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Late Cretaceous – Early Tertiary sedimentation and tectonic inversion in the southern Netherlands

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Abstract

Analysis of the Upper Cretaceous stratigraphy of the Peel Block reveals the basin development of the block to have been influenced by both the inversion of the Roer Valley Graben and Central Netherlands Basin, and the overall Late Cretaceous transgression. Sediments of Santonian to Danian age were deposited on the block. These sediments are compared with the detailed lithostratigraphy of southern Limburg, where Late Cretaceous strata are exposed. Four successions can be recognised in southern Limburg. The two oldest successions, the Santonian Oploo Formation (new name, proposed in the present contribution) and the mainly Early Campanian Vaals Formation, are restricted to the central and northern parts of the block. These siliciclastic formations were deposited under the influence of inversion of the Roer Valley Graben and the Central Netherlands Basin, as well as under the influence of a rising sea level. Towards the north, sands of the Oploo Formation grade into marls and chalks of the Ommelanden Formation. The two youngest successions comprise the largely Late Campanian to Maastrichtian Gulpen and Maastricht Formations and the Danian Houthem Formation. These chalk formations were deposited under the influence of regional subsidence during a sea-level highstand. Subsequent to deposition of the Houthem Formation, a regional regression triggered a change from shallow-marine carbonate to paralic siliciclastic deposition.

Introduction

The Peel Block is located in the southern Netherlands, bordering Germany (Figure 1). During Late Jurassic to Early Cretaceous and Cenozoic times, it formed the northeastern rift shoulder of the Roer Valley Graben. Due to its vicinity to the coal-mining areas of western Germany and of southern Limburg in the Netherlands, and because its Cenozoic cover is relatively thin (400–600 m), the stratigraphy and tectonic evolution of the block were studied extensively. Coal-exploration drilling revealed the top of the Carboniferous to be relatively deep in the north, and demonstrated the unfavourable development of the overburden for underground mining. The southern part, however, was identified as a future area for coal mining (Van Waterschoot van der Gracht 1909, 1918, Tesch 1912).

De Sitter (1942) and Patijn (1963) outlined the major tectonic events in the area, and Pannekoek (1951) stressed the importance of the Late Cretaceous episode of reverse faulting (the ‘post-Senonian overthrusts’), which had been observed previously in Germany. Further exploration of the southeastern part of the block occurred between 1950 and 1955, with a view to develop the Carboniferous coal resources. Following the findings of the Peelcommissie (1963), development of the extensive, but deep coal seams was considered uneconomic, particularly so as the huge natural gas resources in the subsurface of the Netherlands were discovered around this time. The planned exploitation of the coal field near Herkenbosch, for which the ‘Beatrix’ shaft was sunk, thus never took place.

One hydrocarbon exploration well, Grashoek-1, was drilled by the Nederlandse Aardolie Maatschappij (NAM) on the Peel Block in 1970. It was plugged and abandoned at a depth of 410 m below sea level in Cenozoic strata after having encountered oil shows in the Oligocene. Other oil shows in Oligocene rocks have been reported from both sides of the Roer Valley Graben by Van Waterschoot van der Gracht (1909 1918) and Van Riessen & Vandenberghe (1996), respectively. The northern part of the Peel Block was licensed (the 'Buren' licence) to Mobil Producing Netherlands Inc. in the 1988–1993 period (Ministerie van Economische Zaken 1994), but no wells were drilled during this period. The block is currently not under a hydrocarbon-exploration licence, reflecting that it is generally considered unprospective for hydrocarbons. The most recent wells are Oploo-59 and Arcen-1, both water wells, drilled in 1986 and 1987, respectively. Well Arcen-1 currently produces thermal mineral water from the Zechstein for a spa.

The position of the Peel Block within the large-scale tectonic framework of the Netherlands was discussed by Heybroek (1974), and more recently by Burgers & Mulder (1991) and Van Adrichem Boogaert & Kouwe (1993–1997). The Upper Cretaceous stratigraphy in northern Belgium and southern Limburg, as based on outcrop and well data, was reviewed by P.J. Felder et al. (1985), Bless et al. (1987) and W.M. Felder (1996). Data on the Late Cretaceous Subhercynian tectonic inversion in northwestern Europe were published by Kockel (1987), Van Hoorn (1987), Baldschuhn et al. (1991) and Mogensen & Jensen (1995). Case studies on the inversion of the Jurassic – Early Cretaceous basins in the Netherlands (West Netherlands Basin, Broad Fourteens Basin and Central Graben) were published by Van Wijhe (1987), Dronkers & Mrozek (1991), Hooper et al. (1995) and De Jager et al. (1996). The stratigraphy, subsidence and tectonic evolution of the Peel Block and Roer Valley Graben were discussed by Zijerveld et al. (1992), Geluk et al. (1994) and Gras (1995). Recently, a renewed interest in the Chalk Group of the southern Netherlands has arisen from the study of the Cretaceous–Tertiary boundary (Brinkhuis & Smit 1996).

The present study is aimed at the basin development on the Peel Block during the Late Cretaceous and Early Tertiary by means of a stratigraphic review and correlation of the Chalk Group, based on wells and seismic data. The detailed stratigraphy for the Upper Cretaceous in southern Limburg (see Felder 1996) is utilised as an analogue for the block. The observed stratigraphy has important implications for the tectonic history of the block in relation to the adjacent Roer Valley Graben and Central Netherlands Basin. A practical application of the present contribution is in the data about the distribution of Danian chalk deposits, which might in places be suitable for extraction of mineral water.

Database

Key well data comprise the public-domain or 'non-exclusive' wells Arcen-1, Oploo-16, and Liessel-22 (Figure 1).

Arcen-1 is a thermal-water production well drilled in 1987 by the Klein Vink recreation park. Well data comprise a gamma-ray, a sonic, and a resistivity log, as well as lithological descriptions. Wells Oploo-16 and Liessel-22 are coal-exploration wells, drilled in 1911–1912 and 1915, respectively (Van Waterschoot van der Gracht 1918). Well Oploo-16 encountered oil stains in the Oligocene at 200 and 300 m, and an overpressurised water-bearing Chalk section. The top of the Carboniferous was never reached, as an anomalously thick Cretaceous overburden was, unexpectedly, penetrated. Well Liessel-22 showed the top of the Carboniferous to be too deep for coal mining, and the unfavourable lithological development of the Cretaceous made matters worse.

The Cretaceous section of the Maasbommel-1 well was released by NAM for stratigraphic analysis (Gras 1995). Additional published well data allowing regional control comprise Molenbeersel (Bless et al. 1993), Asten-1, Nederweert-1, Loon op Zand-1 and St. Michielsgestel-1 (Van Adrichem Boogaert & Kouwe 1993–1997), America-11, Sevenum-19, Maris-18, Neer-71, Reuver-76, Maasniel-74 and Elmt-77 (Peelcommissie 1963, Van Waterschoot van der Gracht 1909 1918), Emmerich-1 and Wachtendonk-1 (Elberskirch & Wolburg 1962), Straeten-1 (Fabian 1958), Uedem-1 (Klostermann 1992) and several other German wells (Klostermann 1983, Hilden 1988), as well as Bree-201 (De Craen & Swennen 1992), Asten-2 (Heederik 1988) and Waalwijk-1 (Winstanley 1993).

Seismic data comprise the nonexclusive DG8601 seismic line and 115 km of 2D seismic lines acquired by the Geological Survey of the Netherlands in 1982–1983 during a coal-inventory study. Furthermore, Plein et al. (1982) published three regional seismic sections from the adjacent German area. Other literature data have also been used to interpret the geology across the international border (Hilden 1988,

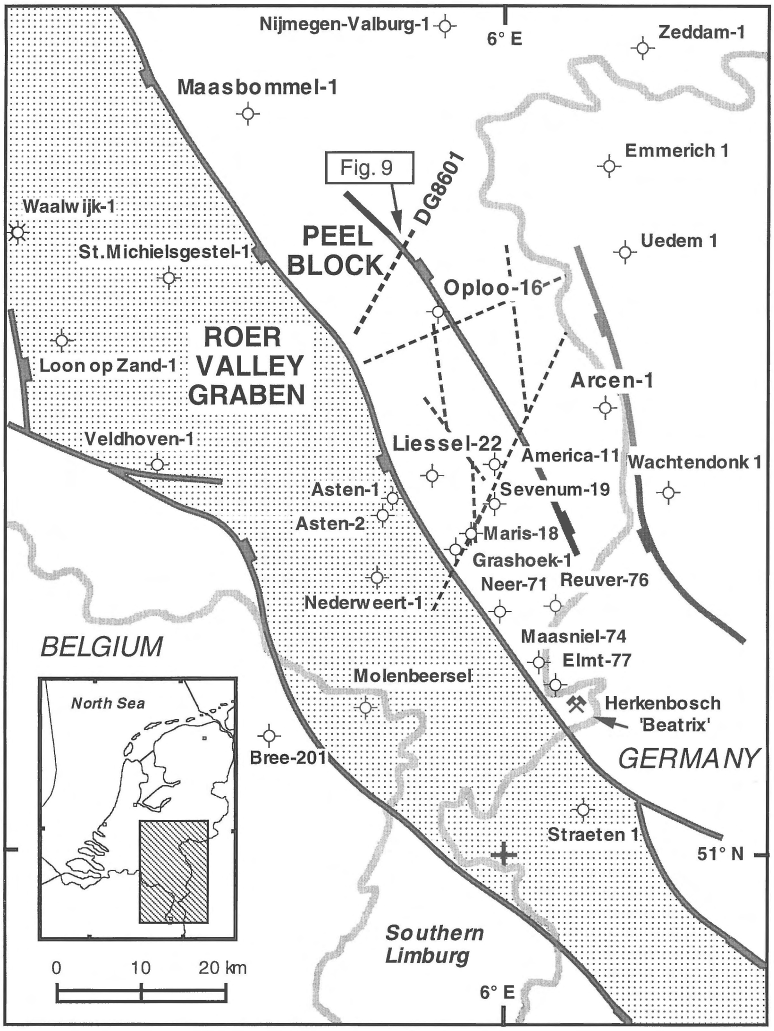

Figure 1. Location map of the study area, showing an overview of the well and seismic database (dashed lines). Solid black lines represent normal faults, with tickmarks indicating their dips.

1995, Klostermann 1983, Plein et al. 1982, Wolf 1985). Figure 1 presents an overview of the database of the present study.

Late Cretaceous regional setting and stratigraphy

The tectonic history of northwestern Europe during the Late Cretaceous and Early Cenozoic was controlled by two major events: the opening of the North Atlantic Ocean and the initiation of the Alpine plate collision (Ziegler 1981). During the Late Cretaceous, a large portion of northwestern Europe and the present North Sea area formed a marine platform bordering the passive Atlantic continental margin. The study area is situated near the southern, landward, margin of this platform. The Late Cretaceous basin was initially bounded to the north by the Fennoscandia continent, to the west by the British Islands and to the south by the London–Brabant Massif and the Rhenish Massif (the Mid-European islands). The platform was connected with the Arctic Ocean, the North Atlantic and, across the Paris Basin, the Tethys. The sediments on this platform were predominantly fine-grained bioclastic limestones. In the North Sea region, these relatively uniform sediments are referred to as the 'Chalk Group'.

The opening of the North Atlantic during the Cretaceous corresponded in the North Sea region with

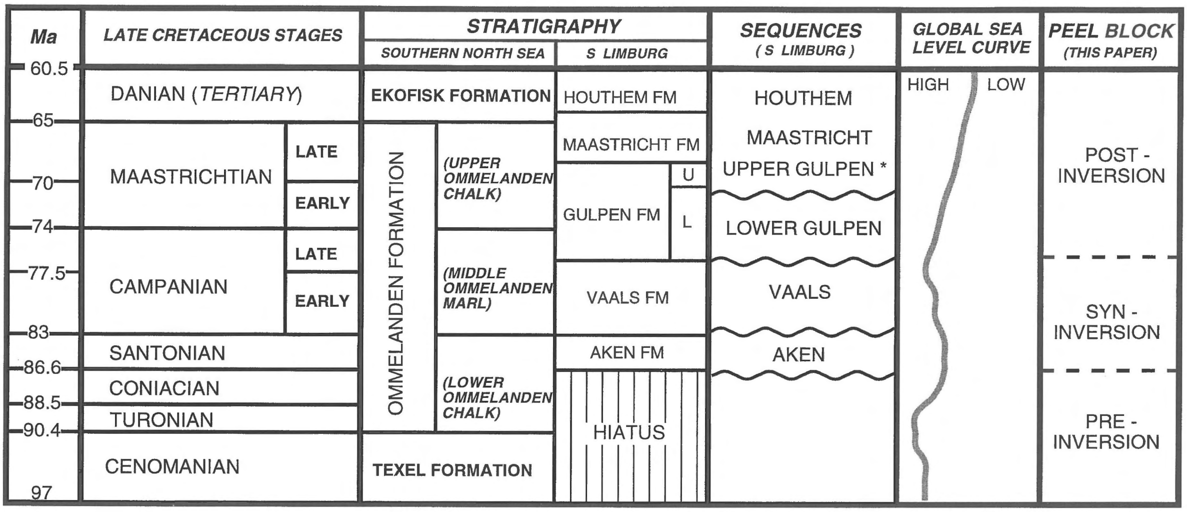

Figure 2. Stratigraphic nomenclature of the Late Cretaceous Chalk Group; southern Limburg area after P.J. Felder et al. (1985), southern North Sea based on Van Adrichem Boogaert & Kouwe (1993–1997). The subdivision of the Ommelanden Chalk Formation is informal. The lower Gulpen Formation includes the Vylen Chalk Member (W.M. Felder 1996); this member is here considered to belong to the Upper Gulpen–Maasticht–Houthem succession (*).

the cessation of rift tectonics and the onset of regional subsidence (Ziegler 1981). The Late Cretaceous acceleration of global sea-floor spreading, as well as climatic changes, are considered to have induced a first-order global sea-level rise (Donovan & Jones 1979). This led to worldwide transgressions and, consequently, to a progressive inundation of the margins of the Late Jurassic – Early Cretaceous rift basins. In NW Europe, the Late Cretaceous transgression inundated the land areas that existed during the Early Cretaceous, leading to immobilisation of clastic sources and to deposition of predominantly bioclastic carbonates.

In the Tethyan realm, plate collision commenced during the Coniacian-Santonian as a result of the convergence of Eurasia and Africa. The resultant compressional stresses may have been transmitted through the crust of the NW European platform, giving rise to the widespread Late Cretaceous inversion tectonics (Ziegler 1981). The onset of the inversion tectonics occurred in Coniacian to Santonian times; the movements are estimated to have lasted 5–7 Ma and ceased during the Campanian (Baldschuhn et al. 1991). In the Netherlands, the inversion of the Late Jurassic to Early Cretaceous rift basins explains the absence of the Chalk Group in these basins. In contrast, thick Chalk Group deposits are found on the former highs around these basins (Heybroek 1974, Hooper et al. 1995, De Jager et al. 1996). The inverted Roer Valley Graben and Central Netherlands Basin formed a barrier that prevented the migration of faunas. Campanian faunas that differ from those of the Peel area have been identified in the Münsterland Basin in western Germany and to the south of the Roer Valley Graben (Arnold 1968, Hilden & Thiermann 1987, Bless et al. 1993).

In the southern Netherlands, the Late Cretaceous transgression progressively overstepped the London–Brabant Massif from the basin in the north. During the Late Maastrichtian, the massif was flooded. There are indications, e.g., the mixing of Tethyan faunas with the northern, Boreal faunas (Bless et al. 1993), for a connection with the southern region across the Paris Basin. Separate stratigraphic subdivisions of the Chalk Group exist for the central and northern Netherlands onshore and offshore areas (Van Adrichem Boogaert & Kouwe 1993–1997) and for the southern Netherlands, mainly the area of southern Limburg around Maastricht (Kuyl 1983, P.J. Felder et al. 1985, W.M. Felder 1996). A correlation of the stratigraphic nomenclatures of the Chalk Group in both regions is presented in Figure 2. The subdivision of the Ommelanden Formation into members, as indicated in this figure, is informal. For a proper understanding of the inversion tectonics, a detailed subdivision of the Chalk Group is a prerequisite, since the movements were synsedimentary (Kockel 1987).

The subdivision into formations for southern Limburg can be applied to the Peel and Venlo blocks

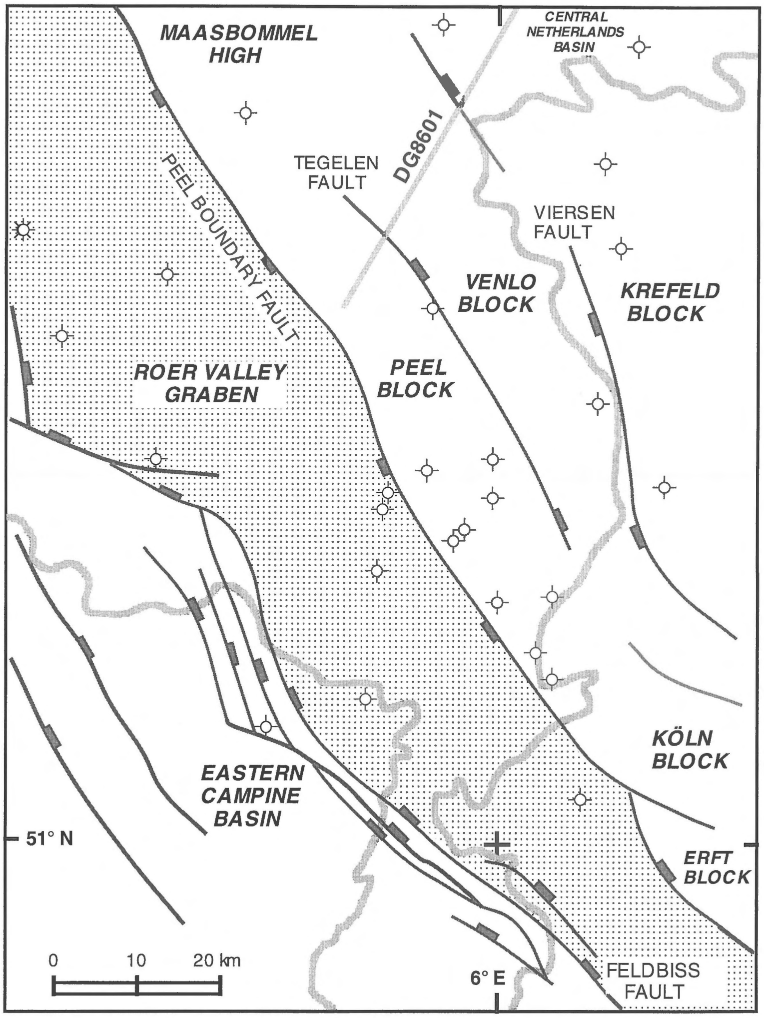

Figure 3. Structural elements of the study area. See Figure 1 for names of wells shown. All faults have a net normal displacement, despite reverse displacement during part of the Late Cretaceous. Tickmarks on the faults display their dip directions.

with just one modification, namely the Aken Formation. This formation comprises in its type area coastal to lagoonal clastic sediments, which differ from the marine clastics encountered in drill holes in the Peel area. We propose the name 'Oploo Formation', after the Oploo-16 well, for these marine sandy sediments.

Structural elements

The structural setting of the study area comprises two Late Jurassic – Early Cretaceous rift basins, the Roer Valley Graben and the Central Netherlands Basin (Figure 3). The Peel Block, together with the Venlo Block, the Krefeld Block and the Maasbommel High, are situated between these basins. The Peel Block is separated from the Roer Valley Graben by the Peel Boundary Fault, a fault with a long history of repeated and even present-day activity (Camelbeeck & Van Eck 1994). The Peel, Venlo and Krefeld blocks together form an intermediate area between the deeply subsided Roer Valley Graben and the Rhenish Massif. The Maasbommel High is the extension of these blocks towards the northwest. The extension of the Peel and Venlo blocks towards Germany is named the 'Köln Block' (Geluk et al. 1994). For overviews of the regional tectonic history of the Roer Valley Graben in relation to the Peel Block, reference is made to Geluk (1990), Geluk et al. (1994) and Gras (1995).

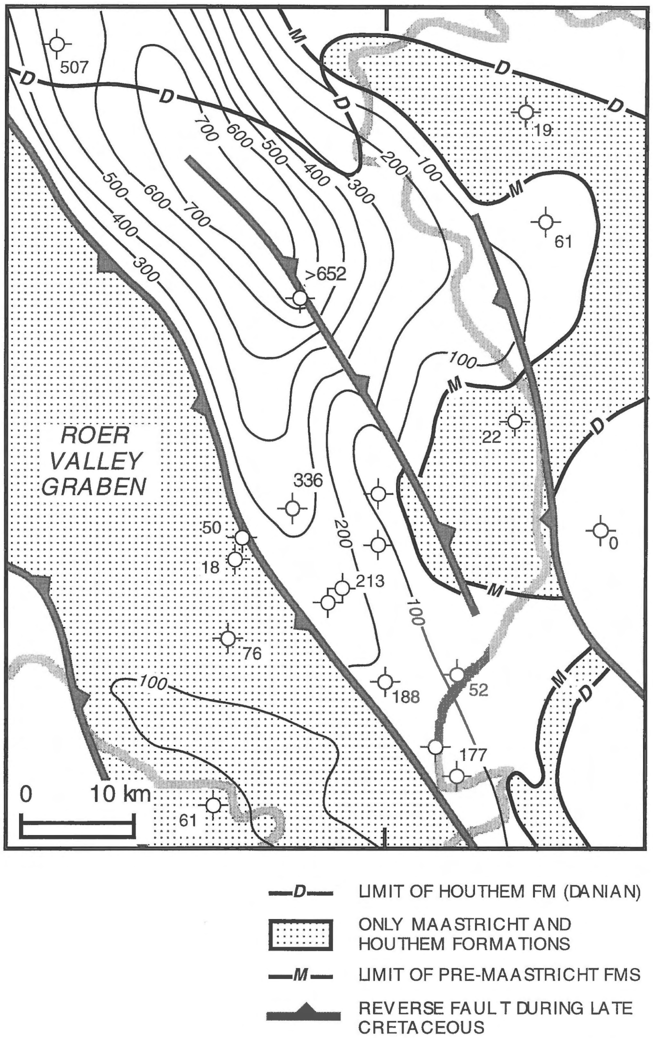

Figure 4. Distribution and isopach map of the Chalk Group, based on seismic and well data and literature sources (Klostermann 1983, Hilden 1988). The contour interval is 100 m.

The *Peel Block* is separated from the Venlo Block by the Tegelen Fault. It forms the shallowest part of the rift shoulder. The thickness of the Chalk Group on the block increases towards the northwest from approx. 100 m to over 700 m (Figure 4). In the southeast of the block, the Chalk Group rests upon Carboniferous rocks.

The *Venlo Block* is characterised by thicker Miocene to Quaternary sediments relative to the Peel Block (Van Adrichem Boogaert & Kouwe 1993–1997). The Chalk Group, on the other hand, is much thinner. In the southeast of the block, this group only comprises sediments of Maastrichtian to Danian age. Towards the Maasbommel High in the northwest, the thickness and chronostratigraphic range of the Chalk Group increase.

The *Krefeld Block* is separated from the Venlo Block by the normal, down-to-the-west Viersen Fault. On the block, entirely within Germany, Oligocene sediments rest directly upon rocks of Carboniferous to Devonian age. Permian and Mesozoic sediments were eroded during the Kimmerian tectonic phases (Plein et al. 1982). Remnants of the Chalk Group of Maastrichtian to Danian age occur locally (Klostermann 1983).

The *Maasbommel High* forms a deeply eroded fault block, with Albian transgressing upon Upper Carboniferous to Triassic rocks (Heybroek 1974, Gras 1995). It is situated to the northwest of the Peel and

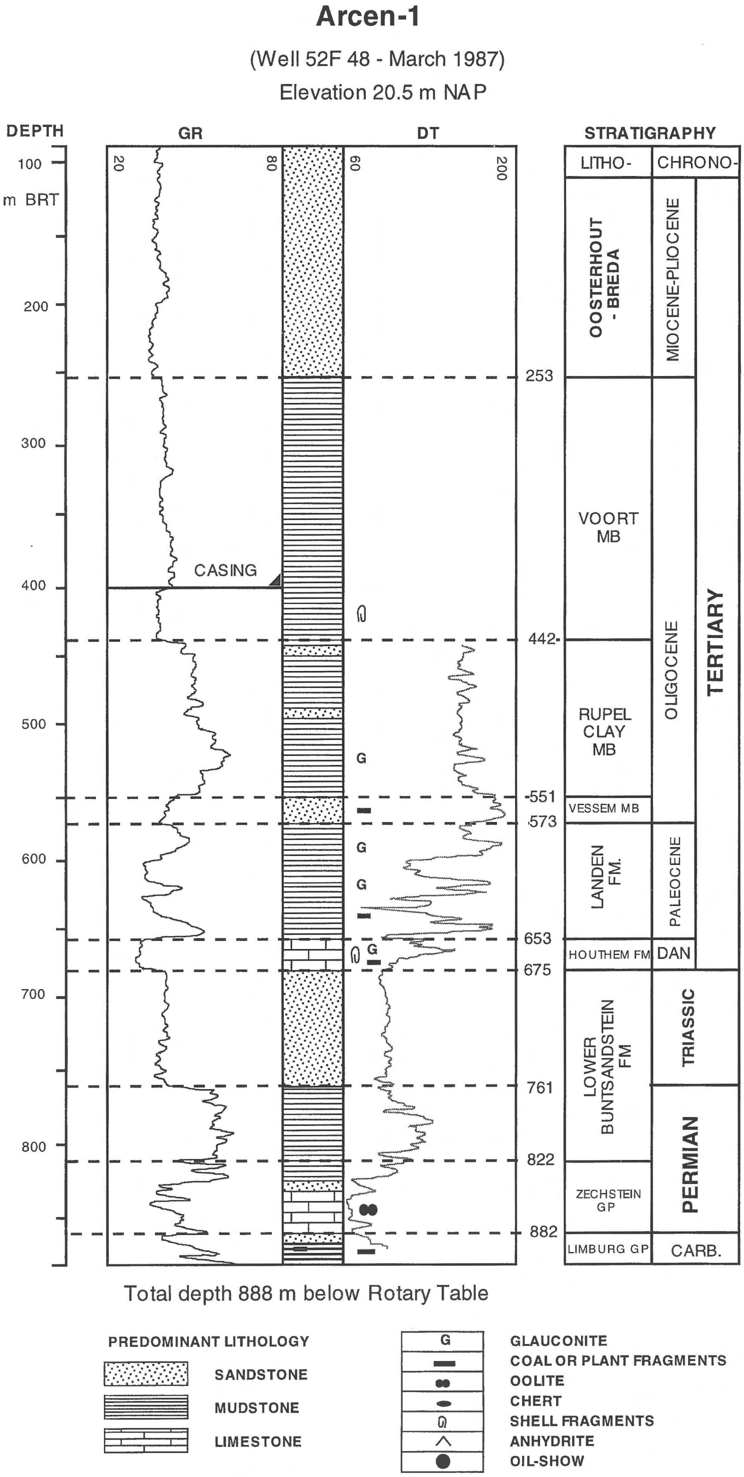

Figure 5. Summarised well log Arcen-1. This nonexclusive well, situated on the Venlo Block, encountered only the youngest part of the Chalk Group, the Houthem Formation of Danian age.

Venlo blocks, the boundary being gradational. During the Late Cretaceous inversion, the Maasbommel High formed a trough between the strongly inverting Roer Valley Graben and Central Netherlands Basin. It comprises a thick Chalk Group succession of Coniacian to Campanian age. Maastrichtian to Danian post-inversion sediments cover these older Chalk Group sediments and are characterised by a rather uniform thickness. In the north of the high, these post-inversion Chalk Group sediments were removed prior to the deposition of Late Paleocene sediments (Gras 1995). Renewed extension during Oligocene and Miocene times reactivated the earlier faults, with the formerly uplifted portions of the Maasbommel High displaying the strongest subsidence.

Upper Cretaceous well data

A range of stratigraphic names are in use for the Late Cretaceous basin-margin sediments in southern Limburg and adjacent parts of Belgium and Germany (Figure 2). In the description below, the stratigraphic names used in the original documents are added between brackets. Depths indicated here are below mean sea level, whilst those in Figures 5–8 refer to elevations.

Arcen-1 (Figure 5), situated on the Venlo Block, penetrated the Early Tertiary (Danian) Houthem Formation between 632–654 m. This interval consists of bioclastic, coarse-grained, partially siliciclastic limestone, locally containing glauconite and lignite. The Arcen-1 well reached a total depth of 867 m, terminating in the Late Carboniferous Limburg Group.

Liessel-22 (Figure 6), situated on the Peel Block, encountered the top of the Chalk Group at a depth of 559 m. Micropaleontological and palynological age determinations (RGD 1980, NITG 1998b) support the interpretation of Danian limestones of the Houthem Formation in the upper 36 m (559–595 m). Between 595 and 613 m, light-grey bioclastic limestones, locally with chert, were penetrated. A Late Maastrichtian age was determined on the basis of nannoplankton and sporomorph assemblages (RGD 1980, NITG 1998b). This unit, 18 m thick, has been attributed to the Maastricht Formation. The 613–633 m interval consists of argillaceous limestones, containing conglomerates and glauconite near the base. This interval, 20 m thick, has been interpreted as the Gulpen Formation, of Late Maastrichtian age. The base of the Gulpen Formation marks a hiatus, comprising

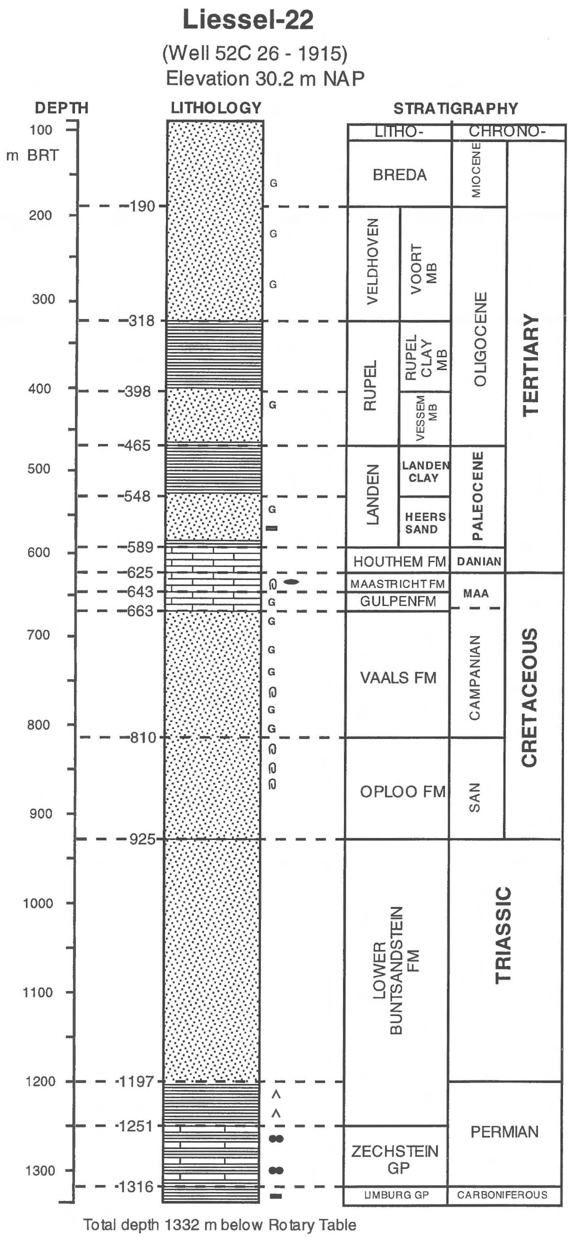

Figure 6. Summarised well log Liessel-22 . The well is situated on the Peel Block. The Cretaceous chronostratigraphy has been investigated paleontologically in the upper part only (see text). Data from Van Waterschoot van de Gracht (1918). Legend in Figure 5.

the Early Maastrichtian (NITG 1998b). The 633–780 m interval comprises glauconitic, argillaceous and bioclastic sandstone, locally with conglomerate beds consisting of iron ore and shell fragments. This section has been interpreted as the Vaals Formation ('Hervens') of Early Campanian age. The 780–841 m interval consists of argillaceous sandstone, locally containing iron-ore conglomerates and shell fragments ('Emscher'). The 841–895 m interval consists of light-yellow sandstones, which were previously interpreted as either Triassic or Upper Cretaceous. Given its colour, this interval is considered to be part of the latter succession. In this case, a Santonian age would be most likely. Below 895 m, Triassic red beds have been penetrated. Well Liessel-22 was drilled to a depth of 1302 m, ending in the Carboniferous Limburg Group.

Oploo-16 (Figure 7) is situated in the transition zone between the Peel Block and the Maasbommel High. The well reached the Chalk Group at a depth of 479 m. Only the uppermost 7 m consist of pure chalk-facies sediments; below these, the thick and atypical section consists largely of glauconite-bearing siliciclastics and argillaceous limestones. In the description below, the stratigraphic names used in the original description by Tesch (1912) are added between brackets. The 479–486 m interval, consisting of bioclastic limestone, is correlated with the Houthem and Maastricht Formations ('Danian, Maastrichtian and Spiennes Chalk') of Late Maastrichtian to Danian age (NITG 1998a). A hiatus, comprising the early Late Maastrichtian and late Early Maastrichtian (NITG, 1998a) occurs at 486 m. The 486–581 m interval consists of light-green, sandy glauconitic limestone with abundant shell fragments and is correlated with the Gulpen Formation ('Nouvelles Chalk') of Late Campanian to early Early Maastrichtian age (NITG, 1998a). The 581–803 m interval, assigned to the 'Early Senonian' (Tesch 1912), consists of argillaceous, glauconitic and bioclastic sandstone. The correlation with the Campanian Vaals Formation ('Herve Greensand') is confirmed by palynological and micropaleontological studies (NITG 1998a, c). The 803–929 m interval consists of fine-grained, locally argillaceous sandstones. This unit is the upper part of the newly proposed Oploo Formation, and is probably time-equivalent to the upper part of the Aken Formation ('Haltern' and 'Recklinghausen Sands'). The interval 929–1130.5 m interval (final depth) consists of glauconitic and argillaceous sandstone grading to sandy bioclastic limestone, and is also assigned to the Oploo Formation ('Emscher Marl', the lower part of the Aken Formation). Micropaleontological dating of the interval here assigned to the Oploo Formation yielded a Santonian age (RGD 1980).

Maasbommel-1 (Figure 8), situated on the Maasbommel High, penetrated a 507-m-thick Late Cretaceous succession, ranging in age from Cenomanian

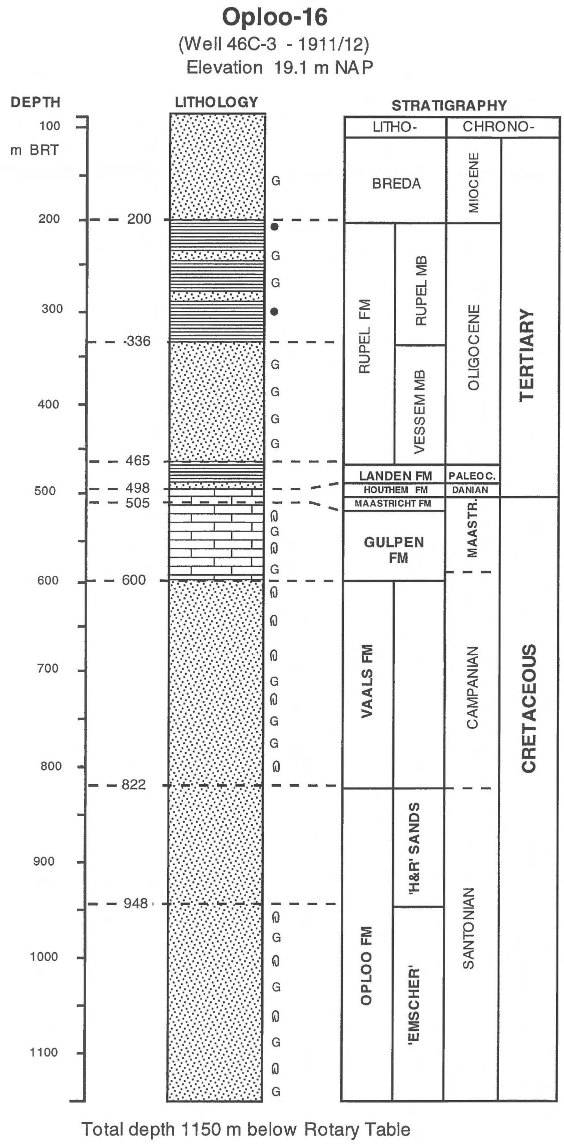

Figure 7. Summarised well log Oploo-16. The well is situated in the northwestern part of the Peel Block. The base of the Chalk Group has not been reached. Data from Tesch (1912). Legend in Figure 5.

to Early Campanian, and was truncated by the base-Tertiary unconformity at 571 m. The Upper Cretaceous subdivision in Maasbommel-1 is based on microfossil and nannofossil analyses of cutting samples over the interval, as well as on lithological descriptions of cutting samples with a 10-m sampling interval. For a description of this subdivision reference is made to Gras (1995). Maasbommel-1 was drilled to a depth of 1705 m in the Late Permian Zechstein Group, after having penetrated mainly Early Triassic strata below

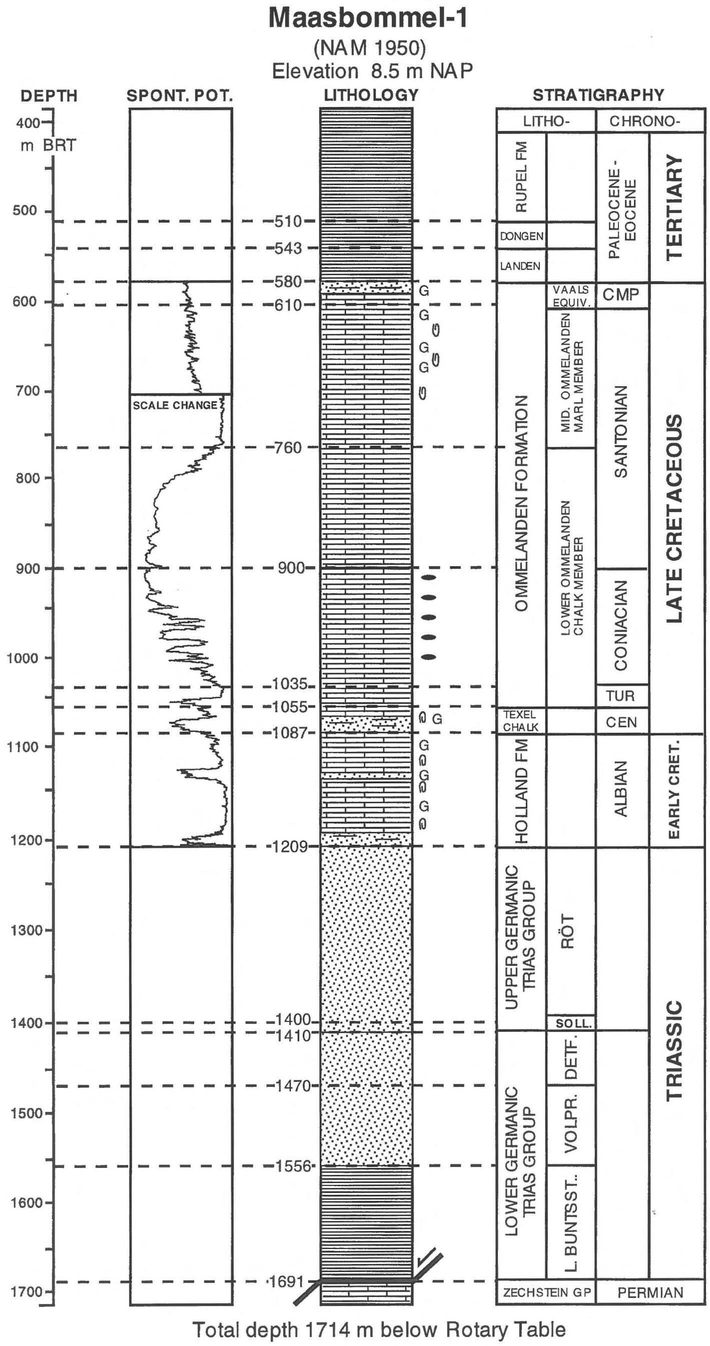

Figure 8. Summarised well log Maasbommel-1. Scale of spontaneous potential log is relative. Data from Thiadens (1963), Gras (1995) and Geluk et al. (1996). Legend in Figure 5.

the Albian sediments (Thiadens, 1963; Geluk et al. 1996).

Seismostratigraphy of the Chalk Group

A seismostratigraphic interpretation of the Chalk Group in the study area was made on the basis of non-exclusive 2-D seismic data mentioned before under the heading 'Database'. The succession can be subdivided into three distinct seismic facies, forming two seismic units, bounded by unconformities.

The occurrence of *seismic facies I* is limited to the Peel Block and the northern part of the Venlo Block. It has a transparent character, with few and discontinuous reflections. Based upon the Oploo-16 and Liessel-22 wells, this facies comprises sandy shallow-marine deposits of Santonian to Campanian age. Towards the north, it grades into seismic facies II, and becomes less transparent, on account of an increasing number of continuous reflectors. This change in seismic facies marks the lithofacies change from siliciclastic sediments into chalk and marls. On the northern parts of the Peel and Venlo blocks, the facies reaches a thickness of up to 250 m. Further north, a marked thickness increase accompanies the facies change. Towards the southeast, this facies thins and on the Venlo Block it is truncated by seismic facies III. The boundary with the underlying Triassic is often difficult to determine, but locally an unconformable relationship is recognised.

Seismic facies II occurs on the Maasbommel High and the northernmost parts of the Peel and Venlo blocks (Figure 9). This facies comprises a thick Chalk Group succession of up to 800 m, with several continuous reflectors alternating with more transparent intervals. It is considered to represent the basinal alternation of marl and chalk that constitutes the Chalk Group of the Maasbommel-1 well (Gras 1995). The contact with the overlying facies III is unconformable.

Seismic facies III occurs throughout most of the study area with a fairly constant thickness of 60–80 m. This facies comprises several continuous high-amplitude reflectors. Its pattern is generally conformable with that of the overlying siliciclastic Tertiairy succession. In the north, it is locally truncated at the base of this succession (Figure 9). On the southeastern part of the Venlo Block, this facies rests directly on Early Triassic rocks. It represents the Maastricht and Houthem Formations, which were deposited in a shallow-marine environment under a highly fluctuating sea level (cf. Haq et al. 1988). The high-amplitude events are considered to represent either emerging surfaces or the subsequent transgressions that cover these surfaces, but given the absence of modern wireline logs to calibrate the seismic signal, this cannot yet be determined definitely.

Synsedimentary faulting

The thickness of seismic facies II is affected by synsedimentary faulting. On seismic profile DG8601 (Figure 9), several low-angle thrust faults affecting its thickness can be identified. The reverse movements occurred during the Santonian inversion and amounted to up to 200 m. Oligocene and Miocene extensional faulting mostly compensated for this reverse faulting, so that the base of the Chalk is presently rather flat compared to the base of the clastic Tertiary. On the southeastern Peel Block, reverse faulting had much less influence. Only minor thickness variations of seismic facies I across faults occur. The facies pinches out towards the Peel Boundary Fault. The Tegelen Fault Zone presents here the only example of Santonian synsedimentary faulting; it represents a narrow NW-SE oriented inverted graben, which contains a 50–100 m thicker seismic facies I relative to the adjacent blocks. In Tertiary times, only the eastern boundary fault has been reactivated, forming the Tegelen Fault.

Upper Cretaceous stratigraphy and paleogeography

The Upper Cretaceous stratigraphy of the Peel Block, Venlo Block and Maasbommel High is illustrated in the well-correlation diagram of Figure 10. The comparison of the stratigraphy of the Peel and Venlo blocks with the detailed stratigraphy of southern Limburg, as recently reviewed by W.M. Felder (1996), allows the tectonic control on sedimentation to be interpreted.

Hauterivian–Albian

North and northeast of the study area, Hauterivian to Albian rocks have been encountered in the Maasbommel-1 and Nijmegen-Valburg-1 wells, as well as in a number of wells in Germany (Hilden 1988). The Hauterivian to Albian transgressions flooded the northern part of this area. Based upon seismic data (Figure 9), the present-day distribution extends as far south as the Oploo-16 well.

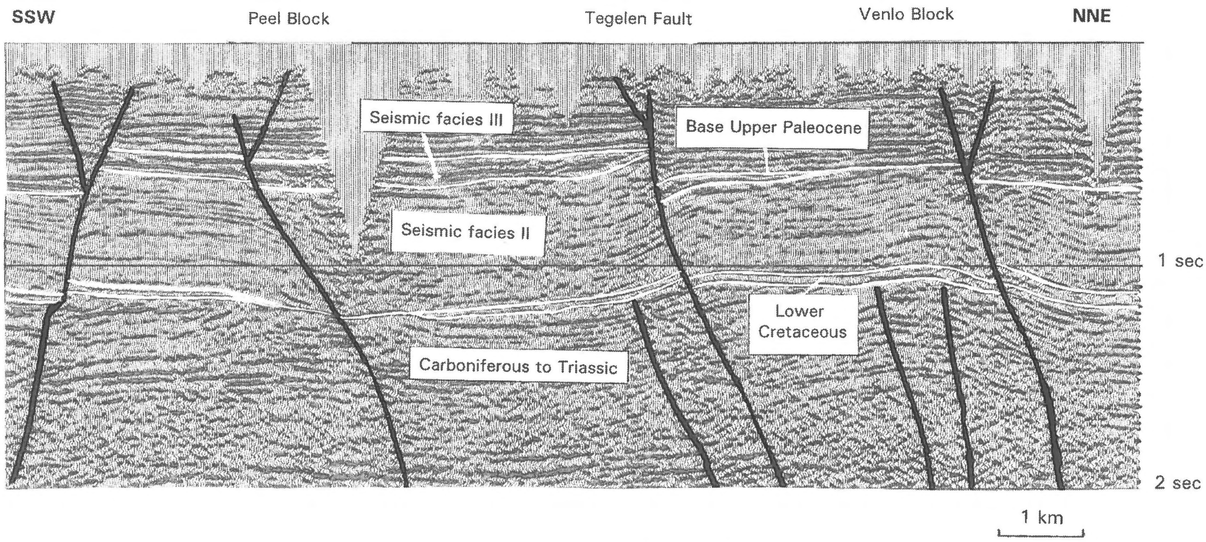

Figure 9. Structure of the Chalk Group on the northwestern parts of the Peel and Venlo blocks (non-exclusive line DG8601, migrated stack, two-way travel times). The Chalk Group in this figure is subdivided into two seismostratigraphic facies. Seismic facies II comprises chalk and marls of Cenomanian to Maastrichtian age; seismic facies III comprises the uppermost Maastrichtian to Danian chalk succession. For location see Figure 1.

Cenomanian-Santonian (Figure 11(a–b))

The Late Cretaceous transgression is represented in the Maasbommel-1 well by shallow-marine, predominantly carbonate sediments. These were deposited near the basin margin during Cenomanian and Turonian times (Figure 11(a)). Deposition of deeper-marine platform-type carbonate sediments followed during Coniacian to Early Santonian times. During the latest Coniacian, the sea had risen to a high-stand level resulting in cessation of clastic supply. The maximum extent of the transgression is interpreted to have occurred during the Early Santonian. Regressive conditions are observed approximately from the Late Santonian onwards, with the deposition of the Middle Ommelanden Marl Member. Most likely these followed the onset of basin inversion in the Roer Valley Graben and the Central Netherlands Basin (Figure 2).

The Santonian succession of Maasbommel-1 grades into a relatively thick coarser-grained siliciclastic succession in Oploo-16 (Figure 10). In this well, shallow-marine argillaceous sandstones and limestones ('Emscher Marl') are overlain by sandstones ('Haltern' and 'Recklinghausen Sands'), representing a regressive trend similar to the Santonian in Maasbommel-1. The base of the succession, our Oploo Formation, has not been reached in Oploo-16. In Liessel-22, the Oploo Formation consists of bioclastic argillaceous sandstones, with relatively clean, fine-grained sandstones near the base and is supposedly of Santonian age. On the southern Peel Block, sediments here attributed to the Oploo Formation were reported from the Elmt-77, Maasniel-74 and Neer-71 wells (Peelcommissie 1963). On the Venlo Block, seismic evidence indicates that the distribution of this formation is more restricted than on the Peel Block, and limited to the northwestern part. On this block, the succession is truncated below Maastrichtian to Danian deposits, implying that the Santonian succession was originally deposited on virtually the entire Venlo Block, but removed afterwards during the Campanian to Early Maastrichtian.

On the southwestern shoulder of the Roer Valley Graben, in southern Limburg, the Santonian Aken Formation rests unconformably upon Paleozoic rocks (Romein 1963) and consists of continental to nearshore sandstones, with rootlet beds, lignites and frequent bioturbation (Felder 1996). A deltaic depositional environment is assumed for these sediments.

Campanian (Figure 11(c))

Sedimentation on the Peel Block in the Early Campanian comprised shallow-marine bioclastic and glauconitic sandstones. These sandstones are of similar lithology and age as the Vaals Formation in southern Limburg. On the block, this formation was encountered in all wells studied. It consists of bio-

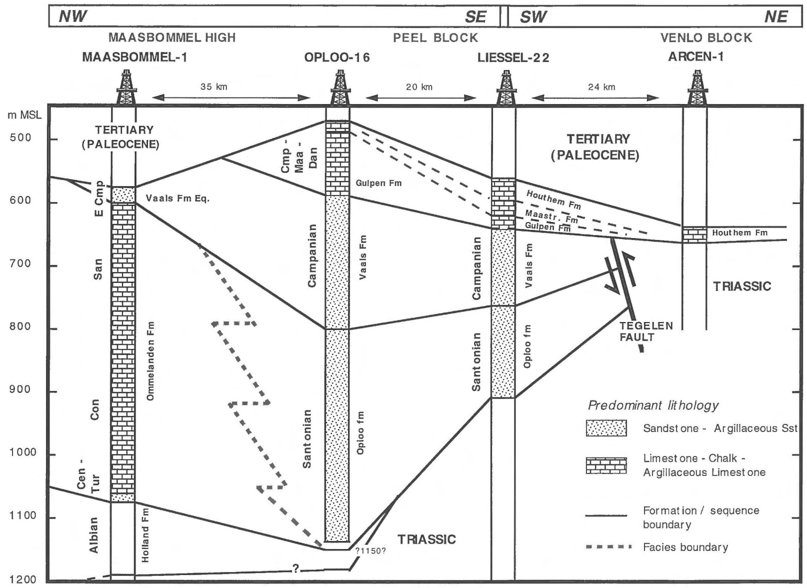

Figure 10. Well correlation diagram of the Chalk Group from the Maasbommel High over the Peel Block to the Venlo Block. Localities are shown in Figure 1, stratigraphic details in Figures 5–8. Depths indicated are below mean sea level.

clastic and glauconitic sandstone and marls, often with abundant shell fragments.

On the Venlo and Krefeld blocks such deposits are generally absent. Campanian sediments occur only in the northwestern part of the Venlo Block. They were deposited under the influence of inversion of the Central Netherlands Basin and Roer Valley Graben and of tilting of the Venlo Block, causing erosion in the southeast of the block.

In southern Limburg, the basal conglomerate of the Vaals Formation, unconformably overlies the Aken Formation. The Vaals Formation in this area comprises mainly siliciclastics with abundant glauconite. Its distribution was described by Romein (1963). The formation occurs on the downthrown sides of the inverted southwesterly graben-bounding faults, as a result of which it is found on the former foot-wall fault block. In addition to this structural control, the siliciclastic shallow-marine facies suggests syn-inversion deposition of the formation.

Maastrichtian–Danian (Figure 11(d))

The Late Campanian and early Late Maastrichtian Gulpen Formation and the late Late Maastrichtian and Danian Maastricht and Houthem Formations comprise yellow to grey, sandy to glauconitic chalk and marl (Klostermann 1983). The present database did not permit a distinction between the lower and the upper Gulpen Formation like in southern Limburg. Palynological studies suggest that the lower Gulpen Formation (Early Maastrichtian) is absent on the southeastern Peel Block (NITG 1998b). In Arcen-1, on the Venlo Block, the Danian consists of unusual, partially siliciclastic facies, representing nearshore sediments under a strong continental influence.

Late Maastrichtian to Danian sediments occur widely throughout the area, and cover, with minor variations in thickness, all structural units. In some places, e.g. the southern Krefeld Block and the Venlo Block, they are truncated below the Oligocene. The succession transgressed on Liassic rocks in the Roer Valley Graben (Nederweert-1, Asten-1) and the Central Netherlands Basin (Emmerich-1), on older Chalk Group sediments on the Peel Block and Venlo Block (Liessel-22, Oploo-16, America-11), and on Upper to Lower Carboniferous on the southeastern parts of the Peel, Venlo and Krefeld blocks (Elmt-77, Wachtendonk-1).

In southern Limburg, an erosional unconformity exists within the lower Gulpen Formation, at the base of the Early Maastrichtian Vylen Chalk Member (W.M. Felder 1996). Locally, this member directly overlies the Paleozoic. It consists of glauconite-bearing chalk with some siliciclastics. The base of the Maastricht Formation (late Late Maastrichtian) is unconformable in this area, and locally the forma-

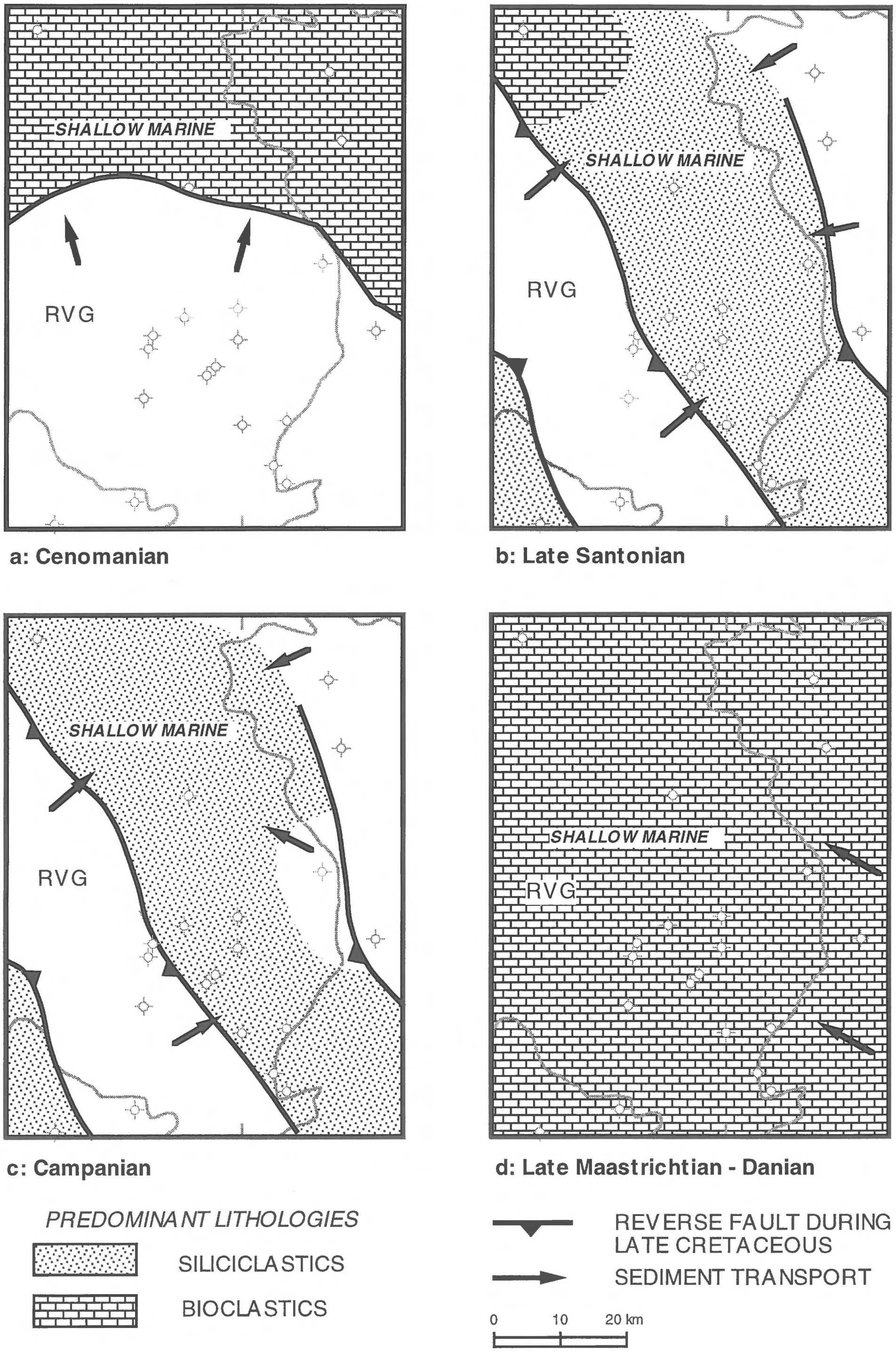

Figure 11. Schematic paleogeographic maps of the studied area. RVG = Roer Valley Graben.

tion rests directly on the Paleozoic. Late Maastrichtian to Danian sediments occur over the entire area. Subsequent to deposition of the Houthem Formation, paralic conditions prevailed.

Discussion

The Peel Block and southern Limburg shared similar structural histories during the Late Cretaceous, both being situated on a margin of the inverting Roer Valley Graben. The present situation differs considerably, however, as the Upper Cretaceous crops out in southern Limburg, whereas it is covered by Cenozoic strata on the Peel Block.

The stratigraphic analysis of the Late Cretaceous and Danian sediments in southern Limburg indicates each of the following formations to have been deposited unconformably and with progressively increased areal distribution: Aken Formation, Vaals Formation, lower Gulpen Formation (excluding Vylen Chalk Member), upper Gulpen Formation (including Vylen Chalk Member), Maastricht Formation and Houthem Formation (Romein 1963, Felder 1996). The Aken, Vaals, Gulpen and Maastricht Formations were recognised by Staring as early as 1860 (Felder 1996). By today's definitions the formations, with some modifications, may be regarded as four successions bounded by unconformities and correlative conformities (Figure 2). Additional minor unconformities have been identified within the formations. Overall, the Late Cretaceous succession shows a transition from siliciclastic to carbonate sedimentation. The Aken and the Vaals Formations consist of clastics only, and the Vylen Chalk Member consists of chalk with some clastics, deposited on the downthrown side of the southwesterly bounding faults of the inverting Roer Valley Graben system. The Aken and Vaals Formations represent the multiphase episodic uplift and subsequent progressive erosion of the Roer Valley Graben, principally during the Santonian and Campanian, under generally rising sea-level conditions. The clastic sediments are considered to have originated from the uplifting graben. They are interpreted as syn-inversion sediments.

A similar model is proposed for the Peel Block, on the opposite side of the inverted graben. The limited well data available suggest a prograding shoreline and progressive inundation of the southern basin margin during Santonian to Danian times. Anomalously thick siliciclastic deposits on the central Peel Block may be attributed to the reverse uplift along the Peel Boundary Fault during Santonian times. This fault shows large normal displacements during its history of repeated reactivation, notably during the Late Jurassic – Early Cretaceous and Cenozoic (Letsch & Sissingh 1983, Geluk et al. 1994). During the reverse reactivation of the fault in the Santonian-Campanian (Gras 1995), a localised shallow-marine depocentre was formed on the central Peel Block and the Maasbommel High. A similar Late Cretaceous depocentre, named the 'Voorne Trough', exists adjacent to and south of the West Netherlands Basin (Heybroek 1974, De Jager et al. 1996). These depocentres are regarded as marginal troughs, bordering the inverted basins (Voigt 1963, Ziegler 1990). The Santonian and Campanian clastic deposition under rising sea-level conditions on the Peel Block would be represented by the sediment accommodation during Stage 4 of the model of the evolution of an inverted basin as proposed in Figure 12.

The Early Maastrichtian witnessed an expansion of the sedimentation area, and a gradual change from clastic to carbonate sedimentation in the Gulpen Formation. This formation is considered to mark the change from syn-inversion to post-inversion. The post-inversion succession is represented by the Maastrichtian and Danian deposits (Gras 1995).

The Roer Valley Graben and the adjacent Peel Block were inundated from the Late Maastrichtian onwards. Late Maastrichtian Chalk Group sediments have been observed within the graben in a geothermal research well Asten-2 (Heederik 1988), in Nederweert-1 (Van Adrichem Boogaert & Kouwe 1993–1997) and in Molenbeersel in northeastern Belgium (Bless et al. 1993). These sediments have been correlated with the Maastricht and Houthem Formations. This implies that, at least from the Late Maastrichtian onwards (approx. 70 Ma), the relative sea-level rise exceeded the rate of inversion, resulting in net subsidence. The occurrence of karst horizons and paleosols in the Late Maastrichtian–Danian succession (Bless et al. 1993) supports a prevailing shallow depositional depth and indicates a near-balance between tectonic subsidence or uplift, sedimentation and sea-level rise.

On the Maasbommel High and in the Central Netherlands Basin, the Maastrichtian-Danian sediments were removed due to Tertiairy erosion. The uplifted and eroded areas comprise large parts of the inverted Late Jurassic – Early Cretaceous basins, and include those parts of the highs that bordered the basins. As a

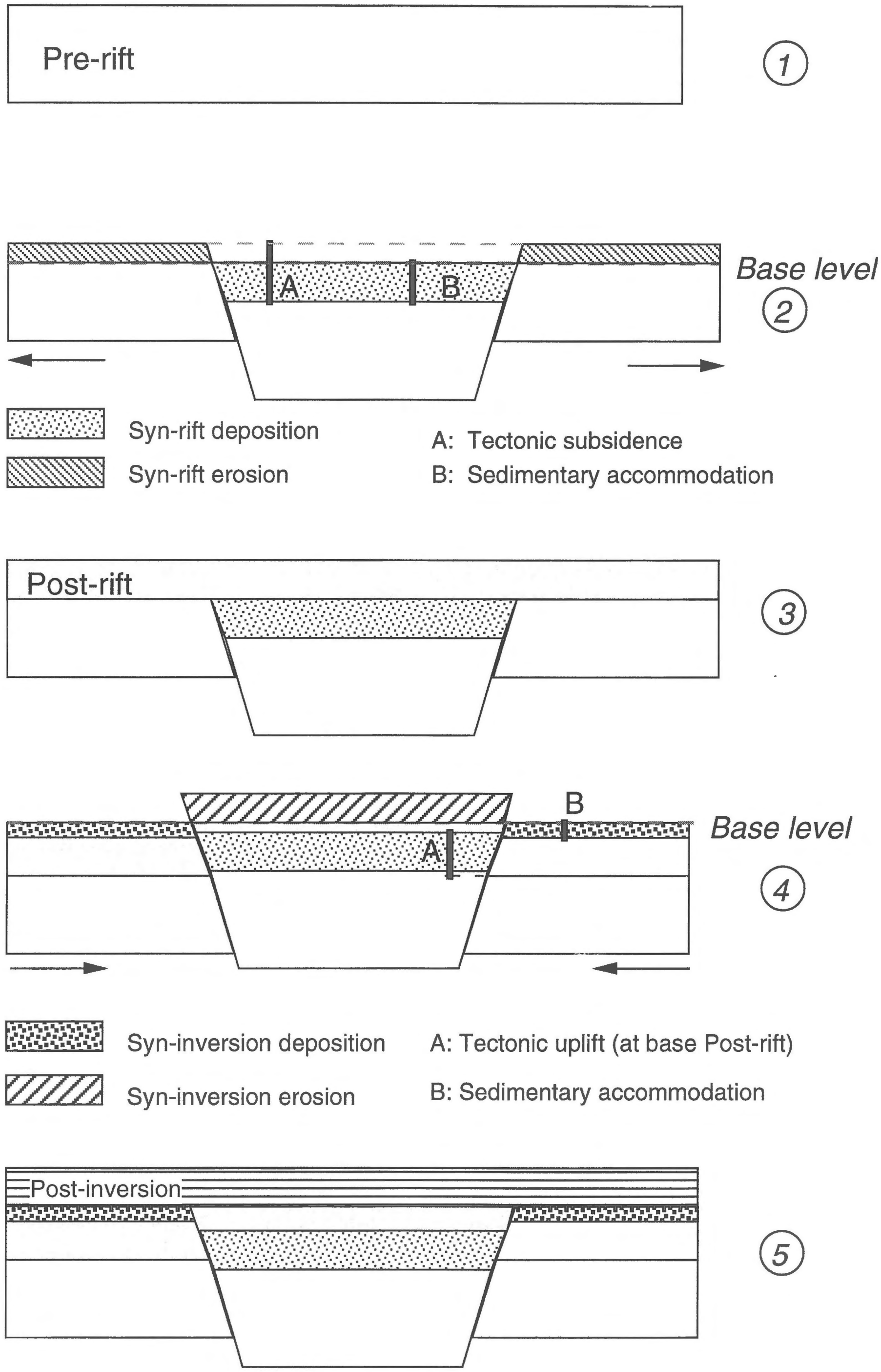

Figure 12. Model of the sedimentary evolution of an inverted graben. Stage 4 represents tectonic inversion under conditions of rising sea level, as in the case for the Santonian and Campanian on the Peel Block. Stage 5 represents post-inversion deposition, e.g., the Maastrichtian and Danian deposition on the Roer Valley Graben and Peel Block.

result, Danian sediments occur only in the northern offshore area of the Netherlands and in the southern Netherlands (Van Adrichem Boogaert & Kouwe, 1993–1997).

The Late Cretaceous history of the Peel Block and the adjacent Roer Valley Graben demonstrates sedimentation under the influence of both tectonic and eustatic controls. Net uplift of the Roer Valley Graben occurred when the rate of tectonic uplift exceeded the rate of the Late Cretaceous sea-level rise. Net subsidence occurred when the rate of sea-level rise exceeded the tectonic uplift. As uplift and subsidence are complementary processes, net uplift in one area caused subsidence in an adjacent area. During net uplift of the Roer Valley Graben in the Santonian, a marginal trough developed on the Peel Block.

In general, the amount of unrepresented time in any stratigraphic section is estimated to be in the range of 90% (Griffith 1996), indicating that preservation of the sedimentary record is relatively rare in geological time. On long-lived positive features such as the Peel Block, hiatuses predominate in the stratigraphic section. These gaps, and the intervening sections, are significant with respect to the subsidence history of the adjacent graben. Subsidence modelling that does not take uplift or nondeposition into account is unlikely to result in meaningful conclusions.

Conclusion

The Peel Block was a structural high during the Late Jurassic – Early Cretaceous rifting of the Roer Valley Graben. Erosion on this block during this rifting truncated the pre-rift succession, consisting of the Permo-Triassic and the Lower Jurassic. During the Late Cretaceous (Coniacian to Campanian), a marine transgression inundated the block from the north. At the same time a localised depocentre developed as a result of compressional stresses related to the reverse reactivation of the Peel Boundary Fault. This area was infilled with shallow-marine clastics of the Oploo and Vaals Formations. During this period, the Roer Valley Graben, the Krefeld Block, the southern part of the Venlo Block and the Central Netherlands Basin formed positive features. The depositional area is envisaged as an estuary, bordered by shoals. During the Campanian the net uplift (tectonic uplift relative to sea level) of the Roer Valley Graben gradually ceased. During the Maastrichtian and Danian, the entire area was flooded and shallow-marine limestones were deposited.

Regarding the lithostratigraphy of the Chalk Group on the Peel Block, a further refinement is proposed: the introduction of a new siliciclastic formation, the Oploo Formation.

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