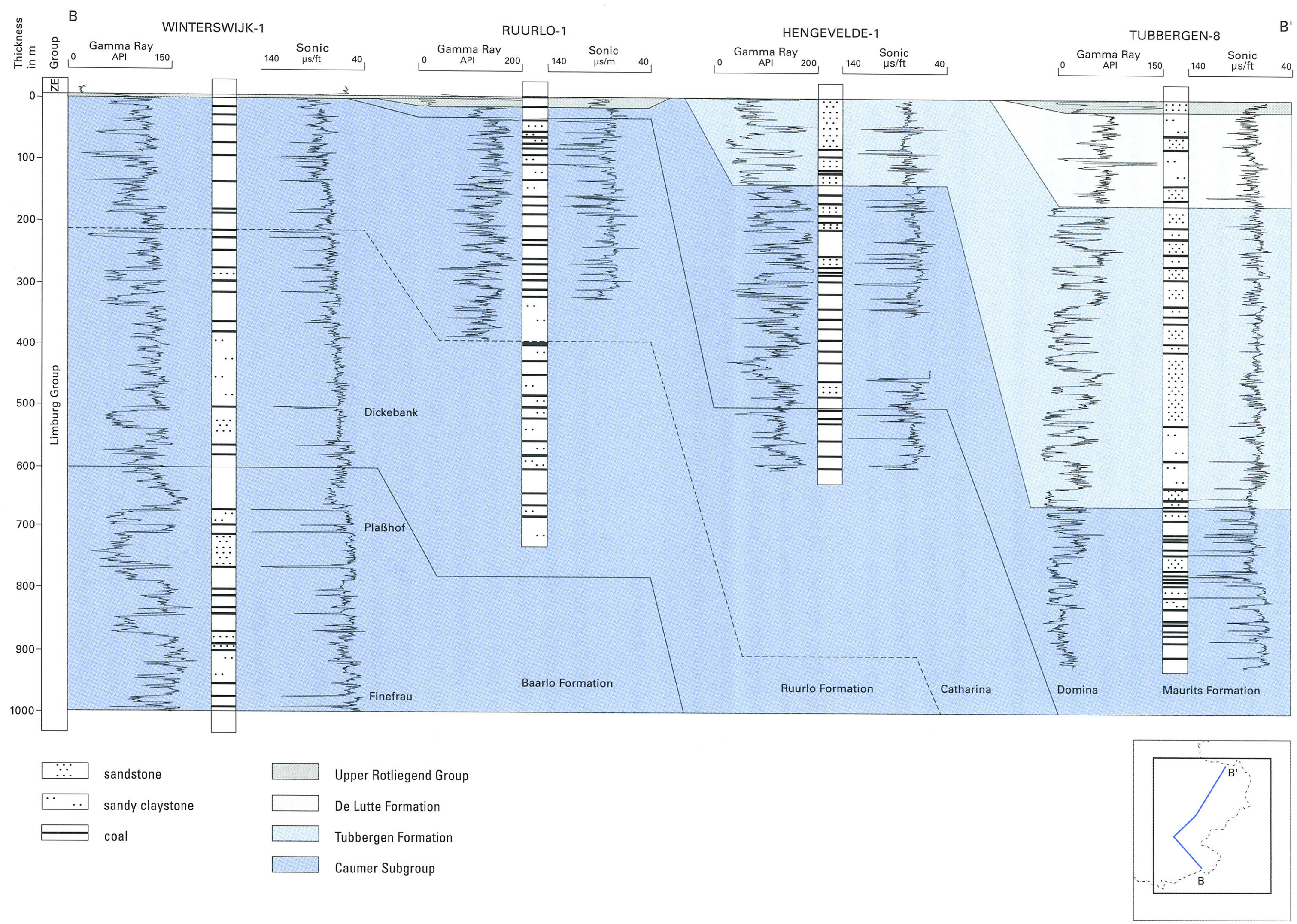


Figure 3.5 Stratigraphic section B-B' of the Caumer Subgroup and Dinkel Subgroup through the map sheet area between the Winterswijk-1, Ruurlo-1, Hengevelde-1 and Tubbergen-8 wells. This section shows outcropping of increasingly younger units of the Limburg Group in a northerly direction. The unconformable coverage by the Upper Rotliegend Group is also shown.

reading results enable a tripartition of the sandstone complex. The lower part demonstrates a coarsening-upward trend, followed by two fining-upward sequences (fig. 3.5). This sandstone complex, the *Schöttelchen Sandstein* (G. Drozdzewski, pers. comm.), with a thickness of 30 to 50 m, has a large lateral extent.

3.3.2 Ruurlo Formation

The Ruurlo Formation, of Westphalian A to Early Westphalian B age, comprises a thick succession of predominantly light-grey silty or argillaceous claystones, with intercalated coal seams and grey to pink sandstone beds. In the formation, while fining-upward sequences prevail, there are also a few coarsening-upward sequences. The sandstones developed as channel sandstones and as sand layers with good lateral continuity. The formation rests conformably on the Baarlo Formation and is also overlain conformably by the Maurits Formation or unconformably by the Upper Rotliegend Group or the Zechstein Group (fig. 3.5 & 3.7). The formation is found throughout the map sheet area.

The Ruurlo Formation contains the equivalents of two major marine bands, namely the Catharina horizon, which reflects the Westphalian A/B boundary, and at the top of the formation the Domina horizon, at the boundary of the Lower and Upper Westphalian B (fig. 3.5). The Catharina horizon is clearly identifiable from well logs (Schuster, 1963, 1968). However, in the map sheet area the fauna of this horizon indicates deposition in a non-marine environment (H. Pagnier, pers. comm.). The Ruurlo Formation has only been completely penetrated in two wells in the south of the map sheet area, with a thickness of 600 to over 700 m.

3.3.3 Maurits Formation

The Maurits Formation, of Late Westphalian B to Early Westphalian C age, mainly comprises light-grey claystones with abundant coal seams. The formation is differentiated from the underlying formation by its fine-grained character and higher abundance of coal (fig. 3.5), which is clearly demonstrated on well logs. The formation is conformably or unconformably overlain by the Tubbergen Formation, or by the Upper Rotliegend, the Zechstein or the Rijnland Group (fig. 3.5, Map 17).

In the Maurits Formation, only a few thin sandstone beds occur. Within the map sheet area there are various indications that the base of the overlying Tubbergen Formation is erosional (see section 3.4.1). Wells reveal that the thickness between the marine Aegir horizon - the boundary between the Westphalian B/C - and the Tubbergen Formation in the north of the map sheet area is approximately 170 m and in the south, less than 100 m, even.

The Maurits Formation is found throughout the map sheet area, with the exception of the extreme south (fig. 3.4) but in the map sheet area has only been penetrated in a few wells. The complete formation reaches a thickness of a maximum of 380 m.

3.4 Dinkel Subgroup

The Dinkel Subgroup in the map sheet area, Early Westphalian C to Early Westphalian D in age, is represented by the Tubbergen Formation.

3.4.1 Tubbergen Formation

The Tubbergen Formation, of Early Westphalian C to Early Westphalian D age, is composed largely of

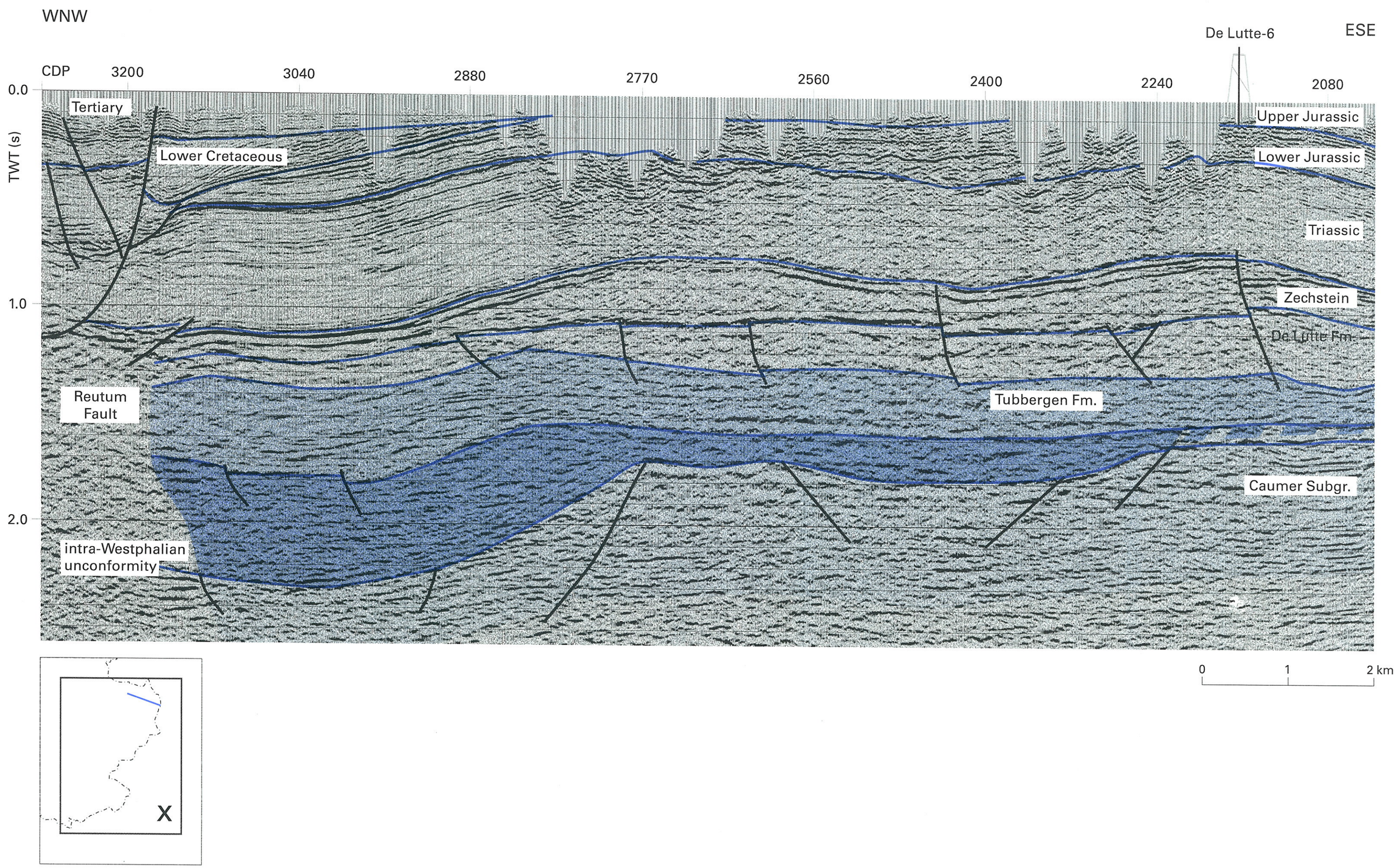


Figure 3.6 Seismic section through the Ems Low. This section shows an intra-Carboniferous unconformity at the base of the Tubbergen Formation. The top of the Tubbergen Formation was only to be indicated with any certainty in the immediate vicinity of the De Lutte-6 well (after Van Tongeren, 1996).

sandstone. The formation lies on the Maurits Formation, separated by a hiatus or a minor angular unconformity and is found in the northern part of the map sheet area. In the extreme northeast of the map sheet area it is conformably overlain by the De Lutte Formation, elsewhere unconformably by the Upper Rotliegend, the Zechstein or the Rijnland Group (fig. 3.4, Map 17).

The formation comprises an alternation of sandstone beds 10 to over 30 m thick and even 100 m in the central part of the formation. The sandstones are separated by 5 to 40 m thick clay/siltstone intervals (fig. 3.5 & 3.7). Sandstone beds constitute 50 to 80% of the formation. The sandstone percentage decreases in a northerly direction. The sandstones consist of medium-coarse, very fine to conglomeratic immature sandstone, comprising poorly rounded grains, predominantly light-grey in colour. The sandstone bodies display good lateral continuity and constitute the reservoir rocks of some gas fields (for example the Rossum-Weerselo, Tubbergen and Oldenzaal fields).

The Tubbergen Formation is marked by a bipartition in seismic facies (fig. 3.6). The bottommost part displays pronounced fluctuations in thickness pattern and is distinguished by an irregular pattern of reflectors. The uppermost part of the formation displays more continuous reflectors and has uniform thickness. The bottommost part of the formation, containing the chaotic seismic facies, has not been reported by drilling but is presumed to consist largely of sandstone (Van Tongeren, 1996).

The claystones in the formation display a greenish-grey colour at the bottom, associated with which are occurrences of a few coal seams. Towards the top, the reddish-brown colour begins to be dominant and the formation becomes devoid of coal seams. The red colouring is partly of primary origin (Selter, 1990; Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996; Van der Meer & Pagnier, 1996). The thickness of the formation ranges from 470 to 495 m, but is thought to be greater in the Ems Low.

3.5 Hunze Subgroup

The Hunze Subgroup, Early Westphalian D to (presumably) Stephanian in age, comprises the De Lutte Formation.

3.5.1 De Lutte Formation

The De Lutte Formation is a succession of reddish-brown and occasionally greenish-grey, silty to very fine-sandy claystones. The succession of claystones contains 5 to 15 m thick sandstones with fair lateral continuity. The only coal-bearing bed in the formation, known in Germany as the *Itterbeck-Horizon* (Tantow, 1993), occurs a few metres above the base (fig. 3.7). This bed marks the boundary between the part with gley soils underneath and the part with caliche and ferruginous soils above. The caliche levels are dominant in the upper part of the formation (Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996; Van der Meer & Pagnier, 1996).

The uppermost part of the formation, approximately 100 m thick, rests on the bottommost part separated by a hiatus or minor unconformity (fig. 3.7); this part is regarded as Stephanian (Tantow, 1993; Pagnier & Van Tongeren, 1996), although this is open to question; palynologically, these deposits reveal an Autunian association (Van de Laar & Van der Zwan, 1996), while palaeobotanically, research points to a Westphalian D age (Van Amerom, 1996; Van der Zwan et al., 1993). In Germany, these deposits are set within the range of the Permian-Carboniferous boundary zone (Stephanian C to Autunian; Plein, 1995).

The formation is a maximum of 650 to over 700 m thick in the extreme northeast of the map sheet area (Tantow, 1993; Pagnier & Van Tongeren, 1996).

3.6 Intrusive rocks

Intrusive rocks have been recovered from the Limburg Group in several wells in the south of the map sheet area. In the Corle-1, Gelria-3 & 5 wells, these are the quartz-doleritic dykes, comprising contact-metamorphic zones on the upper and lower boundary of the dyke. This dyke is a maximum of 23 m thick

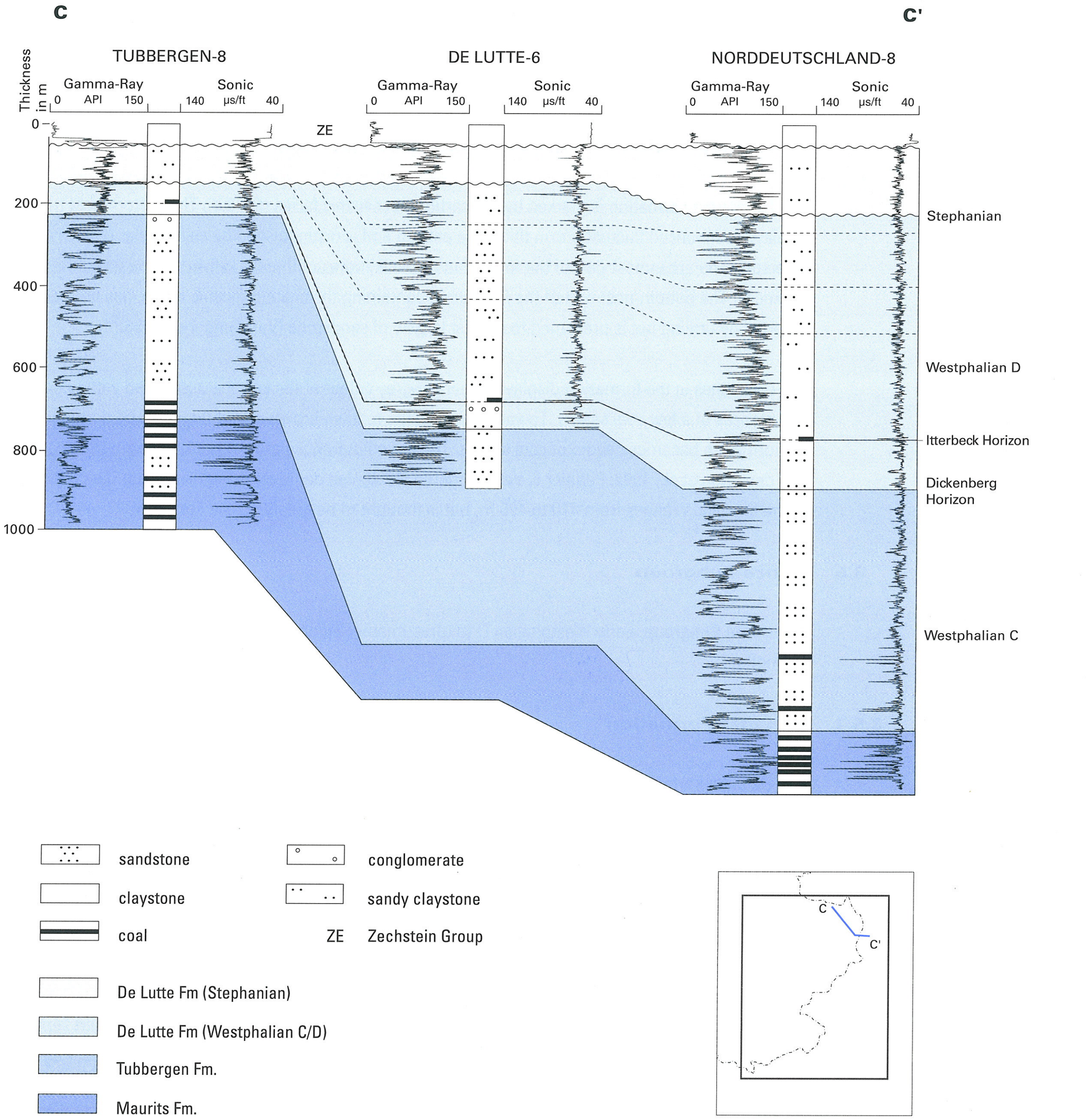


Figure 3.7 Stratigraphic section C-C' of the top part of the Dinkel Subgroup (Tubbergen Formation) and the Hunze Subgroup (De Lutte Formation between the Tubbergen-8, De Lutte-6 and Norddeutschland-8 wells. The top part of the Hunze Subgroup, presumed to be of Stephanian age, rests unconformably upon Westphalian D deposits (after Pagnier & Van Tongeren, 1996). Important correlation horizons within the succession have been indicated.

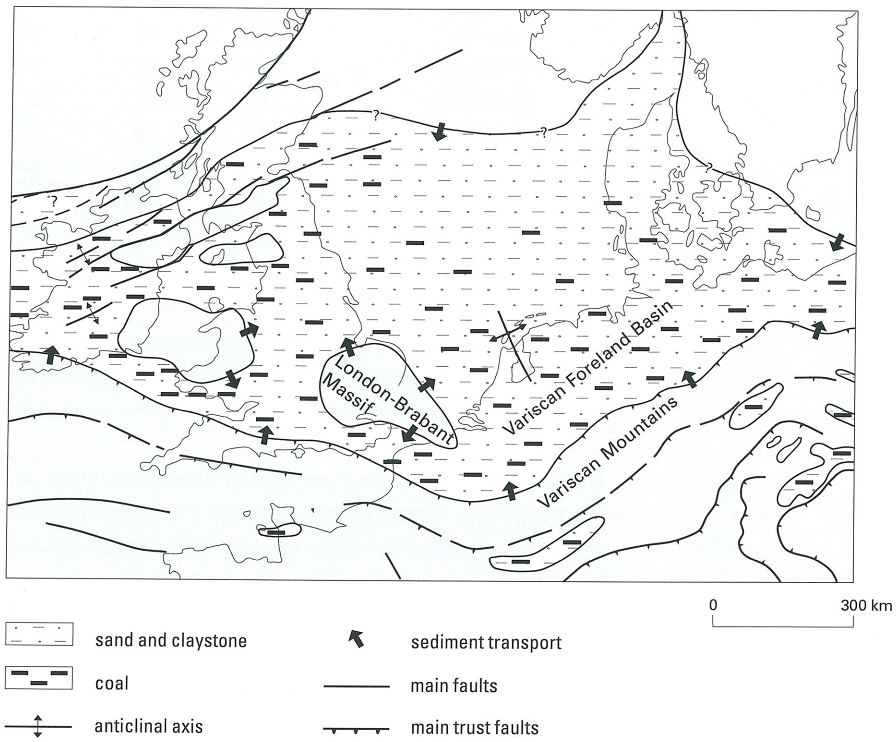
in the Gelria-5 well (Thiadens, 1963). In the Winterswijk-1 well, a 140 m thick diabase was encountered, the most basic rock of which was an olivine-dolerite (RGD, 1978b). This intrusive rock is analysed as being Late Triassic in age.

3.7 Sedimentary development and palaeogeography

The deposits of the Limburg Group reflect the regressive deltaic accumulation of an east-west oriented foreland basin (fig. 3.8). The thick succession displays only gradual transitions between the different facies, which indicates that subsidence and sedimentation maintained each other in a state of equilibrium. 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. 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 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. During this depositional stage, the centre of subsidence shifted from the area to the southeast of the map sheet to the Ems Low (fig. 3.3). The top part of the succession, the Dinkel and Hunze Subgroup, demonstrates here that rivers extended from the west and southeast over the area, depositing coarse-grained sediments. Subsequently, these rivers made way for lakes and flood plains, characterised by fine-grained deposits. These fluvial sediments represent the detritus of the Rhenish Massif to the southeast of the map sheet area and the Netherlands High to the west.

Figure 3.8 Palaeogeography of Northwest Europe at the time of the Late Carboniferous (after Ziegler, 1990).



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 an B made way during the Late Westphalian C for a warm climate with an alternation between wet and dry seasons (monsoon). During the Westphalian D a semi-arid climate even prevailed where on occasion evaporation exceeded precipitation and resulted in the formation of caliche (Pagnier & Van Tongeren, 1996; Selter, 1990; Van der Meer & Pagnier, 1996; Van der Zwan et al., 1993).

3.8 Petrophysical evaluation

The sandstones of the Tubbergen and De Lutte Formations form a major target for exploration in the north of the map sheet area and, during the last 30 years, several gas fields have been encountered (fig. 1.2).

To illustrate a log-evaluation of the Limburg Group reservoir sequence, figure 3.9 shows the results in the case of the Rossum-Weerselo-6 well. The reservoir of the Limburg Group consists of an alternation of fluvial sandstone and claystone. The strong variation in reservoir quality of these sands is inherent to their fluvial character.

In the case of the Rossum-Weerselo-6 well, the variation in porosity is illustrated for the evaluated sands.

Table 3.1 Reservoir characteristics of the sandstones of the Limburg Group in the Rossum-Weerselo-6 well (fig. 3.9)

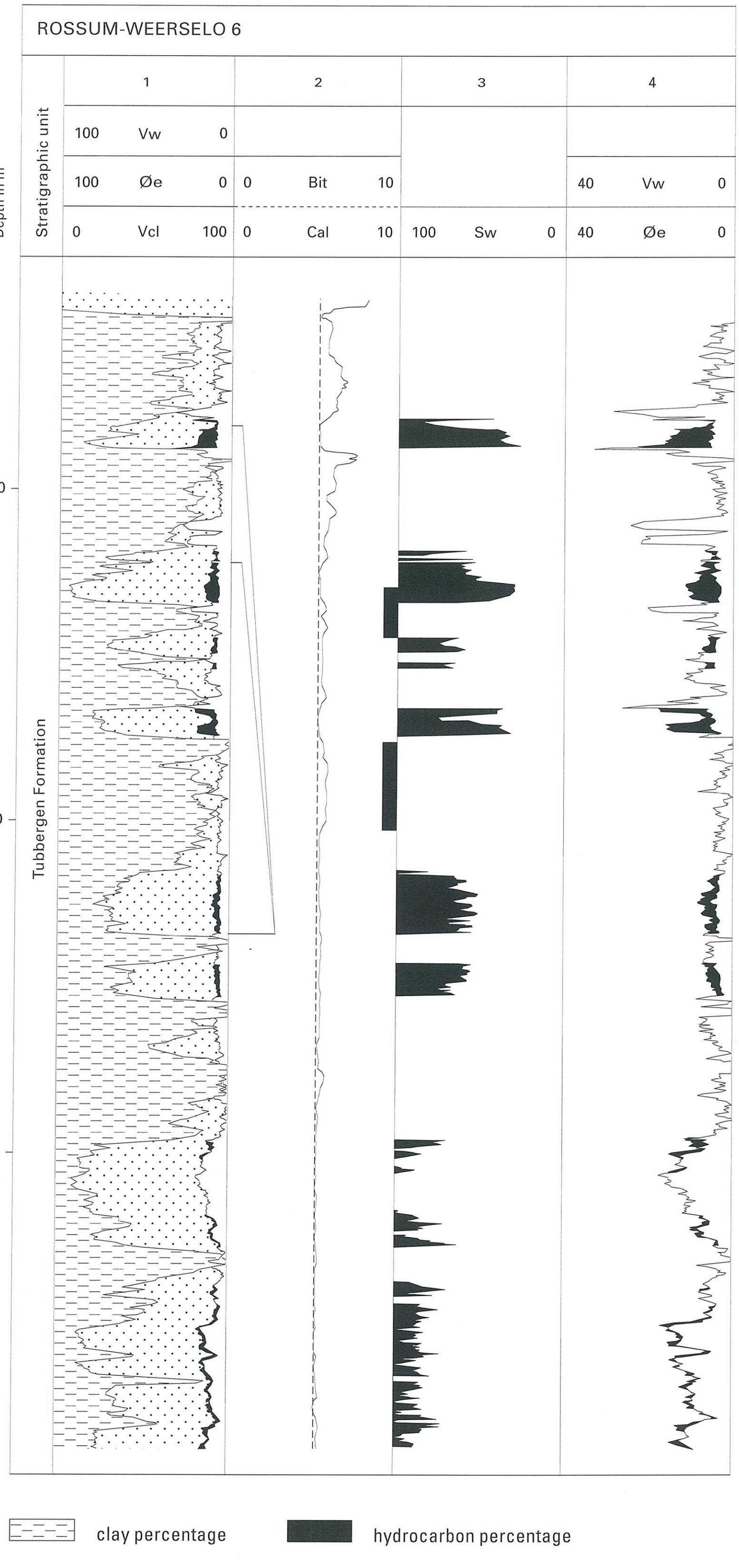
	TVD interval (m)	gross (m)	net (m)	net/gross (%)	porosity (%)	clay content (%)
1	1739.6-1743.9	4.3	3.3	76.7	16.2	29.9
2	1759.3-1767.2	7.9	5.2	65.8	10.6	15.5
3	1772.2-1777.1	4.9	0.7	14.3	8.4	38.9
4	1783.0-1787.2	4.2	3.7	88.1	14.7	25.1
5	1807.7-1817.3	9.6	1.9	19.8	8.5	24.6
6	1821.7-1826.7	5.0	0.4	8.0	8.3	30.0
7	1848.3-1864.3	16.0	14.2	88.8	12.6	17.4
8	1869.5-1894.1	24.6	10.8	76.4	13.0	23.6

Out of 7 selected wells in the map sheet area, core analysis data are available from 4 wells, the Fleringen-1, Oldenzaal-6, Rossum-Weerselo-6 and Tubbergen-Mander-1. Average porosities measured from core data lie between 5 and 13%, whereas average permeabilities are lower than 50 mD.

Appendix C gives the results of the reservoir calculations for the Limburg Group. The cut-off value of the effective porosity is based on the value of 8%. This value is based on core analysis results based on a permeability cut-off of 0.1 mD. For the cut-off of the clay content, the value of 50% has been selected.

Figure 3.10 shows the extent of the Tubbergen Formation, illustrating the distribution of the reservoir average effective porosity (Øem) of the Limburg Group in the map sheet area. The average porosity in the north of the area ranges from 9.7 to 13.3%. The Hengevelde-1 well, lying more to the south, with an average porosity of 16.3%, is a clear anomaly; this high value is related to a high net/gross ratio of 80%. Notable lateral differences occur in the sand distribution of the Tubbergen Formation, owing to the

Figure 3.9 Petrophysical evaluation of the Limburg Group in the Rossum-Weerselo-6 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw (all given in %). The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained from sonic logs; the calculated log porosity was corrected for the clay content. Column 2: borehole diameter (Cal) and bit diameter (Bit), both in inches; furthermore the left margin of the column indicates the tested intervals and the right margin, the core intervals. Column 3: water saturation Sw %. The Indonesia formula, suitable for argillaceous formations, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe (left curve) and the volume of water in the pores Vw (right curve), both in percentages. The depths are the true depths.



anatomy of the fluvial system. Across the entire Tubbergen Formation the net/gross ratio ranges from 37% in the Tubbergen-5 well to 59% in the Tubbergen-Mander-1 well; the average porosity here also appears to be related to this ratio and amounts to 11.2% (Tubbergen-5) and 13.3% (Tubbergen-Mander-1) respectively.

Sandstones, sometimes tens of metres thick, are encountered in the predominantly claystone-bearing deeper part of the Limburg Group (Epen and Baarlo Formations). However, from German literature sources, the porosity of these sandstones can be inferred to be extremely low: in the Baarlo Formation an average of 2.5% and in the Epen Formation less than 0.5% (Beeg, 1963; Tunn, 1963; Tantow, 1993).

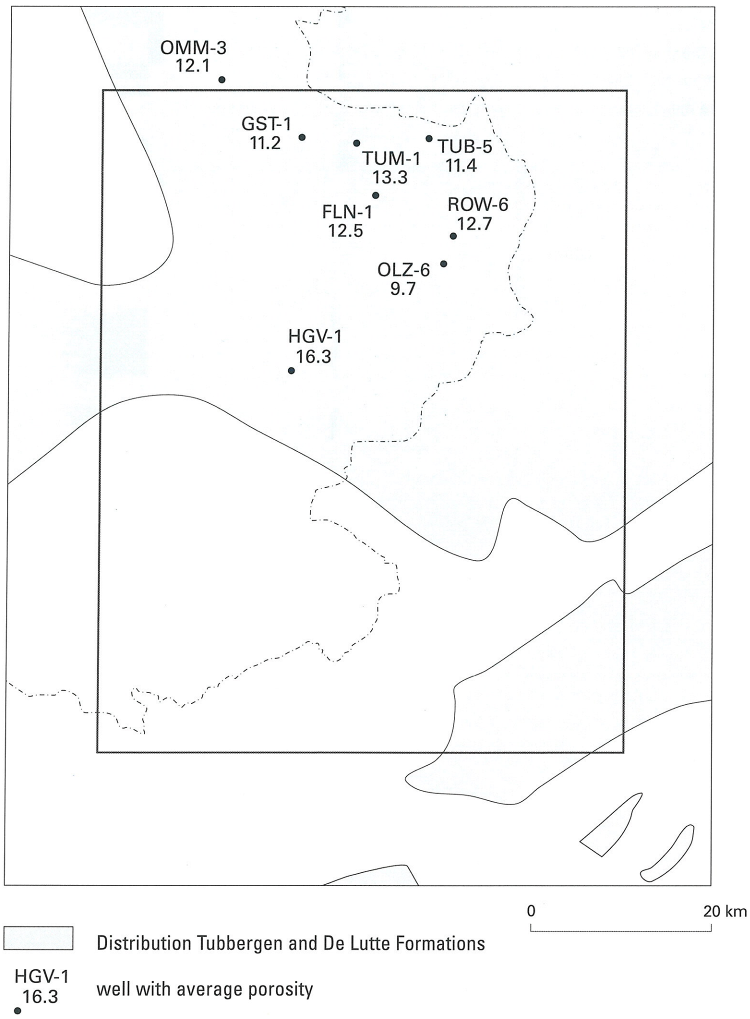


Figure 3.10 Extent of the Tubbergen Formation and De Lutte Formation and the distribution of the average porosity (%) in these formations. The distribution of the Tubbergen Formation and equivalent formations in Germany has been derived from literature (Teichmüller et al. (1984).

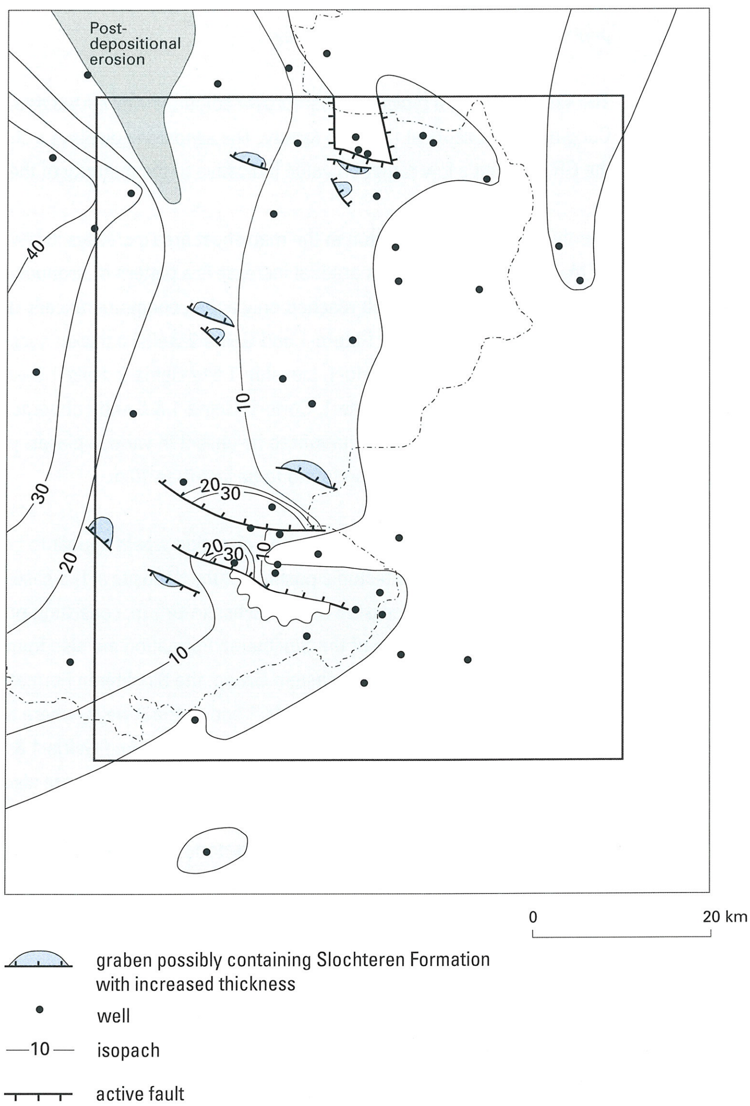
4 Upper Rotliegend Group

4.1 Stratigraphy

The Upper Rotliegend Group, of Late Permian age, is represented within the map sheet area by the Slochteren Formation.

The deposits of the Upper Rotliegend Group rest on several formations of the Limburg Group, separated by the Saalian Unconformity (fig. 3.5). The group occurs in a major part of the map sheet area and is absent on the Dalfsen High, in the east and north of Twente and locally in the Achterhoek (Map 1). In most of the area, the deposits of the group are conformably overlain by deposits of the Zechstein Group (Map 2). Only in a small area, the Dalfsen High, does the Rijnland Group rest unconformably on the Upper Rotliegend Group (Map 17). The depth of the base of the group varies from less than 800 m in the south to over 2400 m in the north of the map sheet area (Map 1).

Figure 4.1 Thickness map of the Upper Rotliegend Group (Slochteren Formation) in the map sheet area, based on well log data. The map indicates a number of structures where thicker Upper Rotliegend deposits are thought to be present.



The thickness of the Upper Rotliegend Group increases in a westerly direction in the map sheet area to over 40 m just outside the map sheet area. However this pattern displays strong local variations (fig. 4.1).

4.1.1 Slochteren Formation

The Slochteren Formation in the map sheet area contains two lithologies, which would appear to be related to the thickness of the formation. Where the formation is only a few metres thick, it consists entirely of conglomerate or conglomeratic sandstone, whereas at places where the formation is thicker than a few metres, it comprises predominantly sandstone.

The sandy conglomerates are typical of the formation in the east and southeast of the map sheet area. This sequence was formerly also referred to as the Zechstein Basal Conglomerate (Brueren, 1959). Nowadays, this conglomerate is regarded as the lateral equivalent of the sandstone-dominated Slochteren Formation to the north and west of the map sheet area (Van Adrichem Boogaert & Kouwe, 1993-1997). The conglomerate layers are no thicker than one to a few metres and comprise a grey coloured, sandy conglomerate cemented with anhydrite or dolomite. The fragments consist of quartz pebbles and coal remains occur locally.

The sandstone has a typical reddish-brown colour, is well sorted and medium to coarse-grained. Conglomerate occurs at the base locally. The sandstone displays a characteristic block-like pattern on the GR logs and a low radiation value indicative of the maturity of the sediment.

The thickness of the formation in the map sheet area increases in a westerly direction to approximately 40 m. Superimposed on this gradual increase is a pattern of pronounced local variations in thickness (fig. 4.1). Amidst wells which reached only a thin, conglomeratically developed Slochteren Formation (such as the Winterswijk-1, Ratum-1 and Gelria-2 wells) a thicker succession of well-sorted sandstone was encountered in the Ruurlo-1, Lievelde-1 and Gelria-3 wells. However, the formation was not encountered in the Hengevelde-1, Corle-1, Gelria-1 & 5 and Tubbergen-Mander-1, 2 & 3 wells. Between these wells, the formation is thought to be absent in various places, particularly in the area where thicknesses in wells have been found to be less than 10 m.

The thickness pattern of the Slochteren Formation would appear to be related to the thickness of the Zechstein Group and the tectonic position of the deposits at the base of the latter group (Maps 2 & 3). In grabens with a thick succession of the Zechstein Group, consisting predominantly of Z1 (Werra) Formation, thicker deposits of the Slochteren Formation are also found, while on structurally high blocks with a thin succession of the Zechstein Group, the Slochteren Formation is either thin or absent. This hypothesis is supported by the Lievelde-1 and Gelria-3 wells, where both the Slochteren Formation and the Z1 (Werra) Formation are thick, and by the Corle-1 and Gelria-1 & 5 wells, where, besides the Slochteren Formation, the Coppershale and the Z1 Carbonate are also absent.

As wells tend mainly to be positioned on tectonically high blocks, this precludes any representative picture of the actual thickness pattern of the Slochteren Formation. Figure 4.1 indicates grabens at the level of the Zechstein Group, which may contain thick sandy successions of the Slochteren Formation. (see also section 5.1.1 and fig. 5.2).

4.2 Sedimentary development and palaeogeography

The Upper Rotliegend Group was deposited on the southeast margin of the intra-cratonic Southern Permian Basin during continental conditions (fig. 12.2). The sediments deposited in the map sheet area are the erosional products of the Variscan mountains lying to the south and east of the area.

The conglomerates and conglomeratic sandstones of the Slochteren Formation were deposited by braided rivers; during the transgression, which initiated deposition of the Zechstein Group, the conglomerates were locally re-deposited. On a basis of their character as revealed by well-logging, the origin of the pure sandstones of the Upper Rotliegend Group has been determined as aeolian. In this area, they tended mainly to level local depressions.

The red staining of the sediments is regarded as the consequence of fluctuations in the watertable shortly after deposition. In periods of a low watertable stand, oxidation of iron-bearing minerals occurred and hematite was formed. This hematite was subsequently dispersed by the groundwater through the sediment in the form of a veneer around the grains (Walker, 1967). The overgrowth as pore-filling cement of the grains during subsequent diagenesis may have been prevented by the presence of these coated quartz grains (Füchtbauer, 1974).

5 Zechstein Group

5.1 Stratigraphy

The Zechstein Group within the map sheet area, of Late Permian age, consists of four evaporite cycles, the Z1 (Werra) to Z4 (Aller) Formation and a sealing claystone, the Zechstein Upper Claystone Formation. The bases of the formations are characterised by transgressive deposits.

The Zechstein Group in most of the map sheet area rests unconformably on the Upper Rotliegend Group; in the east of Twente, however, the group rests conformably on the Limburg Group (Maps 2 & 4). The Zechstein Group is conformably overlain by the Lower Germanic Trias Group (Map 5) and in a few places unconformably by the Altena Group, the Rijnland Group, or the North Sea Supergroup (fig. 6.7, Maps 18 & 19). The formation is heavily fractured and the depth of the base varies within the map sheet area from less than 800 m in the south to over 2400 m in the north of the map sheet area (Map 2). The group varies in thickness from 100 to 500 m, with greater thicknesses occurring in salt structures locally.

The succession of the group is illustrated by a stratigraphic section (fig. 5.1).

5.1.1 Z1 (Werra) Formation

The Z1 (Werra) Formation is composed of the Coppershale, the Z1 Carbonate, Z1 Lower Anhydrite, the Z1 Salt and the Z1 Upper Anhydrite Members.

The formation has a thickness of less than 100 m in the southwest of the map sheet area and over 500 m in the east part of Twente. As a result of extreme thickness fluctuations of the rock salt, this trend is locally disrupted. These differences in thickness are attributable partly to salt flow, as well as to the expression of a highly differentiated subsidence pattern during the deposition of the formation. Seismic data have revealed that grabens and half grabens developed, with a stratigraphic throw of over 200 m (fig. 5.2). It was in these structures that deposition of rock salt occurred.

The *Coppershale* lies at the base of the formation, and consists of a dark, fine-laminated claystone, with a high content of organic material. The thickness is only 0.5 to 1 m, but owing to the characteristic peak on the gamma-ray log the unit can be clearly distinguished and has a broad regional extent.

The *Z1 Carbonate* consists of a grey-brown limestone of fine-grained dolomite. Oolites occur at a few places in the north of the map sheet area; in the centre of the map sheet area the unit contains anhydrite nodules (Brueren, 1959). The unit is in general only a few metres thick and displays an upwardly decreasing clay content. The unit is absent in the northeast and around Winterswijk owing to erosion.

The *Z1 Anhydrite* is present throughout the map sheet area. Where the Z1 Salt is found, the unit is subdivided into the Z1 Lower Anhydrite and the Z1 Upper Anhydrite Member (fig. 5.1). An exception to this is formed by the southwest of the map sheet area, where the Upper Anhydrite is very thin or absent and the Z2 Salt immediately overlies the Z1 Salt (Zeddam-1, Isselburg-1 & 2 wells). The sequence thickens in a northerly direction to approximately 50 m in the south to over 200 m in the extreme north of the area; in addition to this gradual increase, the unit displays major thickness variations owing to synsedimentary active faulting. The greatest thicknesses occur where the rock salt is thin or absent. Oil traces have been found at several places in the unit.

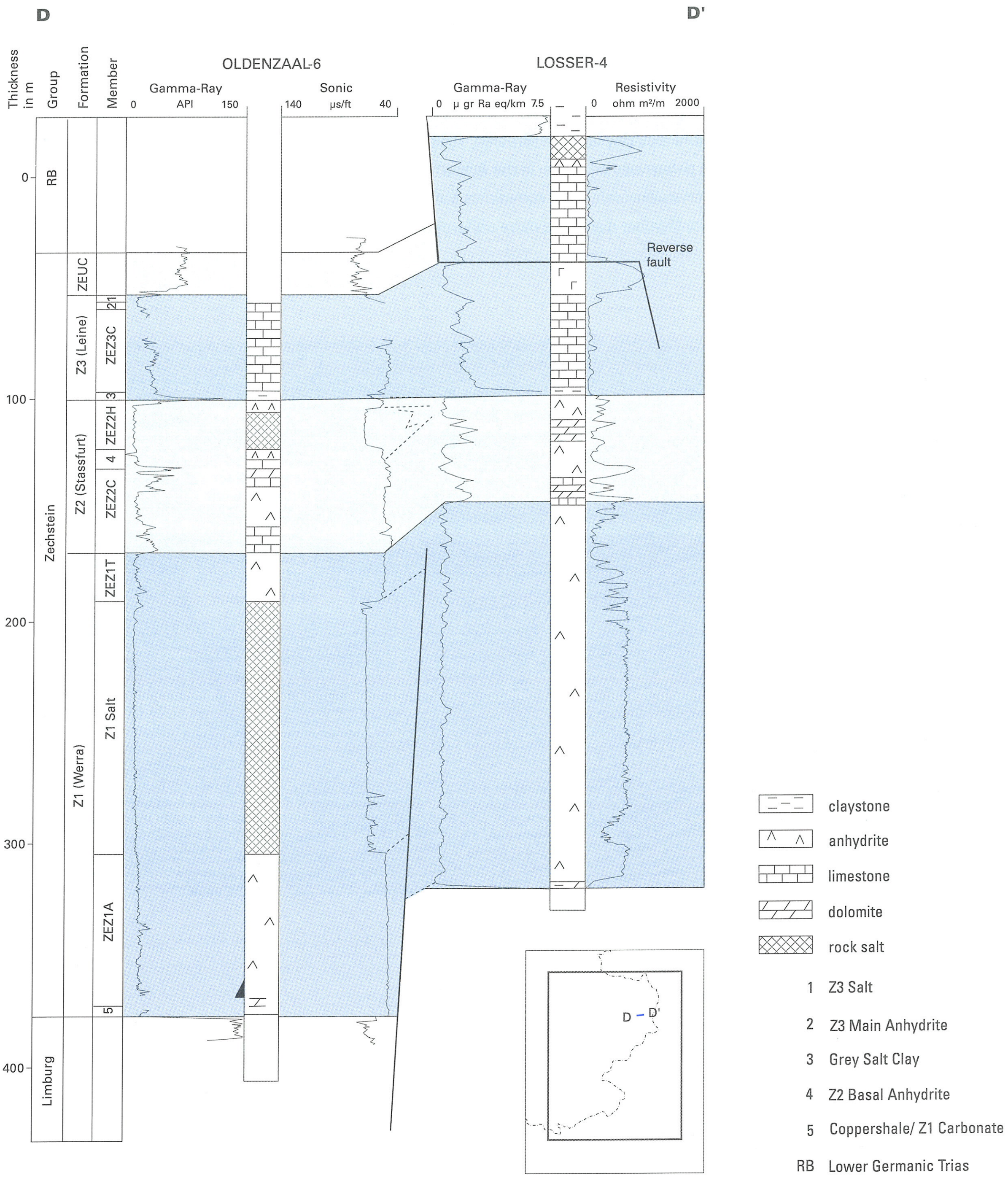
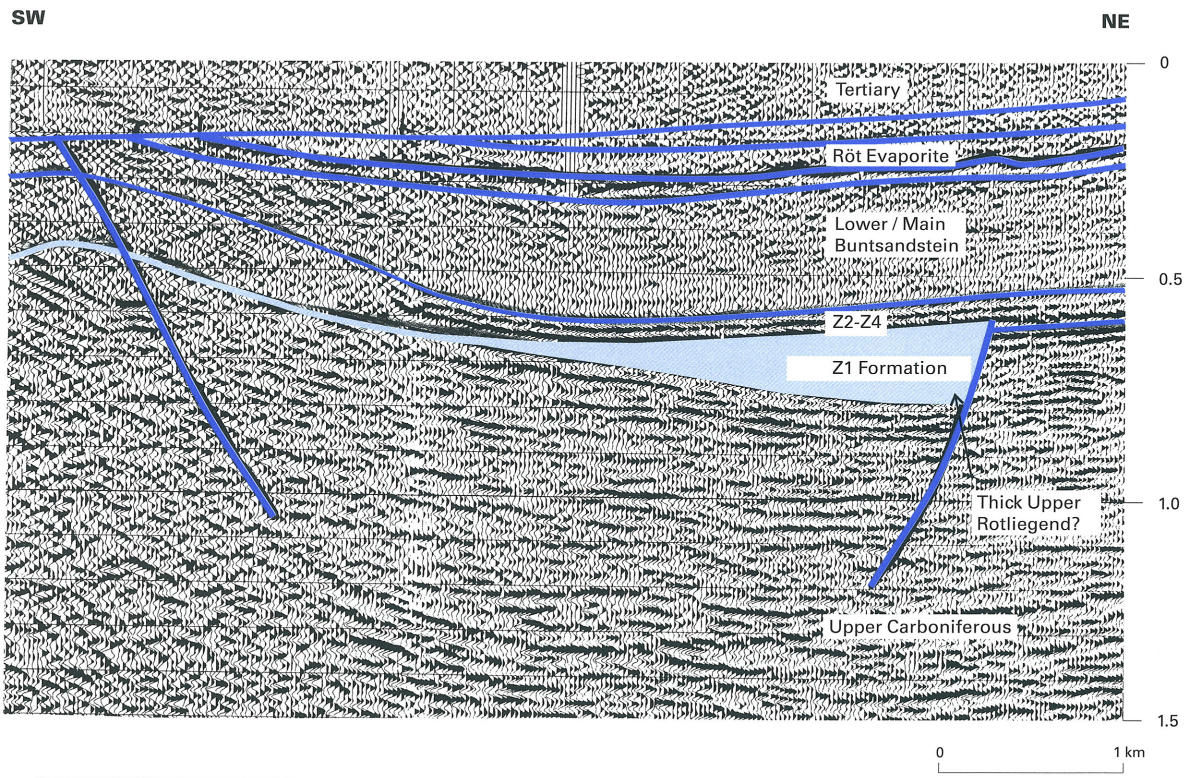


Figure 5.1 Stratigraphic section D-D' of the Zechstein Group and the log pattern in the Oldenzaal-6 and Losser-4 wells. This sections shows the influence of the synsedimentary tectonics during the deposition of the Z1 (Werra) Formation. The Oldenzaal-6 well shows the filling up of a graben with salt, while the Losser-4 well is situated on a tectonic high block, where no salt was deposited. The repetition of the Z3 Carbonate in the Losser-4 well is a consequence of reverse faulting during the Sub-Hercynian phase. The reference-level is the base of the Z3 (Leine) Formation.

The *Z1 Lower Anhydrite* consists of a dark-grey anhydrite, with clay and dolomite at the top. The unit may display pronounced differences in thickness over small distances, ranging from 10 m to over 150 m, attributable to synsedimentary active faulting.

The *Z1 Upper Anhydrite* consists of a white to bluish-grey anhydrite, sometimes laminated with dark-grey bituminous clay laminae (Brueren, 1959). From a few of the wells (such as Tubbergen-5), cores of this unit perspirated oil drops. In the Achterhoek the Z1 Upper Anhydrite Member consists of a grey, coarse, crystalline anhydrite, sometimes brecciated and comprising salt crystals. The Z1 Upper Anhydrite Member displays a more uniform thickness development than the Z1 Lower Anhydrite



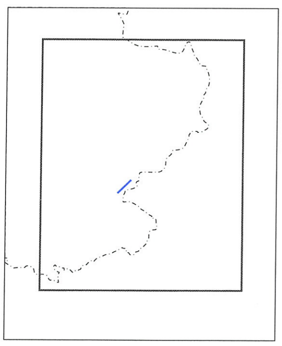


Figure 5.2 Seismic section including an example of a half graben, that has been filled up with deposits from the Z1 (Werra) Formation. These deposits comprise anhydrite and rock salt. The younger deposits of the Zechstein Group were not affected by active faulting. Likewise, thicker deposits of the Rotliegend group are expected in the half graben than in areas outside this structure.

Member. The thickness in the southern part of the map sheet area is 16 to 40 m and 30 to 120 m in the north. This unit does not occur in the extreme southwest of the map sheet area (fig. 5.5).

The *Z1 Salt* occurs virtually throughout the map sheet area, with only a few exceptions (fig. 5.2 & 5.3). The thickness exhibits pronounced differences, owing to synsedimentary active faulting and salt flows and in the Tubbergen salt-structure reaches a maximum 900 m.

Deposition of the Z1 Salt occurred in three prominent depocentres in the area, namely in Twente, slightly further to the south in Germany and in the vicinity of Winterswijk (fig. 5.3). The greatest primary thickness is reached in Twente, where the salt is locally over 400 m thick. In the other depocentres the unit reaches a thickness of over 300 m.

In the area between Winterswijk and Wesel, intercalations of potassium-magnesium salts occur at two different levels in the middle of the approximately 350 m thick salt succession. The thickness of the

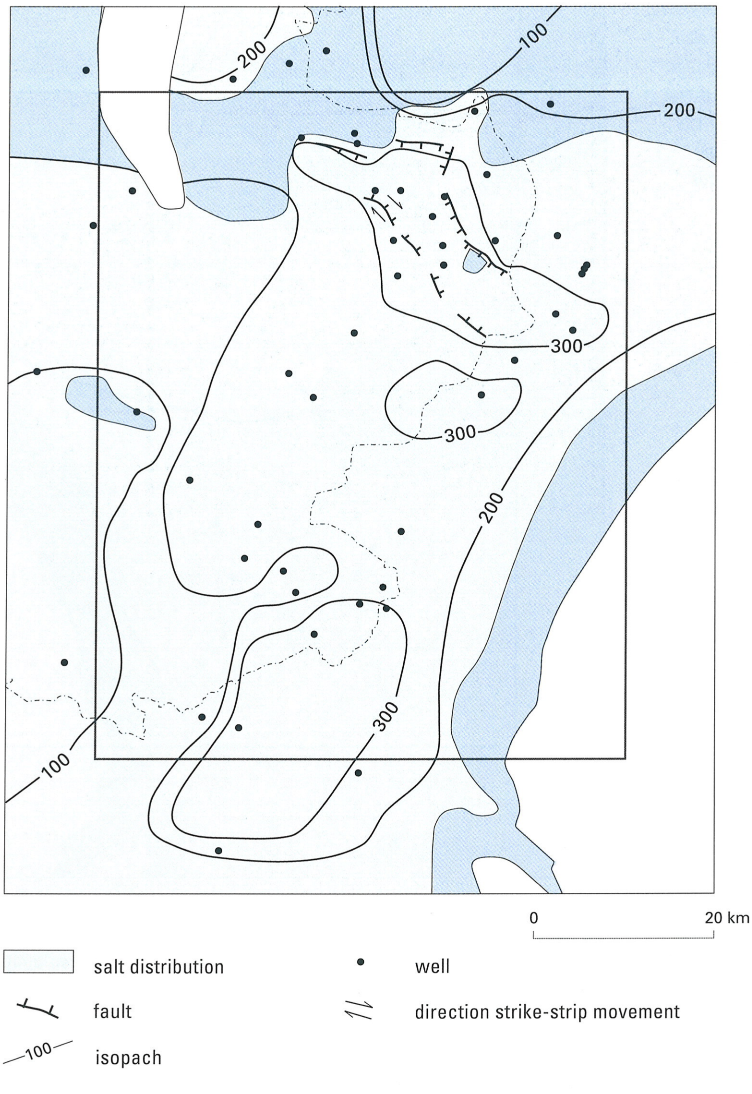


Figure 5.3 Thickness map and distribution of rock salt within the Z1 (Werra) Formation. In three depocentres, the formation reaches a considerable thickness, in excess of 300 m. In the northernmost depocentre, a clear relation with active faulting can be ascertained.

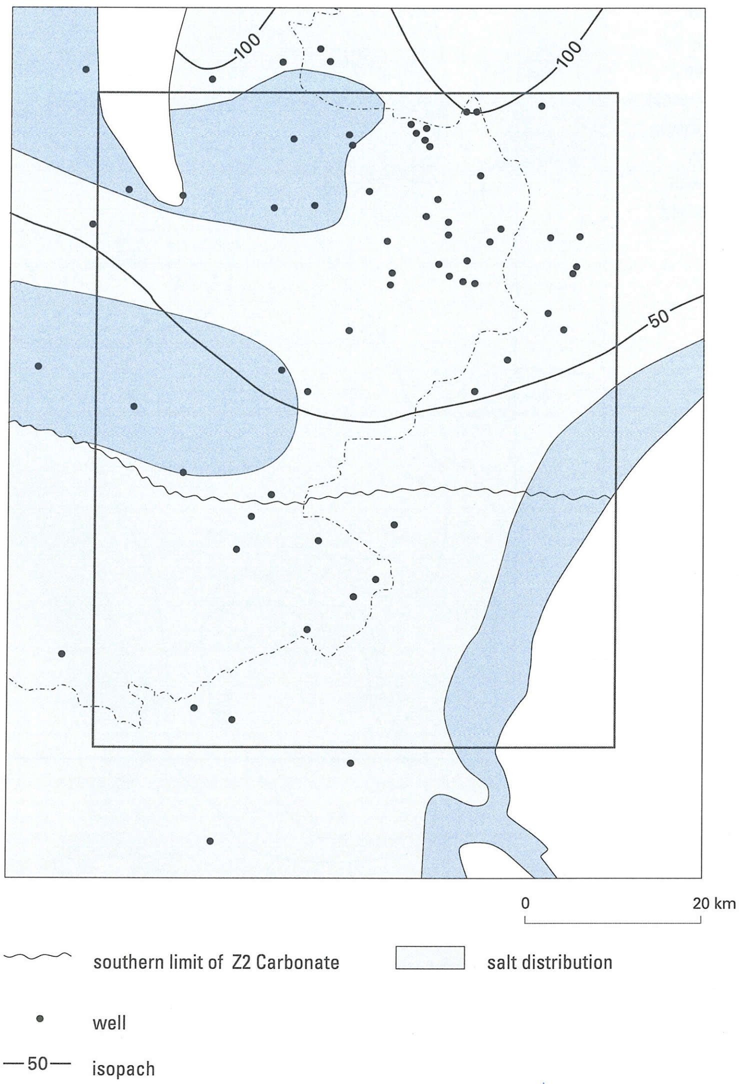
layers near Winterswijk is 10 to 30 m; the KCl content ranges from 12 to nearly 25% (Hissink & Van Kampen, 1911; Boeke, 1913; Van Waterschoot van der Gracht, 1909, 1918).

The Z1 Salt Member may be absent locally in the area of normal occurrence; this phenomenon is found in, for example, the Losser-4, Lochem-2 and Gelria-2 wells (fig. 5.1). The explanation for this may lie in the presence of more elevated fault blocks during deposition of the Zechstein Group, where no salt deposition took place.

5.1.2 Z2 (Stassfurt) Formation

The Z2 (Stassfurt) Formation is composed of the Z2 Carbonate, Z2 Basal Anhydrite, Z2 Salt and Z2 Roof Anhydrite Members. In the south of the map sheet area the formation consists entirely of rock salt and anhydrite. The formation thickens in a northwesterly direction from approximately 50 to 100 m.

Figure 5.4 Thickness map of the Z2 (Stassfurt) Formation. This also indicates the distribution of rock salt and the southernmost extent of the Z2 Carbonate Member. The formation displays a gradual increase in thickness towards the north.



The *Z2 Carbonate* is present in most of the area, with the exception of the southern part. The member is composed of a dolomitic limestone, with an intercalated anhydrite horizon 10 to 15 m thick. Oolite layers occur in the northern part of the map sheet area. The unit increases in thickness from 10 m to over 50 m. Towards the south it grades laterally into rock salt and anhydrite (fig. 5.5). The best reservoir characteristics occur where the Z2 Carbonate shows small brittle fractures and fissures.

The *Z2 Basal Anhydrite* is found in the same areas as the preceding member, which is composed of a massive white anhydrite, ranging laterally from 5 to 20 m in thickness.

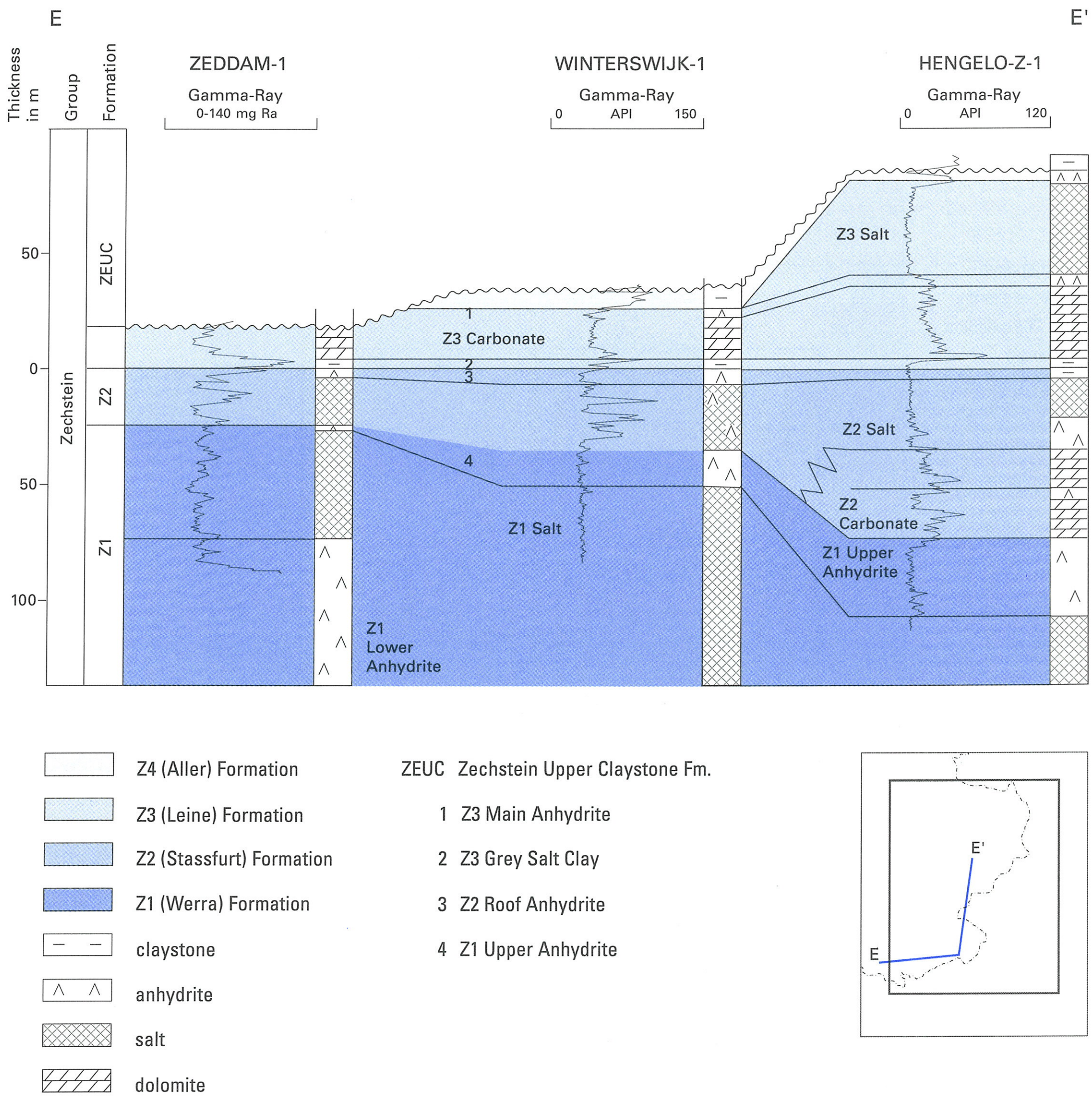


Figure 5.5 Stratigraphic section E-E' of the Z2 (Stassfurt) Formation and younger deposits in the Zeddam-1, Winterswijk-1 and Hengelo-Z-1 wells. The thinner succession in the south and the hiatuses appearing within it indicate that this area was situated at the end of the Zechstein Group deposits along the edges of the basin. The reference-level is the base of the Z3 (Leine) Formation.

Z2 Salt occurs virtually throughout the map sheet area, with the exception of a small area in the northwest and the centre (fig. 5.4). In the south of the area the unit is around 30 m thick, whereas in the north, in the Tubbergen salt-structure, the thickness may even exceed 100 m. The unit comprises white to light-grey halite, sometimes coarse crystalline in texture. Thin potassium-magnesium salt layers (up to 2 m thick) at the top of the unit are found in the extreme south and north of the map sheet area. The KCl content in the south is 4 to 15% and in the north, over 18% (Brueren, 1959).

It is notable that in the southwest of the map sheet area the Z2 Salt rests on the Z1 Salt with a normal stratigraphic contact (Zeddam-1 well); this has also been observed in the adjacent German territory (Isselburg-1 & 2 wells; Wolburg, 1957). This fact has up to now only been recorded in these specific wells in the Zechstein Basin.

The *Z2 Roof Anhydrite* is a 3 to approximately 10 m thick pure anhydrite, which overlies the Z2 Salt throughout the area. In Twente, the anhydrite is laminated and displays flow structures locally (Brueren, 1959).

Figure 5.6 Thickness map and distribution of rock salt within the Z3 (Leine) Formation. The extent of the rock salt is increasingly restricted to the northern part of the map sheet area.

5.1.3 Z3 (Leine) Formation

In the Z3 (Leine) Formation, the Grey Salt Clay, the Z3 Carbonate, the Z3 Main Anhydrite and the Z3 Salt Members can be distinguished. Within the map sheet area, the formation displays an increase in thickness from 20 m in the southwest to over 200 m locally in the extreme northeast (fig. 5.6).

The *Grey Salt Clay* is a well-bedded, dark-grey to black claystone approximately 5 m thick. The claystone contains anhydrite and rock-salt crystals. The unit is highly suitable for regional correlations owing to the characteristic peak on the gamma-ray log (fig. 5.1 & 5.6).

The *Z3 Carbonate* consists of light coloured limestone and dolomite in the south of the map sheet area and a dark coloured massive dolomite in the north. Oolite horizons are found in the bottom part of the unit. In the northern part of the map sheet, anhydrite sometimes occurs in the unit. The unit increases in a northerly direction from 15 m in the Achterhoek to over 40 m in Twente.

The *Z3 Main Anhydrite* is composed of a massive, light coloured anhydrite. The unit thickens in a northerly direction from approximately 5 m in the south to between 10 and 20 m in the north of the area. The thickness may sometimes exhibit a pronounced variation over relatively small distances and increase by several tens of metres (Tubbergen-4, 5, 7 & 8 wells).

The *Z3 Salt* is present in the centre and north of the map sheet area. The thickness in the centre is 20 to 40 m, and in the north, 30 m to, locally, 200 m. The salt consists of colourless halite, with local orange, pink and brown coloured zones. The lowest part of the salt contains a 2 to 4 m thick anhydrite bed.

5.1.4 Z4 (Aller) Formation

The Z4 (Aller) Formation is subdivided into the Red Salt Clay, the Z4 Pegmatite Anhydrite and the Z4 Salt Members. The formation thickens in a northerly direction, from less than 10 m to over 20 m (fig. 5.7).

The *Red Salt Clay* is a reddish-brown to greenish sandy to dolomitic claystone, approximately 5 m thick.

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

The *Z4 Salt* is only found in the northern part of the map sheet area, a maximum of 15 m thick. The unit comprises colourless to reddish-brown halite.

5.1.5 Zechstein Upper Claystone Formation

The Zechstein Upper Claystone Formation rests on the deposits of the Z4 (Aller) Formation (fig. 5.1), separated by a hiatus. The deposits, 20 m thick in the south to 50 m in the northeast of the map sheet area, consist of anhydritical red and grey claystones. These claystones are characterised by low acoustic velocities.

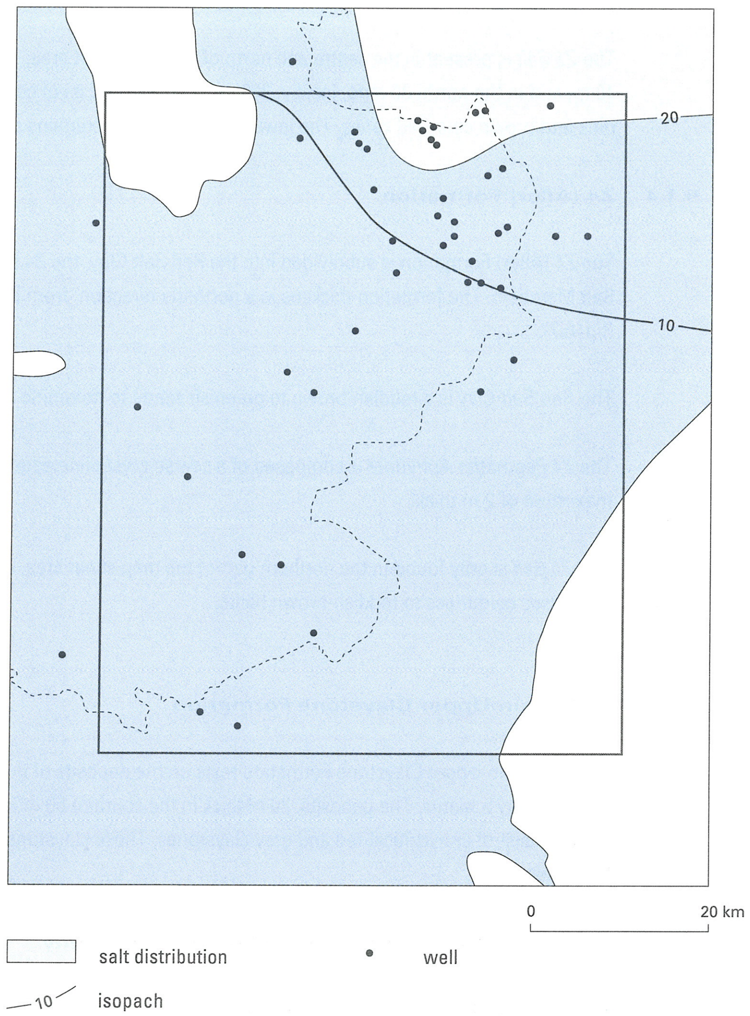
5.2 Sedimentary development and palaeogeography

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

In the Zechstein Group the four evaporite cycles represent a succession of transgressions and regressions. During the first three transgressive periods, clays and carbonates were deposited when fairly normal saline conditions prevailed. After the third transgression the conditions in the basin were permanently hypersaline. Arid climate conditions increased the salinity during the regressive phase of the cycle, resulting in evaporite deposits. These large-scale sea-level fluctuations are presumed to be related to the alternation of Late Permian glacials and interglacials (Ziegler, 1990).

The deposition of the Z1 (Werra) Formation began with a transgression, while deposition of the Coppershale occurred in an anoxic environment in a basin with a restricted water circulation (Taylor, 1986). A thin succession of carbonates was subsequently deposited in an initially deep marine setting (>50 m water depth). During the deposition, the setting rapidly became shallower; the interbedding of anhydrite nodules in the topmost part of the carbonate indicates sabkha-like depositional conditions. In the south of the map sheet area, erosion of the Coppershale and the Z1 Carbonate occurred locally.

Figure 5.7 Thickness map and distribution of rock salt within the Z4 (Aller) Formation. In the greater part of the map sheet area, the formation only comprises red coloured claystone. Only in the extreme north of the map sheet area is rock salt present.



During deposition of the Z1 Anhydrite, the entire map sheet area was part of a shallow platform, where rapid precipitation of anhydrite occurred. The load formed by a thick sequence (50-200 m) of relatively heavy mineral anhydrite as well as a tectonic differentiation of the substrate (Geluk et al., 1997) triggered an intense reactivation of old (Variscan) fault zones, resulting in the formation of a number of fault-bounded depressions in this platform area, particularly in the east of the map sheet area (fig. 5.2 & 5.3). These depressions were fairly isolated from the more northerly main basin; although influx of seawater from the main basin was possible, a return flow of water was significantly impeded. Precipitation of rock salt only took place in the depressions; no deposition occurred on the tectonically high blocks during this period. In the most northerly (isolated) depressions, a certain amount of brine exchange with the main basin is thought to have taken place; here, only rock salt was precipitated. Depressions in the most southerly part of the map sheet area, in the vicinity of Winterswijk, were more or less excluded from the exchange of brine with the main basin, resulting in a further increase in salinity and precipitation of potassium-magnesium salts. By the end of deposition of the Z1 (Werra) Formation, the depressions had been levelled and after a subsequent minor transgression, almost the entire map sheet area was covered by anhydrite. This transgression did not get as far as the most southwesterly part of the area: this part of the area appears to have been slightly higher by the end of deposition of the Z1 (Werra) Formation. The remaining course of the Zechstein was marked by the absence of any major differential active faulting.

The Z2 (Stassfurt) Formation began with a transgression, while normal saline conditions in the greater part of the area prevailed, with the exception of the area to the south of the line Deventer - Lochem - Eibergen. The palaeogeography of the area during deposition of the Z2 Carbonate is thought to show a remarkable analogy with recent examples on the southern margin of the Persian Gulf in Abu Dhabi (Purser, 1973; Van der Baan, 1990). Oolite beds were deposited in a high-energetic marine setting, and fine-grained lagoonal deposits, algal mats and anhydrite in a sabkha setting. In the extreme south, there was a vast salt lake on the margin of the basin, with alternating deposition of anhydrite and rock salt. The absence of the Z1 Anhydrite in the southwestern part of the area places the Z2 Salt in direct stratigraphic contact with the Z1 Salt. An increasing concentration of the brine in the basin facilitated the deposition of anhydrite and rock salt; owing to the position of the map sheet area on the margin of the Southern Permian Basin, only a thin succession was deposited. Some of the higher blocks are completely devoid of salt deposits. The decrease in salinity of the Z2 Roof Anhydrite reflects the onset of the third large transgression of the Zechstein.

The transgression of the Z3 (Leine) Formation throughout the map sheet area initiated deposition of carbonate under shallow-marine conditions. It is thought that the depositional conditions showed a close analogy with those of the carbonates in the Persian Gulf; this is indicated by the presence of oolites, algal mats and the occurrence of anhydrite (Van der Baan, 1990). An increasing salt concentration of the water in the basin subsequently triggered deposition of anhydrite and rock salt. Deposition of the salt only occurred in the northern part of the map sheet area.

The hypersaline character of the brine in the Southern Permian Basin, the alternation of salt and claystone and the sparser areal distribution of the Z4 Salt point to a gradual change from a marine to a continental evaporite basin. The position on the margin of the basin is apparent from the more limited extent of the Z4 Salt to the extreme north of the map sheet area.

The clays of the Zechstein Upper Claystone Formation rest on the Z4 (Aller) Formation separated by a hiatus; these clays represent the transition of the evaporite deposits of the Zechstein Group to the lacustrine deposits of the Lower Germanic Triassic Group.

5.3 Petrophysical evaluation

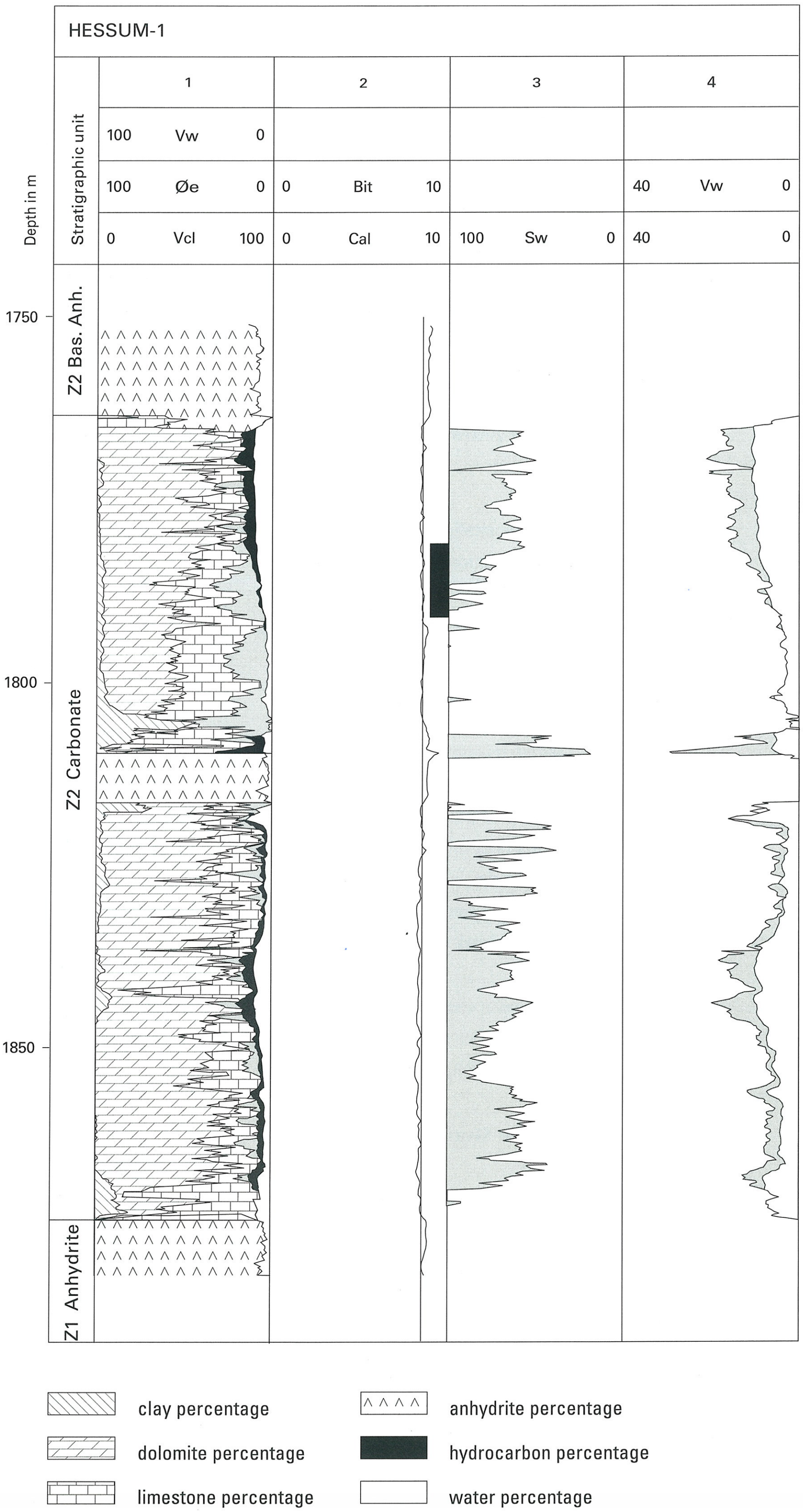
In 1948, the NAM discovered commercially exploitable amounts of natural gas in Zechstein carbonate reservoirs in the south of the province of Drenthe. Since that time, the Z2 and Z3 Carbonate have formed a successful target for exploration in The Netherlands (Van Adrichem Boogaert & Burgers, 1983). In the map sheet area, four gas fields have been revealed in the Z2 and Z3 Carbonate (fig. 1.2). To illustrate log evaluations of the reservoir sequence of the Z2 and Z3 Carbonates, figure 5.8 shows the results in the case of the Hessum-1 well.

Core analyses are available of four of seven of the selected wells in the map sheet area (Rammelbeek-2, Geesteren-1, Hessum-1 and Tubbergen-5). The average core porosities and permeabilities are in general low (3-11% and 0-8 mD for the Z3 Carbonate; 1-8% and 0-1 mD for the Z2 Carbonate). This picture is confirmed by data from the Bentheim gas field, immediately to the east of the map sheet area (Heidorn & Kessler, 1959).

Appendix E gives the results of the reservoir calculations of the Zechstein Carbonates. A 2% cut-off value for porosity has been used, and the value of 50% for the clay content.

The Z2 and Z3 Carbonates in the map sheet area are predominantly platform deposits, with possible occurrence of dolomitisation. The porosity is low and permeability is indicated by the presence of fissures and small fractures.

Figure 5.8 Petrophysical evaluation of the Z2 Carbonate Member in the Hessum-1 well. Column 1: clay content Vcl, effective porosity Øe and pore volume water Vw, all given in percentages. The clay content was determined with the use of gamma-ray logs. The effective porosity was obtained from use of the 'complex lithology model' (density, neutron and sonic logs), in which the porosity present was corrected for the clay and hydrocarbons present. Column 2: borehole diameter (Cal) and bit diameter (Bit), both in inches. The well was not tested. On the right margin of the column the core interval is indicated by a black bar. Column 3: water saturation Sw %. The Archie formula, was applied to determine the water saturation (Fertl, 1987). Column 4: effective porosity Øe (left curve) and the volume of water in the pores Vw (right curve), both in percentages. The depths are the true depths.



6 Lower and Upper Germanic Trias Groups

6.1 Stratigraphy

The Triassic deposits consist predominantly of red and green coloured clastics and grey coloured carbonates, marls and evaporites. Within the Triassic deposits, the Lower and Upper Germanic Trias Groups can be distinguished. Deposits of a Late Permian to Ladinian age are present within the map sheet area.

With the exception of the Friesland Platform, the Triassic deposits are found throughout the map sheet area. The greatest thickness, over 1100 m, is reached in the northeastern part (Map 6). In the west of the area, the thickness is reduced locally owing to subsequent erosion. The deposits rest conformably on the Zechstein Group and are unconformably overlain by the Altena, the Niedersachsen or the Rijnland Group, or by the North Sea Supergroup (Maps 16, 17 & 18).

The depth of the base of the Triassic deposits ranges from less than 400 m in the vicinity of Winterswijk to over 2000 m in the extreme north of the map sheet area (Map 5). The Triassic deposits are heavily fractured.

The lithostratigraphic composition of the Triassic deposits is illustrated by the wells (fig. 6.1 & 6.5) and a log correlation section (fig. 6.2).

6.2 Lower Germanic Trias Group

6.2.1 Stratigraphy

Within this group in the map sheet area, four formations can be distinguished, the Lower Buntsandstein, the Volpriehausen, the Detfurth and the Hardegsen Formations. The first-mentioned formation is composed predominantly of claystones and siltstones, and the other formations of an alternation of sandstones and claystones. The last-mentioned formations are referred to in combination as the Main Buntsandstein Subgroup (fig. 6.1). Within the group, minor unconformities occur at the base of the Volpriehausen and Detfurth Formations, which may well have caused some tens of metres of erosion locally (Geluk & Röhling, 1997).

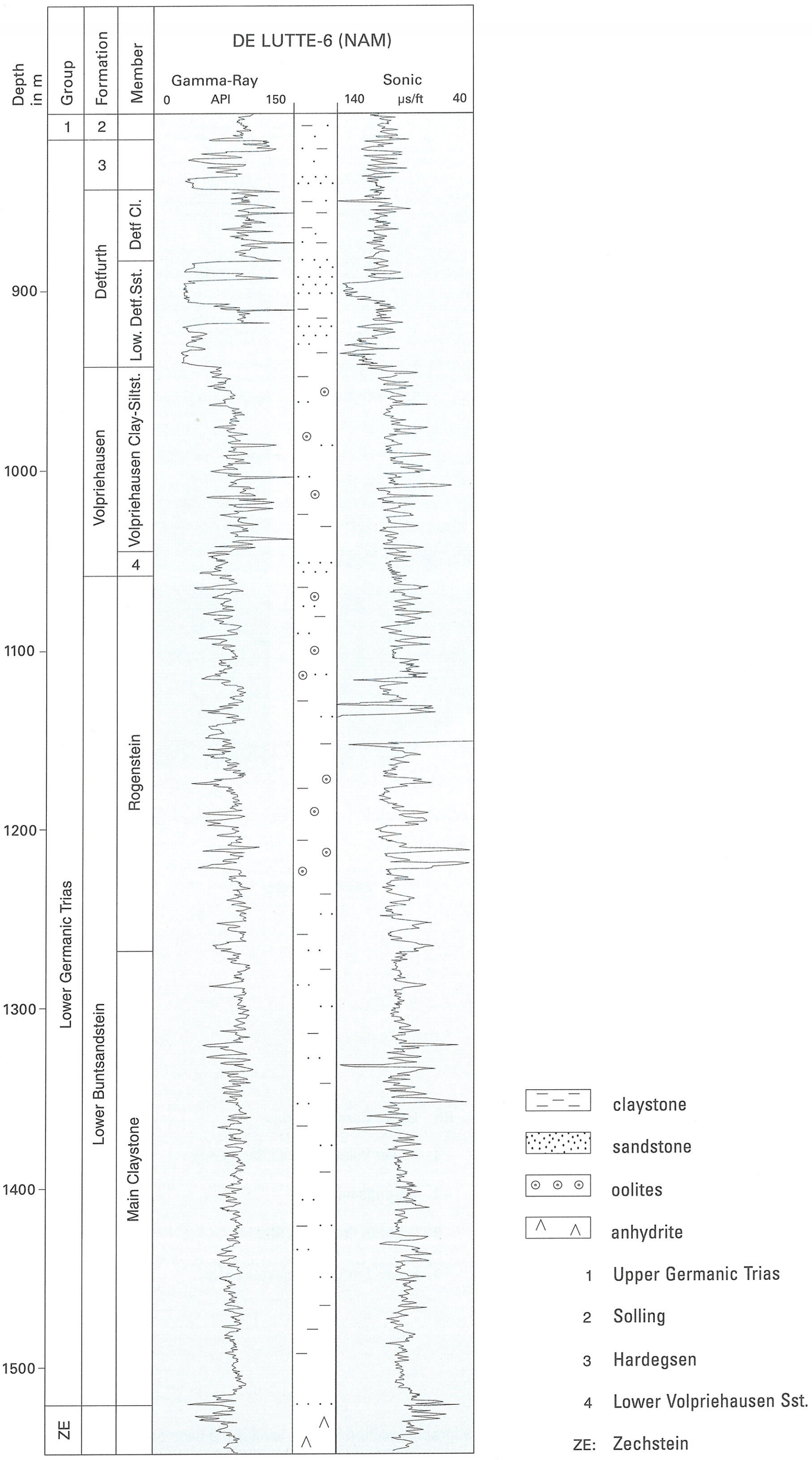
The Lower Germanic Trias Group, of Late Permian to Scythian age, rests conformably on the Zechstein Group, and is unconformably overlain by the Upper Germanic Trias (fig. 6.4), the Niedersachsen or the Rijnland Group, or by the North Sea Supergroup.

6.2.2 Lower Buntsandstein Formation

This formation is composed of the Main Claystone and the Rogenstein Members (fig. 6.1 & 6.2). Separated by a sharply defined boundary marking a minor unconformity, the formation is overlain by the Main Buntsandstein Subgroup, or unconformably by the Upper Germanic Trias, the Niedersachsen or the Rijnland Group, or by the North Sea Supergroup. The formation has a highly uniform thickness and lithology and its transparent character makes it clearly identifiable on seismic sections. The thickness increases in a northerly direction from 275 m in the extreme south to approximately 360 m (fig. 6.3).

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

Figure 6.1 Stratigraphic division and log pattern of the Lower Triassic Group in the De Lutte-6 well. This well is located in the Ems Low, and displays a relatively complete succession of the Main Buntsandstein Subgroup.



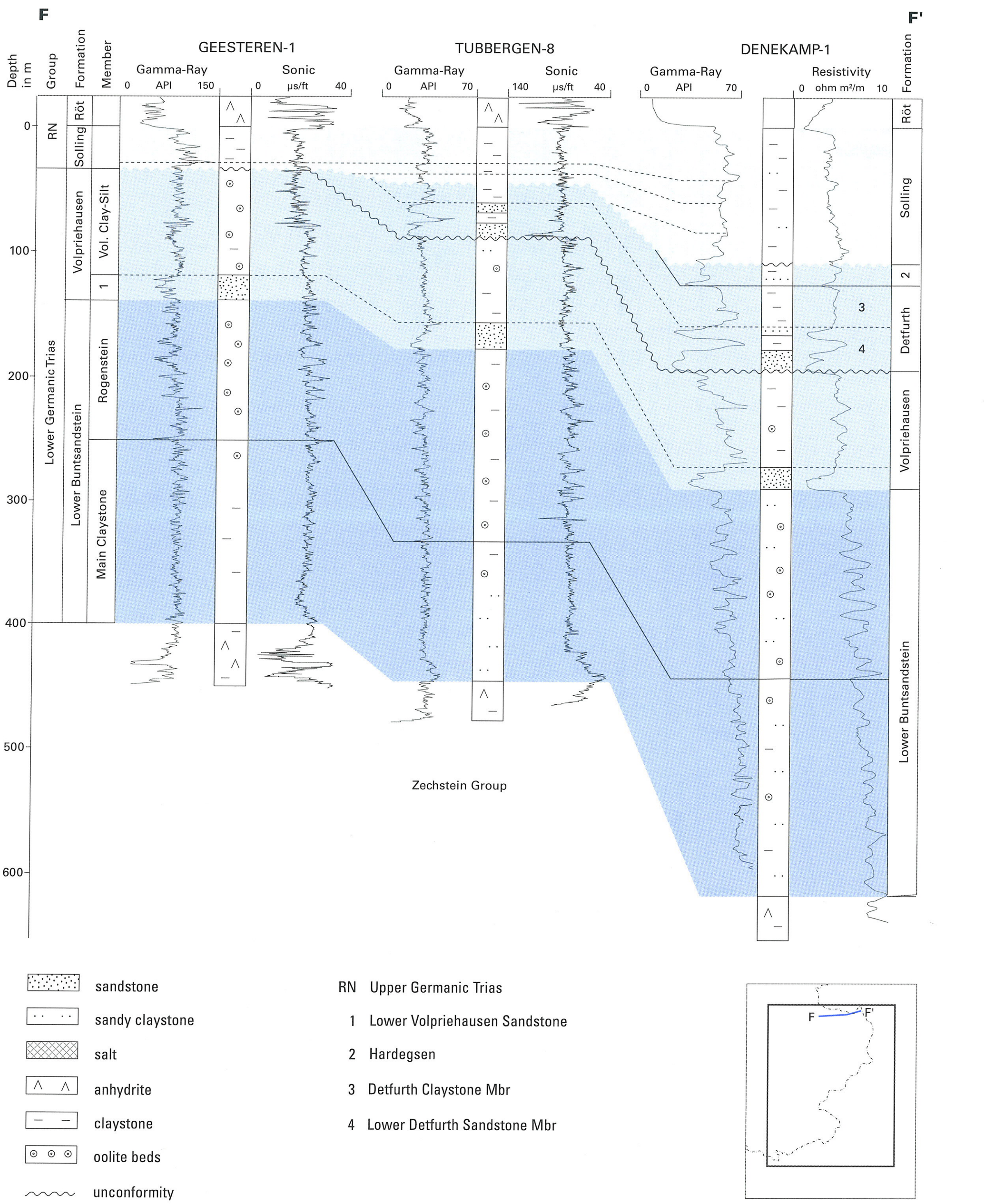


Figure 6.2 Stratigraphic section F-F' of the Lower Germanic Trias Group and the Solling Formation in the Geesteren-1, Tubbergen-8 and Denekamp-1 wells. The reference-level is the base of the Röt Formation. The deeper cutting down of the base of the Solling (Hardegsen) unconformity in a westerly direction is clearly visible, as well as the thinning of the bottommost part of the Solling Formation in a westerly direction.

correlatable on a regional scale in the northern Netherlands and western Germany and gives a highly uniform picture (Geluk & Röhling, 1997). The thickness of the complete member is 150 to 200 m.

The *Rogenstein* consists of red and green coloured fine-sandy claystones and siltstones with many layers of mica and oolite beds. The member also consists of a cyclical succession of coarser and finer deposits but, in contrast to the Main Claystone, displays frequent occurrences of oolites at the base of the cycles, which give the sequence its characteristic appearance. Desiccation cracks are abundant in the fine-grained deposits. Towards the south, the oolite beds grade into sandstones. The oolite beds give the Rogenstein a characteristic log reading on account of the low gamma-ray values, high density and high acoustic velocity. Approximately 75 m above the base, four to six characteristic beds occur, which can be identified throughout the area (fig. 6.1 & 6.2). The sequence thickens in a northerly direction from 90 to 160 m. In the south, the reduced thickness was caused principally by the deeper truncation of the base of the Volpriehausen Formation.

6.2.3 Main Buntsandstein Subgroup

This subgroup consists of an alternation of claystone, siltstone and sandstone. Within the map sheet area, the subgroup thickens in an easterly direction from approximately 50 m in the extreme northwest

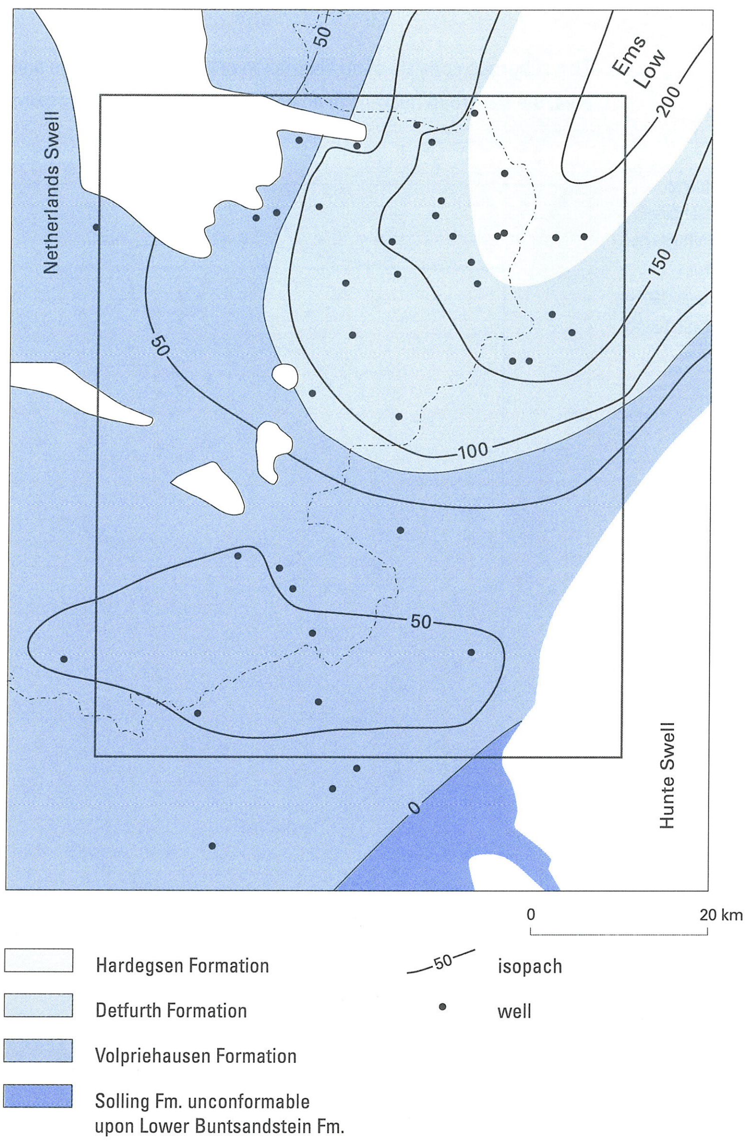
Figure 6.3 Thickness map and extent of the Lower Buntsandstein Formation. The formation thickens in a northerly direction from approximately 275 m to over 350 m in places. This map has been based on well data.

to over 200 m in the northeast. Within the subgroup, three formations can be distinguished, the Volpriehausen, the Detfurth and the Hardegsen Formations (fig. 6.1 & 6.4).

The difference in the thickness of this subgroup is determined by erosion prior to deposition of the Solling Formation, and, to a lesser degree, by erosion prior to deposition of the Detfurth Formation. In the Ems Low, in the east of the map sheet area, this erosion was the slightest and all the formations are present; in the northwest of the map sheet area the erosion was the most pronounced and only a part of the Volpriehausen Formation has been preserved. More extreme erosion occurred to the southeast of the map sheet area, where the entire Main Buntsandstein Subgroup was removed (fig. 6.4).

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

Figure 6.4 Thickness map of the Main Buntsandstein Subgroup. This map also indicates which formation is at the top of this subgroup. This map has been based on well data. Data for the German part have been derived from Röhling (1991) and Wolf (1985).



6.2.3a Volpriehausen Formation

The Volpriehausen Formation is subdivided into the Lower Volpriehausen Sandstone and Volpriehausen Clay-Siltstone Members. Separated by a hiatus, the formation rests on the Lower Buntsandstein Formation and in the northeast is unconformably overlain by the Detfurth Formation and in other parts of the map sheet area by the Solling Formation. The formation reaches the greatest thickness, nearly 100 m, in the Ems Low, in the northeast of the map sheet area. In the west and south, erosion has reduced the thickness to between 35 and 80 m.

The *Lower Volpriehausen Sandstone* rests on the underlying formation separated by a sharply defined boundary, and is overlain by the Volpriehausen Clay-Siltstone, also separated by a sharply defined boundary. The sandstone is in general fine-grained and calcareous. The sequence thickness, 10 to 15 m, is fairly uniform in this area.

The *Volpriehausen Clay-Siltstone* consists of a cyclically composed sequence of red, fine-sandy clay-siltstone consisting of red to green fine-grained sandstone beds. The sandstone beds sometimes contain oolites. The unit rests with a sharply defined boundary on the Lower Volpriehausen Sandstone and is unconformably overlain by the Lower Detfurth Sandstone or the Solling Formation. The most complete succession, over 80 m, has been preserved in the Ems Low; towards the east and south, the thickness has been reduced to 20 - 70 m.

6.2.3b Detfurth Formation

The Detfurth Formation is subdivided into the Lower Detfurth Sandstone and Detfurth Claystone Members. The formation is present in the northeast of the map sheet area. The Detfurth Formation rests unconformably upon the Volpriehausen Formation and is conformably overlain by the Hardegsen Formation or unconformably by the Solling Formation. The formation reaches the greatest thickness, over 70 m, in the Ems Low in the extreme northeast. Towards the west, the thickness rapidly decreases to 0 m, in consequence of the erosion at the base of the Solling Formation.

The *Lower Detfurth Sandstone* consists of a complex of medium-fine to coarse-grained, reddish-brown sandstone and likewise red coloured clay-siltstone layers. The unit displays a highly consistent composition within the area and is divided into two sandstone intervals by the intercalation of a clay-siltstone sequence. The bottommost sandstone interval, approximately 20 m thick, comprises a red coloured clay-siltstone sequence, 5 to 7 m thick. The sandstones display a block-like character on well logs, or an upwardly increasing clay content. The sandstone is cemented with carbonate, anhydrite or quartz. The 10 m clay-siltstone sequence between both sandstone intervals is reddish-brown, and contains a few thin carbonate layers. The topmost sandstone interval, 10 m thick, generally exhibits a block-like character on well logs.

The *Detfurth Claystone* is composed of fine-sandy or silty, predominantly reddish-brown coloured claystone. The claystone contains some of fine to medium sandstone beds cemented with carbonate or quartz. Abundant desiccation cracks are to be found in the claystone (Wolburg, 1961). The maximum thickness of the unit exceeds 35 m in the Ems Low; towards the west, the thickness is reduced owing to truncation of the base of the Solling Formation. Owing to its character on well logs, the unit forms an excellent marker for log correlations.

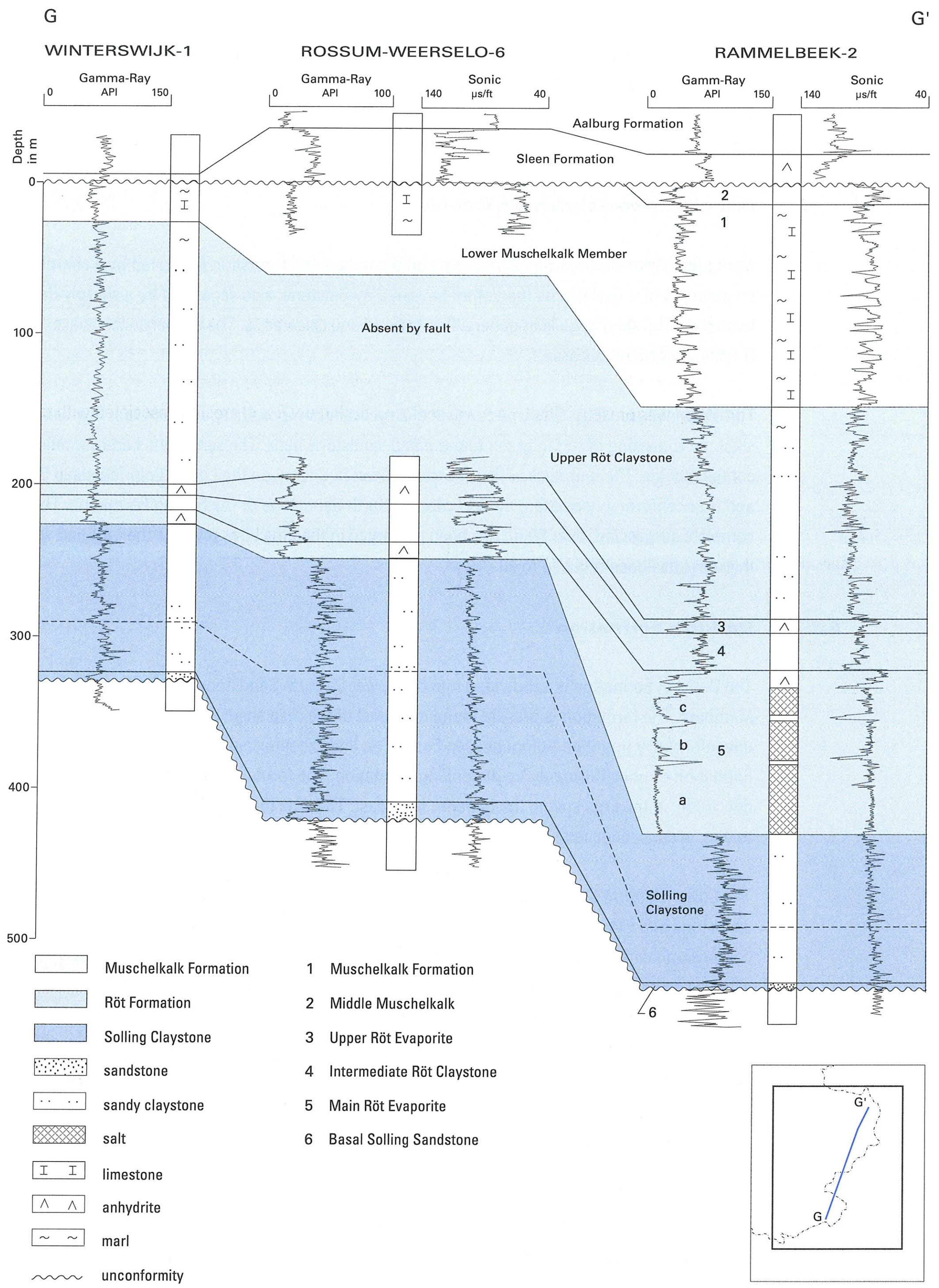


Figure 6.5 Stratigraphic section G-G' of the Upper Germanic Trias Group of the Winterswijk-1, Rossum-Weerselo-6 and Rammelbeek-2 wells. The reference-level is the base of the Altena Group (Sleen Formation). The section shows the Upper Germanic Trias Group becoming increasingly more complete in a northerly direction. In the Rossum-Weerslo-6 well, approximately 100 m of the Röt Formation are absent owing to a fault.

6.2.3c Hardegsen Formation

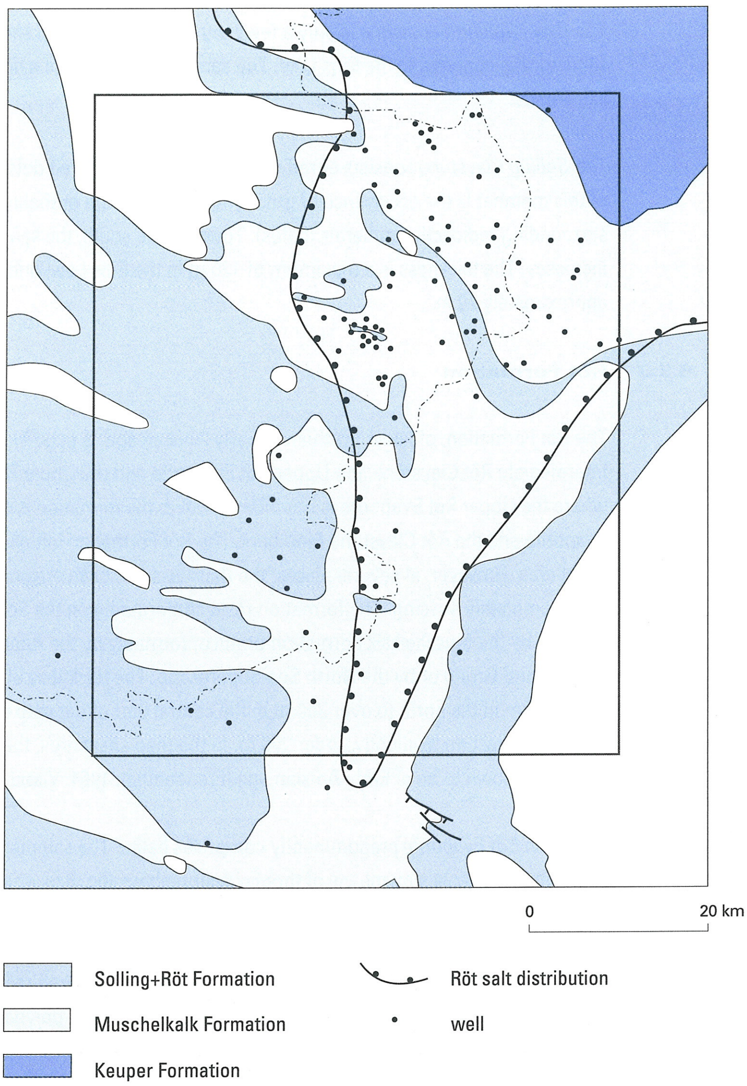
Deposits of the Hardegsen Formation have only been encountered in a few wells in the Ems Low. This formation consists of a rapid alternation of thin layers of medium sandstone cemented with carbonate or quartz, and silty or fine-sandy claystone. The deposits are reddish-brown and locally grey in colour. Owing to erosion, the thickness of the formation in The Netherlands is only a maximum of 25 m.

6.3 Upper Germanic Trias Group

6.3.1 Stratigraphy

The Upper Germanic Trias Group, of Late Scythian to Ladinian age, is composed predominantly of an alternation of claystone, limestone and evaporite. Within the Upper Germanic Trias Group in this area, the Solling, the Röt and the Muschelkalk Formations can be distinguished (fig. 6.5). The Keuper Formation was present initially, but was removed during uplift and erosion associated with the Early

Figure 6.6 Extent of the Solling, Röt and Muschelkalk Formations within the map sheet area. The distribution of rock salt within the Main Röt Evaporite Member has been indicated. This map has been based on wells and seismics; data for the German part have been derived from Hilden (1988) and Wolburg (1967).



Kimmerian phase. However, the last-mentioned formation is found to the north of the map sheet area (fig. 6.7). The Solling and the Röt Formation are informally referred to in combination as the *Upper Buntsandstein*.

The group is present in the east of the map sheet area; in the northwest and locally in the west, the group is not present (fig. 6.6). The group rests on the Lower Germanic Trias Group separated by an unconformity and is overlain, also unconformably, by the Altena, the Niedersachsen or the Rijnland Group or by the North Sea Supergroup.

6.3.2 Solling Formation

The Solling Formation is divided into the Basal Solling Sandstone and the Solling Claystone Members. The formation rests unconformably on the Lower Germanic Trias Group, and is conformably overlain by the Röt Formation or unconformably by the Rijnland Group or the North Sea Supergroup. The formation reaches the greatest thickness of over 120 m in the Ems Low; towards the south and west the thickness decreases to approximately 70 m.

The *Basal Solling Sandstone* is only a few metres thick in the map sheet area. The presence of this sandstone is confined to the Ems Low. The sandstone consists of a limey, reddish-coloured, fine-grained calcarenite.

The *Solling Claystone* consists of red or reddish-brown coloured dolomitic silty claystone; characteristic of this member is the occurrence of green mottles which are probably the product of reduction surrounding radioactive minerals (halos). Towards the south, the sand content in the sequence increases. The thickness is a maximum of 120 m in the Ems Low, and decreases outside this low to approximately 70 m.

6.3.3 Röt Formation

The Röt Formation, of latest Scythian to Early Anisian age, is subdivided into the Main Röt Evaporite, the Intermediate Röt Claystone, the Upper Röt Evaporite and the Upper Röt Claystone Members. At places where the Upper Röt Evaporite is not differentiated, the formation is subdivided into the Main Röt Evaporite and the Röt Claystone Members. The Röt Formation initially occurred throughout the map sheet area. However, at several places, the thickness has been erosionally reduced or the formation is even completely missing. The formation rests conformably on the Solling Formation and is conformably overlain by the Muschelkalk Formation or unconformably by the Altena (fig. 6.7), the Niedersachsen or the Rijnland Group or by the North Sea Supergroup. The thickness of the Röt Formation ranges from a good 225 m in the north to over 300 m in the central part of the map sheet area, and decreases in a southerly direction to slightly under 200 m. In the map sheet area, the bottommost part of the formation has been shown to be of Early Anisian age (Freudenthal, 1964; Visscher 1966).

The *Main Röt Evaporite* predominantly comprises halite. The salt member can be differentiated into four different salt intervals by means of three claystone beds (fig. 6.5) which are regionally well-correlatable (Trusheim, 1971; Wolburg, 1961). From bottom to top, these salt cycles have been designated by the letters a to d in the map sheet area (Harsveldt, 1980). The thickness of these layers decreases upwardly. Layers a - c predominantly comprise light-grey or bright coloured rock salt, whereas layer d mainly comprises reddish coloured rock salt: a result of the mixing of polyhalite and reddish coloured claystone. The salt layers a and c are the thickest; layer a exhibits a considerable variation in thickness, from 10 to 50 m, layer c, from 15 to 25 m, is much more constant in thickness. Layers b and d are in general only a few metres thick. The salt layers are separated by claystones, dolomite and anhydrite.

At the base of the Main Röt Evaporite, an occasional dm-thick anhydrite layer occurs, while the top of the evaporite comprises a 10 to 15 m thick anhydrite sequence, with intercalated thin claystone layers. The Main Röt Evaporite achieves its greatest thickness, over 110 m, in the Ems Low. In addition, also to the southeast of the Gronau Fault Zone, thicknesses of over 100 m are found locally (e.g. the wells Buurse-6, and Twente-Rijn-156 & 159). At places where no rock salt is present and the sequence consists predominantly of anhydrite, the thickness is over 20 m. Figure 6.6 shows the areal extent.

The *Intermediate Röt Claystone* comprises a reddish-brown claystone, with a uniform thickness of 25 to 35 m. Owing to its high gamma-ray value, this member is easily distinguishable from the underlying and overlying evaporite members by well log readings.

The *Upper Röt Evaporite* is developed in the map sheet area in anhydrite facies. The succession consists of an alternation of anhydrite and thin claystone layers. The thickness of the sequence ranges from 5 to 15 m.

The *Upper Röt Claystone* consists of purple, bright orange-red, dark-red, reddish-brown or green claystone. The claystone is often silty or sand-bearing; gypsum nodules are also found. In the uppermost part, approximately 50 m thick, the claystones alternate with marl and thin limestone layers. The unit is 135 to over 200 m thick in the Ems Low in the east of the map sheet area.

6.3.4 Muschelkalk Formation

The Muschelkalk Formation in the map sheet area, of Middle Anisian to Ladinian age, is subdivided into the Lower Muschelkalk, the Muschelkalk Evaporite, the Middle Muschelkalk Marl and the Upper Muschelkalk Members. The Muschelkalk Evaporite and the Middle Muschelkalk Marl are informally referred to in combination as the *Middle Muschelkalk.* The present areal extent and the thickness of this formation are strongly determined by uplift and erosion resulting from the Early Kimmerian and subsequent tectonic phases; consequently, the most complete succession of the formation can be found in the extreme northeast of the map sheet area (fig. 6.7). In other places, only a considerably reduced succession of the Lower Muschelkalk is encountered. In the south and west of the map sheet area the formation is completely absent over large areas. The formation is unconformably overlain by the Altena (fig. 6.7), the Niedersachsen or the Rijnland Group or by the North Sea Supergroup. The thickness of the formation is a maximum of 200 m.

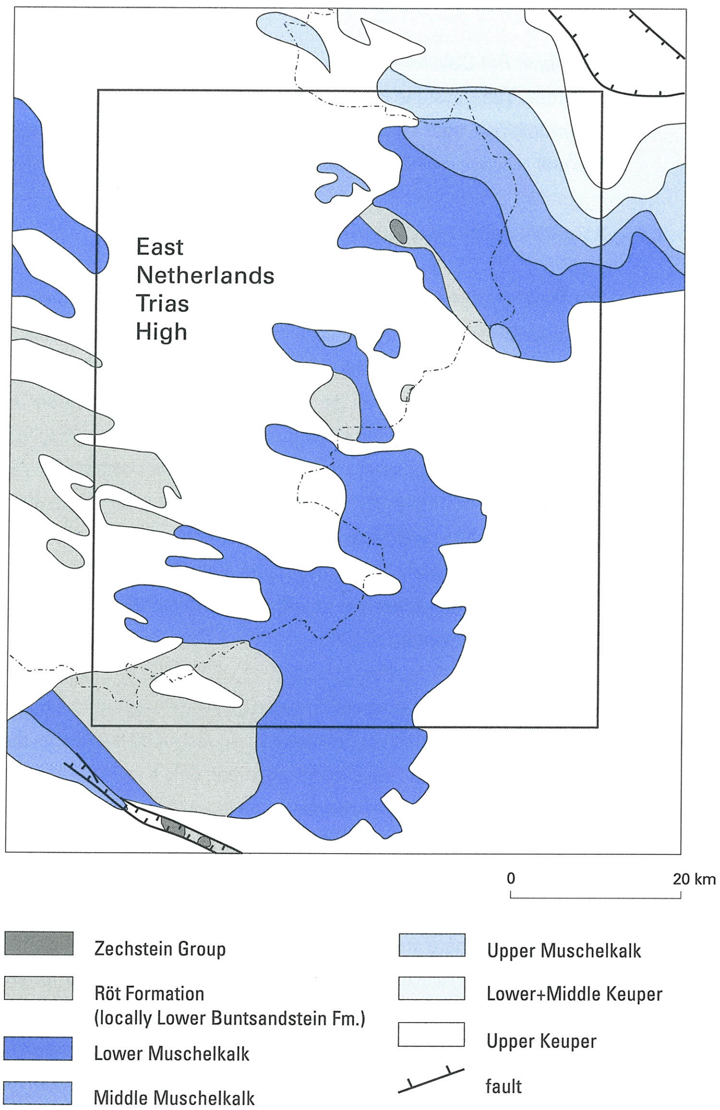
The *Lower Muschelkalk* occurs throughout a wide extent of the map sheet area. In the greater part of the map sheet area, the unit is unconformably overlain by the Altena, the Niedersachsen or the Rijnland Group or by the North Sea Supergroup; here, only a few tens of metres of this member have been spared from erosion. In the northeast, the Lower Muschelkalk reaches a thickness of 130 m and is unconformably covered by the Muschelkalk Evaporite. To the east of Winterswijk, this unit has been exposed in the *Winterswijkse Kalk- en Steengroeve [Winterswijk Quarry].* The unit consists of a grey, marly to argillaceous limestone, with intercalations of dolomite, marl and claystone. In the basal part of the formation, there are additional intercalations of reddish and chocolate-brown coloured claystone beds. In the quarry, 6 dolomite layers have been found, 0.4 to 1.2 m thick (Harsveldt, 1963, 1973). These dolomite layers form the top of a sedimentary sequence, which starts with marly sediment, upwardly grading into dolomitic limestone with desiccation cracks and wave ripples. These sequences are 2 to 6 m thick (RGD, 1981). Tempestites (storm deposits) have also been identified in these sequences (De Boorder et al., 1985).

In the Lower Muschelkalk, a considerable number of fossil and mineral finds have been made in the *Winterswijkse Kalk- en Steengroeve*, concentrated mainly in the storm deposits. Minerals found include pyrite, celestine, sphalerite, marcasite and galenite (De Boorder et al., 1985); fossils findings were brachiopods, molluscs and gastropods, as well as of fish and saurian remains and saurian footprints (Oosterink, 1986).

The *Muschelkalk Evaporite* is only present in a small area in the extreme northeast, and very locally to the southwest of the Gronau Fault Zone (fig. 6.7). The unit consists of an alternation of anhydrite and dolomitic marl and is approximately 25 m thick.

The *Middle Muschelkalk Marl* occupies roughly the same areal extent as the Muschelkalk Evaporite. The succession consists of a grey dolomitic marl and, on account of an upwardly increasing clay content, has a characteristic reading on well logs, displaying an increasing natural radioactivity and a decreasing acoustic velocity. The thickness is 25 to 30 m.

Figure 6.7 Subcrop map of the Early Kimmerian Unconformity. Deposits of the Sleen Formation rest, separated by a large hiatus, upon older deposits of the Triassic, or even upon the Zechstein Group. This map has been based on wells and seismics; data for the German part have been derived from Hilden (1988) and Wolburg (1969).



The *Upper Muschelkalk* has only been encountered in both the Denekamp wells, with erosionally reduced thickness. The member, which is here incomplete, is 15 m thick and consists of a succession of light-brown to grey dolomite and marl. However, to the northeast of the map sheet area, it is present in its entirety.

6.4 Sedimentary development and palaeogeography

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: the Hardegsen phase, which gave rise to a hiatus between the Lower and the Upper Germanic Trias Groups (fig. 6.4) and the Early Kimmerian phase, which resulted in a large hiatus between the Upper Germanic Trias Group and the Altena Group (fig. 6.7).

The Lower Buntsandstein Formation consists predominantly of brackish to salt-water lacustrine deposits. The cyclical character displayed by these deposits is ascribed to the so-called Milankovitch cyclicity, with a periodicity of 100,000 years (Geluk & Röhling, 1997). The oolites in the topmost part of the Lower Buntsandstein Formation were formed in brackish water, in a high-energetic setting, during periods of low clastic influx (Peryt, 1975). The red colour of the sediments and desiccation cracks reflect periods when the lake dried out.

During deposition of the Main Buntsandstein Subgroup, fluvial systems prograded episodically from the south to cover the entire map sheet area. The deposition of sands (Lower Volpriehausen Sandstone, Lower Detfurth Sandstone) thus alternated with that of fine-grained lacustrine deposits (Volpriehausen Clay-Siltstone, Detfurth Claystone). At the base of these sandstones, minor unconformities have been revealed; before the deposition of the Detfurth Formation in particular, relatively pronounced erosion occurred, which resulted in the absence of the top part of the Volpriehausen Clay-Siltstone (Geluk et al., 1996; Geluk & Röhling, 1997).

The unconformity at the base of the Upper Germanic Trias Group (Solling Formation) is prominently present in the map sheet area. In the west, on the Netherlands Swell, the group overlies the oldest deposits of the Main Buntsandstein Subgroup, and in the Ems Low, the youngest deposits (fig. 6.4). This group displays an alternation from a continental to a more marine depositional environment.

The Solling Formation reflects a transgression into the basin from an easterly direction. Closing of the connection with the sea and evaporation of the water present in the basin resulted in the deposition of the salt and anhydrite of the Main and Upper Röt Evaporites. These were followed by a sequence of claystones. The top part of the Röt Formation reflects the persevering transgression, with a gradual return to normal-marine conditions in the basin, demonstrated by the increase in the number of interbedded limestone beds. As a result of this transgression, the sediment source area was increasingly submerged by the sea, and the clastic sediment deposition changed over to a limestone-dominated succession of the Muschelkalk Formation. The Lower Muschelkalk was deposited in a marine to supratidal setting, while the renewed closing of the connection between the Northwest European Basin and the ocean triggered deposition of the Muschelkalk Evaporite and the Middle Muschelkalk Marl. Subsequently, the Upper Muschelkalk was deposited, again during normal-marine conditions.

7 Altena Group

7.1 Stratigraphy

The Altena Group, of youngest Late Triassic to Middle Jurassic age, consists predominantly of dark coloured claystones, which were deposited in a marine environment. The group is subdivided into the Sleen, the Aalburg, the Posidonia Shale, the Werkendam and the Brabant Formations.

Within the map sheet area, the deposits of the Altena Group rest on the Upper Germanic Trias Group, separated by the Early Kimmerian unconformity, and locally on the Lower Germanic Trias or the Zechstein Group (fig. 6.7). The deposits occur as erosional relics throughout the map sheet area (Maps 7 & 8). The group reaches its greatest thickness, 500 m, immediately to the east of the Gronau Fault Zone (Map 8). The deposits are covered by the Niedersachsen Group and the Rijnland Group, separated by the Late Kimmerian unconformity (Maps 17 & 18). The North Sea Supergroup rests on these deposits locally (Map 19).

The depth of the base of the deposits ranges from surface level in the east and southeast of the map sheet area to over 1100 m to the east of the Gronau Fault Zone (Map 7).

The development of the group is illustrated by the Oldenzaal-1 well (fig. 7.1).

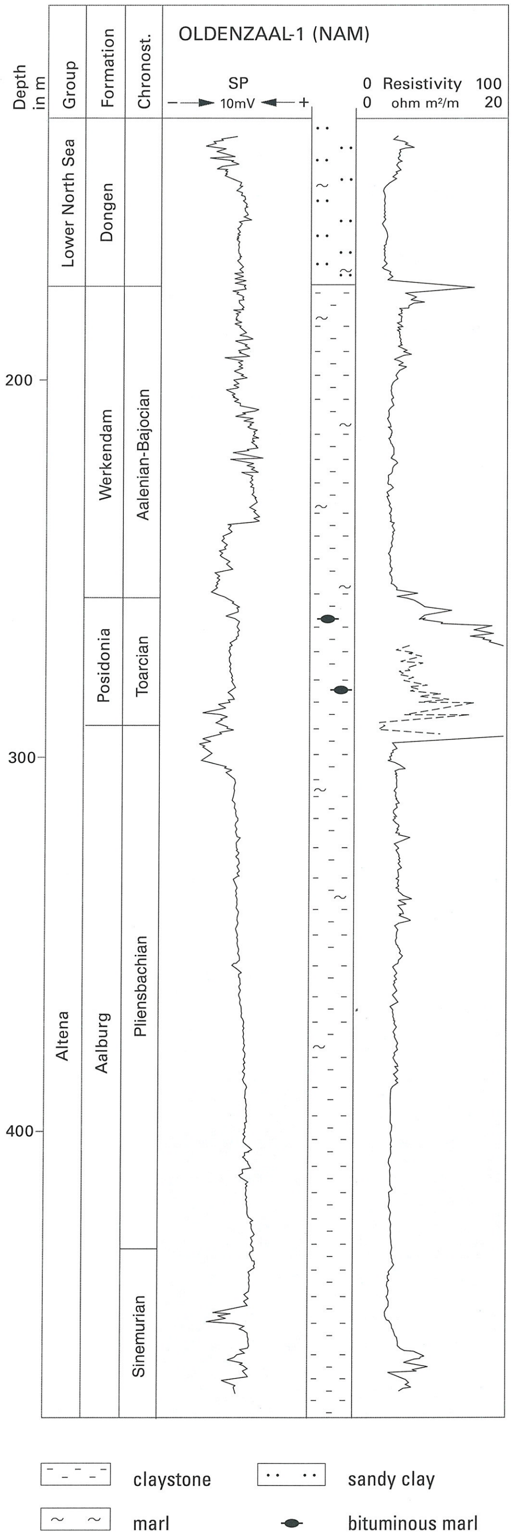
7.1.1 Sleen Formation

The Sleen Formation, of Rhaetian age (RGD 1988b), occurs within virtually the entire areal extent of the Altena Group. The formation rests unconformably on the Solling, the Röt, the Muschelkalk or the Keuper Formation and locally on the Zechstein Group (fig. 6.7), and is conformably covered by the Aalburg Formation and sometimes unconformably by deposits of the Niedersachsen or the Rijnland Group or by the North Sea Supergroup (Maps 17, 18 & 19). The deposits comprise black, sometimes bituminous claystone and shale, with abundant pyrite, fossil and plant remains in patches. The formation is subdivided in two parts by a thin sandstone. The topmost part of the formation may have a red flamed appearance. The formation is from 5 to over 30 m thick.

7.1.2 Aalburg Formation

The Aalburg Formation, of Hettangian to Pliensbachian age (Gerth, 1955; Herngreen & De Boer, 1974), is also found virtually throughout the areal extent of the Altena. The formation rests conformably on the Sleen Formation and is conformably overlain by the Posidonia Shale Formation or unconformably by the Brabant Formation, the Niedersachsen and the Rijnland Groups or the North Sea Supergroup. Lithologically, the formation has a monotonous character and comprises greenish-grey to black, sometimes calcareous claystone with thin limestone beds. In addition, a few organic-rich claystone beds are found in the bottommost part of the formation (Herngreen & De Boer, 1974). In the formation there are abundant occurrences of ammonites, belemnites and molluscs. The present extent and thickness of the formation are generally erosionally based. The depositional thickness of the formation increases in a westerly direction from over 350 to 550 m. Iron oolites are found in the formation in several places to the south of the map sheet area (Hoffmann, 1962).

Figure 7.1 Stratigraphic division and log pattern of the Altena Group in the Oldenzaal-1 well.



7.1.3 Posidonia Shale Formation

The Posidonia Shale Formation, of Toarcian age, consists of a dark organic-rich claystone with a few carbonate beds. The formation rests conformably on the Aalburg Formation, and is covered, also conformably, by the Werkendam Formation. The formation, which is 30 to 40 m thick, only occurs in a few places within the map sheet area, namely in the Gronau Graben and the Achterhoek and in the Lower Saxony Basin in the area lying adjacent in Germany (fig. 7.2). Research on the formation in Germany (in the vicinity of Weseke, to the southeast of Winterswijk,) revealed an average 5.95% content of organic material (4.84 to 7.73%; Hoffmann, 1962)

7.1.4 Werkendam Formation

The Werkendam Formation, of Aalenian age (Herngreen & De Boer, 1974), occupies approximately the same areal extent as the Posidonia Shale Formation. The formation within the map sheet area has only

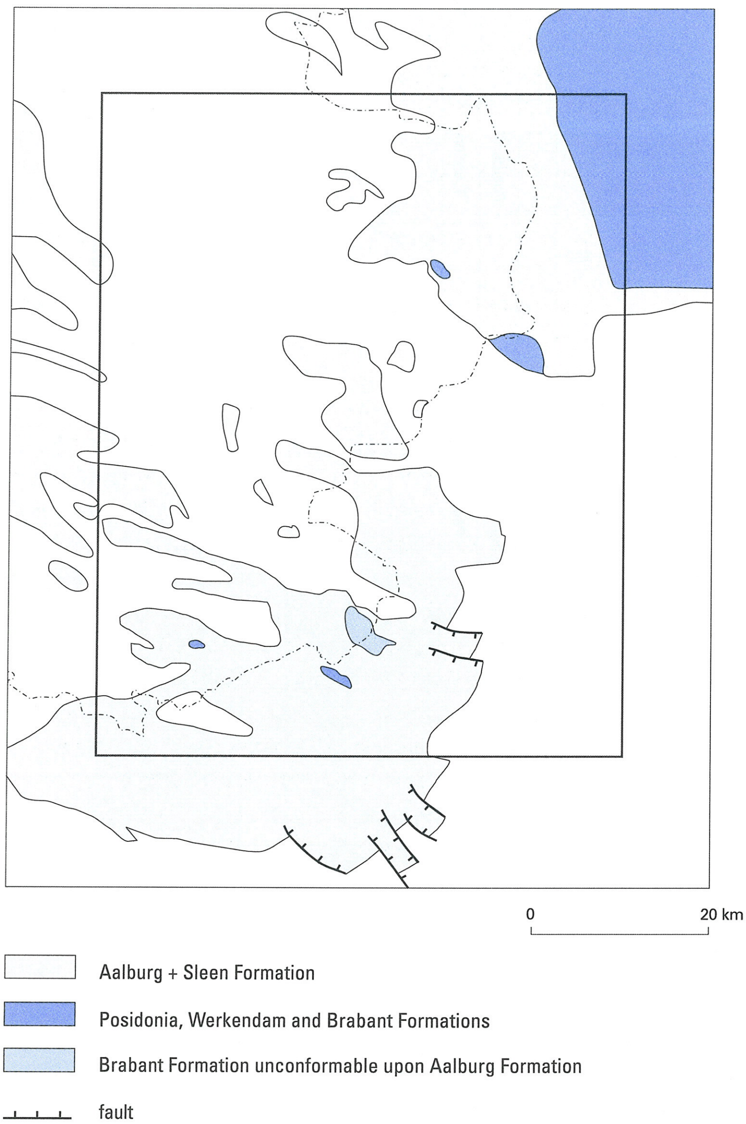


Figure 7.2 Extent of the various formations of the Altena Group. In the greater part of the Central Netherlands Basin, only the Sleen and Aalburg Formations occur; in the Lower Saxony Basin, the succession is more complete and the Posidonia Shale, Werkendam and Brabant Formations are also represented. To the east of Winterswijk, the Brabant Formation rests locally unconformably upon the Aalburg Formation. The map has been based on wells and seismics. Data for the German part have been derived from Baldschuhn et al. (1996), Binot et al. (1991) and Meyer (1969).

been encountered in the Gronau Graben, with a thickness of over 100 m (Meyer, 1969). The thickness in the Achterhoek is around 50 m. The formation is represented by the *Lower Werkendam Member*, consisting predominantly of dark coloured claystone, with alternations of light coloured marls and a few beds containing iron oolites. To the east of the map sheet area, the formation is found extensively in the Lower Saxony Basin, where it reaches a thickness of over 150 m (Meyer, 1969).

7.1.5 Brabant Formation

Deposits of the Brabant Formation, of Bajocian to Middle Callovian age, have only been documented in the eastern Achterhoek (Dirven, 1995; Herngreen et al., 1983). From this formation, the Lower Brabant Limestone Member and the informal *Klomps member* are thought to be present (Van Adrichem Boogaert & Kouwe, 1993-1997). The base of the formation has not been reached, but from the various wells, a thickness of approximately 125 m can be inferred (Dirven, 1995).

The deposits of the Brabant Formation rest on the Aalburg Formation unconformably or separated by a hiatus. The formation is composed predominantly of dark-grey to black claystone, with a fluctuating carbonate content, containing intercalations of 10 m-thick, non-fossiliferous, greyish-grey, glauconitic claystone with carbonate layers and an argillaceous, also glauconitic sandstone bed. The limestone from the *Klomps member* displays a certain affinity with the Middle Brabant Limestone Member in the West Netherlands Basin (Dirven, 1995). The formation is overlain unconformably by the Rijnland Group or the North Sea Supergroup.

7.2 Sedimentary development and palaeogeography

The end of the Triassic is characterised by a major change in the depositional environment. After a long period of continental or shallow-marine depositional conditions, a transgression during the Late Triassic (Rhaetian) favoured an open-marine depositional environment which extended over a large part of North Western Europe. With the transgressive deposits of the Sleen Formation, sedimentation in the map sheet area resumed. A brief regressive period at the end of deposition of this formation gave the top of the Sleen Formation more of a lagoonal character, superseded by a sea-level rise and deposition of the shallow-marine sediments of the Aalburg Formation. The thin organic-rich layers indicate stagnation of the circulation in the basin. The greatest subsidence was initiated in the west of the map sheet area. The influence of the Rhenish Massif, to the southeast of the map sheet area, is revealed in the formation of iron oolites, occurring in a zone around the perimeter of this high. The Early Toarcian is marked by a major period of euxinic sedimentation, presumably caused by the stratification of a warm, salt-water body from the Tethys Sea and cold Arctic sea water in present Western Europe, initiating the deposition of the bituminous Posidonia Shale Formation. Open-marine conditions were again re-established during deposition of the Werkendam Formation which, in response to tectonic movements and erosion, is found very infrequently, in the vicinity of the Gronau Fault Zone. Marine deposits of the Brabant Formation in a small area to the east of Winterswijk rest on the Aalburg Formation unconformably or separated by a hiatus.

8 Niedersachsen Group

8.1 Stratigraphy

Deposits of the Niedersachsen Group are composed of variegated fine-clastic sediments, with intercalated limestone and evaporite layers. In the map sheet area the group comprise the Weiteveen and the Coevorden Formations, respectively of Late Jurassic and earliest Cretaceous age (fig. 8.1).

The occurrence of the deposits is mainly confined to the Lower Saxony Basin, where the group achieves a thickness of 500 m (Map 10). In the Central Netherlands Basin the group is only found locally, mainly as thin deposits. In a graben to the west of Hengelo, however, the group is over 200 m thick (Maps 9 & 10). The original areal extent of the group comprised both the Lower Saxony as well as the Central Netherlands Basin, but the deposits of the latter were largely removed as a result of erosion consequent to inversion of the basin at the end of the Cretaceous.

The deposits of the Niedersachsen Group rest unconformably on the Altena and the Upper Germanic Trias Groups (Map 17) and are unconformably overlain by the Rijnland Group or the North Sea Supergroup (Maps 18 & 19).

The depth of the base of the deposits ranges from a few tens of metres below surface level in the Achterhoek to over 900 m in the extreme southeast of Twente (Map 9). The lithostratigraphic development of the group is illustrated by a section (fig. 8.2).

8.1.1 Weiteveen Formation

The Weiteveen Formation, of Late Kimmeridgian to Portlandian age, is only found in the northeastern part of the map sheet area. The formation rests unconformably on the Altena or locally on the Lower or the Upper Germanic Trias Group. The formation is covered by the Coevorden Formation, conformably or separated by a hiatus, or unconformably by the Rijnland Group or the North Sea Supergroup.

The formation comprises a succession of light-grey to red coloured fine-grained claystone, marl and fine sandstone, and intercalated anhydrite and limestone. Immediately to the east of the map sheet area, halite intercalations are also found in the formation (Bischoff & Wolburg, 1963; Meyer, 1969; Schott, 1950).

The formation occurs predominantly in the Lower Saxony Basin, where a thickness of over 300 m is reached in the Gronau Graben (fig. 8.3). Seismic data, supported by biostratigraphic research (RGD, 1995a), reveal that intensive movements took place along the southern part of the Gronau Fault Zone during deposition of the formation. In the Lower Saxony Basin, the formation is absent above the

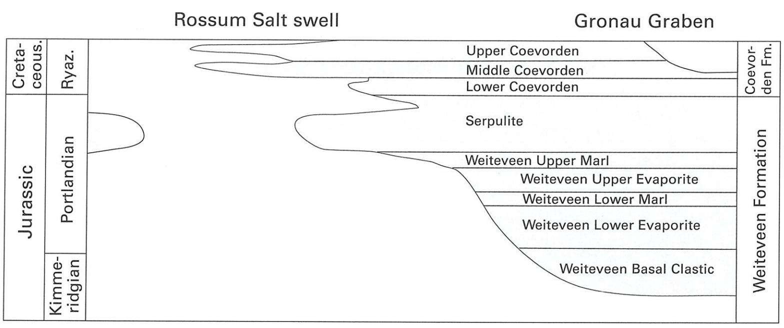


Figure 8.1 Lithostratigraphic diagram of the subdivision of the Niedersachsen Group in the map sheet area. The most complete succession is encountered in the Gronau Graben. During deposition of the group, a gradual enlargement of the sedimentation area occurred, with the result that towards the west, increasingly younger units were found at the base of the group.

Rossum salt-structure, and is thinner above other salt accumulations, caused predominantly by the absence of the bottommost members of the formation. Outside the map sheet area, the thickness of the formation further increases in an easterly direction to over 1000 m (Bischoff & Wolburg, 1963; Gramann et al. 1997; Meyer, 1969; Schott, 1950).

In the Central Netherlands Basin, the formation is found locally, at a thickness of some tens of metres. From the development of the sediments of the same age to the west of the map sheet area, it may be concluded that a connection between these two areas once existed and that the lack of deposits is a consequence of uplift and erosion during the inversion in the Late Cretaceous.

Within the Weiteveen Formation, the Weiteveen Basal Clastic, the Weiteveen Lower Evaporite, the Weiteveen Lower Marl, the Weiteveen Upper Evaporite, the Weiteveen Upper Marl and the Serpulite Members can be distinguished. The enlargement of the sedimentation region during deposition of the Weiteveen Formation is reflected by the greater areal extent of the younger units. Furthermore, it is highly likely that the Weiteveen Formation here contains various intraformational hiatuses, owing to deposition on the margin of the Niedersachsen and the Central Netherlands Basins.

The subdivision of the Weiteveen Formation into six members used in The Netherlands, is virtually analogous to the subdivision of the Malm into six zones in the adjacent part of Germany, described by Bischoff & Wolburg (1963) and Gramann et al. (1997).

The *Weiteveen Basal Clastic*, Portlandian or possibly Late Kimmeridgian in age, consists of a succession of variegated sandstone, siltstone and a few conglomerates at the base of the formation. Within the map sheet area, the unit has only been encountered in two wells (Enschede-2, Oldenzaal-2) in the Gronau Graben. The thickness is a minimum of 44 m although the complete member has not been penetrated.

The *Weiteveen Lower Evaporite*, of Portlandian age, is characterised by the occurrence of anhydrite, carbonate and dolomite beds in a predominantly grey coloured succession of marls and claystone. In the eastern part of the area, this member lies at the base of the formation (Oldenzaal-4, Rammelbeek-1 & 2, De Lutte-2 & 4 wells). This member achieves its greatest thickness, over 90 m, in the Gronau Graben. Outside this graben, the sequence is 10-30 m thick.

The *Weiteveen Lower Marl*, of Portlandian age, consists of a blue-grey marly succession between the two evaporite sequences in the Weiteveen Formation. The member, which can be clearly identified on logs by its block-like character and high gamma-ray readings, is 7 to over 40 m thick. In the Tubbergen-6 well, this unit lies at the base of the formation.

The *Weiteveen Upper Evaporite*, of Portlandian age, is a dark-grey marl interval with a relatively high dolomite and anhydrite content. Locally, shell beds occur within this sequence, as well as carbonate and dolomite concretions. Above the De Lutte salt-structure, this sequence lies at the base of the formation (De Lutte-1 well). The member varies in thickness from 12 to over 40 m in the vicinity of the Gronau Fault Zone.

The *Weiteveen Upper Marl*, of Portlandian age, consists predominantly of a dark-grey coloured marly claystone, with a few limestone and anhydrite intercalations. The thickness of the sequence ranges between 20 and 30 m; the greatest thickness, over 40 m, occurs in the vicinity of the Gronau Fault Zone.

The *Serpulite Member*, of Late Portlandian age, is composed of a blue-grey calcareous claystone to marl interval, with intercalated layers of serpulite fragments, shell beds and anhydrite. The member lies to the west of the Gronau Fault Zone at the base of the formation (e.g. the Twente-Rijn wells and Almelo-

Oost-1 well); this is also the case in a number of wells in the Lower Saxony Basin (Denekamp-1 & 2, Rossum-Weerselo-2).

8.1.2 Coevorden Formation

The Coevorden Formation, of Ryazanian to possibly earliest Valanginian age, is found mainly in the Lower Saxony Basin and, only very locally, in the Central Netherlands Basin. Unlike the Weiteveen Formation, the sediments of the Coevorden Formation in the Lower Saxony Basin differ from those

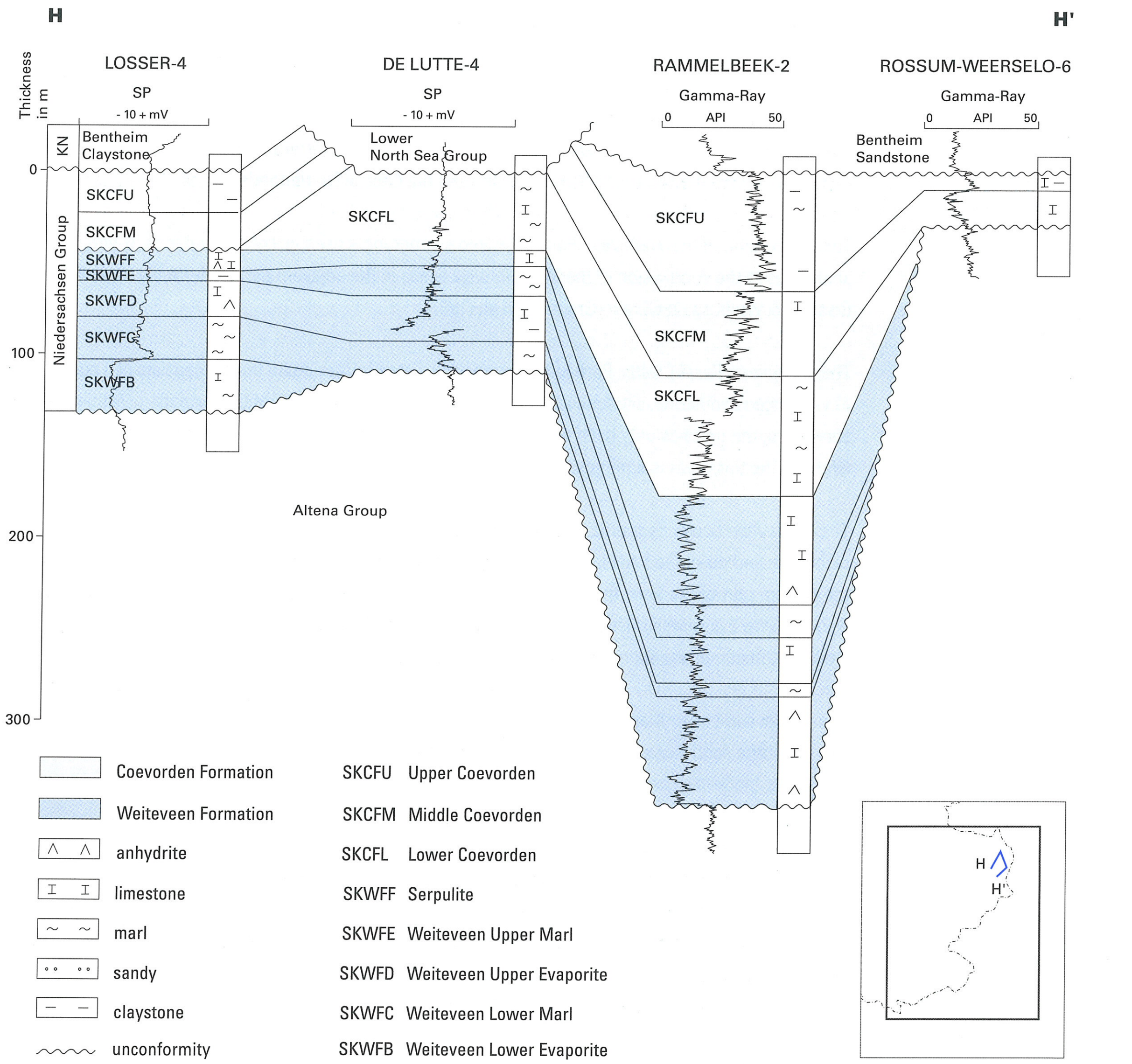


Figure 8.2 Stratigraphic section H-H' of the Niedersachsen Group in the Losser-4, De Lutte-4, Rammelbeek-2 and Rossum-Weerselo-6 wells. This section has been compiled on a basis of log correlations, and shows the onlap of the Niedersachsen Group on the De Lutte and the Rossem salt swells and the influence of the palaeo-relief on the development of the group. Unconformities are found within the group locally.

lying further to the west in the Central Netherlands Basin (Rijks Geologische Dienst, 1993b,c). The Coevorden Formation comprises a predominantly dark coloured succession of clays, alternated with carbonate beds. Towards the east, the carbonate ratio in the formation decreases and the claystones dominate (Schott, 1950). Towards the west, the sediments pass into an alternation of claystone, sandstone and coal (Rijks Geologische Dienst, 1993c).

In the greater part of the area, the Coevorden Formation overlies the Weiteveen Formation conformably or separated by a small hiatus. However, on the Rossum salt-structure, the formation rests unconformably on the Altena Group. The Coevorden Formation is subdivided into the Lower Coevorden, the Middle Coevorden and the Upper Coevorden Members. An occasional hiatus is found locally in the bottommost part of the formation, apparent from the absence of the Lower Coevorden. The greatest thickness of the formation, over 330 m, is reached along the southern part of the Gronau Fault Zone. Towards the east, the thickness further increases to nearly 500 m around Bentheim (Meyer, 1969). The subdivision of the Coevorden Formation allows good correlation with the subdivision of the German Wealden (Wolburg, 1949), based on the ostracods. The Lower Coevorden is analogous with Wealden 1, 2 and partly with 3, the Middle Coevorden with the Wealden 3 and 4 and the Upper Coevorden with the Wealden 5 and 6 (Van Adrichem Boogaert & Kouwe, 1993-1997).

The *Lower Coevorden* is a succession of grey coloured claystones. The occurrence of carbonate beds and shell horizons is confined predominantly to the basal part of the formation. The thickness of this sequence ranges from 80 to 120 m. The greatest thickness, 140 m, occurs in the Gronau Graben (Enschede-2 well). The succession is either thin (8 to 20 m) or else is absent in its entirety above the Rossum and Itterbeck-Denekamp salt-structure (Rossum-Weerselo-3 to 7; Denekamp-1 & 2 wells) and in the vicinity of Losser-4 well the Middle Coevorden rests upon the Weiteveen Formation with a hiatus (fig. 8.2).

The *Middle Coevorden* consists of grey silty to sandy claystones, which are distinguished from the underlying and overlying members by their greater carbonate content. In the adjacent area of Germany foraminifera have been encountered in this sequence, which reflect a certain marine influence (Wolburg, 1949). Above part of the Rossum salt-structure, the succession rests unconformably upon the Altena Group and above the Tubbergen-Denekamp salt-structure, upon the Weiteveen Formation. The sequence is absent above the top of the Rossum salt-structure. Here, the thickness is relatively slight (8-25 m). In the remaining part of the area, the thickness is normally around 50 m. The greatest thicknesses, 110 to 150 m, occur in the Gronau Graben.

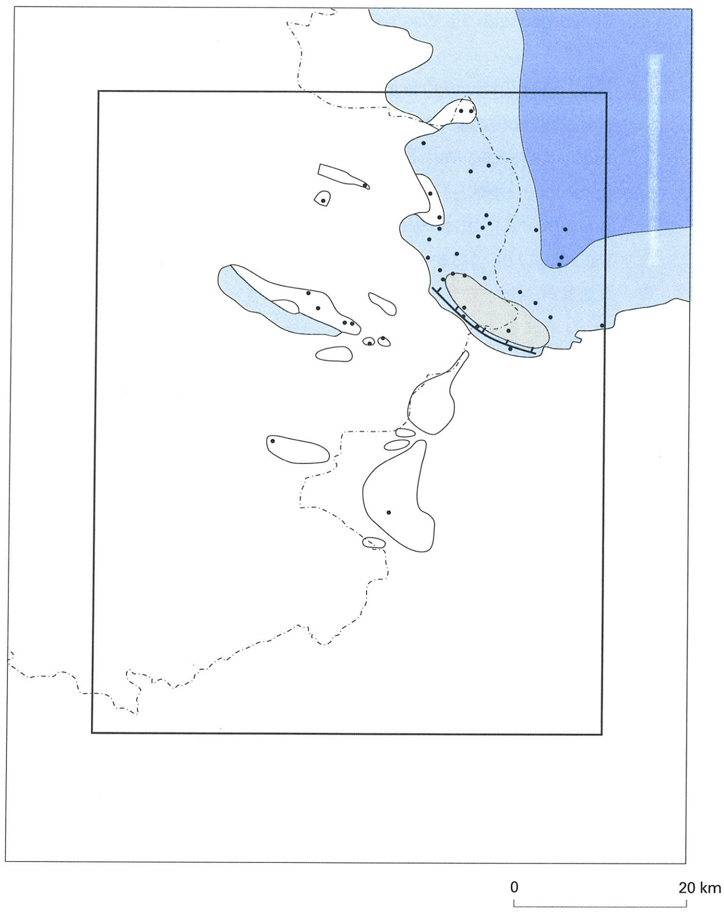
The *Upper Coevorden* comprises brownish-grey, sometimes fine-sandy deposits. The deposits have been found to contain shell horizons and iron oolite layers. Thin bituminous deposits (Paper Shale) are found in the deposits; immediately to the east of the map sheet area in Germany these have been exposed in the vicinity of Suddendorf (Kemper, 1992). Bituminous deposits appear to be less well developed within the map sheet area. The greatest thicknesses occur in the east of the area (65 m) and near the Gronau Fault Zone (100 to 160 m). In other parts, the thickness is 5 to 35 m. Above the top of the Rossum salt-structure, the member rests unconformably on the Altena Group.

8.2 Sedimentary development and palaeogeography

The deposits of the Niedersachsen Group were laid down in the Lower Saxony Basin and the Central Netherlands Basin. As these basins originally had no direct connection with the open sea, this initiated the deposition of sediments in a fresh, brackish water to hypersaline setting. During deposition of the group the Lower Saxony Basin gradually became less isolated from the open sea, which is revealed by the changeover from the evaporitic setting of the Weiteveen Formation to the lacustrine and sometimes marginally marine setting of the Coevorden Formation (Wolburg, 1949).

The deposits of the Weiteveen Formation in the map sheet area reflect the enlargement of the Lower Saxony Basin to the west. The oldest sediments, the Weiteveen Basal Clastic Member, were deposited only in a depression immediately along the southern branch of the Gronau Fault Zone and consist of fine-grained lacustrine sediments, with local intercalations of fluvial sand and gravel deposits. Subsequently, alternating hypersaline and lacustrine conditions again predominated and fine-clastic

Figure 8.3 Extent of the Niedersachsen Group. The map sheet area is situated on the western margin of the Lower Saxony Basin, where a salt basin was located. The contour of the area of subsidence in the Gronau Graben has been indicated. The present extent of the Niedersachsen Group is related to a number of smaller occurrences with relatively young deposits at the base; the other occurrences have been removed by erosion. Data for the German section have been derived from Baldschuhn et al. (1991) and Schott (1950).



outline Upper Jurassic salt basin

area of subsidence related to Southern Gronau Fault

Serpulite or Coevorden Fm. at the base of the Niedersachsen Group

• well

sediments and evaporites were deposited. During this deposition the sedimentation area spread from the previously mentioned depression over the majority of the area to the east of the Gronau Fault Zone. It was not until the deposition of the youngest unit of the Weiteveen Formation, the Serpulite, that the sedimentation area began to extend over the area to the west of the Gronau Fault Zone. However, from the fine-grained and evaporitic character of the sediments, one may deduce that this area supplied virtually no sediments and was located at around water level in the Lower Saxony Basin.

Deposition of the Coevorden Formation occurred on the west margin of a fresh to brackish water basin. During the Middle and Upper Coevorden in particular, a few marine incursions occurred from a northerly direction (Central North Sea Graben, Vlieland Basin). The sediments consist mainly of fine-clastic deposits, laid down from suspension, while the carbonates are considered to have been storm deposits or hard grounds (Van Adrichem Boogaert & Kouwe, 1993-1997). During deposition of the Coevorden, the sedimentation area gradually extended over all the salt doming-induced highs in the area.

9 Rijnland Group

9.1 Stratigraphy

The Rijnland Group, of Valanginian to Albian age, comprises (glauconite-bearing) sandstones, siltstones, claystones and marls, deposited in a marine setting. The sediments of the Rijnland Group were accumulated in a gradually deepening open-marine setting. The group is subdivided into the Vlieland Sandstone Formation, the Vlieland Claystone Formation and the Holland Formation (fig. 9.1). The two first-mentioned formations together form the Vlieland subgroup. The group exhibits a number of hiatuses, which are found at the base of the various sandstones as well as in the claystones and marls. Seismically, these hiatuses are normally not detectable.

The Rijnland Group is present in the northern and northeastern part of the map sheet area, with a few minor occurrences in the southeastern part (Maps 11 & 12). In the remaining part of the map sheet area the group was subsequently eroded. The base of the group is 100 to 400 m deep in the Lower Saxony Basin and deepens in a northeasterly direction to over 1800 m (Map 11). The group is around 100 m thick (Map 12) on the Friesland Platform. In the Central Netherlands Basin, occurrences of the formation are largely restricted to a few local erosional remnants; in the Lower Saxony Basin, the thickness displays a highly varying pattern, mainly due to erosion.

The base of the group is diachronous and varies in age from Valanginian in the Lower Saxony Basin to Late Albian on the Tubbergen and Dalfsen High. The group rests unconformably on deposits of the Limburg, the Upper Rotliegend, the Zechstein, the Lower Germanic Trias, the Upper Germanic Trias, the Altena or the Niedersachsen Group (Map 18). The Rijnland Group in the north and in one area in the southeast of the map sheet area is conformably overlain by the Chalk Group (Map 13); in the east, the group is unconformably overlain by the North Sea Supergroup (Map 19). The differences in thicknesses therefore only partially reflect depositional variations.

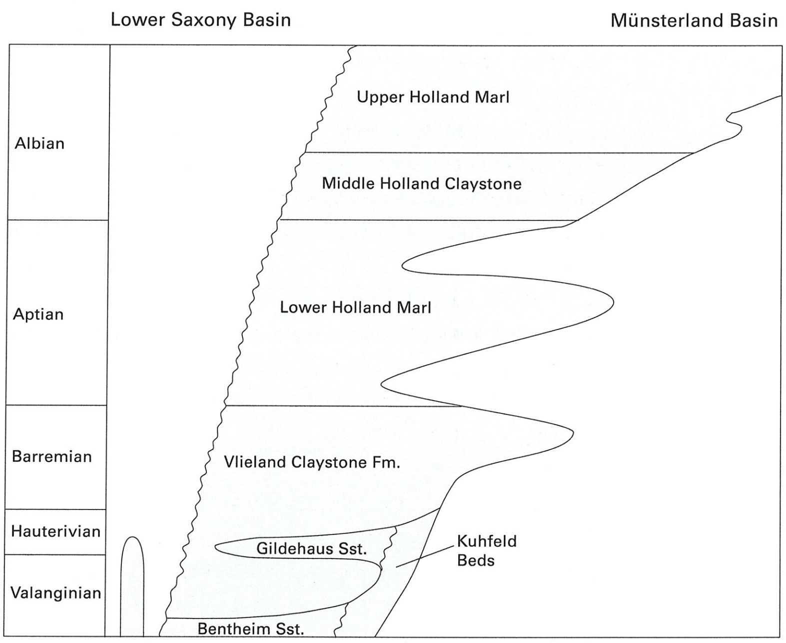


Figure 9.1 Lithostratigraphic diagram of the subdivision of the Rijnland Group based on a correlation between the Lower Saxony Basin and the Münsterland Basin. The group is absent in the Lower Saxony Basin, largely as a result of later tectonic movements. In the Münsterland Basin, incipient sedimentation is reflected by the Upper Holland Marl.

9.1.1 Vlieland subgroup

The Vlieland subgroup, Valanginian to Barremian in age, is present in the northeastern part of the map sheet area and in a few places in the south. The succession is completely absent in the northwest of the map sheet area owing to non-deposition and elsewhere is absent as a result of erosion during the Late Cretaceous or Tertiary.

The deposits of the Vlieland subgroup in the basins rest conformably or separated by a hiatus on deposits of the Niedersachsen Group. Around the highs, the deposits rest conformably on the Altena, the Lower Germanic Trias and the Upper Germanic Trias Groups or locally on the Zechstein Group.

Within the subgroup, the Vlieland Sandstone Formation and the Vlieland Claystone Formation can be identified. Near the palaeo highs, the group is largely composed of sandstones, while in the former basins the claystones of the Vlieland Claystone Formation are the most prominently present. The development of the subgroup in Twente has been delineated by Römer (1970, 1977a, 1977b).

9.1.1a Vlieland Sandstone Formation

The Vlieland Sandstone Formation in the east of the area comprises two sandstone sequences, the Bentheim Sandstone and the Gildehaus Sandstone Member, separated from each other by the claystones of the Vlieland Claystone Formation. In the Almelo Graben and to the south of the Gronau Fault Zone, this formation also contains massive sandstone intervals (fig. 9.2 & 9.3); the first-mentioned represent a distinctive development of the Gildehaus Sandstone. The sandstones to the south of the Gronau Fault Zone are informally known as the *Kuhfeld Beds*. These sequences are Valanginian to Barremian in age. In Twente and the Achterhoek these sands are important reservoir sources for the supply of drinking water.

The *Bentheim Sandstone* consists of a complex of sandstone layers separated by thin claystone beds. This member rests conformably or unconformably on the Bentheim Claystone, but occasionally directly on the Coevorden Formation or older deposits. The irregular thickness pattern of the underlying unit is presumed to be related to channels cutting into the base of the Bentheim Sandstone. The member is conformably overlain by the Ruinen Member.

The Bentheim Sandstone is composed of extremely well sorted quartz sands containing negligible amounts of clay and carbonate cement. The member is characterised by a blocked pattern on the gamma-ray logs. The cement present is kaolinite, siderite and carbonate (Kemper, 1976), with some occurrences of glauconite. The sandstone also contains driftwood and clay clasts, while fossils are virtually absent. The sandstone occurs broadly speaking in the area to the south of the Tubbergen High (RGD, 1995b) and to the east of the Gronau Fault Zone. The thickness of this sandstone ranges from 15 to almost 70 m, with the greatest thicknesses occurring around the Bentheim Anticline (Rammelbeek-1 & 2 and Oldenzaal-5 wells) and immediately to the east of the Gronau Fault Zone. To the east of the map sheet area, the sandstone exhibits outcrops at several places including Bad Bentheim and Gildehaus (Kemper, 1976; Hinze, 1988).

The *Gildehaus Sandstone* in the basins rests conformably or, via a hiatus, upon the Westerbork Member. At the margins of the Tubbergen High, locally the unit rests unconformably on the Lower Germanic Trias or the Upper Germanic Trias Group (Tubbergen-2 well). The sandstone is overlain generally conformably or, via a hiatus, by the Vlieland Claystone Formation but locally may also be overlain unconformably by the Holland Formation (Almelo-2 well; RGD, 1994c) or the North Sea Supergroup.

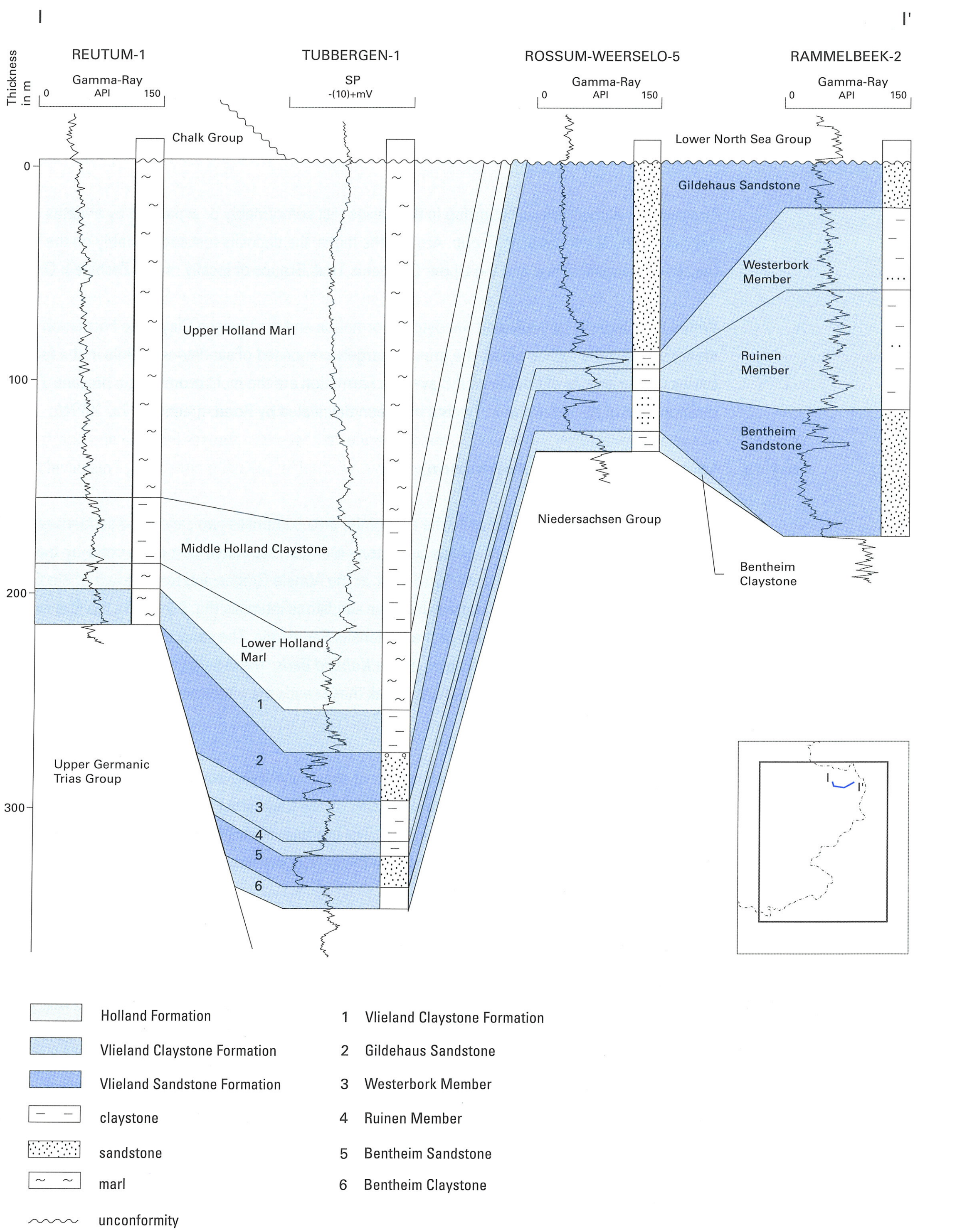


Figure 9.2 Stratigraphic section I-I' of the Rijnland Group based on log correlation and biostratigraphic research. This section clearly shows the difference between the complete succession as found in the Lower Saxony Basin (Rammelbeek-2 well) and the thinner succession on the Tubbergen High as a result of onlap (Reutum-1 well).

The Gildehaus Sandstone consists of a poorly sorted, yellow to mottled grey spiculitic, calcareous, argillaceous fine sandstone to fine marlstone. The sandstone contains a large number of macrofossils (bivalves, molluscs) and driftwood is present locally. The quartz, carbonate and clay content exhibits pronounced lateral variations. The bottommost part of the sandstone has a 40% carbonate content in places. The clay content tends to increase rapidly in an easterly direction. Eastwards, the sequence grades considerably more rapidly into claystone than the Bentheim Sandstone. The sands are cemented with dolomite, siderite and ankerite. There are considerable variations in the thickness of the sandstone, from 5 m on the Tubbergen High to over 210 m in the Almelo Graben. Around the Bentheim Anticline great thicknesses are attained locally, from 100 to nearly 200 m. In this area, the sandstone lies immediately below Tertiary or Quaternary deposits, and is a reservoir source for the supply of drinking water. The uppermost part of the Gildehaus Sandstone crops out at Losser, which accounts for the informal name *Losser sandstone.*

In the western part of the Almelo Graben (Almelo-2, 3 & 4 wells), the Gildehaus Sandstone, Hauterivian to Barremian in age (RGD, 1994a, c), is represented by a poorly sorted, greenish-grey, conglomeratic sandstone and a dark clay mass. The conglomerate constituent comprises limonite and quartz pebbles. Several claystone intercalations occur within this succession, several metres thick. This development has been previously described by 't Hart (1969).

The name *Kuhfeld Beds* is used in the map sheet area and the adjacent area of Germany to denote proximal, massive sandstone Ryazanian-Valanginian to Hauterivian in age (Herngreen, 1973; Herngreen et al., 1994). Occurrences of this sandstone are restricted to the area to the south of the Gronau Fault Zone (fig. 9.1 & 9.3). The deposits are composed of white sandy clay and argillaceous fine sand. Pyrite and coal or wood fragments are generally found. Immediately across the German border, to the east of Winterswijk, layers of quartz pebbles also occur (Herngreen et al., 1994). This sequence may reach thicknesses of over 200 m to the southeast of Winterswijk and in Germany.

In the transitional zone between the *Kuhfeld Beds* and the argillaceous basin deposits, three additional sandstones can be distinguished in Twente and adjacent parts of Germany, the *Dichotomite Sandstone, Grenzsandstein and Noricum Sandstone.* These sandstones occur in the Ruinen and Westerbork Members of the Vlieland Claystone Formation respectively. However, they have not been incorporated in the official lithostratigraphic nomenclature. The sandstones have been encountered in several shallow wells in and around Enschede (Harsveldt, 1977) and the adjacent part of Germany (Kemper, 1976, 1992). The thickness of the individual sandstones is 15 to 20 m.

9.1.1b Vlieland Claystone Formation

Within the area where the Vlieland Claystone Formation and the Vlieland Sandstone Formation interfinger, from old to young the Bentheim Claystone, the Ruinen and the Westerbork Members are distinguished. Where the Vlieland subgroup is devoid of sandstones, the Vlieland Claystone Formation is not subdivided into members.

The Vlieland Claystone Formation, of Valanginian to Barremian age, consists of a dark grey to dark brown coloured claystone, with a varying silt/sandstone content. The formation often contains fine pyrite and siderite. The small carbonate content is characteristic. The formation has a maximum thickness of approximately 300 m around the Bentheim Anticline; the thickness increases even further towards the east, probably to over 700 m. In the actual depocentres of the basin, the formation is absent owing to inversion movements and erosion.

The *Bentheim Claystone*, of Early Valanginian age, is encountered in the basins within the map sheet area. The member is composed of a silty, fossil-rich claystone. Brackish water fossils are found in the basal part, and almost exclusively marine fossils above (Kemper, 1976). The thickness of this succession ranges from a few metres to over 50 m (Rammelbeek-2 well); the thickness pattern is thought to be related to the pre-depositional erosion of the Bentheim Sandstone.

The *Ruinen Member*, of Late Valanginian age, consists of a dark grey, fossiliferous, silty, calcareous claystone. The member also contains siderite. The thickness ranges from 10 to 50 m, with the greatest thickness around the Bentheim Anticline. A thin sandstone bed separates the Ruinen Member from the overlying Westerbork Member. The contact with the Westerbork Member is slightly unconformable.

The *Westerbork Member*, of Early Hauterivian age, comprises dark grey to black marl and clay. At the base of the succession there is a thin, glauconitic marker sandstone bed, the *Grenzsandstein*. The

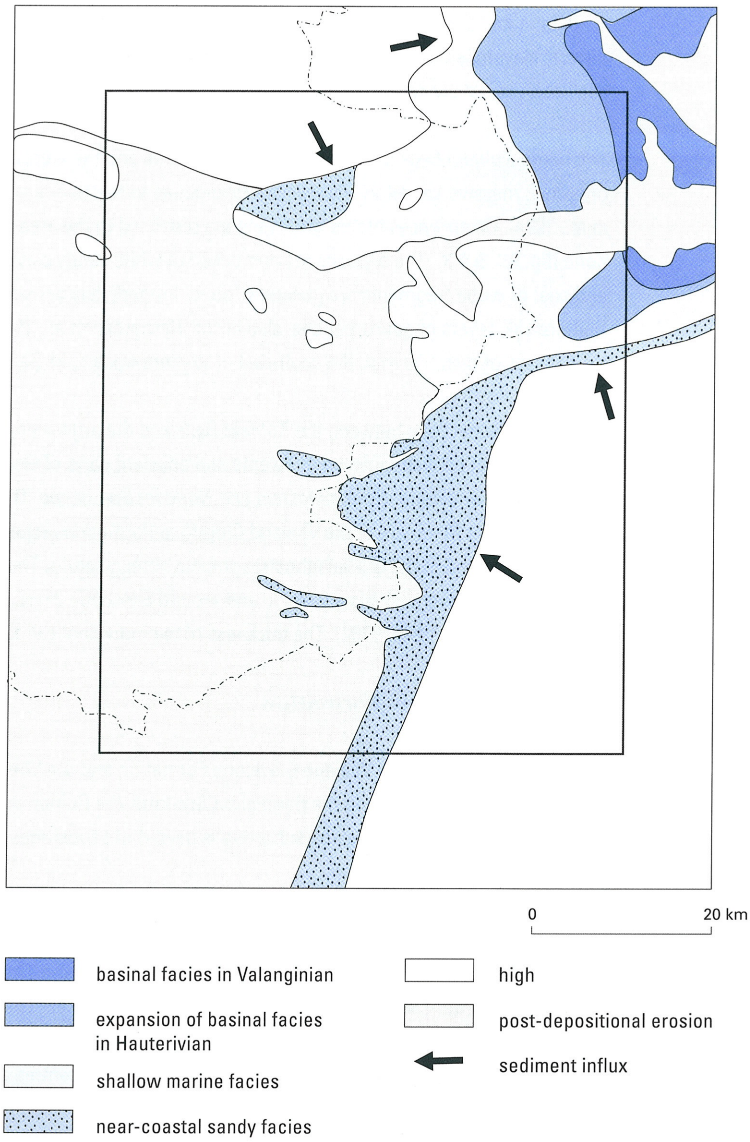


Figure 9.3 Extent and facies distribution of the Rijnland Group in the map sheet area. In the western part of the map sheet area, the group is absent owing to erosion during the Late Cretaceous. This map has been based on wells and seismics. Data for the German part have been derived from Baldschuhn et al. (1996) and Kemper (1976, 1992).

sequence is 30 to 40 m thick in the north of the map sheet area and over 100 m thick in the vicinity of the Gronau Fault Zone.

9.1.2 Holland Formation

The occurrence of the Holland Formation is restricted to the margins of the Central Netherlands Basin and the highs in the north of the map sheet area. The formation is also found extensively along the margin of the Lower Saxony Basin and in the Münsterland Basin (fig. 9.4). Within the formation, the Lower Holland Marl, the Middle Holland Claystone, the Upper Holland Marl and the Holland Greensand Members can be distinguished. The formation reaches its greatest thickness, over 300 m, in the northern part of the Central Netherlands Basin. In the Lower Saxony Basin in Germany, the formation attains a thickness of over 500 m to the north of Bentheim (Kemper, 1976). It should be observed that the formation in the actual depocentres of these basins was removed by erosion subsequent to the inversion movements.

The formation in the Central Netherlands Basin and the Lower Saxony Basin rests conformably or separated by a slight hiatus on the Vlieland Claystone Formation and in the vicinity of the Reutum-1 well, very locally, unconformably on the Altena and the Upper Germanic Trias Group (RGD, 1996). On

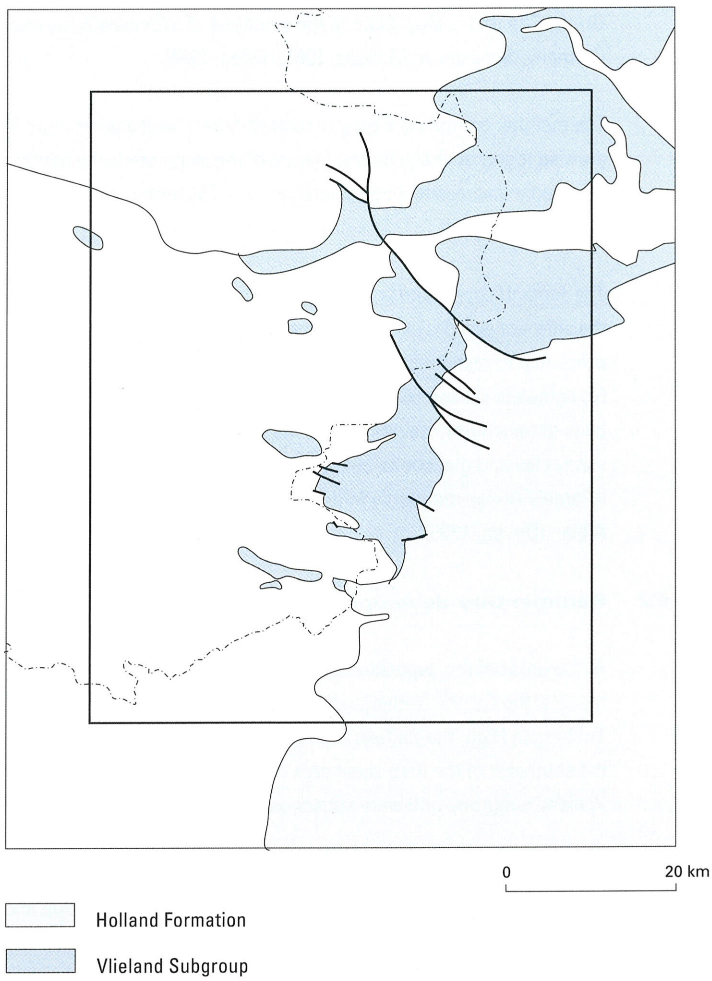


Figure 9.4 Geological map of the top of the Rijnland Group, showing the extent of the Vlieland subgroup and the Holland Formation. This map has been based on wells and seismics. Data for the German part have been derived from Baldschuhn et al. (1996).

the Tubbergen High (RGD, 1994b), Dalfsen High, Friesland Platform and in the Münsterland Basin the uppermost part of the formation rests unconformably on the Limburg, the Upper Rotliegend, the Zechstein, the Lower Germanic Trias or the Upper Germanic Trias Group. The formation is overlain conformably or separated by a slight hiatus by the Chalk Group or unconformably by the North Sea Supergroup.

The *Lower Holland Marl* is found only along the flanks of the Tubbergen High and Dalfsen High and also locally in the vicinity of the Gronau Fault Zone. To the east of the map sheet area the unit is found in a number of places. The Lower Holland Marl is composed of a grey, sometimes reddish-brown argillaceous marl. In the Almelo Graben, conglomerates, of Aptian age, occur locally ('t Hart, 1969; RGD, 1994a). The thickness increases to 30 m towards the basins.

The *Middle Holland Claystone*, of Early Albian age, is found at more places on the Tubbergen High than the Lower Holland Marl and consists of a grey, marly clay. The clay content is higher than that of the underlying and overlying successions, which is reflected by a higher natural radioactivity. The current maximum thickness in the basins is over 75 m.

The *Upper Holland Marl,* Middle Albian to presumably earliest Cenomanian in age, covers the Friesland Platform, Dalfsen High and Tubbergen High. Here, the unit rests unconformably on deposits of the Limburg Group, Upper Rotliegend Group, Zechstein Group or the Lower or Upper Germanic Trias Group. The unit is also found to the southeast of Winterswijk, as well as in the Münsterland Basin in Germany (Schuster & Wolburg, 1963; Hilden, 1995).

The member comprises a grey to reddish-brown argillaceous marl. In the uppermost part lighter colours are also found. A characteristic feature of the sequence is the upwardly decreasing clay content, reflected in decreasing natural radioactivity. The member reaches a thickness of 180 m on the Tubbergen High.

The *Holland Greensand* is encountered in various shallow wells to the southeast of Winterswijk and in the adjacent part of Germany (*Rothenberg-Sandstein*; Kemper, 1976). There, the Holland Greensand is presumed to rest directly upon the *Kuhfeld Beds.* The sequence is overlain by the Upper Holland Marl. No complete section of the *Kuhfeld Beds* has been recovered from a single well; the information has been obtained from several wells. The Holland Greensand is composed of an alternation of dark, silty, sandy clay and glauconite-bearing sands (greensands), and calcareous sands. The age of the sequence is largely Aptian and partly Middle Albian. The sequence contains a hiatus that spans a part of the Lower Albian (Dirven, 1995).

9.2 Sedimentary development and palaeogeography

At the onset of the deposition of the Rijnland Group, the development was controlled by two subsidence regions, the Central Netherlands Basin and the Lower Saxony Basin. These basins were bounded by the Tubbergen High, the Dalfsen High and the Friesland Platform in the north and the Münsterland Basin in the southeast of the map sheet area (fig. 9.3). The highs supplied sediment during the deposition of the Vlieland subgroup and were subsequently flooded during the deposition of the Holland Formation.

The initiation of deposition of the Vlieland subgroup is marked by an important transgression, which terminated the lacustrine conditions of the Coevorden Formation and preluded a long period of marine sedimentation.

Along the flanks of the highs, deposition of the Vlieland subgroup was predominantly characterised by the accumulation of sands (*Kuhfeld Beds*), while towards the basin centres these sands rapidly became thinner and the clay and silt deposits became thicker. Along the margins of these basins, deposition of sand or clay was determined by the relative sea-level: highstands gave rise to clay or silt deposition (Bentheim Claystone, Ruinen and Westerbork Members), and at relatively low stands sands were accumulated (Bentheim Sandstone and Gildehaus Sandstone Members), distinguishable by great differences in sedimentary settings.

The Bentheim Sandstone was deposited as a coastal barrier complex, which was subjected to strong longitudinal and tidal currents along the margins of the Lower Saxony Basin and in the Central Netherlands Basin (Kemper, 1976, 1992). In response to these strong currents, clay settling was prohibited and deposition of well-sorted sandstone occurred.

After deposition of the Bentheim Sandstone, a sea-level rise favoured a decrease in sediment influx and an enlargement of the basin facies, initiating deposition of the Ruinen and Westerbork Members.

The Gildehaus Sandstone was deposited in a period during which the current was considerably weaker. Kemper (1992) suggests that a more humid climatic environment led to an increased influx of erosional products from the highs into the basins. Owing to the weaker current, the Gildehaus Sandstone contains more clay than the Bentheim Sandstone.

Subsequent to the deposition of the Gildehaus Sandstone, a sea-level rise again induced deposition of predominantly fine-grained material; only in the immediate proximity of the highs did sand deposition persist. This period was marked by negligible expansion of the area of sedimentation over the highs, or by the subsequent erosion of any pre-existing sediments.

During deposition of the Holland Formation, argillaceous marls and clays were deposited in the basins (Lower Holland Marl and Middle Holland Claystone), while in the southeast, glauconitic sands were deposited in shallow-marine conditions (Holland Greensand). This was superseded by a prominent sea-level rise, the Albian transgression, identified throughout Western Europe (Crittenden, 1987). During this transgression all the highs in and around the map sheet area were flooded, thus terminating the influx of clastic material, reflected by the increase in carbonate content of the Upper Holland Marl.

10 Chalk Group

10.1 Stratigraphy

The Chalk Group, Cenomanian up to and including Campanian in age within the map sheet area, is composed of a succession of well cemented, light coloured, fine-grained pelagic chalk and marly limestones. A characteristic feature of these sediments is that the main constituents are calcareous skeletons of planktic and benthic organisms with very little influx of terrigenous material (Van Adrichem Boogaert & Kouwe, 1993-1997). The thickness of the group within the map sheet area is over 1000 m in the north and to the southeast of the area over 1500 m (Map 14, fig. 10.1).

The Chalk Group is not found in the majority of the area, in response to the inversion and erosion of the Central Netherlands and Lower Saxony Basins. Within the map sheet area the deposits are present in the northwest and in a small area in the extreme southeast. A major occurrence is situated to the southeast of the area in the Münsterland Basin. In the northwestern part, the depth of the base of the group increases in a northerly direction from 200 to over 1700 m. In the extreme southeast, on the other hand, the base of the formation lies at a depth of Mean Sea Level (NAP) (Map 13). To the southeast of Winterswijk the formation is found in a few outcrops in the vicinity of Kotten.

The Chalk Group in the map sheet area is subdivided into the Texel and the Ommelanden Formation. The Houthem Formation, while not present in the map sheet area, is however encountered in the area to the southwest in Germany, where the formation rests unconformably on the Altena Group (Emmerich-1 well; Elberskirch & Wolburg, 1962).

The group rests conformably or separated by a hiatus on the Holland Formation. The Chalk Group is unconformably overlain by the clastic sediments of the North Sea Supergroup. The succession of the group is illustrated in the Tubbergen-Mander-1 well (fig. 10.2).

10.1.1 Texel Formation

The Texel Formation, Cenomanian to possibly earliest Turonian in age, is found in the north and southeast of the map sheet area and to the east of the area in the Münsterland Basin. The Texel Marlstone and the Plenus Marl Members are distinguished in the formation. The thickness of the formation is 60 to 80 m on the Tubbergen High and increases in the direction of the Central Netherlands Basin to over 110 m. In the Münsterland Basin the formation is similar in thickness.

The *Texel Marlstone*, of Cenomanian age, consists of alternating white marls and limestone beds in the bottommost 10-20 m, with limestone beds above.

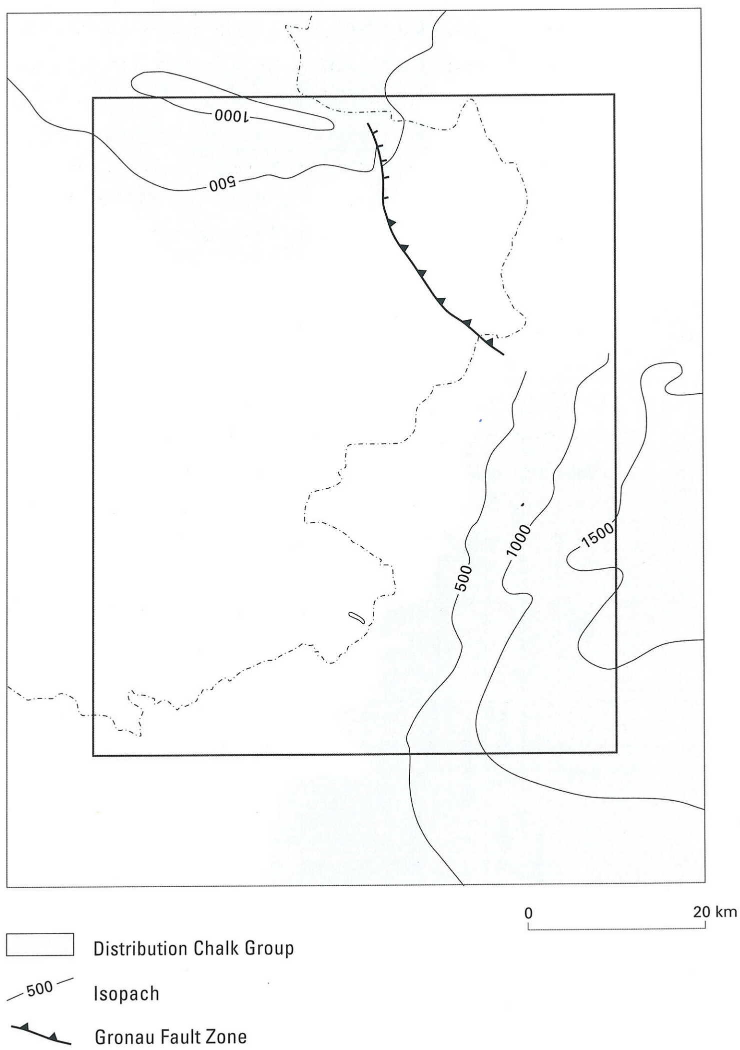
The *Plenus Marl*, latest Cenomanian to possibly earliest Turonian in age, consists of a calcareous, dark-coloured laminated claystone, with a highly characteristic well-log reading. The sequence is generally 1 to 2 m thick.

10.1.2 Ommelanden Formation

The Ommelanden Formation is found in the north and to the east of the map sheet area (fig. 10.2). The formation is not subdivided into members. However, log correlation supported by biostratigraphic datings facilitates identification of the different Cretaceous stages, based on the classification in northwest Germany established by Baldschuhn & Jaritz (1977).

The formation consists, at the base, of massive limestone of Turonian age, succeeded by more marly sequences of Santonian and Coniacian age. These are overlain by a more calcareous succession of the Campanian which, in the lower part, consists of consolidated calcareous sand, upwardly grading into massive chalks. These chalks contain abundant chert nodules. Great thicknesses may be attained, in excess of 1000 m, particularly in the deposits of the Santonian to Campanian. Seismics reveal unconformities on the Tubbergen and the Dalfsen Highs in the vicinity of the Central Netherlands Basin within the Ommelanden Formation, which are demonstrated by well calibration as being located in the Santonian to Early Campanian succession.

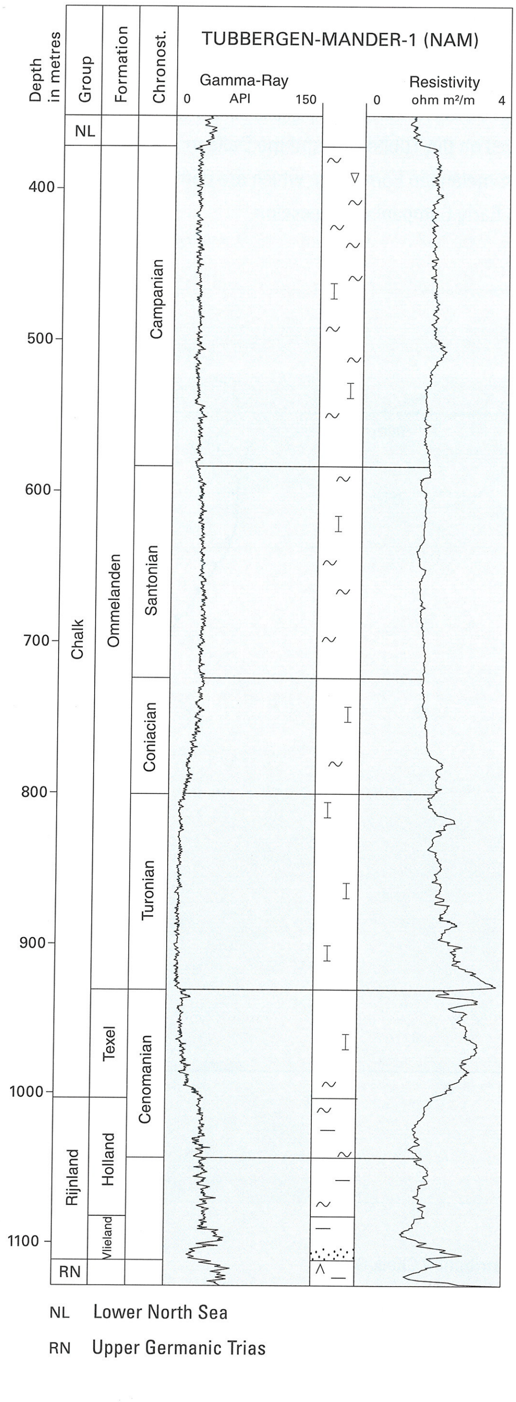
Figure 10.1 Thickness and extent of the Chalk Group. The present occurrence of this group is restricted to the Friesland Platform in the northwest and the Münsterland Basin in the southeast. In the other areas, the group is absent owing to erosion. The map has been based on wells and seismics. Data for the German part have been derived from Hilden (1995).



10.2 Sedimentary development and palaeogeography

The eustatic sea-level rise which had already commenced during deposition of the Rijnland Group developed into a global transgression during the deposition of the Chalk Group. The coastline migrated to the south of The Netherlands, receding from the map sheet area. This resulted in an increase in the carbonate content in the Texel Formation. The Plenus Marl, at the top of this formation, reflects a period

Figure 10.2 Stratigraphic division and log pattern of the Chalk Group in the Tubbergen-Mander-1 well. The age of the succession has also been indicated, as determined by log correlation with wells published by Baldschuhn & Jaritz (1977).



NL Lower North Sea

RN Upper Germanic Trias

during which anoxic conditions in the basins prevailed worldwide. The broad extent of this sequence indicates a maximum highstand.

The Ommelanden Formation was deposited under low energetic conditions on a shallow carbonate platform. Sea-level fluctuations resulted in variations in the ratio of marl and clay. Tectonic movements during the Sub-Hercynian phase are mainly responsible for the current areal extent and initiated pronounced subsidence of the former highs of the Lower Cretaceous. During the Late Campanian to Danian, the sea gradually invaded the inverted basins, where the originally accumulated basinal sediments were subsequently eroded preceding deposition of the North Sea Supergroup.

11 North Sea Supergroup

11.1 Stratigraphy

The North Sea Supergroup, of Tertiary and Quaternary age, is predominantly composed of clays and sands. The supergroup is subdivided by intraformational hiatuses into the Lower North Sea, Middle North Sea and Upper North Sea Groups. The supergroup rests unconformably on the Lower Germanic Trias, the Upper Germanic Trias, the Altena, the Niedersachsen, the Rijnland and the Chalk Groups (Map 19). Different groups may be encountered at the base owing to unconformities within the supergroup. Within the map sheet area, the sediments of the North Sea Supergroup were mainly deposited in a shallow-marine environment; the youngest deposits are of terrestrial origin.

The North Sea Supergroup is found virtually throughout the map sheet area. To the east of Twente and the Achterhoek and in adjacent parts of Germany, the Tertiary deposits are not present and the group consists exclusively of Quaternary deposits. The position of the supergroup on the eastern margin of the North Sea Basin is reflected in the increasing depth of the base of the supergroup in a northwesterly direction, ranging from a few metres to over 700 m (Map 15). The composition of the supergroup is illustrated by a west-east trending section (fig. 11.1). During deposition of the group, a number of faults were active in Twente and the Achterhoek (Maps 15 & 16).

The description of the deposits of the North Sea Supergroup is based mainly on reports by the Rijks Geologische Dienst (1984a; 1984b), the map sheet 28O/29 (Rijks Geologische Dienst, 1993a) and the top Tertiary map (Rijks Geologische Dienst, 1996). The Tertiary deposits are discussed extensively in the *Toelichting bij de Geologische Kaart van Nederland 1:50.000* and in Zagwijn (1989).

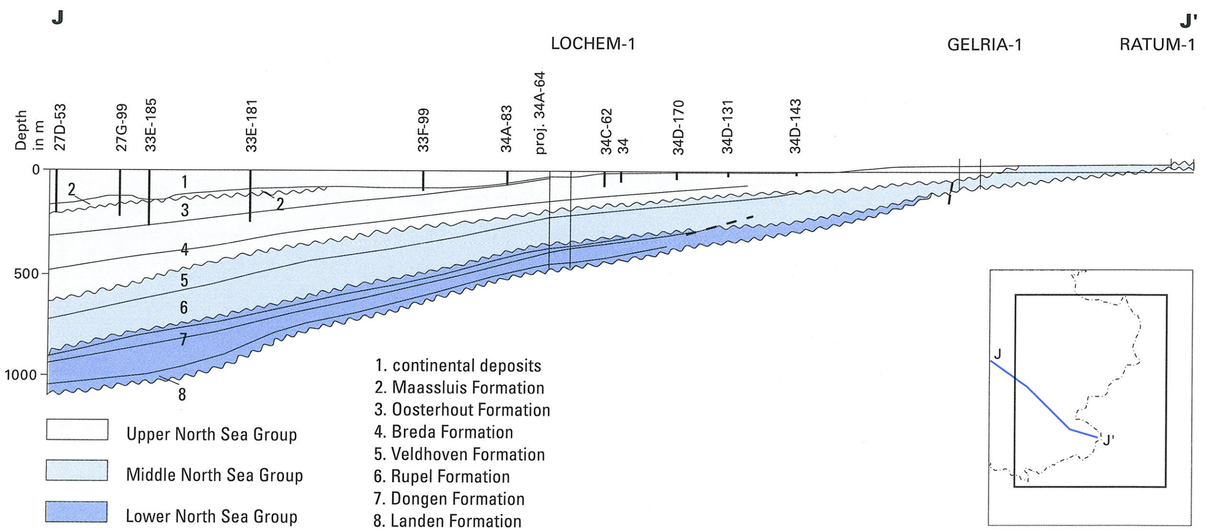


Figure 11.1 Structural section J-J' of the North Sea Supergroup, based on wells and seismics. This section clearly shows the onlap of the supergroup in an easterly direction, with the result that increasingly young units of the group are found at the base. The erosion likewise becomes greater in this direction, resulting in increasingly older units outcropping (after Rijks Geologische Dienst, 1984a).

11.1.1 Lower North Sea Group

The Lower North Sea Group comprises the Landen and Dongen Formations. The group is found throughout the map sheet area, with the exception of the east of Twente and the Achterhoek.

The *Landen Formation*, of Late Paleocene age (RGD, 1983), has a limited areal extent and is restricted to the Reutum Graben and the southwest of the map sheet area. The formation consists of moderately to substantially sandy clays, with scattered occurrences of quartz pebbles. The deposits are glauconite-bearing, with a few cemented horizons. The thickness reaches a maximum of 45 m in the Reutum Graben and almost 40 m in the west of the map sheet area.

The *Dongen Formation*, of Eocene age, forms the bottommost part of the Tertiary in the majority of the area (fig. 11.2). The formation is widespread, with the exception of parts of the Twente and Achterhoek regions and adjacent parts of Germany. The formation is subdivided into five members: the Basal Dongen Sand, the Basal Dongen Tuffite, the Ieper, the Brussels Sand and the Asse Members. The most complete succession is found in the northwest; elsewhere in the map sheet area, only the bottommost members were not affected by erosion. The formation lies in a widespread area at the base of the Lower North Sea Group.

The *Basal Dongen Sand* comprises a basal sequence of greenish-grey, mud-bearing sand and brownish-grey sandy clay, with sporadic occurrences of glauconite. This sequence, underlying the Basal Dongen Tuffite, is found locally and reaches a thickness of a few metres.

The *Basal Dongen Tuffite* is composed of an alternation of brown clay with small tephra layers. The sequence is clearly identifiable on well logs by its low natural radioactivity and a high acoustic velocity. The sequence is found in the western part of the map sheet area with a fairly constant thickness of around 15 m.

The *Ieper Member* is composed of glauconite-bearing, greyish-green, sandy clays and argillaceous sands. The deposits increase in thickness in a northwesterly direction to over 180 m. In the east of the area, this member lies at the base of the North Sea Supergroup.

The *Brussels Sand* consists of grey to greyish-green, fine to moderately coarse sands. The unit contains a large proportion of glauconite and fragments of shells and echinoderms. The thickness of the sand increases in a westerly direction from 30 to 90 m.

The *Asse Member* comprises greenish-grey clay, with a fluctuating sand content. The member is only a few metres thick.

11.1.2 Middle North Sea Group

The deposits of the Middle North Sea Group, of Oligocene age, are found in a large part of the map sheet area. In the southeast and in Germany, this group lies at the base of the North Sea Supergroup (fig. 11.2). The Rupel Formation and the Veldhoven Formation can be differentiated within the group.

The *Rupel Formation*, of Early Oligocene age, occurs virtually throughout the map sheet area, with the exception of the east of Twente and the Achterhoek and adjacent parts of Germany. The formation is subdivided into the Vessem and the Rupel Clay Members. A more detailed subdivision is applied in the east of The Netherlands, where the formation occurs in the shallow subsurface and is well documented from many shallow wells (Van den Bosch et al., 1975, Van den Bosch, 1984; Van Adrichem Boogaert & Kouwe, 1993-1997). The thickness of the formation increases in a westerly direction to over 100 m in the northwest of the map sheet area. The formation is unconformably overlain by the Veldhoven Formation or by deposits of the Upper North Sea Group.

The *Vessem Member* (formerly the Berg Sand Member) occurs at the base of the formation within its entire distribution area. At the base, the succession consists of the greyish-green, glauconite-bearing, non-calcareous, poorly sorted sand (known locally as the Ootmarsum Sand), succeeded by argillaceous, fine sands. Around Winterswijk, the coarse-grained deposits are not present. The average thickness range is 10 to 25 m.

The *Rupel Clay* (formerly the Boom Clay) consists of dark grey, heavy clays, with several septaria beds. The deposits contain a large number of bituminous horizons, which are darker in colour. In the uppermost part of the sequence, sandy intercalations are found. The thickness pattern is strongly

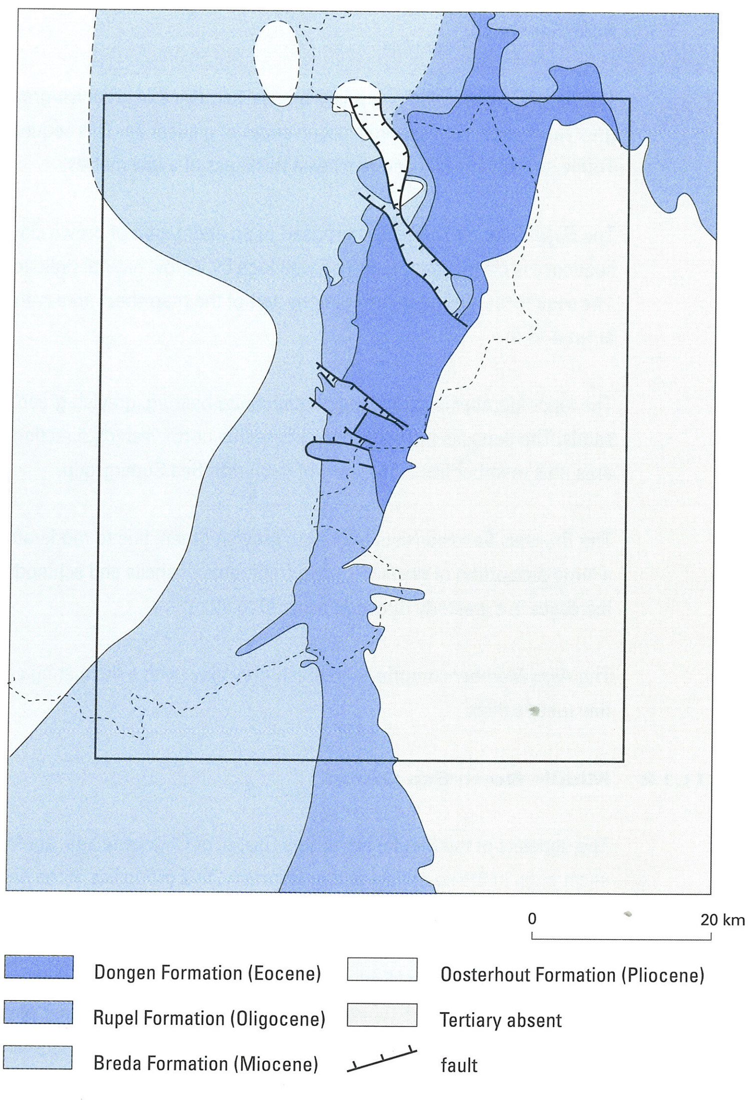


Figure 11.2 Subcrop map of the various Tertiary formations, below the Quaternary. This map has been based on interpretation from well logs and data from literature (Rijks Geologische Dienst, 1996). Data for the German part have been derived from Baldschuhn et al. (1996).

determined by the degree of erosion; the Rupel Clay reaches thicknesses up to around 100 m in the northwest of the map sheet area.

The *Veldhoven Formation*, of Late Oligocene age, is found locally in the Reutum Graben and in the western part of the map sheet area. The formation comprises dark green to dark grey sandy clays and moderately coarse sands. The formation rests upon the Rupel Formation separated by a hiatus and is unconformably overlain by the Upper North Sea Group. The formation achieves thicknesses up to 110 m in the Reutum Graben and the northwest of the map sheet area.

11.1.3 Upper North Sea Group

Tertiary deposits of the Upper North Sea Group, of Middle Miocene to Quaternary age, are found in the Reutum Graben and the western part of the map sheet area. The Quaternary deposits occur throughout the map sheet area. (Map 16; fig. 11.1 & 11.2). Within the group, the Breda, Oosterhout and Scheemda Formations can be identified.

The *Breda Formation*, of Miocene age, comprises a complex of green and black sands and brown to black clays. In particular, the high percentage of glauconite is characteristic of the formation. Several horizons of shells also occur. Four characteristic lithological units are found within the formation (Van den Bosch et al., 1975). The formation may exhibit considerable differences in composition laterally, owing to the presence of several intraformational unconformities (Rijks Geologische Dienst, 1993a). The formation thickens in a northwesterly direction to over 200 m.

The *Oosterhout Formation*, of Pliocene age, is composed of well sorted, greenish-grey, argillaceous, very fine sands, containing little glauconite. The formation occurs in the Reutum Graben and in the western part of the map sheet area. The formation achieves a thickness of 50 m. In the northwest of the map sheet area this marine formation passes laterally into the predominantly fluvial and nearshore Scheemda Formation.

The *Scheemda Formation*, of Pliocene age, occurs in the Reutum Graben and the northwest of the map sheet area. The formation consists predominantly of sands. The bottommost part comprises well-sorted, fine sands, whereas upwardly the sorting diminishes and the grain size coarsens. The formation is the lateral equivalent of the coeval Oosterhout Formation. The thickness pattern of the formation is irregular; the maximum thickness may exceed 30 m.

The remaining Quaternary formations consist of sand, clay and gravel, deposited in predominantly terrestrial, and partly glacial conditions. Their thickness increases in a northwesterly direction from a few metres to over 160 m.

11.2 Sedimentary development and palaeogeography

During deposition of the North Sea Supergroup, the map sheet area lay on the 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). The sedimentation was also influenced by sea-floor movements. This resulted in several hiatuses in the sedimentary succession. During periods of high stand, the deposits were predominantly clays, whereas periods of low stand initiated the accumulation of sands or arenaceous clays. At extreme low stand, no deposition at all took place or erosion even occurred; the position on the margin of the basin favoured the occurrence of large hiatuses in the sedimentary succession.

The sediments of a large part of the North Sea Supergroup were deposited in a marine setting. At extreme low stand, no deposition at all took place or erosion even occurred. During periods of high stand the deposits were predominantly clays, whereas during periods of low stand, sands or arenaceous clays were accumulated. At extreme low stand, no deposition at all took place or erosion even occurred. During deposition of the Dongen Formation, the Lower North Sea Group experienced a period of relatively high stand, when clay was mainly deposited. A drop in sea level brought deposition of this formation to an end.

The Middle North Sea Group exhibits a rapid rise in sea level with high stand during deposition of the Rupel Clay. During a regressive phase, deposition of the Veldhoven Formation occurred.

During deposition of the Upper North Sea Group, the sea level fluctuated sharply. This is reflected in the alternation of sand and clay in the Breda and Oosterhout Formations. The sea level also exhibited a gradual drop, favouring a transition from marine to terrestrial deposits. During the youngest geological history, inland ice and peri-glacial conditions played a significant role in this area.

12 Geological history

12.1 Introduction

This chapter gives an overview of the geological history of the map sheet area from the Middle Devonian to the Quaternary. The older history is described by Franke (1990), Ziegler (1988, 1989, 1990). The Quaternary is described in detail in the geological maps, inter alia, Rijks Geologische Dienst (1975, 1993a, 1996) and has been the subject of several publications, inter alia, Zagwijn (1989).

The geological history of each subsequent period is illustrated by the different tectonic phases that were active in the map sheet area (fig. 1.6). During the Late Carboniferous and earliest Permian these phases were, in succession, the Sudetic, Asturian and Saalian phases of the Variscan Orogeny, related to the forming of the Variscan Mountains in Central Europe. The Late Triassic to earliest Cretaceous period was marked by the Kimmerian extensional tectonic phases, which were responsible for the formation of the major structural units. During the Sub-Hercynian phase in the Late Cretaceous, a compressive stress field was responsible for a brief change (inversion) in the direction of movement of the major structural elements. Pyrenean and Savian phases during the Tertiary were associated with the Alpine Orogeny. Compressive deformation reflects the collision between Africa and Europe. The resulting uplift of the Alps had a pronounced effect on the supply of sediment. The tectonic phases, together with the climate and the sea level, were the determining factors in the development of the area.

The specific development of the map sheet area has been examined in a regional context (fig. 12.1). The major tectonic structures discussed in this chapter are illustrated in figure 1.7.

12.2 Basin development, sedimentation and tectonics

12.2.1 Devonian

During the Caledonian Orogeny (Cambrium-Silurian) a vast landmass was formed, the Old Red Continent, in the present North Sea region. During the Early Devonian, however, a regime of extensional stresses initiated the formation of a large basin in Central Europe, the Rheno-Hercynian Basin. This basin continued to be a pronounced region of subsidence until the Carboniferous. Owing to a decrease in extensional stresses and a cyclical rise in sea level, the area of sedimentation extended significantly during the Middle and Late Devonian, reducing the former Old Red Continent to a number of smaller highs at the end of the Devonian (Ziegler, 1990).

During the Devonian, the map sheet area was situated on the northern margin of the Rheno-Hercynian Basin (Ziegler, 1990). The Early Devonian of The Netherlands is insufficiently documented, but, during the Middle Devonian (fig. 2.2a), the west of the map sheet area was part of the Old Red Continent (Bless et al., 1980; Rijks Geologische Dienst, 1993b). In the east of the map sheet area, sedimentation of sands and clays occurred, presumably in a shallow-marine environment. Further to the east, reef limestones formed in a shallow-marine environment (Wolburg, 1970b).

A major transgression during the Late Devonian flooded the highs and the map sheet area was completely submerged by the sea (fig. 2.2b). From the uniform thickness development of the Upper Devonian deposits, it may be inferred that the subsidence of the area was predominantly of a thermal nature. This was accompanied by contemporaneous uplift of a number of areas (including the Mid-German High, London-Brabant Massif), with a consequent increase in the supply of clastic material, thus impeding further reef growth. Both within and to the east of the map sheet area, predominantly fine-grained clastic sediments were deposited, while to the south of the area, sandy deposits are found around former highs (Wolburg, 1970b).

12.2.2 Carboniferous

During the Early Carboniferous, the subsidence of the Rheno-Hercynian Basin persisted. A further rise in the sea level drastically restricted the influx of clastic material. To the north of the basin, a vast carbonate platform was created, which is presumed to have occupied the greater part of the map sheet area. A brief phase of extensional tectonics, the Bretonian phase, initiated differential surface movements during the Early Carboniferous, creating depressed areas at a number of places in this vast carbonate platform (Ziegler, 1990). One such area, a pronounced East-West oriented trough, lies to the south and southeast of the map sheet area, where a condensed succession of clays and carbonates was deposited in a deep-water setting (fig. 2.2c).

The history of the Late Carboniferous and earliest Permian was determined by the Variscan Orogeny. The evolution of the Variscan Mountains to the south of the present Netherlands had an obvious impact on the geological history of the map sheet area. The Variscan Orogeny marks the closure of the Proto-

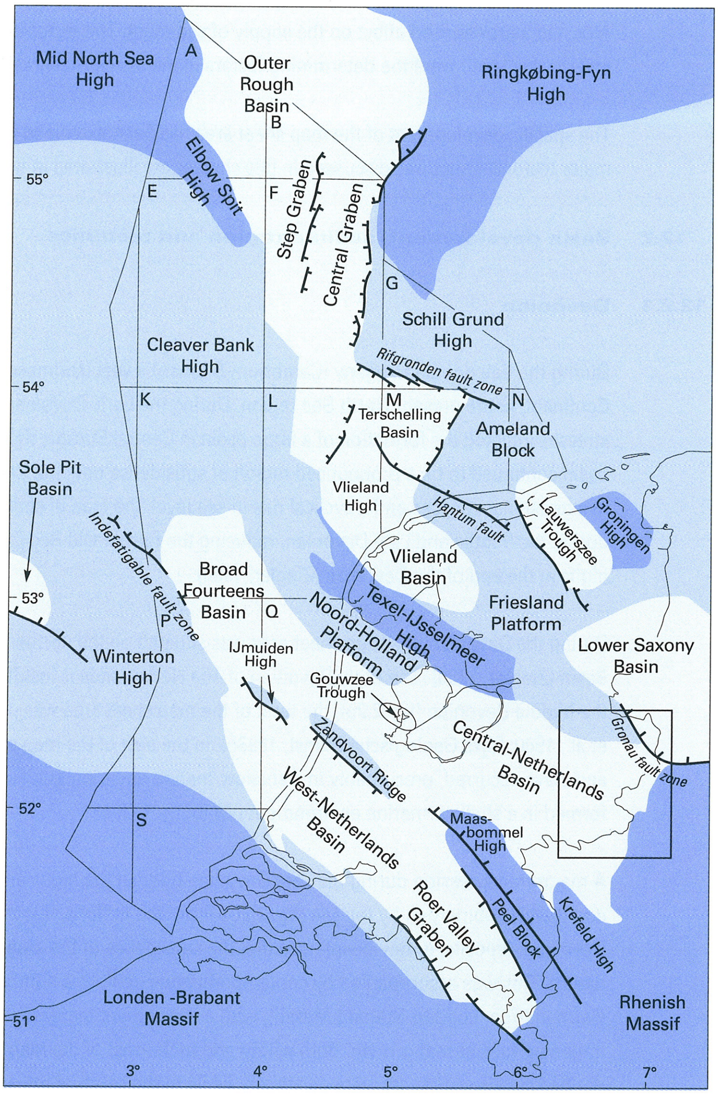


Figure 12.1 Overview of the principal structural elements in The Netherlands during the Mesozoicum (after Van Adrichem Boogaert & Kouwe, 1993-1997) The position of the map sheet area has been outlined.

Tethys and the formation of the supercontinent Pangaea (Ziegler, 1990). Three orogenic deformation-phases are identified: the Sudetic, Asturian and Saalian tectonic phases, during which the deformation front migrated increasingly further to the north. This is manifested in the map sheet area by the progression of the depocentre in a northerly direction, from the Ruhr Basin to the south in the Namurian and oldest Westphalian into the Ems Low in the northeast during the youngest Westphalian and Stephanian (Drozdzewski, 1992).

The position of the Variscan orogenic front cannot be unequivocally determined throughout the area. Franke & Hoffmann (1997) place the front of the fold belt to the north of the Münsterland-1 well, based on seismic evidence. Their assumption is that organic-rich basin deposits played an important role as overthrust plane, along which the northwardly movements were accommodated. The position of the front within the map sheet area is assumed to have been partly determined by the palaeogeographic development of the Lower Carboniferous (compare fig. 1.7 & 2.2c). The Lower Carboniferous basin deposits formed one of the overthrust planes, while the rheological properties of the carbonate platform to the north prevented further accommodation of such horizontal movements. In consequence, on the transition between the basin facies and the carbonate platform, the slope of the shear direction changed from more or less horizontal in the basin facies to more vertical in the platform facies, with the result that the southern fringe of the platform facies coincides with the Variscan orogenic front (Geluk, 1997). Within this model, the characteristic Carboniferous tectonics of the Ruhr Basin can be adequately interpreted as thin-skin tectonics (Franke & Hoffmann, 1997).

The Sudetic phase, at the beginning of the Late Carboniferous, reflects the collision between Gondwana (Africa and South America) and Laurasia (Europe, North America and Asia). The N-S oriented compressive stress fields 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. 3.8), following drastic subsidence from the beginning of the Late Carboniferous. This basin became the depocentre of vast quantities of erosion products from the fold belt. The depositional setting during the Late Carboniferous displays a clear tendency of regression, ranging from principally marine influenced delta and pro-delta deposits during the Namurian to paralic and subsequently fluvial deposits during the Westphalian. During the latest Westphalian A and the Westphalian B, the fluvial influence on the sedimentation became more pronounced and large-scale peat formation occurred in marshes in between the rivers. Owing to the more pronounced subsidence in the southern part of the map sheet area, the peat formation here was more extensive than in the north and east (Drozdzewski, 1992, 1993). Episodically, brief transgressions occurred, persisting into the Westphalian C. These transgressions, attributed to glacio-eustatic sea-level changes (Ziegler, 1990), invaded vast areas, facilitated by the flat relief of the basin. During the Westphalian C and D the climate became drier owing to the gradual northward drift of the area away from the equator (Van der Zwan et al., 1993; Pagnier & Van Tongeren, 1996).

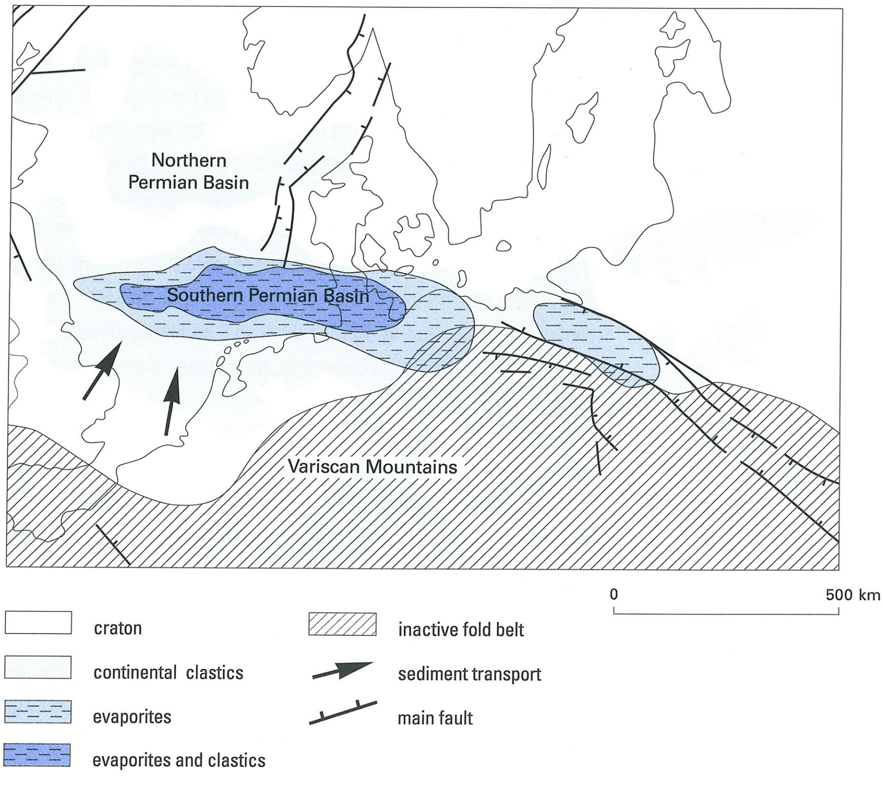
The Asturian and Saalian deformation phases initiated the northward migration of the Variscan orogenic front (Lorentz & Nicholls, 1976), causing the deposits in the foreland basin to become strongly folded and move northwards, along low-angle overthrust planes. The northern boundary of this zone of intense deformation is situated immediately to the south of the map sheet area (Geluk, 1997; fig. 1.7 & 3.2). During the Westphalian C, the influence of this folding phase was perceptible in the map sheet area and pronounced movements were initiated along the Gronau Fault Zone. In the southern part and to the northwest of the map sheet area, uplift is presumed to have already occurred (Bless et al., 1977; Van Tongeren, 1996). From the Early Westphalian C onwards, sedimentation increasingly concentrated in the Ems Low in the east of the map sheet area (Füchtbauer et al., 1991). It may be assumed that sedimentation during Westphalian D and Stephanian also occurred outside the Ems Low. Within the map sheet area, these deposits were subjected to erosion during the last part of the Variscan Orogeny. The Saalian deformation phase during the Stephanian and the earliest Permian is the last phase of the Variscan Orogeny. The NNW-SSE trending compressive stress-field was succeeded by E-W trending extension. To the north of the Variscan Mountains, NW-SE trending, mainly dextral, transversal fault systems developed. In the map sheet area strike-slip movements produced uplift, tilting and erosion (Van Tongeren, 1996).

The Asturian and in particular the Saalian phase made a considerable impact on the map sheet area. The Saalian phase, in particular, was marked by the NW-SE trending framework which was to have such a determining effect on subsequent geological history. The subcrop map of the Saalian Unconformity (fig. 3.3) shows that profound erosion in the south of the map sheet area even reached the Westphalian A. The unconformable overlying Stephanian deposits are also a clear indication of movements during the Asturian phase.

12.2.3 Permian

At the end of the Saalian tectonic phase in the Early Permian, a vast landmass was formed. Intensive strike-slip deformation of this area in Germany induced extensive volcanic activity and pronounced deformation of other areas (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 a vast intracratonic continental basin: the Southern Permian Basin, in which 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).

Figure 12.2 Palaeogeography of Northwest Europe during the beginning of the Late Permian, showing the position of the Southern Permian Basin (after Ziegler, 1990).



During the entire Early Permian and part of the Late Permian, the map sheet area formed part of the Variscan Mountains on the southern margin of the basin. This long period was marked by severe erosion of the Carboniferous deposits, which produced the present geological pattern (fig. 3.3). In the Asturian and Saalian phases, erosion removed more than 1700 m of the Limburg Group in the south of the map sheet area, whereas this was probably less than 300 m in the extreme northeast.

Not until the Late Permian did the map sheet area form part of the Southern Permian Basin (fig. 12.2). Aeolian and fluvial sands and conglomerates of the Upper Rotliegend Group were deposited in arid climate conditions. This occurred first in the west, gradually spreading to the east (Map 1). The Variscan orogenic front more or less coincided with the southern boundary of the sedimentation area. Normal faulting and transverse movements led to the formation of a few small grabens in the south and north of the map sheet area (fig. 4.1). Here, besides conglomerates, aeolian sands were accumulated (Slochteren Formation). On the highs surrounding these grabens, sedimentation was either absent or minimal, being then predominantly conglomeratic. As the rate of sediment accumulation in the Southern Permian Basin did not keep pace with subsidence of the area, the basin subsequently became situated below the palaeo sea-level (Glennie, 1986).

Graben formation in the North Atlantic/Arctic area combined with a eustatic sea-level rise initiated the forming of an open connection between the Barentsz Sea in the north and the Southern Permian Basin. In response to this, a very rapid transgression occurred in the basin, which had already subsided below the palaeo sea-level (Glennie, 1983, 1986). 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 on the other. Major transgressions mark the bases of the different cycli.

Transtensional movements during the deposition of the Z1 (Werra) Formation, governed by an E-W extension, caused a prominent, southwards enlargement of the sedimentation area, entailing a transection of the Variscan Mountains. The area of subsidence which ensued formed a subbasin of the Southern Permian Basin, which had been separated from the main basin by an elevated barrier situated to the north of the map sheet area. This high was surrounded by an anhydrite platform (fig. 5.3). The area of subsidence was composed of a series of relatively small pull-apart structures, grabens and half grabens, where loading caused by rapidly accumulated anhydrite on a differentiated substrate gave rise to intensification of the already present differences in relief (fig. 12.3). This produced considerable differences in thickness in the Z1 (Werra) Formation. This relief was levelled by rock salt. The differential movements ceased during the deposition of the Z1 (Werra) Formation; the younger deposits of the Zechstein Group cover the relief like a blanket (Geluk et al., 1997).

Tectonic movements during the Z1 (Werra) Formation in Northwest Germany have been described by M. Ziegler (1989). There are indications (Geluk et al., 1997; Rijks Geologische Dienst, 1993b) that tectonic movements during the Z1 (Werra) Formation form a separate phase at the end of the Variscan Orogeny. This phase induced strike-slip deformation of the foreland basin and locally the collapse of the Variscan Mountains.

During the deposition of the Z2 (Stassfurt) to Z4 (Aller) Formation, the area of salt sedimentation gradually shifted to the northeast; the southern and central part were subsequently incorporated in a fringe area of the Southern Permian Basin. Here, sedimentation only occurred during the initial transgressions. These transgressions favoured normal marine conditions during the Z1 (Werra) up to and including Z3 (Leine) Formations, but during the Z4 (Aller) Formation a transition to terrestrial depositional 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. There are indications of minor extensional active faulting, preceding the deposition of the Zechstein Upper Claystone Formation (Geluk et al., 1997), which, however, had only a minor effect on the area.

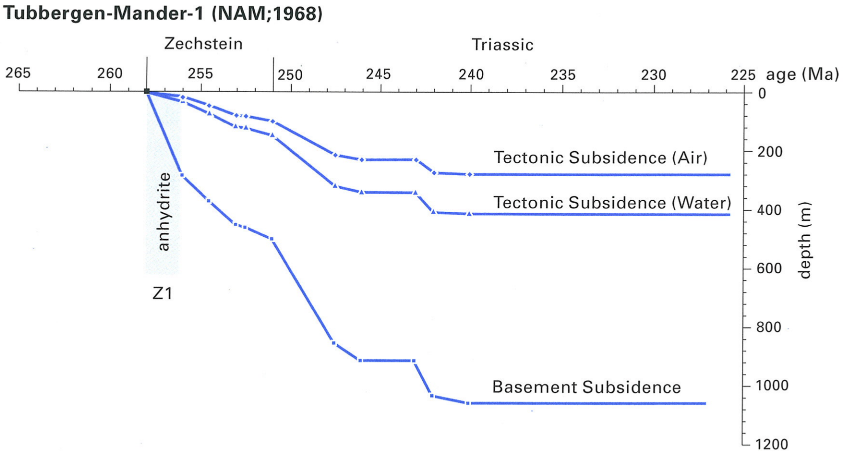
12.2.4 Triassic

The Triassic is characterised initially by extremely uniform basin subsidence. The Southern Permian Basin persisted and is therefore often referred to as the Permo-Triassic Basin. As a result of two phases of extensional tectonics, the basin was modified during the Triassic and transected by several NNE-SSW trending elements, including the Ems Low, the Glückstadt Graben, the Horn Graben and the Central North Sea Graben (Ziegler, 1990). The clastics transported during the Triassic originated from the Variscan Mountains situated in the south.

Sedimentation in the area initially occurred in a lacustrine to playa environment. Uplift of the source areas, 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. In the west and the southeast of the area, two highs emerged, the Netherlands Swell and the Hunte Swell, where erosion exceeded 300 m. These highs were continuously connected in the south, though further to the north separated from each other by the NNE-wards deepening Ems Low, where only about 100 m was removed by erosion. Owing to these movements, only the bottommost deposits of the Main Buntsandstein Subgroup have been preserved on the highs (fig. 6.4).

The movements of the Hardegsen phase comprise three, relatively brief subphases of extensional movements, separated by longer periods of regional subsidence. During these periods, the differences in sediment accumulation between the highs and the Ems Low were minimal; the present differences in thickness are principally the result of erosion and reflect negligible depositional differences (Geluk & Röhling, 1997). As well as this regional uplift and erosion, a number of NW-SE oriented faults were reactivated, in which locally intensive erosion occurred in the Lower Buntsandstein Formation.

Figure 12.3 Reconstruction of the subsidence illustrated by the Tubbergen-Mander-1 well during the Late Permian and Early Triassic. The observed pronounced subsidence during deposition of the Z1 (Werra) Formation was principally caused by the loading of the substrate by anhydrite (after Geluk et al., 1997).



The Hardegsen phase was followed by a long period of incipient thermal subsidence, which was to persist until the Middle Keuper (Carnian). The Early Triassic structures, such as the Ems Low and the Netherlands Swell, subsided uniformly (Geluk et al., 1996). The lacustrine deposits of the Solling Formation covered the entire area like a blanket. During the Middle Triassic, the Permo-Triassic Basin achieved a connection with the open ocean in the east, and a sea-level rise facilitated a slow transgression (Vail et al., 1977). This transgression stagnated a number of times, culminating in the deposition of evaporites throughout the basin (Main Röt Evaporite, Upper Röt Evaporite and Muschelkalk Evaporite Members).

During the Late Anisian, a marine environment was established in the area. Within a wide range of the map sheet area 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). Subsequent erosion removed these deposits from a large part of the area. The Muschelkalk Formation in basin facies is presumed to have been deposited in the map sheet area, with rock salt in the *Middle Muschelkalk*. During the deposition of the Keuper Formation, the area appears to have subsided slightly less than areas to the northeast.

From the Carnian (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 and the opening of the Atlantic Ocean (Ziegler, 1990). This was manifested by four major extensional phases, the Kimmerian phases, dominating the structural evolution of Northwest Europe. They are related to the pronounced hiatuses in the stratigraphic succession, for practical considerations.

The first one, the Early Kimmerian tectonic phase, initiated pronounced differentiation in the area. Subsidence occurred in the Ems Low. Owing to a change in orientation of the stress-field (ENE-WSW oriented extension), this structure differs in situation and shape from the Ems Low at the time of the Carboniferous and the Early Triassic. In the map sheet area, the degree of erosion increased in a southwesterly direction, to over 400 m, which can be deduced from the outcropping deposits (fig. 6.7). During this phase, major active faulting occurred in the area, causing the Zechstein salt to be mobilised locally and intrude into fault zones. This occurred in the case of the Gronau Fault Zone and in the Bislich Graben.

The entire map sheet area remained part of a high for a long period; it was not until the distinctive Rhaetian transgression that marine sediments of the Sleen Formation cover the ensuing relief. The area where this is found is also referred to as the East Netherlands Triassic High. Elsewhere, to the east and west, this relief was covered by deposits of the Red Keuper Claystone and Dolomitic Keuper Members (Germany: *Steinmergelkeuper*). The primary thinning of the afore-mentioned Keuper members in the direction of the high suggest that the relief was more pronounced in the map sheet area than in the surrounding areas.

12.2.5 Jurassic

The Rhaetian (latest Triassic) marked the onset of regional subsidence of the area. In combination with a sea-level rise, this initiated the deposition of fine-grained marine sediments. The deposits of the Early and Middle Jurassic are now found in separate basins, and in the map sheet area they have been considerably reduced in thickness (Map 8). Nonetheless they were once deposited in a single, continuous, vast area, extending from the former Permo-Triassic Basin to the Paris Basin, inferred from the uniform composition and the fine-grained character of the deposits. To the southeast of the map sheet area, there was a high present in this marine basin, the Rhenish Massif. Its influence on the sedimentation was, however, minimal. At the end of the Early Jurassic (Toarcian), a period of stagnation set in in the marine basins, initiating deposition of organic-rich sediments (Posidonia Shale Formation) in large parts of Northwest Europe. In the map sheet area these deposits have been preserved locally (fig. 7.2).

Little is known about the Middle Jurassic owing to a large hiatus in the sedimentary succession. The Mid Kimmerian tectonic phase during the Middle Jurassic (Aalenian-Bathonian) in essence took place to the north of the map sheet area. A large area was uplifted, comprising the central North Sea and the northern parts of The Netherlands and Germany (Ziegler, 1990). Sediments were transported from this elevated area to basins situated further to the south. These sandy sediments are unlikely to have reached the map sheet area. The uplift in the North Sea was accompanied by contemporaneous local uplift in the southeast of the map sheet area, initiating erosion of the Posidonia Shale and part of the Aalburg Formation. The deposits of the Bathonian to Callovian rest unconformably on the Aalburg Formation. The Middle Jurassic deposits suggest a regressive trend.

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 boundary of the Berriasian-Valanginian. The ENE-WSW trending extensional stresses resulted in the reactivation of a number of distinctive structures in Northwest Europe, such as the Central North Sea Graben, the West and Central Netherlands Basins and the Lower Saxony Basin. Within the map sheet area intensive fault movements were initiated (such as the Gronau Fault Zone). The extensional stresses also instigated movement of the rock salt and initiated a number of salt swells, such as the Itterbeck-Denekamp, Rossum, De Lutte and Tubbergen salt-pillows.

The Oxfordian and Kimmeridgian marked the onset of very pronounced subsidence in the Lower Saxony Basin (Baldschuhn et al., 1991; Betz et al., 1987; Gramann et al., 1997). The basin was asymmetrical in shape, with the most depressed areas situated in the southern part. The Central Netherlands Basin subsided less intensively, subsidence being concentrated mainly in parts of this basin to the west of the map sheet area.

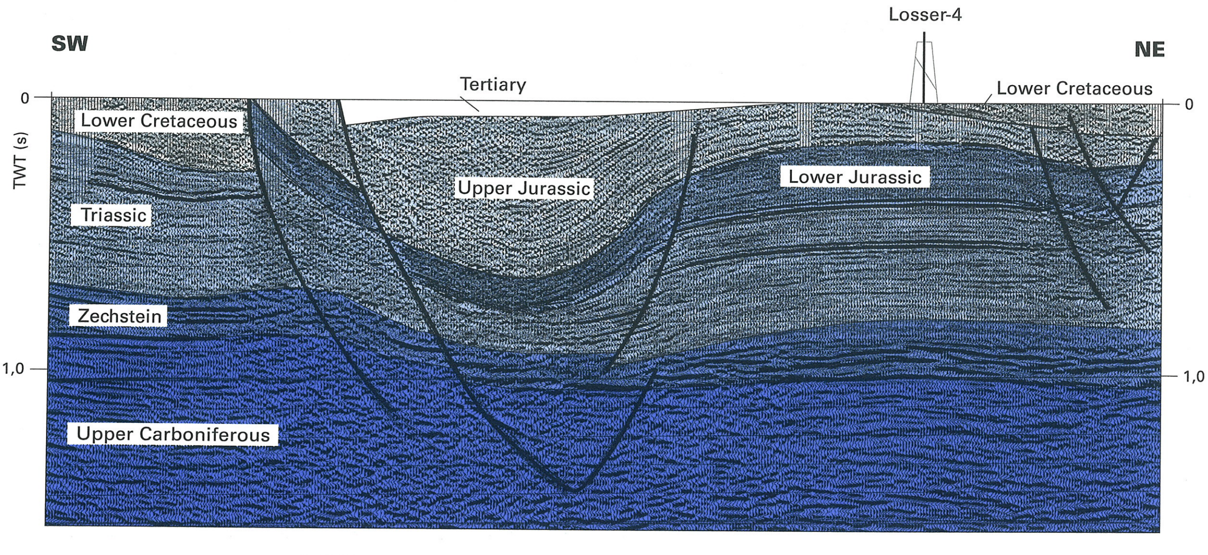
The Lower Saxony Basin was connected to the Central Netherlands Basin, which is demonstrated by the similarities of the sedimentary succession in both composition and age (Rijks Geologische Dienst, 1993c). This connection was subsequently removed by the inversion. During the Late Jurassic, the basins were isolated from other, marine basins, one consequence of which was the deposition of an evaporitic succession.

During the first pulse of the Late Kimmerian phase, fault movements and erosion occurred. In the map sheet area, which was situated along the flanks of the above-mentioned basins, the erosion was 300 to over 600 m. In the centre of the basins, virtually no erosion took place. Strong differential fault movements are indicated by the thickness pattern of the deposits of the Altena and the Lower Saxony Group in the Gronau Graben (fig. 12.4; Maps 8 & 10). The consequence of the uplift and erosion was that deposits of the Altena Group became exposed in the Lower Saxony Basin and mainly Upper Germanic Trias Group deposits in the Central Netherlands Basin. In the last-mentioned area, only scattered, remnants of the Altena Group are found (Map 17). On the highs (Friesland Platform, Münsterland Basin), owing to the large hiatus in the succession, the actual erosional history cannot be reconstructed with any degree of certainty.

The oldest Late Jurassic sediments can be found in the Gronau Graben and further to the east in the Lower Saxony Basin. From here, the area of sedimentation spread further out across the map sheet area. During the youngest part of the Portlandian, the differential movements decreased and the area of sedimentation extended further over the salt structures and the highs flanking the basin (Serpulite Member). The highs are also thought to have been largely covered by a thin succession of sediment.

12.2.6 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). By the end of the Early Cretaceous, the sedimentation had extended over the entire map sheet area. The Cretaceous transgression was probably a response to the increased rates in sea-floor spreading and the associated enlargement in volume of the mid-oceanic ridges (Pitman, 1978; Donovan & Jones, 1979). The subsidence continued, until in the Late Cretaceous



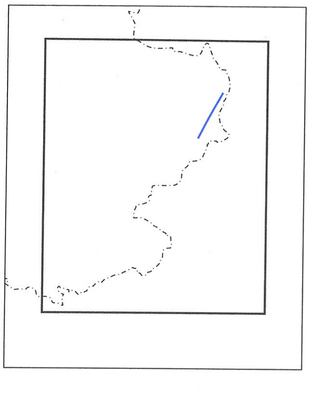


Figure 12.4 Seismic section across the Gronau Fault Zone. Observe the pronounced thickening of the Upper Jurassic deposits of the Gronau Graben. These present a clear indication of synsedimentary movements during the Late Jurassic.

inversion movements associated with the Sub-Hercynian phase initiated uplift of the basin areas and a subsidence of the former highs.

Initially, lacustrine sediments were deposited in the map sheet area (Coevorden Formation). During the Ryazanian, the basin subsidence was regionally confined and the area of sedimentation with respect to the Late Jurassic extended even further to the south and north. The southernmost extent is thought to have been immediately to the north of Winterswijk.

Brackish water influx in the Lower Saxony Basin (Wolburg, 1949) indicate a connection with the Vlieland Basin and the Central North Sea Graben for short periods; marine sediments of the same age have been recovered from these basins. During the oldest Valanginian, the Lower Saxony Basin and the Central Netherlands Basin became connected to the afore-mentioned marine basins in response to a sea-level rise.

The second pulse of the Late Kimmerian phase, during the earliest Valanginian, favoured an accentuation of the relief around the basins. The Tubbergen High, Dalfsen High, Friesland Platform and Münsterland Block were subjected to strong uplift, and profound erosion took place here (Map 18). The large quantity of erosional material accumulated as sand around these highs in a shallow-marine setting (Bentheim Sandstone, Gildehaus Sandstone, *Kuhfeld Beds*). The finer components were deposited in the central parts of the basins. The Lower Saxony Basin and presumably also the Central Netherlands Basin continued their intense subsidence. During the Hauterivian and Barremian, the area of sedimentation extended further over the adjacent highs.

During the Aptian a brief regression took place, coinciding with the Austrian tectonic phase (Ziegler, 1990). These movements favoured the reactivation of highs in the north of the area and caused a hiatus in the sedimentary succession. In the vicinity of the Gronau Fault Zone the entire succession of the Rijnland Formation was locally removed by erosion and deposits of the Late Aptian rest on those of the Upper Germanic Trias Group or the Altena Group.

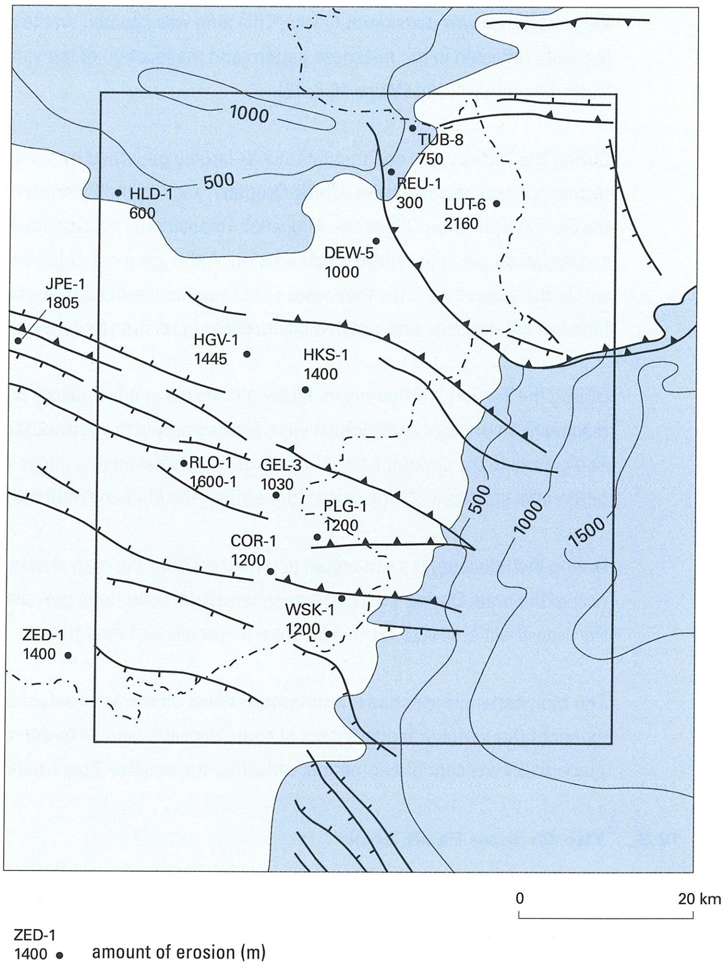
The movements of the Austrian tectonic phase were followed by the onset of regional subsidence of the entire area. During the Late Aptian and particularly the Albian, all the highs in and around the map sheet area were flooded by the sea. This Albian transgression has been identified throughout Northwest Europe (Crittenden, 1987). The sea-level rise continued during the Albian to Turonian. The marine area in Northwest Europe prominently enlarged. The influx of clastic material decreased, clays and marls being deposited in a shallow-marine sea (Upper Holland Marl) and thick successions of marl and limestone during the Cenomanian and Turonian. The greatest subsidence continued to be concentrated in the Central Netherlands and Lower Saxony Basins, but the differences in subsidence had drastically diminished and active faulting is thought to have virtually ceased (Baldschuhn et al., 1991).

This period of regional subsidence came to an end during the Coniacian, as a result of major plate reorganisation 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, 1987) 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 (Map 20, section 1), the inversion of the former Upper Jurassic/Lower Cretaceous basins in the area and pronounced depression of the former highs (Baldschuhn et al., 1991; Tantow, 1992). These original highs subsequently formed the marginal troughs of the elevated areas and the degree of subsidence is related to the extent of uplift of the adjacent basins (Voigt, 1963). In the Lower Saxony Basin, virtually the entire succession of the Cretaceous was eroded as a result of the inversion. The very pronounced inversion was accompanied here by the intrusion of magma, resulting in the formation of the *Vlotho* and *Bramsche Massifs* (Teichmüller et al., 1984).

In the Central Netherlands Basin, the uplift and erosion were more pronounced than the preceding subsidence, causing the erosion not only of virtually the entire Upper Jurassic to Upper Cretaceous succession, but in addition a part of the underlying deposits (Maps 6, 8, 10, 12 & 14). The deposits of the Chalk Group are present in great thicknesses on the Tubbergen High, Dalfsen High and Friesland Platform, as well as in the Münsterland Basin. The fact that the thickness of the Upper Cretaceous deposits in the Münsterland Basin is greater than on the Friesland Platform is attributed to a greater absolute degree in uplift in metres of the Lower Saxony Basin with respect to the Central Netherlands Basin.

Different types of fault reactivation produced a great variation in the degree of uplift. For each individual well, the degree of erosion was first estimated based on the regional-geological development. Subsequently, this estimate was calibrated from compaction analyses of the Lower Buntsandstein Formation (Van Wijhe et al., 1980) and the coalification of the top of the Limburg Group. The uplift near the western flank of the Lower Saxony Basin exceeds 2000 m and in an easterly direction increases further to over 3500 m. In the Central Netherlands Basin, an increase in the extent of uplift can be

Figure 12.5 Reconstruction of the fault movements and the degree of erosion during the Sub-Hercynian phase. The thickness of the eroded succession has been deduced from the regional-geological development, supported by modelling of the coalification history and the degree of compaction of the Lower Buntsandstein Formation.



observed in the direction of the former basin centre of less than 1000 to locally in excess of 2000 m (fig. 12.5). The differences in the extent of inversion between these basins are directly related to the subsidence during the Late Jurassic and Early Cretaceous, which in the Lower Saxony Basin was much greater than in the Central Netherlands Basin (Baldschuhn et al., 1991).

At the end of the Cretaceous, the tectonic instability decreased and during the Campanian to Danian, the inverted basins were again covered by sediment, as revealed in the adjacent parts of Germany, where, on the southern margin of the basin, Danian deposits rest upon the Altena Group (Elberskirch & Wolburg, 1962). In the map sheet area, however, these sediments underwent renewed erosion, preceding the Late Paleocene or Eocene. This was due either to a drop in sea level or to a probable upward aftereffect of the inverted basins and the surrounding areas. Sediments of the Maastrichtian and Danian are consequently absent in a vast area between the northern part of Germany and the southern Netherlands.

12.2.7 Cenozoic

The Tertiary and Quaternary evolution is determined by the development of the North Sea Basin, which has controlled the sedimentation pattern up to the present time. During the Tertiary and the Quaternary, a rising sea level combined with continuing regional subsidence in the central part of the North Sea resulted in the deposition of over 3500 m of sediment (Ziegler, 1990). In the map sheet area, however, the subsidence was considerably less. This area was situated on the eastern margin of the basin, which is clearly reflected in the thickness pattern and the location of the various extensional limits within the North Sea Supergroup (Maps 15 & 16).

During the Tertiary, the sedimentation was largely governed by sea-level changes and by a number of tectonic phases related to the Alpine Orogeny, such as the Pyrenean (transition Eocene-Oligocene) and the Savian (transition Oligocene-Miocene). Depositional succession of the North Sea Supergroup consequently displays hiatuses and erosion. Although most of the deposits were in actual fact deposited within the map sheet area, they were subsequently removed by erosion. This can be concluded from the facies of the deposits and isolated occurrences in relation to deposits outside the map sheet area.

During the Tertiary, further active faulting occurred in a few places only. These originated from reactivations of older faults which were formed during the previously mentioned tectonic phases. Particularly in the Gronau Fault Zone, large offsets developed above all in the Reutum Graben, where differential subsidence took place from around the Miocene until the Quaternary.

During the Pliocene, the sea began to withdraw from the map sheet area, commencing with the north part of the area. During the Quaternary, terrestrial conditions prevailed and the present topography of the map sheet area was formed by several glacials and interglacials.

The Münsterland Basin had a pronounced effect on the areal extent of the Tertiary units. This outer extent of the Tertiary deposits runs at some distance parallel to the margin of this basin. This is presumably a recent phenomenon, reflecting the positive Quaternary surface movements.

12.3 The Gronau Fault Zone

Within the map sheet area, the Gronau Fault Zone is a major element with a long history. The fault zone separates the Central Netherlands Basin from the Lower Saxony Basin. The Carboniferous history has been described by Van Tongeren (1996); the post-Carboniferous history of this fault comprises part of a special study within the framework of the activities involved in the research for this map sheet area (Grönloh, 1995).

The fault zone consists of three elements; the South Gronau Fault, the West Gronau Fault and the Reutum Fault (fig. 1.7; section 1.7.2). The fault zone displays a clear change in direction; in the extreme northeast, the Reutum Fault runs almost N-S, the South Gronau Fault display a NNW-SSE orientation, while on German territory, the fault zone deflects to an E-W direction. The West Gronau Fault is a NW-SE oriented branch of the southern extremity of the Reutum Fault. The orientation of the stress-field dictated the degree of activity of various elements during the course of geological history.

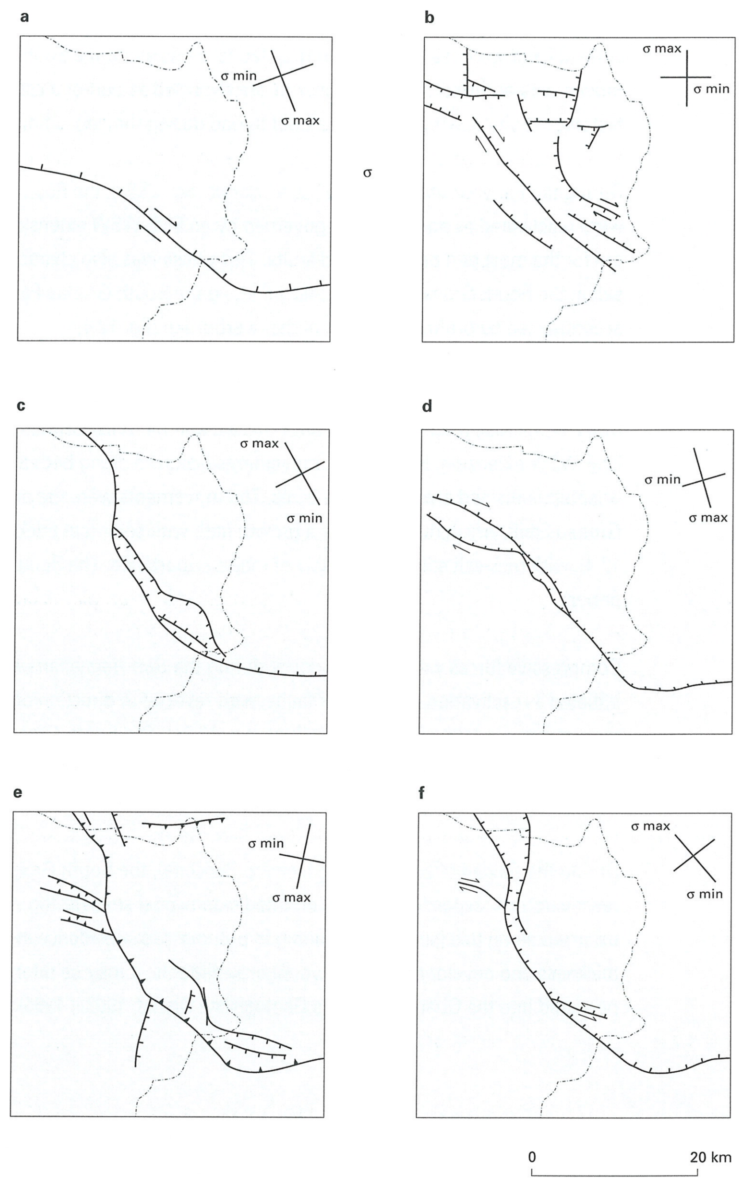


Figure 12.6 Reconstruction of tectonic pulses in the Gronau Fault Zone.
a. Variscan Orogeny (Late Carboniferous)
b. Late Permian
c. Early Kimmerian phase (Late Triassic)
d. Late Kimmerian phases (Late Jurassic - Early Cretaceous)
e. Sub-Hercynian phase (Late Cretaceous)
f. Savian phase (Tertiary)

Major movements along the Gronau Fault Zone occurred during all the tectonic phases in the period spanning Carboniferous to the present time. In the intervening time, predominantly regional, thermal subsidence took place in the area, or else the lack of sediments prohibits a reliable reconstruction of the fault movements.

During the *Asturian and Saalian phase* (Westphalian C to Autunian; fig. 12.5a) the Osning Fault Zone together with the South Gronau and the West Gronau Faults formed the southern boundary of the Ems Low. Under the influence of a NNW-SSE oriented compressive stress-field, right-lateral movements took place along this fault zone, initiating subsidence in the Ems Low to the north of this fault zone (Van Tongeren, 1996). During the Westphalian D, these differential movements were superseded by thermal subsidence and the sedimentation area once again spread from the Ems Low across the entire map sheet area. The Stephanian to Autunian was also characterised by movements along the Gronau Fault Zone and the area to the south of the fault zone underwent profound erosion.

In the *Late Permian* (fig. 12.5b), governed by an E-W oriented extension, the Reutum and the West Gronau Fault were reactivated as normal faults, while along the South Gronau Fault, right-lateral movements occurred. These movements are regarded as part of a Late Variscan relaxation phase. The tectonic activity only took place in a brief period during the deposition of the Z1 (Werra) Formation.

During the *Early Kimmerian phase* (Late Triassic; fig. 12.5c), the Reutum and the South Gronau Faults were reactivated as normal faults, governed by an ENE-WSW extension. The faults in this tectonic phase are for the most part newly formed faults. This phase was also characterised by intrusion of Zechstein salt in the South Gronau Fault. Further SE along the South Gronau Fault, salt accumulation took place, accompanied by profound erosion of the overburden (fig. 12.4).

During the *Late Kimmerian phases* (Late Jurassic to Early Cretaceous; fig. 12.5d), intensive normal fault movements took place along the South Gronau and the West Gronau Faults, under the influence of an ENE-WSW extension. Right-lateral movements occurred along both the newly-formed ESE-WNW oriented faults and older, Variscan faults. The movements were the most pronounced along the South Gronau Fault, which manifested as a growth fault with sediment thickening towards the fault plane (fig. 12.4), with rock-salt solution probably of major importance. The Reutum Fault was inactive during this period.

Compressive forces with a N-S tendency during the *Sub-Hercynian phase* (Coniacian-Campanian) initiated a reactivation of many old faults, with reversal in direction of movement, and right-lateral movements along the Gronau Fault Zone (fig. 12.5e). The South Gronau, the West Gronau and the Reutum Faults were reactivated. Many of the vertical movements which were initiated along the faults during the Late Kimmerian phases, were compensated during these inversion movements.

During the *Savian phase* (Late Oligocene to Pliocene), the South Gronau and the Reutum Faults were reactivated, in response to NE-SW oriented extensional stresses (fig. 12.5f). Left-lateral movements also occurred along this fault zone, resulting in pronounced subsidence in the Reutum Graben. From the thickness and development of the younger sediments, it may be inferred that the fault movements persisted into the Quaternary (Rijks Geologische Dienst, 1993a, 1996).

12.4 Geochemical evaluation and burial history

12.4.1 Introduction

Coal seams from the Limburg Group play an important role within the map sheet area. This is due partly to the fact that these layers in the most southerly part of the area occur at less than 1000 m depth, making them available for potential applications (mining, coal gasification and coal-bed methane production). The coal seams have, moreover, yielded hydrocarbons during the entire course of geological history, one example being the natural gas captured in the rock after genesis and now present in several places in the area (fig. 1.2). The natural oil traces encountered in various wells in the Achterhoek and Twente are illustrative.

In addition to the coal from the Limburg Group, potential oil or gas-source rocks are present in the Aalburg and the Niedersachsen Groups. These, however, have been preserved only locally in this area and therefore play no significant role in hydrocarbon generation.

The coal of the Limburg Group is of the kerogen type III (plant material). The group is also thought to contain several intervals of lacustrine source rocks belonging to the kerogen type I/II (algal material), which is inferred from the presence of the natural oil encountered in the Corle-1 well, the abundant oil traces in the top of the Limburg Group and the presence of such intervals in western Netherlands (De Jager et al., 1996). Of these lacustrine source-rock intervals, only the Geverik Member at the base of the Limburg Group allowed identification. The clayey parts of the Geul and the Caumer Subgroups are also thought likely to contain various thin, organic matter-rich intervals.

The coal-bearing of the Limburg Group is restricted to the Caumer Subgroup. This subgroup, 1400 to 2000 m thick, displays a considerable difference in coal-bearing. In the bottommost formations of the subgroup, the Baarlo and the Ruurlo Formations, the coal-bearing ranges from 1 to 1.6%, while in the top part of the subgroup, the Maurits Formation, this is around 3.5%. These differences are related to the facies of the specific formations. Lacustrine deposits generally have thin, laterally continuous coal seams, whereas fluvial successions are characterised by thick, laterally discontinuous coal seams.

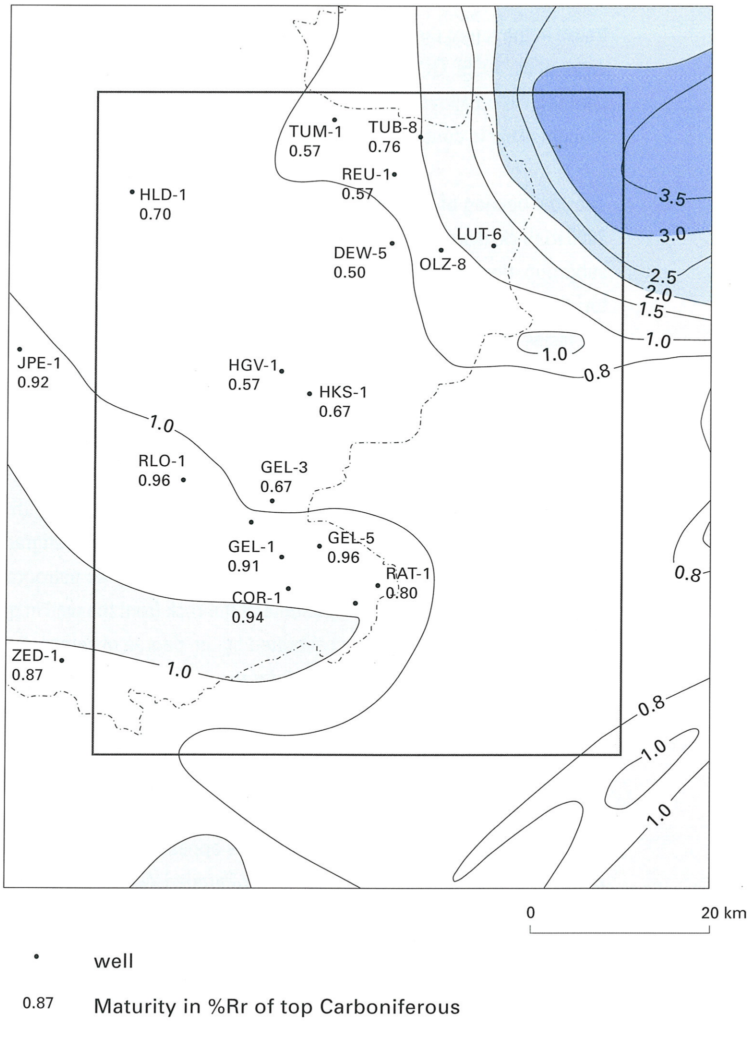
By modelling the burial history, the degree of coalification of the gas-source rock in a well can be determined. The burial history can be inferred from the stratigraphic sequence penetrated. The duration and lithology of the accumulated sequences in the case of each of the multiple hiatuses in the succession are extrapolated from the thickness trend of the stratigraphical successions in the adjacent area. The modelled coalification must be adjusted using the petrographic and geochemical measurements on organic components of the rock from the well in question. The Mesozoic burial history has, furthermore, been calibrated by the degree of compaction of the Lower Buntsandstein Formation (see Van Wijhe et al., 1980 for the methodology). Once the coalification interval for a particular period has been established, the process of gas generation from the source rock can subsequently be determined.

The reconstruction of the burial history of the map sheet area is complex, on account of the many deformation phases and abundant hiatuses appearing in the succession. The following are the principal geological uncertainties: (1) the quantity of eroded Westphalian-Stephanian and Triassic-Cretaceous deposits, as well as the time of erosion, and (2) the palaeo-heat flow.

The reconstruction of the burial history assumes a differentiated loading of the entire map sheet area by Westphalian-Stephanian deposits. The greatest thickness is presumed to be in the Ems Low and the slightest thickness on the Achterhoek High. In the reconstruction of the thickness of the Triassic deposits, pronounced uplift of the entire area during the Early Kimmerian phase is assumed, with the least erosion likewise occurring in the Ems Low. In respect of the Jurassic and Early Cretaceous, the greatest subsidence is also found in the Lower Saxony and Central Netherlands Basins. The most pronounced uplift in these basins took place during the Sub-Hercynian phase in the Late Cretaceous. With respect to the highs around these basins, the most pronounced uplift has been set in the Early Cretaceous. In the analysis of each well, the reconstruction of the burial history has been carried out in the greatest possible detail (RGD, 1995d).

The palaeo-heat flow within the area has undergone intense fluctuation during the course of time. Particularly in the vicinity of the intrusive rocks occurring in the area (see section 3.6), the heat flow was extremely high for brief periods locally. Because of the low values of the calculated theoretical coalification at the time of the magmatic activity, related to the slight burial depth, the modelling is based on a constant heat flow.

Figure 12.7 Contour map of the degree of coalification at the Carboniferous surface (%Rr). This contour map has been based on data from the wells shown. Data for the German part have been derived from Koch et al. (1997).



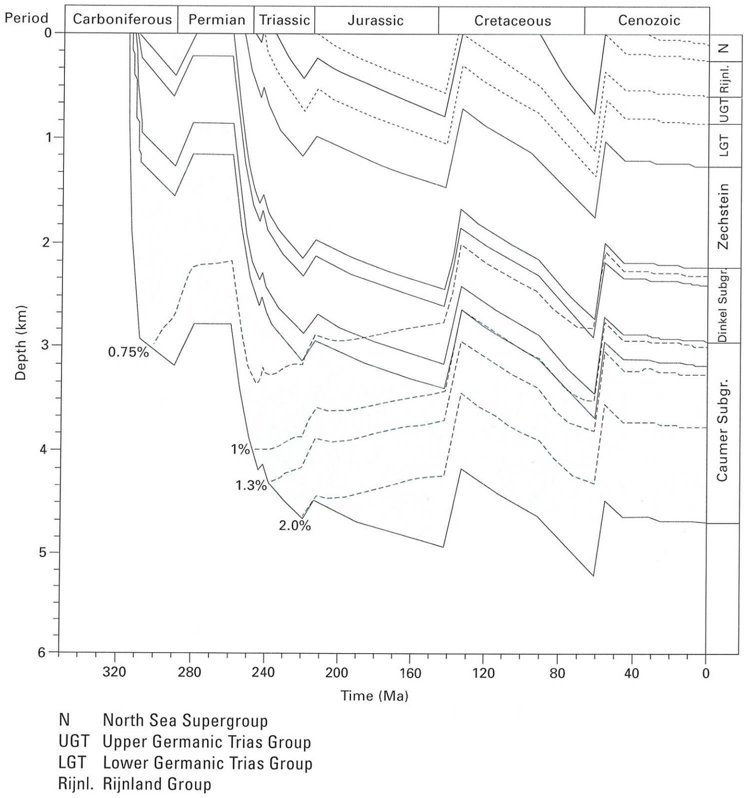


Figure 12.8a Burial history diagram of the Tubbergen-8 well on the Tubbergen High. Gas was generated from coal seams lying in the gas window (%Rr: 0.9-1.3). The gas generation from the Westphalian has been shown to occur during the Jurassic and Cretaceous.

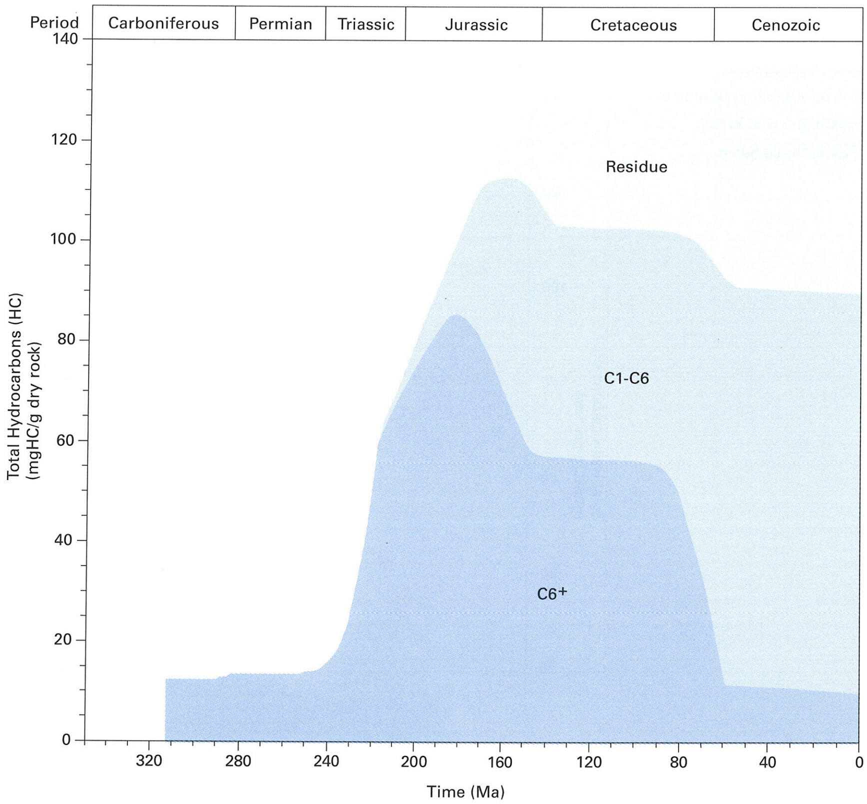
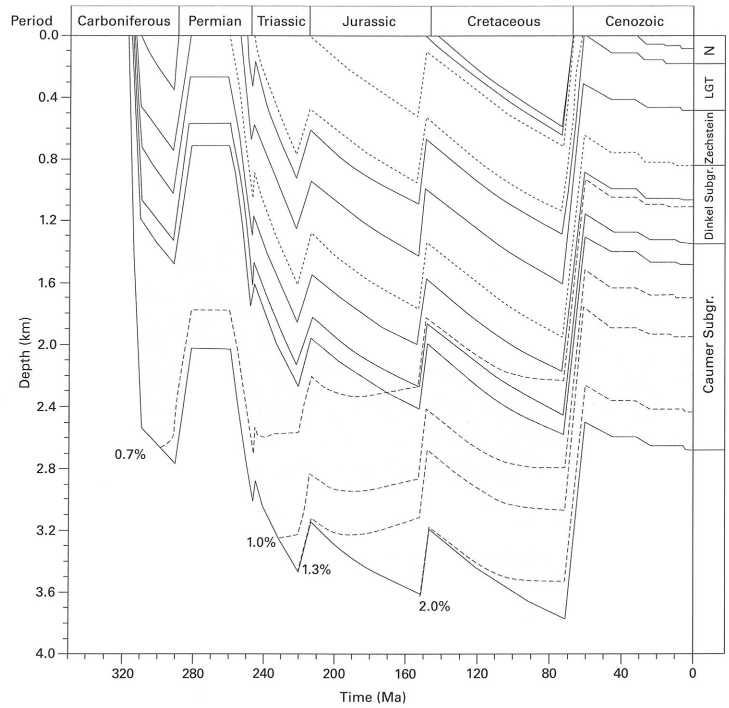


Figure 12.8b Hydrocarbon generation as a function of time in the Tubbergen-8 well on the Tubbergen High.



N North Sea Supergroup
LGT Lower Germanic Trias Group

Figure 12.9a Burial history diagram of the Hengevelde-1 well in the Central Netherlands Basin. Gas was generated from coal seams lying in the gas window (%Rr: 0.9-1.3). The gas generation from the Westphalian has been shown to occur during the Jurassic and Cretaceous.

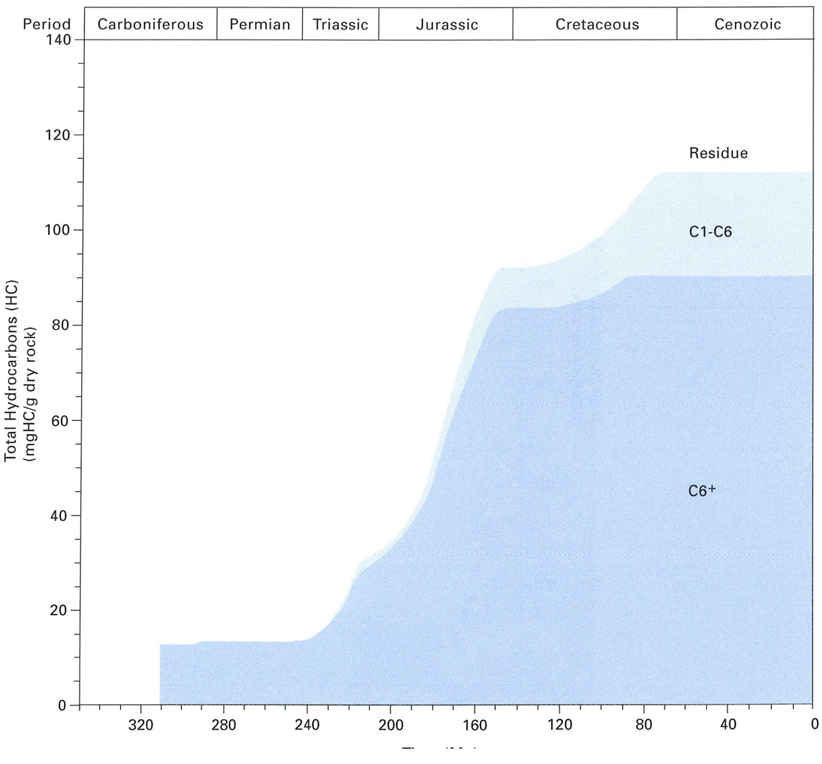


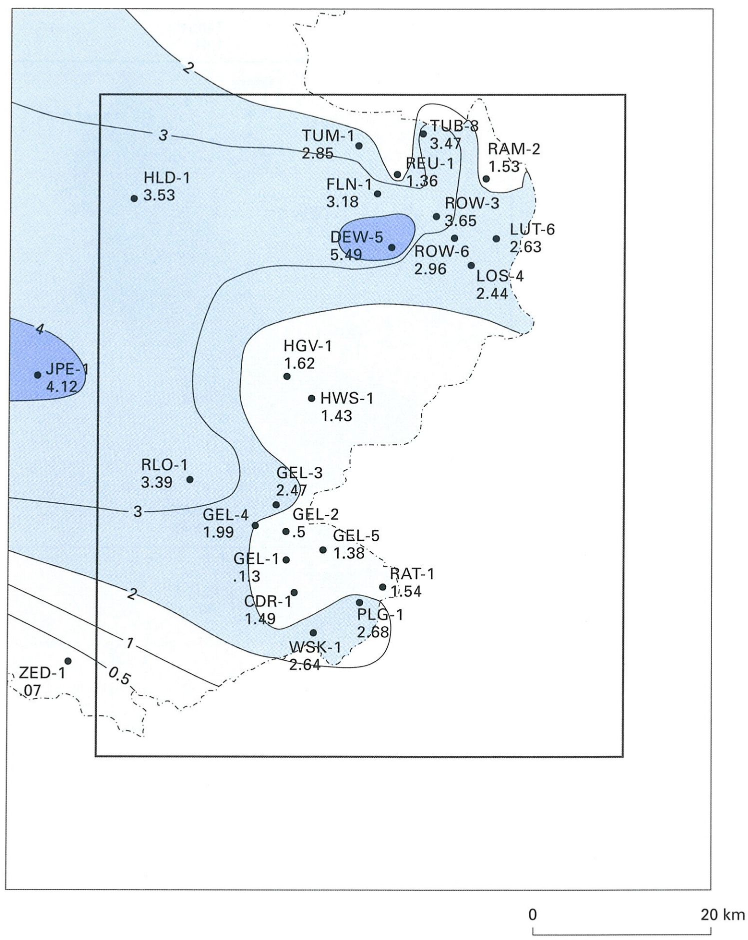
Figure 12.9b Hydrocarbon generation as a function of time in the Hengevelde-1 well in the Central Netherlands Basin.

A study was made of the maceral material of the Limburg and the Zechstein Groups from 25 wells within the map sheet area in order to test the burial model. The degree of coalification was determined from various parameters such as vitrinite reflections (%Rr), RockEval Tmax and various geochemical indices, such as the Oxygen and Hydrogen indices.

12.4.2 Results

The geographical distribution of the wells studied enables a reconstruction to be made of the entire map sheet area. Of the 25 wells investigated, reliable vitrinite-reflection analyses were obtained from 22 of them. These data, supplemented by the literature data (Koch et al., 1997), enable a good understanding of the coalification of the top of the Limburg Group, presenting a picture of increasing coalification in a northerly direction of values below 1%Rr in the Dutch part to over 3%Rr to the northeast of the map sheet area in Germany (fig. 12.7). These high values originate from the additional heat generation produced by the *Bramsche Massif*, a large intrusive body from the Late Cretaceous.

Figure 12.10 Contour map of the hydrocarbon generation during the Jurassic (in $10^9 m^3/km^2$) in the map sheet area. The largest quantities were generated in the Central Netherlands Basin. Towards the edges of the basin, the generation manifestly decreased.



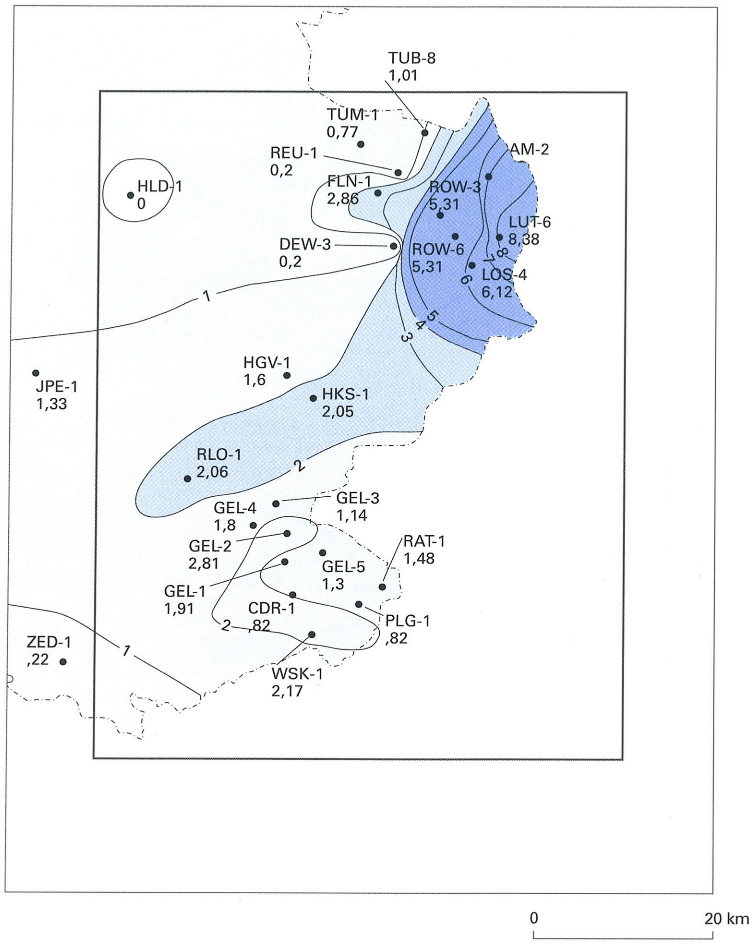
• JPE-1 4.12 well with hydrocarbon generation in $10^9 m^3/km^2$

The burial depth history of the area is illustrated by the Tubbergen-8 well (fig. 12.8a) with respect to the Friesland Platform and the Hengevelde-1 well (fig. 12.9a) with regard to the eastern part of the Central Netherlands Basin. In both wells, the top part of the Limburg Group reaches the oil window, and gas generation was not initiated until approximately 1000 m below the top of the group. The generated hydrocarbons nonetheless display notable differences, the most striking of which is in the significantly greater gas generation in the Tubbergen-8 well (compare figs. 12.8b and 12.9b).

The initial coalification stage occurred already at the end of the Carboniferous as demonstrated by both wells. However, this resulted in only a minor expulsion of hydrocarbons. This expulsion ended with the uplift and erosion associated with the Variscan Orogeny.

The second phase of hydrocarbon generation took place in the Triassic-Cretaceous time span. The principal generation in the Central Netherlands Basin occurred during the Jurassic (fig. 12.10). In view of the uniform subsidence history, the same probably applies to the Lower Saxony Basin situated to the east of the map sheet area. The quantities of hydrocarbons generated in an absolute sense were between 3 and $6*10^9 m^3/km^2$. Towards the margins of the basin, the quantity of generated hydrocarbons rapidly decreased to below $1*10^9 m^3/km^2$.

Figure 12.11 Contour map of the hydrocarbon generation during the Cretaceous (in $10^9 m^3/km^2$) in the map sheet area. The largest quantities were generated in the Lower Saxony Basin.



• JPE-1 4,12 well with hydrocarbon generation in $10^9 m^3 / km^2$

During the Cretaceous, a reorganisation of the subsidence pattern occurred. The Lower Saxony Basin, in particular, began to subside intensively, while in the Central Netherlands Basin subsidence occurred at a slightly lesser rate. The contour map of gas generation during the Cretaceous (fig. 12.11) demonstrates that the area with the highest generation became the boundary area between the Lower Saxony and the Central Netherlands Basin, with the quantity of generated hydrocarbons increasing in an absolute sense to 5 to $8*10^9 m^3/km^2$. With the uplift and erosion related to the inversion movements in the Late Cretaceous, gas generation in the map sheet area came to an end. In the Tertiary, only in the vicinity of the Gronau Fault Zone were small quantities of gas generated.

The distribution of the gas fields encountered in the area (fig. 1.2) reveals that these are situated particularly in or near the area where the greatest generation occurred during the Cretaceous. In addition to this, the presence of rock salt was presumably of importance for the sealing of the reservoirs in the Limburg Group. Furthermore, the forming of gas traps enabled the limestone and dolomite to act as reservoirs above the salt. In the western part of the map sheet area, where less gas was generated in an absolute sense, the absence of a thick rock salt layer and the leakage along faults are thought to be the main reasons for gas fields not being present.

With respect to occurrences of oil in the area, it can be said that the Limburg Group in a large part of the area lies within the oil window, suggesting the extreme likelihood of potential oil accumulations. However, a more detailed picture of the lacustrine oil-source rocks and more information on their areal extent are prerequisites for the exploration of such accumulations.

Appendices

Appendix A

Seismic data used

Survey/Line	*Year*	*Owner*	*2D/3D*
7060*	1970	NAM	2D
7160*	1971	NAM	2D
7260*	1972	NAM	2D
7320*	1973	NAM	2D
7321*	1973	NAM	2D
7322*	1973	NAM	2D
7510*	1975	NAM	2D
7612*	1976	NAM	2D
7710*	1977	NAM	2D
8011*	1980	NAM	2D
8231*	1982	NAM	2D
8601C en D	1986	DG	2D
8727*	1987	NAM	2D
872802	1987	NAM	2D
893040	1989	NAM	2D
85(EN)(V)*	1985	Petroland	2D
87-AK*	1987	Akzo	2D
ANE-83*	1983	Amoco	2D
BW82*	1982	Petroland	2D
CN80*	1980	BP	2D
CN81*	1981	BP	2D
CN8301	1983	BP	2D
Almelo	1985	NAM	3D
Almelo-stad	1986	NAM	3D
Tubbergen	1985	NAM	3D
Wierden	1988	NAM	3D
Twente	1993	NAM	3D

BP = B.P. Exploratie Maatschappij B.V.
DG = Delft Geophysical
NAM = Nederlandse Aardolie Maatschappij B.V.
*random figure

Appendix B

Overview of wells used

No.	*Well*	*Code*	*Owner*	*Final depth*	*Year completed*
1.	Almelo-1	AMO-01	BPM	617	1943
2.	Almelo-2	AMO-02	BPM	584	1944
3.	Almelo-3	AMO-03	NAM	1548	1954
4.	Almelo-4	AMO-04	NAM	1199	1956
5.	Bergentheim-Hardenberg-1	BHH-01	NAM	2420	1959
6.	Beckum-1	BKM-01	KNZ	482	1952
7.	Borne-1	BOR-01	Akzo	544	1982
8.	Buurse-1 (Usselo-1)	BUU-01	KNZ	403	1919
9.	Buurse-2 (Usselo-2)	BUU-02	KNZ	396	1920
10.	Buurse-3 (Usselo-3)	BUU-03	KNZ	390	1920
11.	Buurse-4 (Usselo-4)	BUU-04	KNZ	398	1927
12.	Buurse-5 (Usselo-5)	BUU-05	KNZ	386	1927
13.	Buurse-6 (Usselo-6)	BUU-06	KNZ	385	1928
14.	Buurse-7 (Usselo-7)	BUU-07	KNZ	389	1930
15.	Buurse-8 (Usselo-8)	BUU-08	KNZ	381	1932
16.	Buurse Sluis-1	BSL-01	ROVD	370	1909
17.	Buurse School-1	BUS-01	ROVD	917	1910
18.	Collendoornerveen-1	CLDV-01	NAM	2839	1990
19.	Corle-1	COR-01	ROVD	1284	1923
20.	Delden-Twickel	DED-01		573	1886
21.	Delden-2	DED-02	Akzo	686	1982
22.	Denekamp-1	DEN-01	NAM	1889	1952
23.	Denekamp-2	DEN-02	NAM	2425	1952
24.	Den Velde-1	DVD-1	NAM	3026	1986
25.	Deurningen-Weerselo-1	DEW-01	BPM	259	1942
26.	Deurningen-Weerselo-2	DEW-02	BPM	240	1943
27.	Deurningen-Weerselo-3	DEW-03	BPM	393	1943
28.	Deurningen-Weerselo-4	DEW-04	NAM	1606	1955
29.	Deurningen-Weerselo-5	DEW-05	NAM	2190	1968
30.	Eibergen-1	EIB-01	ROVD	751	1902
31.	Enschede-1	ENS-01	BPM	482	1943
32.	Enschede-2	ENS-02	BPM	596	1943
33.	Fleringen-1	FLN-01	KNZ	1968	1966
34.	Gelria-1 (Lichtenvoorde)	GEL-01	M&H	1017	1925
35.	Gelria-2 (Groenlo)	GEL-02	M&H	941	1925
36.	Gelria-3 (Hupsel)	GEL-03	M&H	1329	1928
37.	Gelria-4 (Groenlo-Meinsink)	GEL-04	M&H	1358	1927
38.	Gelria-5 (Meddeho)	GEL-05	M&H	1263	1927
39.	Geesteren-1	GST-01	NAM	2400	1971
40.	Hengelo-Z-1	HEN-01	KNZ	1521	1966
41.	Hengevelde-1	HGV-01	RGD	1500	1985
42.	Hessum-1	HES-01	CON	2223	1968
43.	Haaksbergen-1	HKS-01	NAM	1008	1950
44.	Hellendoorn-1	HLD-01	NAM	1493	1977
45.	Haarle-1	HLE-01	NAM	1747	1971

continued Appendix B

No.	*Well*	*Code*	*Owner*	*Final depth*	*Year completed*
46.	Joppe-1	JPE-01	RGD	1495	1985
47.	Kloosterhaar-1	KLH-01	NAM	2670	1981
48.	Lochem-1	LOM-01	BPM	595	1943
49.	Lochem-1	LOM-02	BPM	1029	1944
50.	Losser-1	LOS-01	BPM	276	1942
51.	Losser-2	LOS-02	BPM	616	1942
52.	Losser-3	LOS-03	BPM	622	1943
53.	Losser-4	LOS-04	NAM	1914	1958
54.	Lichtenvoorde-2	LTV-02	NAM	733	1952
55.	De Lutte-1	LUT-01	NAM	367	1942
56.	De Lutte-2	LUT-02	NAM	413	1943
57.	De Lutte-3	LUT-03	NAM	394	1943
58.	De Lutte-4	LUT-04	NAM	1461	1946
59.	De Lutte-5	LUT-05	NAM	1408	1956
60.	De Lutte-6	LUT-06	NAM	3206	1989
61.	Lievelde-1	LVD-01	NAM	2295	1975
62.	Oldenzaal-1	OLZ-01	BPM	568	1942
63.	Oldenzaal-2	OLZ-02	BPM	587	1942
64.	Oldenzaal-3	OLZ-03	BPM	315	1942
65.	Oldenzaal-4	OLZ-04	BPM	594	1943
66.	Oldenzaal-5	OLZ-05	BPM	420	1943
67.	Oldenzaal-6	OLZ-06	NAM	2228	1981
68.	Oldenzaal-7	OLZ-07	NAM	1990	1982
69.	Oldenzaal-8	OLZ-08	NAM	2618	1983
70.	Ommen-1	OMM-01	BPM	659	1943
71.	Ommen-2	OMM-02	NAM	1548	1949
72.	Ommen-3	OMM-03	NAM	2788	1979
73.	Ootmarsum-1	OOT-01	BPM	688	1943
74.	Oele-Zegger-1	OZG-01	KNZ	493	1929
75.	Oele-Zegger-2	OZG-02	KNZ	463	1929
76.	Plantengaarde-1	PLG-01	ROVD	1134	1909
77.	Raalte-1	RAL-01	BPM	685	1943
78.	Raalte-2	RAL-02	BP	1679	1983
79.	Rammelbeek-1	RAM-01	NAM	1076	1955
80.	Rammelbeek-2	RAM-02	NAM	2606	1970
81.	Ratum-1	RAT-01	ROVD	1380	1911
82.	Reutum-1	REU-01	NAM	2551	1970
83.	Rossum-Weerselo-1	ROW-01	BPM	748	1943
84.	Rossum-Weerselo-2	ROW-02	NAM	1230	1955
85.	Rossum-Weerselo-3	ROW-03	NAM	2453	1968
86.	Rossum-Weerselo-4	ROW-04	NAM	2193	1971
87.	Rossum-Weerselo-5	ROW-05	NAM	2047	1972
88.	Rossum-Weerselo-6	ROW-06	NAM	2256	1976
89.	Rossum-Weerselo-7	ROW-07	NAM	2250	1977
90.	Rossum-Weerselo-8	ROW-08	NAM	2540	1978

continued Appendix B

No.	*Well*	*Code*	*Owner*	*Final depth*	*Year completed*
91.	Rossum-Weerselo-9	ROW-09	NAM	2393	1978
92.	Ruurlo-1	RLO-01	RGD	1503	1984
93.	Sibculo-1	SIB-01	BPM	655	1944
94.	Twekkelo-1	TKO-01	KNZ	294	1951
95.	Twekkelo-2	TKO-02	KNZ	402	1951
96.	Twekkelo-3 (Mensinkshoek)	TKO-03	KNZ	346	1929
97.	Tubbergen-1	TUB-01	BPM	667	1943
98.	Tubbergen-2	TUB-02	BPM	589	1944
99.	Tubbergen-3	TUB-03	NAM	1251	1949
100	Tubbergen-4	TUB-04	NAM	1477	1951
101	Tubbergen-5	TUB-05	NAM	2824	1967
102	Tubbergen-6	TUB-06	NAM	772	1952
103	Tubbergen-7	TUB-07	NAM	1543	1954
104	Tubbergen-8	TUB-08	NAM	3206	1967
105	Tubbergen-9	TUB-09	NAM	3024	1973
106	Tubbergen-10	TUB-10	NAM	3122	1974
107	Tubbergen-11	TUB-11	NAM	3212	1976
108	Tubbergen-12	TUB-12	NAM	3030	1976
109	Tubbergen-Mander-1	TUM-01	NAM	2456	1968
110	Tubbergen-Mander-2	TUM-02	NAM	1859	1973
111	Tubbergen-Mander-3	TUM-03	NAM	2530	1978
112	Twente-Rijn-1	TWR-001	KNZ	374	1935
113	Twente-Rijn-2	TWR-002	KNZ	371	1935
114	Twente-Rijn-3	TWR-003	KNZ	387	1935
115	Twente-Rijn-4	TWR-004	KNZ	385	1935
116	Twente-Rijn 5	TWR-005	KNZ	384	1936
117	Twente-Rijn-10	TWR-010	KNZ	400	1940
118	Twente-Rijn-20	TWR-020	KNZ	398	1950
119	Twente-Rijn-30	TWR-030	KNZ	451	1953
120	Twente-Rijn-50	TWR-050	KNZ	380	1958
121	Twente-Rijn-71	TWR-071	KNZ	345	1962
122	Twente-Rijn-72	TWR-072	KNZ	360	1961
123	Twente-Rijn-81	TWR-081	KNZ	395	1963
124	Twente-Rijn-104	TWR-104	KNZ	491	1965
125	Twente-Rijn-107	TWR-107	KNZ	479	1965
126	Twente-Rijn-119	TWR-119	KNZ	462	1966
127	Twente-Rijn-131	TWR-131	KNZ	425	1967
128	Twente-Rijn-156-A	TWR-156a	Akzo	511	1975
129	Twente-Rijn-159	TWR-159	Akzo	510	1969
130	Twente-Rijn-168	TWR-168	Akzo	504	1970
131	Twente-Rijn-200	TWR-200	Akzo	552	1970
132	Twente-Rijn-247	TWR-247	Akzo	469	1973
133	Twente Rijn-303	TWR-303	Akzo	482	1981
134	Twente-Rijn-336	TWR-336	Akzo	444	1987
135	Twente-Rijn-385	TWR-385	Akzo	479	1992

continued Appendix B

No.	*Well*	*Code*	*Owner*	*Final depth*	*Year completed*
136	Vriezenveen-1	VRV-01	BPM	701	1944
137	Wierden-1	WIR-01	NAM	848	1949
138	Weerselo-1	WLO-01	BPM	889	1943
139	Winterswijk-1	WSK-01	NAM	5009	1978
140	Zeddam-1	ZED-01	NAM	1964	1954

BPM = Bataafsche Petroleum Maatschappij (1940-1945: consortium BPM/Elwerath)
BP = B.P. Exploratie Maatschappij B.V.
CON = Continental Netherlands Oil Company
KNZ = Koninklijke Nederlandse Zoutindustrie N.V.
M&H = Nederlandse Maatschappij voor het Verrichten van Mijnbouwkundige Werken-Hope & Co.
NAM = Nederlandse Aardolie Maatschappij B.V.
RGD = Rijks Geologische Dienst
ROVD = Dienst der Rijksopsporing van Delfstoffen

German well-data derived from literature references:

No.	*Well*	*Final depth*	*Lit. ref.*
141	Alfred-1 (Dingden 1)	1349	Van Waterschoot (1909)
142	Bentheim-1	1232	Hinze (1988)
143	Bentheim-2	901	Thiermann (1968)
144	Bentheim-11	2546	Thiermann (1968)
145	Borkenwirthe-1		Wolburg (1961)
146	Coesfeld-Süd-1	930	Wolburg (1957)
147	Gildehaus Süd-1	765	Thiermann (1968)
148	Gildehaus-Z-1	1683	Thiermann (1968)
149	Gronau-49	158	Thiermann (1968)
150	Gronau-50	192	Thiermann (1968)
151	Gronau-DEA-1	1890	Thiermann (1968)
152	Gronau-DEA-2	749	Thiermann (1968)
153	Gronau-Z-1	1511	Wolburg (1961)
154	Gronau-Epe-1	1789	Wolburg (1961)
155	Homer-1	1000	Wolburg (1969)
156	Isselburg-1	1422	Wolburg (1957)
157	Isselburg-2	1968	Wolburg (1957)
158	Isselburg-3	4367	Wolburg (1970a)
159	Itterbeck-1	844	Bentz (1947)
160	Münsterland-1	5956	Richwien et al. (1963)
161	Neu Gronau-2	692	Thiermann (1968)
162	Nordhorn-Z-1	2817	Hinze (1988)
163	Norddeutschland-8	3426	Hinze (1988)
164	Ochtrup-Z-1	2153	Thiermann (1968)
165	Oeding-1	1328	Van Waterschoot (1909)
166	Salzreich I	1091	Thiermann (1968)
167	Salzreich II	720	Thiermann (1968)
168	Salzreich III	472	Thiermann (1968)
169	Vardingholt-1	1000	Wolburg (1957)
170	Vreden-1	1229	Van Waterschoot (1909)
171	Weseke-1	1319	Bentz (1947)
172	Wielen-Z-1	2735	Schuster (1962)
173	Westenberg-2	200	Van Waterschoot (1909)

A number of these wells are also documented in the Deutscher Planungsatlas (1976). In addition, detailed interpretations of Upper Jurassic sequences of a considerable number of wells have been derived from Bischoff & Wolburg (1963).

Appendix C

Reservoir calculations Limburg Group

The calculations in the three tables were carried out for the entire Limburg Group, the De Lutte Formation and the Tubbergen Formation respectively. Cut-off values applied: clay content Vcl(co)=50 %; effective porosity Øe(co)=8 %. The cut-off value of the effective porosity is based on core data from wells in map sheet V (Rijks Geologische Dienst, 1993c). Wells in which not all of the indicated sequence was evaluated of the Limburg Group or the Tubbergen Formation respectively are marked with *.

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

Limburg Group (Tubbergen Formation, De Lutte Formation)

Well	*Gross*	*Reservoir*		
		Net	Øem	Vclm
DVD-1	216.8	90.4	12.2	21.4
FLN-1*	139.3	70.7	12.5	24.7
GST-1*	216.1	75.2	11.2	27.4
HGV-1	123.0	98.0	16.3	26.5
OLZ-6*	250.9	72.9	9.7	19.2
OMM-3*	30.3	7.7	12.1	32.2
ROW-6*	168.7	48.2	12.7	21.8
TUB-5*	630.2	203.8	11.4	20.3
TUM-1*	432.3	255.2	13.3	16.0

De Lutte Formation

Well	*Gross*	*Reservoir*		
		Net	Øem	Vclm
OLZ-6	18.8	0.8	8.4	19.7
ROW-6	14.3	0.0		
TUB-5	145.3	19.9	11.0	31.4

Tubbergen Formation

Well	*Gross*	*Reservoir*		
		Net	Øem	Vclm
DVD-1	216.8	90.4	12.2	21.4
FLN-1*	139.3	70.7	12.5	24.7
GST-1*	216.1	75.2	11.2	27.4
HGV-1	123.0	98.0	16.3	26.5
OLZ-6*	232.1	72.1	9.7	19.2
OMM-3*	30.3	7.7	12.1	32.2
ROW-6*	154.4	48.2	12.7	21.8
TUB-5*	484.9	183.9	11.4	19.1
TUM-1*	432.3	255.2	13.3	16.0

Show, status and test data Limburg Group

Well	Show	Status	Test	Interval	Yield	Flow	Unit
DVD-1	gas	GAS	RFT	2987-3218			DCDT, DCCU
			PRP1	2977-3149	G	265(pa)	DCDT
FLN-1	-	D&A	DST1	1761-1770	-		ROSL, DCDT
			DST2	1761-1786	SWCM+G	2950	ROSL, DCDT
GST-1	-	D&A	-				
HGV-1	oil	D&A	-				
OLZ-6	gas	D&A	RFT	1896-2211	-		DCHL, DCDT
OMM-3	-	D&A	-				
ROW-6	-	GAS	PRP1	2076-2152	G	90(pa)	DCDT
					C	1(pa)	
					W	0.2(pa)	
			PRP2	2047-2152	G	250(pa)	DCDT
					C	3(pa)	
					W	9(pa)	
TUB-5	-	GAS	PRP	2154-2383	G	275	ROSL, DCHL,
					C	3	DCDT
					W	1	
TUM-1	-	D&A	-				

Legend appendices D and F

Status:

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

Test:

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

test interval in metres log depth

Yield:

G = gas
C = condensate
W = water
M = mud
GCM = gas cut mud
SWCM = salt water cut mud

(u) = in uppermost chamber of RFT
(l) = in lowermost chamber of RFT
pa = post acidity

Unit = formation or member

ZEZ3G = Grey Salt Clay
ZEZ3C = Z3 Carbonate
ZEZ2C = Z2 Carbonate
ROSL = Slochteren Formation
DCHL = De Lutte Formation
DCDT = Tubbergen Formation
DCCU = Maurits Formation

Reservoir calculations Z2 Carbonate and Z3 Carbonate

Cut-off values applied: clay content Vcl(co)=50 %; effective porosity Øe(co)=2 %. The cut-off value of the effective porosity is based on core data.
Wells in which not all of the indicated sequence was evaluated are marked with * . ZEZ2C is missing in WSK-1 well; ZEZ3C was not evaluated owing to incompleteness of the well-log data of TUB-5 well.

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

Z3 Carbonate

Well	*Gross*	*Reservoir*		
		Net	Øem	Vclm
CLDV-1	9.4	6.3	5.9	9.5
GST-1	36.1	32.3	6.5	2.6
HES-1	41.3	40.9	9.7	2.7
LUT-6	27.4	20.2	7.2	6.9
OLZ-6*	19.0	9.3	4.3	5.8
RAM-2	27.4	11.9	3.7	3.0
WSK-1	17.5	16.8	11.0	4.0
Bentheim[1]	45	40	4.1	

Z2 Carbonate

Well	*Gross*	*Reservoir*		
		Net	Øem	Vclm
CLDV-1	62.3	61.1	16.5	3.4
GST-1	32.3	25.7	6.4	3.3
HES-1	56.0	56.0	8.8	3.5
LUT-6	70.6	3.2	21.9	5.7
OLZ-6	35.0	1.6	5.3	2.7
RAM-2	55.4	2.5	2.9	1.8
TUB-5*	30.8	11.4	5.6	4.9
Bentheim[1]	40	18	3.5	

[1] Average value for the entire gas field; after Heidorn & Kessler (1959).

Show, status and test data Z2 Carbonate and Z3 Carbonate

Well	*Show*	*Status*	*Test*	*Interval*	*Yield*	*Flow*	*Unit*
CLDV-1	gas	GAS	RFT1	2425-2471	G (u)		ZEZ2C
					G (l)		
			PRP2	2416-2472	G	3800 (pa)	ZEZ2C
					C	110 (pa)	
					W	10 (pa)	
CLDV-1	gas	D&A	RFT	2375-2386	-		ZEZ3C, ZEZ3G
GST-1	-	D&A	-				
HES-1	-	D&A	-				
LUT-6	-	GAS	PRP	?	G	2700 (pa)	ZEZ2C
OLZ-6	-	D&A	-				
RAM-2	gas	SUS	PRP	2057-2110	G	1000 (pa)	ZEZ2C
					C	230 (pa)	
					W	2 (pa)	
RAM-2	-	SUS	PRP	1975-2000	G	100 (pa)	ZEZ3C
					C	160 (pa)	
TUB-5	-	D&A	DST7	1769-1780	GCM+C		ZEZ2C
			DST8	1769-1790	GCM+C	500	ZEZ2C
			DST9	1769-1814	GCM+C	3000	ZEZ2C
WSK-1	-	D&A	-				

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The maps were compiled by
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Printing
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Explanation:

The explanation was written by
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Design
BRS Premsela Vonk, Amsterdam
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Printing
Sdu Grafisch Bedrijf, Den Haag

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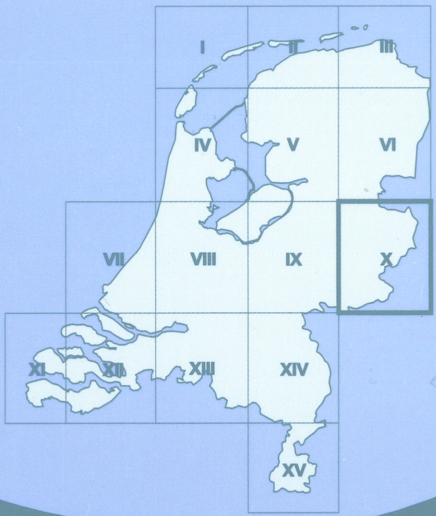
ISBN 90-6743-525-2.

NITG-TNO, 1998 - Geological Atlas of the Subsurface of The Netherlands, Explanation to map sheet X: Almelo-Winterswijk, Haarlem.

This publication is a translation of the Dutch version ISBN 90-6743-526-0

Deze publikatie is vertaald vanuit het Nederlands ISBN 90-6743-526-0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