

Stratigraphy and tectonics of the Roer Valley Graben

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Abstract

The Roer Valley Graben is the most prominent Cenozoic tectonic feature in the Netherlands onshore, filled with up to 2000 m of predominantly Upper Oligocene to Quaternary sediments. It forms the northwestern branch of the Rhine Graben rift system. To the northeast the graben is bordered by a major faultzone, the Peel Boundary Fault, and to the southwest by a number of downstepping faults.

The Roer Valley Graben developed upon pre-existing sedimentary basins of Carboniferous, Triassic to Early Jurassic and Late Jurassic age. The Cenozoic graben is structurally closely related to the Late Jurassic basin and to the area affected by inversion tectonics at the end of the Cretaceous.

Differential subsidence of the Roer Valley Graben started during the Late Oligocene. Displacements along the Peel Boundary Fault were recorded from the Late Oligocene onwards. Initially the average displacement was 0.01 mm a^{-1} , but it increased during the Quaternary to 0.8 mm a^{-1} . Fault displacements at the southwestern boundary faults of the Roer Valley Graben are smaller than at the Peel Boundary Fault.

Introduction

On April 13, 1992 a major earthquake with a local magnitude of 5.9 on the Richter scale caused considerable damage in the Netherlands, Belgium and Germany. The epicentre was situated 7 km southwest of Roermond. The earthquake was generated by dip-slip movements along the downward continuation of the Peel Boundary Fault and had a focal depth of about 20 km (Paulssen et al. 1993). Several strong aftershocks, up to a local magnitude of 4, were registered in the following days. Fault-plane solutions and focal depths of these aftershocks clearly show that they can be contributed to both the Peel Boundary Fault and the Feldbiss Fault.

The above mentioned faults are the northeastern and southwestern boundary faults of the Cenozoic Roer Valley Graben. This graben, which forms part of the northwestern branch of the Rhine Graben rift system (Ziegler 1990), stretches out from Euskirchen in Germany to 's Hertogenbosch in the Netherlands, cov-

ering part of northeastern Belgium as well (Fig. 1). The subsiding area is delimited by the Brabant Massif, Ardennes and Eifel in the southwest and by the Rhenish Massif in the east. It is the most prominent Cenozoic tectonic feature in the Netherlands, filled with up to 2000 m of Cenozoic deposits.

Ahorner et al. (1976) and Houtgast (1992) pointed out that the northwestern branch of the Rhine Graben rift system has displayed a high level of seismicity from historical times onwards. Deep-seated fault zones, still active under the influence of the present-day stress field, frequently generate tectonic earthquakes.

The objectives of this paper are to describe the geological setting and the polyphase geodynamic evolution of this area since the Carboniferous. Special attention will be paid to the Late Neogene to Quaternary subsidence history of the Roer Valley Graben, its bordering faults, and the geological evolution of the adjacent units.

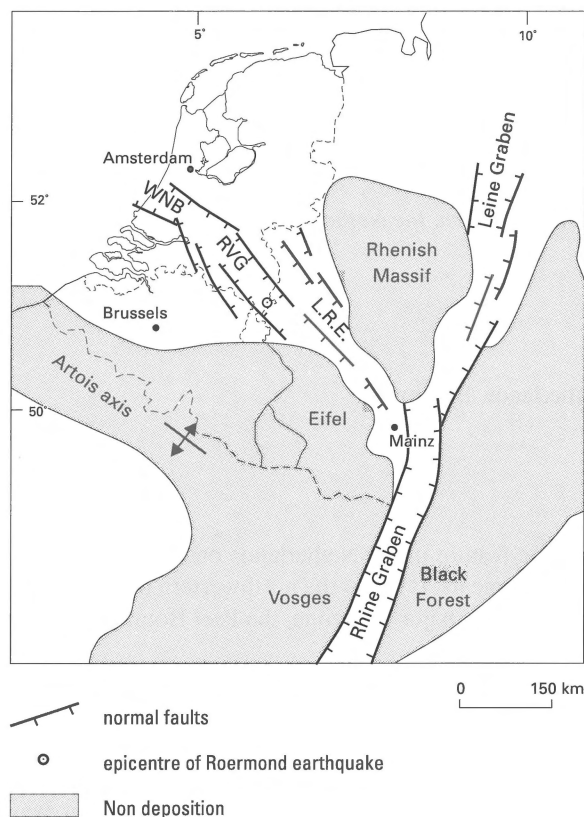


Fig. 1. Overview of the Rhine Graben system in northwest Europe. WNB: West Netherlands Basin; RVG: Roer Valley Graben; LRE: Lower Rhine Embayment (after Ziegler 1982).

Structural framework

Faults and fault blocks

Based on the Cenozoic subsidence pattern, the north-western branch of the Rhine Graben rift system can be divided into a number of tectonic units (Fig. 2). These are, from northeast to southwest:

1. the Krefeld Block, a relatively high block which borders the subsiding area,
2. an area of intermediate subsidence, comprising the Venlo Block, the Peel Block and the Köln Block,
3. the areas of strong subsidence, namely the Roer Valley Graben and the Erft Block,
4. the Eastern and Western Campine Blocks; areas of intermediate subsidence west and southwest of the graben, and
5. the Brabant Massif, bordering the subsiding area, where Lower Paleozoic basement rocks subcrop beneath a Cretaceous and Tertiary cover.

The Roer Valley Graben is asymmetric and NW-SE trending. It is bordered by a series of antithetic faults at the southwestern margin (the Feldbiss, Neeroeteren and Heerlerheide Faults), with throws in the order of 100–400 m, and a discrete faultzone, the Peel Boundary Fault, with throws up to 1000 m at the northeastern side. Based on the Mesozoic structural development, the graben can be divided into two parts:

1. A southeastern part, which was mildly deformed during the Kimmerian tectonic phases. It was mainly influenced by the uplift of the Rhenish and Brabant Massifs. The Midi-Aachen Variscan overthrust is crosscut (and nearly obliterated) by the graben system.
2. A northwestern part, showing intense wrench-faulting, which caused strong subsidence during Middle Jurassic to Early Cretaceous times, followed by complex inversion tectonics during the Late Cretaceous. The boundary between the southeastern and northwestern units is gradual and located near the E-W Veldhoven Fault. Towards the northwest the graben passes into the much wider West Netherlands Basin.

This study mainly deals with the southeastern part of the Roer Valley Graben, the region where the Roermond earthquake occurred.

Deep crustal structure

The deep crustal structure of the area can be inferred from a deep seismic line, located approximately 35 km northwest of the epicentre of the earthquake. The line is orientated in a NNE-SSW direction, perpendicular to the strikes of the faults. The interpretation by Remmelts & Duin (1990) shows that the Peel Boundary Fault cannot be traced below the base of the Carboniferous, situated at a depth of approximately 7–8 km (Fig. 3).

The base of the lower crust, corresponding to the seismic reflection originating from the Moho, shallows from an average depth of 30 km beneath the Peel Block to a depth of 27 km beneath the centre of the Roer Valley Graben. Towards the south, underneath the Brabant Massif, the depth of the Moho strongly increases, attaining 38 km in the Belgian offshore (Rijkers et al. 1993). The Belcorp geotraverse showed the Brabant Massif to be almost completely transparent (Bouckaert et al. 1988).

As the deep seismic line over the Roer Valley Graben displays no indications for faults or shear zones that cut through the middle and lower crust, the pure-

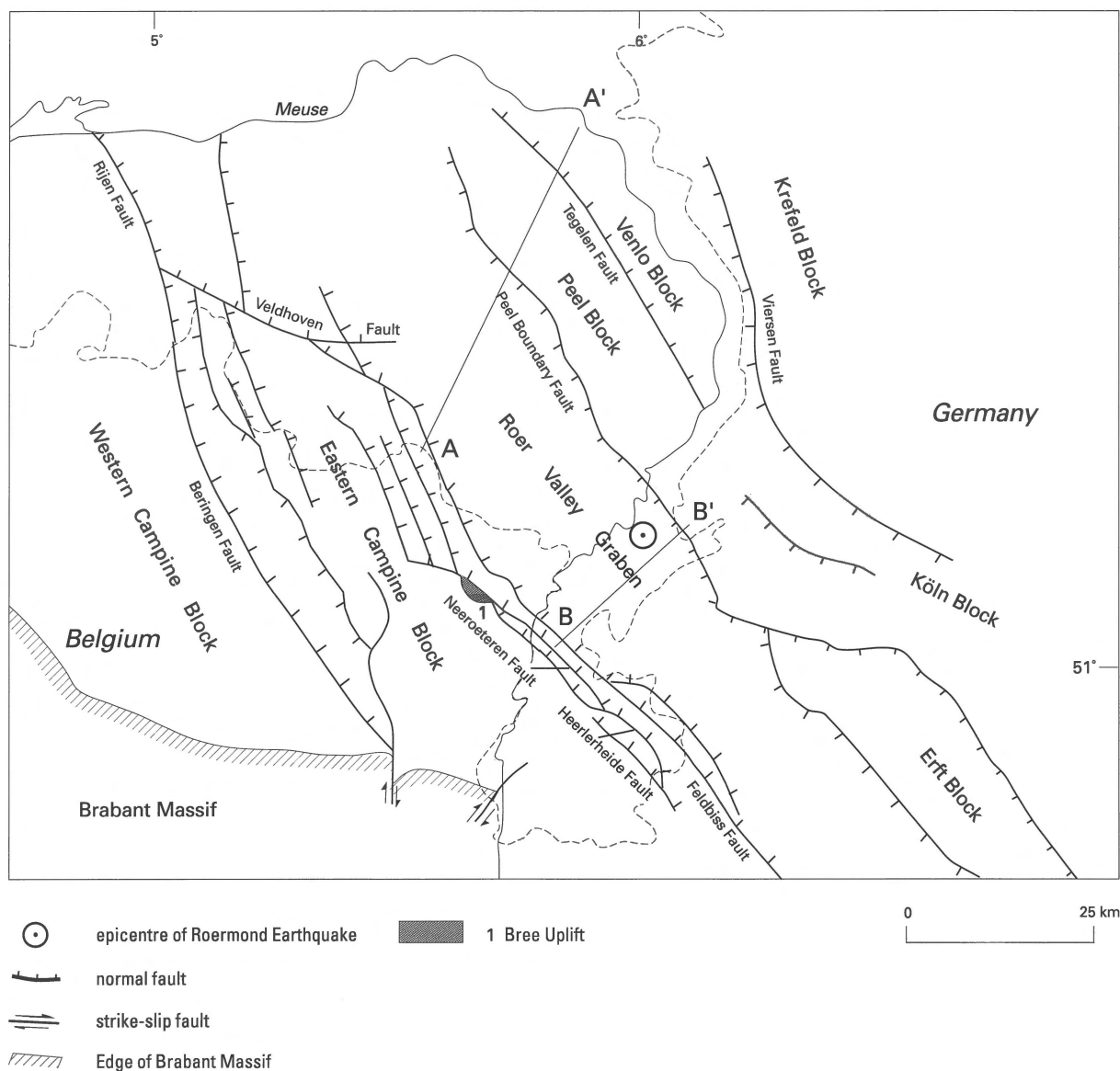


Fig. 2. Structural framework of the area, showing the main fault blocks and main faults at base Tertiary. After maps of Demyttenaere (1989), Langenaeker & Duser (1992), Belgische Geologische Dienst, Geologisches Landesamt Nordrhein-Westfalen (1988) and Van Doorn & Lezers Vis (1985). A–A': location of profile shown in Fig. 3; B–B': profile shown in Fig. 4.

shear McKenzie model for uniform stretching of the lithosphere seems to be applicable in this area. The β -factor for crustal stretching, as derived from the change in crustal thickness, is estimated at approximately 1.30–1.34 (Zijerveld et al. 1992). From the tectonic subsidence of various wells a β -factor 1.06–1.11 was calculated for the period Oligocene to recent (Zijerveld et al. 1992) and from fault heaves at the base of the Tertiary a β -factor of 1.04 for the Cenozoic (Geluk 1990). The difference between these β -

factors can be explained by the fact that the variation in crustal thickness includes a significant component of pre-Cenozoic extension, whereas the β -factor calculated from fault heaves at the base of the Tertiary reflects the Cenozoic extension. The lower value of the β -factor from fault-heaves with respect to the tectonic subsidence can be the consequence of lower resolution of the fault-heaves methods. A considerable amount of the extension may be accommodated by small faults

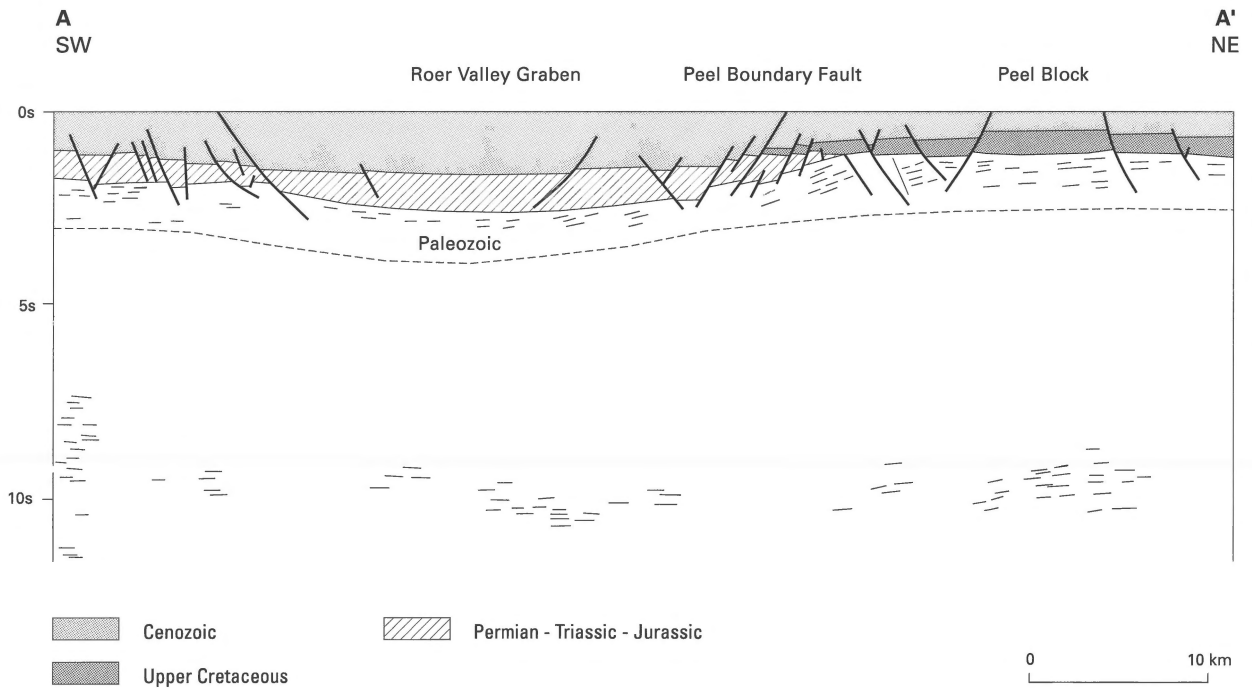


Fig. 3. Line drawing of the southern section of the deep seismic line 8601. The location is shown in Fig. 2. Note that the distribution of the Upper Cretaceous is limited to the Peel Block and the distribution of the Permian and Triassic to the Roer Valley Graben. On this seismic line, the Peel Boundary Fault cannot be traced deeper than approximately 2.5 s. The dashed line below the Paleozoic represents the top of the basement. The upper crust is transparent, the lower crust at around 10 s displays spike-type reflections (after Remmelts & Duin 1990).

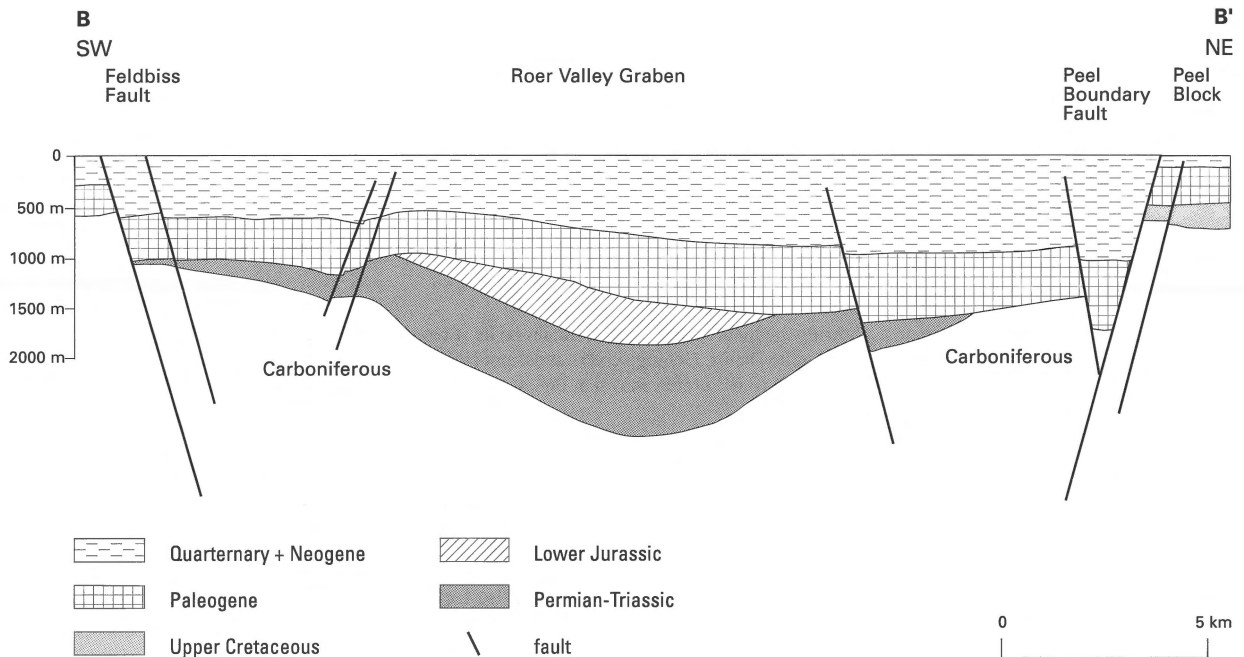


Fig. 4. Depth profile showing a NE-SW section through the Roer Valley Graben near the epicentre of the 1992 Roermond earthquake. Note that several units can be recognised within the graben, and that the main subsidence occurred near faults. The Cenozoic graben overlies a Mesozoic basin, but the outlines of the graben do not coincide with this basin. The profile location is shown in Fig. 2.

that remain undetected on seismic records (Marret & Allmendinger 1992).

Stratigraphy and geological history

Carboniferous

The oldest deposits known from boreholes in the graben are of Carboniferous age and represent the Westphalian A, B, and C; their estimated total thickness amounts to some 2500 m. Regional geological knowledge indicates that they are underlain by a further 2000 m of Namurian and Dinantian clastics, limestones and evaporites and a Devonian sequence of unknown thickness and composition (Delmer 1963; Geol. Landesamt Nordrhein-Westfalen 1988). In the Campine Basin, located southwest of the Roer Valley Graben, Westphalian deposits include an additional 500 m of Westphalian D below the combined Asturian and Saalian unconformity, whereas the Peel Block was uplifted by some 500 m (Peelcommissie 1963). The subcrop of the Carboniferous deposits below the Asturian and Saalian unconformity suggests that controlling fault patterns existed during Late Westphalian-Autunian times. The patterns show a similar orientation to the fault systems delineating the Cenozoic Roer Valley Graben.

Deformation of the Carboniferous deposits north of the Variscan thrust front was limited to block-faulting and tilting of the strata, partly along strike-slip faults (Bouckaert & Dusar 1987). The amount of Variscan displacement along the Peel Boundary Fault cannot be reconstructed in detail, because of the low quality of the seismic signal as recorded from deeper horizons in the Roer Valley Graben.

Permian and Mesozoic

A thick Permian-Triassic-Jurassic sequence unconformably overlies the Upper Carboniferous deposits in the Roer Valley Graben. Outside the graben and near its boundary the section may be strongly reduced in thickness or even be completely removed by Middle Jurassic to Cretaceous erosion, related to the Late Kimmerian tectonic phases. Upper Cretaceous sediments then directly overlie Carboniferous strata (Figs 3–5).

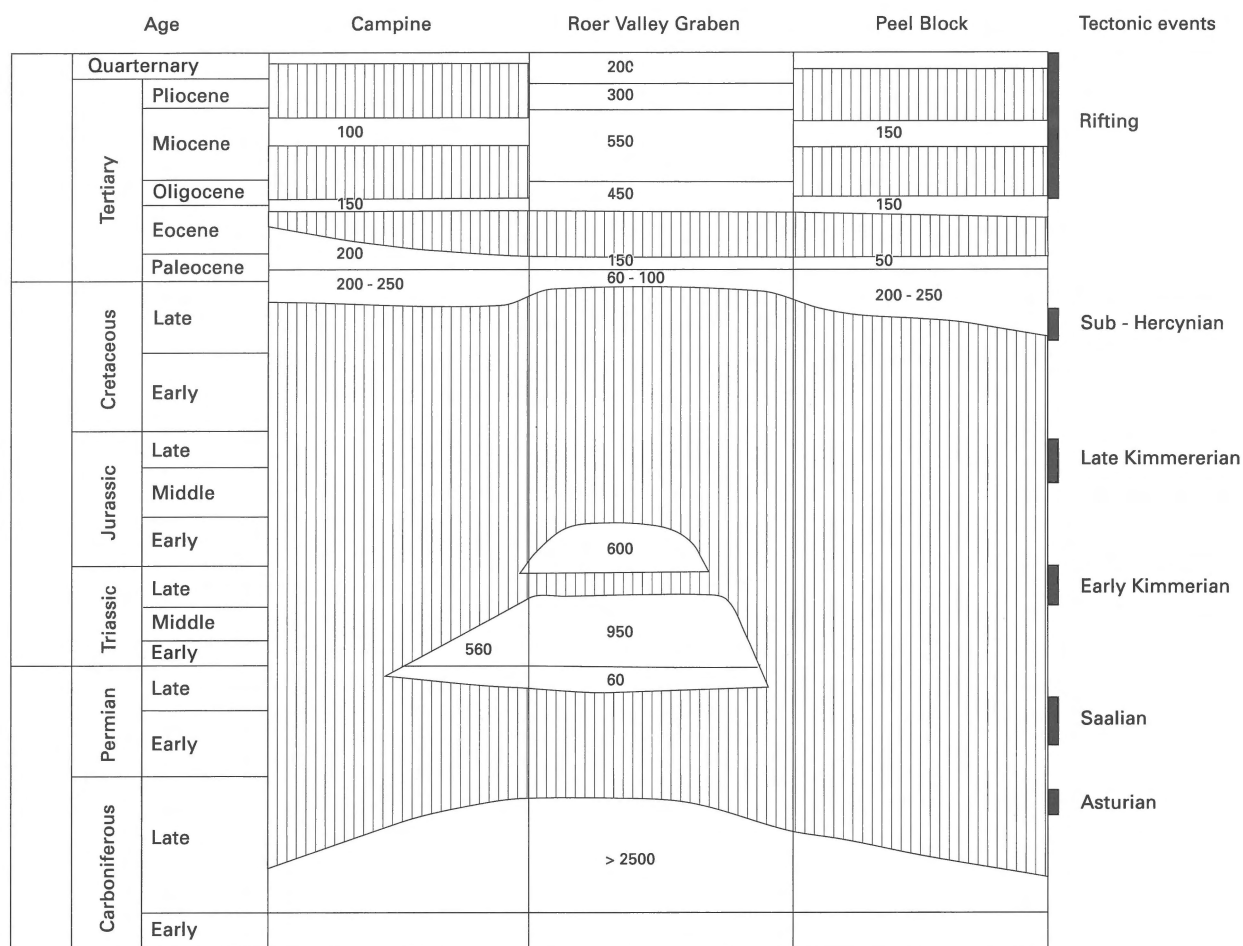
No differential subsidence of the graben occurred during the Permian. The graben merely acted as a fault-bounded platform. Sandstones and conglomerates of

the Upper Rotliegend Group of Late Permian age (0–10 m) cover the Carboniferous sediments. These coarse clastics are succeeded by or may be reworked into much younger deposits of the Zechstein Group (Late Permian). The thickness of the Zechstein Group varies from 10 to 60 m.

The Triassic sequence, resting conformably on the Zechstein Group, reaches a thickness of 950 m in the Roer Valley Graben. A rapid subsidence of the graben floor occurred in the Triassic and appears to have included the Peel Block and the Eastern Campine Block. Well data and seismic information give indications for little syndepositional faulting, thus the subsiding area was not fault-bounded. Triassic strata attain the greatest thickness in the southwestern part of the graben (Fig. 3). Lower Triassic sandstones and claystones make up the greatest part (700 m), with 350 m of Lower Buntsandstein, 200 m of Main Buntsandstein and 150 m of Upper Buntsandstein (Solling and Röt Formations). The thickness of the Middle and Upper Triassic series increases from 160 m at the southwestern margin (Legrand 1961) up to 250 m in the central part. Thinning of the Triassic sequence towards the Peel and Eastern Campine Blocks (Figs 3–5) is for the major part the result of the Late Kimmerian erosion, and to a lesser extent of intra-Triassic erosion.

Marine sediments of the Keuper, Rhaetian and Lower Jurassic transgress over Middle Triassic strata. On the graben's eastern flank, the Keuper rests on older parts of the Muschelkalk than in the centre of the graben. The Rhaetian and Lower Jurassic series is preserved only in the graben where it reaches a thickness of 600 m. An unconformity is not evident between the Triassic and Jurassic sequences on reflection seismics; therefore, it is assumed that these deposits were draped over the Peel and Campine Blocks as well. In the upper part of the Lower Jurassic some onlap onto the margins of the graben occurs (Demyttenaere 1989), indicating differential movements of the Peel and Campine Blocks relative to the Roer Valley Graben.

In the study area a hiatus, corresponding to the Late Kimmerian tectonic phase, covers the timespan between the Middle Jurassic and Late Cretaceous. During much of this period erosion presumably prevailed. In the northwestern part of the Roer Valley Graben a pull-apart basin was formed which was delimited by E-W trending strike-slip faults. Uplift of the Peel and Campine Blocks occurred during the Middle Jurassic to Early Cretaceous, and was associated with regional uplift of the Brabant and Rhenish Massifs (Legrand 1961; Patijn 1963; Van Wijhe 1987). The



||||| Hiatus

Fig. 5. Stratigraphic diagram, summarising the development of the Campine, Roer Valley Graben and Peel Block. Maximal sediment thicknesses in m.

uplift of the Brabant Massif by at least 2000 m (Van den Haute & Vercoutere 1990) resulted in a reversal of dips on Variscan fault blocks into a monoclinial flexure, downdipping towards the Roer Valley Graben (Bouckaert & Duser 1987; Fig. 4).

Tectonic inversion of the Roer Valley Graben area, during the Sub-Hercynian tectonic phase, commenced during or possibly before the Early Campanian. The onset of the inversion cannot be dated exactly, since pre-Campanian strata are absent.

During the inversion the Jurassic basins or lows became uplifted and suffered erosion, whereas previously high areas subsided. Faults, active during the Late Kimmerian tectonic phase acted as reversed faults during inversion (Rossa 1986). Inversion movements

ceased during the Maastrichtian (Bless et al. 1987, 1993; Bless 1991). The Upper Cretaceous sediments on the Peel and Campine Blocks are of Santonian, Campanian and Maastrichtian age and comprise calcarenites, chalk, greensands and marls. On both blocks the thickness of the Upper Cretaceous deposits increases towards the northwest, from less than 200 m to more than 700 m. The inverted graben area was flooded during the Late Maastrichtian; carbonate sequences in the Roer Valley Graben attain a thickness of 30 to 70 m.

Cenozoic

The oldest Cenozoic deposits are Lower Paleocene calcarenites of the Houthem Formation, which attain a

thickness of some 30 m. Minor thickness and facies differences between the Peel and Eastern Campine Blocks and the Roer Valley Graben reflect tectonic quiescence in the area. The carbonates are succeeded by 60 m of continental sands and clays assigned to the Lower Paleocene Maasmechelen Formation. This unit is thickest in the graben and thus testifies to an episodic downwarping of the area. It is followed by Middle and Upper Paleocene sands, marls and claystones of the Heers and Landen Formations (Demyttenaere & Laga 1988). Intermittent inversion movements can be detected along faults in the Eastern Campine Block during the Early Tertiary (Rossa 1986).

A regional hiatus corresponds to part of the Late Paleocene and the Eocene. This hiatus increases in stratigraphic range towards the southeast on the graben shoulders and towards the graben centre. In the Oligocene sedimentation resumed with the accumulation of sands and clays forming the Rupel Formation (150 m). Deposition of this formation took place concurrent with a mild tensional regime, with throws on individual faults not exceeding 20 m (Demyttenaere 1989).

The Late Oligocene marked a dramatic change; from this time onwards the strongest subsidence took place in the Roer Valley Graben (Demyttenaere 1989; Geluk 1990). The Veldhoven Formation shows an increase in thickness from less than 25 m on the Western Campine Block to 350 m in the graben. On the Peel and Eastern Campine Blocks, this formation attains a thickness of approximately 100 m. In the graben the formation consists of up to 200 m of sands (Voort Sand) and 150 m of clay (Veldhoven Clay). Rapid subsidence of the graben was partly matched by tilting of the Eastern Campine Block, as can be deduced from the onlap of the Voort Sands on reflection-seismic profiles.

For the Roermond area, movements along the Peel Boundary Fault as reflected by changing sedimentary thicknesses across individual faults are first noticeable during the Late Oligocene; they amount to 50 m. During the Miocene, Pliocene and Quaternary, sedimentation became increasingly restricted to the Roer Valley Graben. The Miocene sequence of clays and sands on the shoulders of the graben still amounts up to 125 m, but in the graben the thickness reaches more than 500 m. Strong movements occurred along the Peel Boundary Fault and the Feldbiss Fault. The Pliocene and Quaternary sediments reach a thickness of 300 and 200 m, respectively, and they are limited almost entirely to the graben (Zagwijn 1989).

Faulting and differential subsidence

Peel Boundary Fault

The Peel Boundary Fault is considered as the main fault within a narrow fault zone, with a width of up to one km. The zone is composed of a varying number of synthetic and antithetic faults, whereby the period of activity can vary from fault to fault. In map view, the fault zone has an anastomosing character, with a variable throw along the fault. Towards the northwest the fault zone widens and the throw along the individual faults decreases. The cumulative throw at the base of the Tertiary is 500 to 1000 m, and at the base of the Miocene 400 to 800 m (Figs 3, 4, 6).

It is assumed that the different faults making up this fault zone merge at depth into a single high-angle fault. Assuming that the focal centre of the earthquake did occur at its faultplane, it indicates the localisation of strain in deeper parts of the brittle upper crust. The Peel Boundary Fault probably dips steeply into the crust to a depth of at least 15 km, corresponding to the calculated minimal depth of the Roermond earthquake. From deep seismic investigations in the southern North Sea, the occurrence of low-angle shear zones in the lower crust directly beneath the northern flank of the London-Brabant Massif is assumed (R.H.B. Rijkers pers. comm.). In view of this, it is possible that similar shear zones do exist in the lower crust beneath the Roer Valley Graben and were reactivated during the Roermond earthquake.

In the area of the epicentre, the Peel Boundary Fault was apparently not or only mildly reactivated during the Late Kimmerian tectonic phases (Middle Jurassic-Early Cretaceous). The uplift of the Peel Block resulted in flexuring and tilting of the Mesozoic strata towards the Roer Valley Graben (Fig. 3), and not in important fault reactivation. However, during the Sub-Hercynian inversion phase the Peel Boundary Fault was clearly reactivated. This can be deduced from positive flower structures in the western part of the Peel Block, as is evident on reflection seismic lines. This compressional structure resulted from transpressional strike-slip movements during the inversion.

The fault zone at the southwestern boundary of the Roer Valley Graben

The fault zone at the southwestern boundary of the Roer Valley Graben comprises three parallel faults, the Feldbiss, Neeroeteren and Heerlerheide Faults. Maxi-

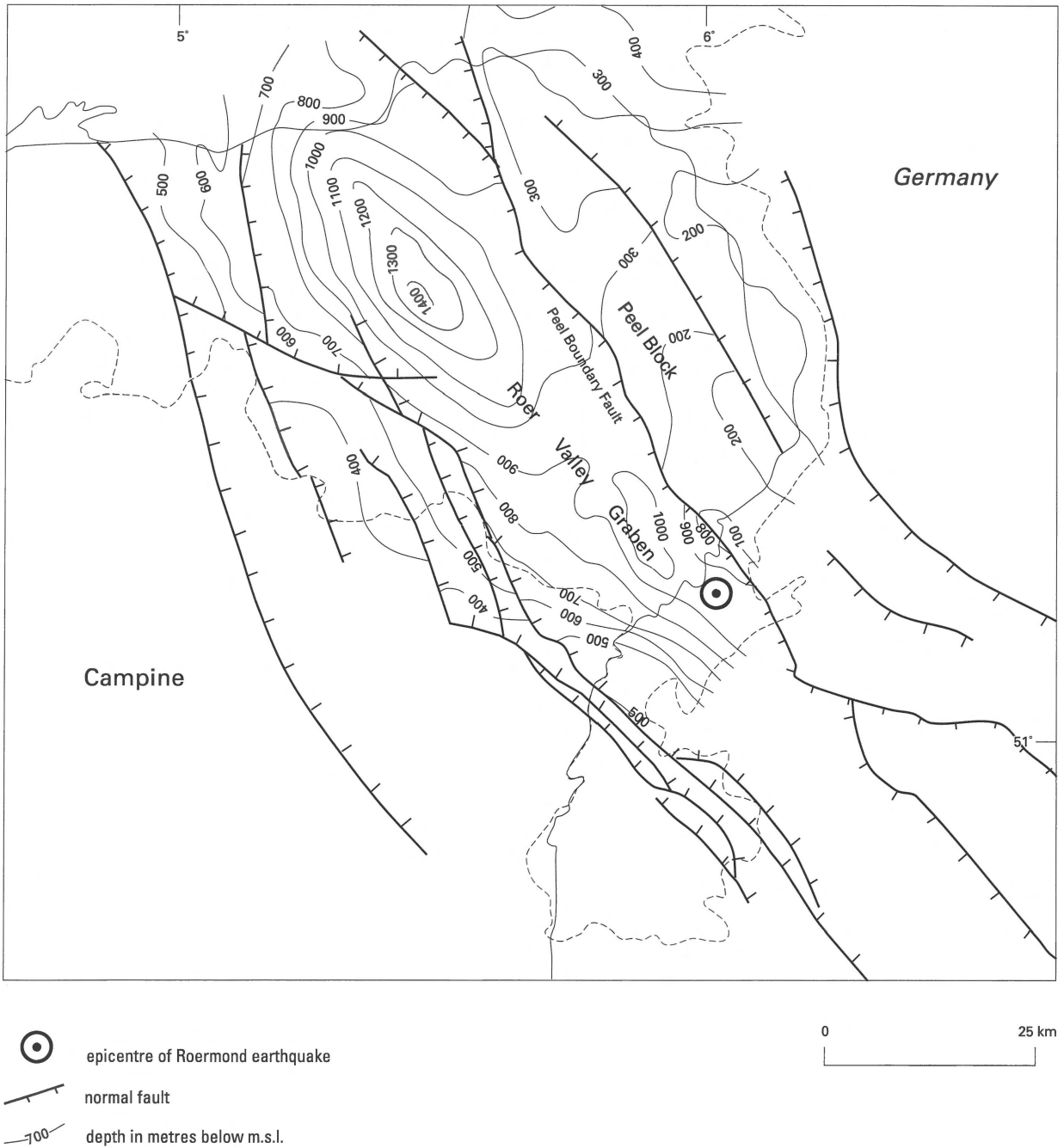


Fig. 6. Depth map of the base Miocene below msl, showing the strong differential subsidence in the southeastern part of the Netherlands since the Miocene. Subsidence in the northern part of the Roer Valley Graben is greater than in the southern part, where the epicentre of the 1992 Roermond earthquake is situated.

mal downthrow can vary considerably along the strike of the faults. Total throw across the complex southern boundary at the top of the Carboniferous and the base of the Miocene amounts to 800 and to 400 m,

respectively (Rossa 1986). This boundary differs from the northwestern boundary by the presence of a series of downstepping faults, with a width up to 5 km. The correlation between faults recognised on Dutch and

Belgian territories is not always clear (Legrand 1968). In this paper, the nomenclature of the faults sensu Demyttenaere (1989) is applied. Towards the west, the two southern branches (Neeroeteren and Heerlerheide Faults) join up to form the Bree Uplift, before splitting again more to the west at Bree (Bouckaert et al. 1981). West of the Bree Uplift, the Neeroeteren Fault changes direction from NW-SE to NNW-SEE and splits up into different branches (Fig. 2).

The recognition of the Bichterweerd scarp at the base of the Maas valley bottom gravels forms the best proof for extending the Feldbiss Fault from its South Limburg section into the Campine. The throw along this scarp attains 10 m for the Late Pleistocene Saalian, and 2–3 m for the younger Weichselian. No evidence for faulting during the latest Pleistocene or Holocene has been found along the scarp (Paulissen et al. 1985). The scarp apparently forms the Quaternary expression of the Feldbiss Fault.

The Rijen Fault, further to the northwest continues towards the south-southeast into the Beringen Fault, which marks the westernmost occurrence of the Cenozoic extension related to the Roer Valley Graben (Vandenbergh 1982). The E-W trending Veldhoven Fault forms a link between the Feldbiss Fault and the Rijen and Beringen Faults.

Seismic interpretation revealed that the maximal throw was located at the southernmost, Heerlerheide Fault, during the Kimmerian deformation phases, and at the Neeroeteren Fault during the Tertiary (Rossa 1986).

The Roer Valley Graben and wrenching

In a regional structural context it is concluded that the assumed dip-slip character on the faultplane of the Roermond earthquake (Paulssen 1992) is related to contemporaneous lateral translation between deep basement blocks. Strike-slip movements are deduced from the regional tectonic setting, the Cenozoic normal fault pattern and the offset of the Permo-Triassic subcrop pattern. By translation of the Rhenish Massif to the north with respect to the Brabant Massif, a sinistral transtensional wrench basin was formed in between, the Roer Valley Graben. The orientation of the present-day regional stress is NW-SE (Klein & Barr 1986). Van den Berg (1994) indicates present-day dextral movements along the Peel Boundary Fault.

The southwestern margin of the Roer Valley Graben is also characterised by strike-slip movement. The Bree Uplift along the Neeroeteren Fault probably represents

a positive flower structure. Variscan dextral strike-slip faults and associated positive flower structures are also inferred for the major faults delimiting the eastern part of the Brabant Massif and crosscutting into the Eastern Campine Block (Dusar & Langenaeker 1992).

Cenozoic subsidence of the Roer Valley Graben

Differential subsidence

Well data document the increasing Cenozoic subsidence of the Roer Valley Graben relative to the Peel Block. Tectonic subsidence curves have been calculated with the backstripping method for several wells in the graben by Zijerveld et al. (1992) and are shown in Fig. 7. The wells Veldhoven-1 and St. Michielsgestel-1 are located in a Middle to Late Jurassic rift basin, whereas the well Nederweert-1 lies in the mildly deformed southeastern part of the graben. The area of maximum subsidence since the Late Oligocene lies in between these wells in the graben (Fig. 6). Subsidence curves for the Cenozoic of the three wells are in good accordance with each other. The wells in the graben show an increase in Cenozoic subsidence, whereas the Liessel-22 well, situated on the Peel Block, shows decreasing subsidence during the Cenozoic. This documents the increase in differential movements between these tectonic units during the Tertiary.

The subsidence during the Late Neogene and Quaternary has been analysed in detail for two shallow boreholes near the epicentre of the earthquake. The wells Linne (well code 58D-313) and Herten (58D-76) lie on either side of the Beegden Fault, a conjugate fault of the Peel Boundary Fault (Fig. 8). Both wells have been analysed on their pollen content (De Jong 1982; Zagwijn 1960). Correlation of the pollen zonation with the astronomically tuned $\delta^{18}\text{O}$ variations as observed in the deep sea-record provides a good chronostratigraphic framework. The amount of accumulated sediments has not been corrected for compaction; this is regarded not to influence seriously the trend of the subsidence curves. The subsidence of the sites is primarily controlled by the local dynamics of the Peel Boundary Fault in conjunction with the Beegden Fault. The accommodation rate of these predominantly sandy fluvial sediments is an approximation of the tectonic subsidence (Van den Berg 1993).

The general shape of the curves is very similar, although they belong to different fault blocks. Phases of acceleration and deceleration in subsidence occurred throughout the last 8 Ma. During the Miocene through

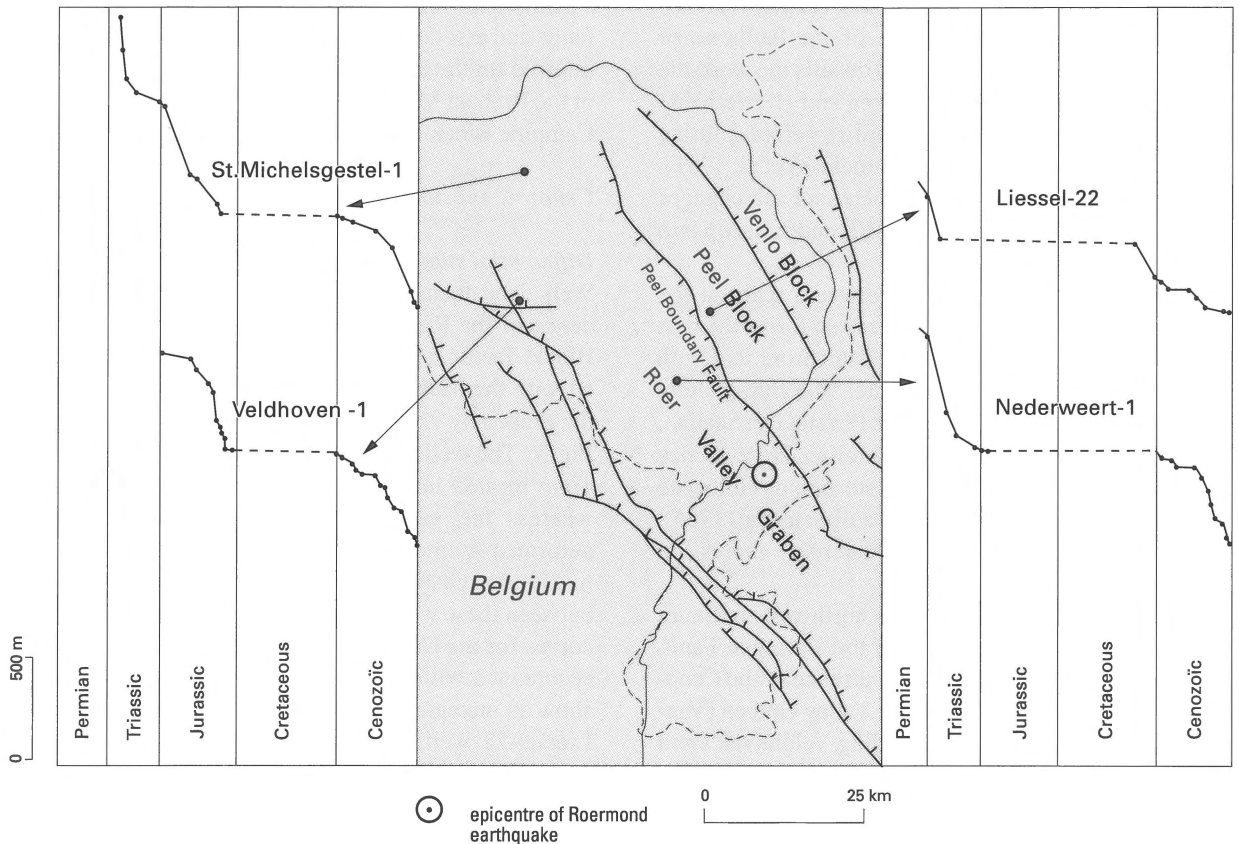


Fig. 7. Tectonic subsidence of the Roer Valley Graben area. The wells Nederweert-1, Veldhoven-1 and St. Michielsgestel-1 represent the subsidence of the graben; the Liessel-22 well that of the Peel Block. Erosion has not been accounted for. All wells were backstripped and tectonic subsidence curves calculated by Zijerveld et al. (1992).

Late Pliocene, these phases lasted several million years. During the Late Pliocene through Pleistocene, they get increasingly shorter. Hiatuses in the Pleistocene record of the Roer Valley Graben coincide with deceleration in the uplift curve at the southern flank of the graben. During the Pleistocene the dynamics of both areas are, therefore, apparently coupled, in contrast to the Late Tertiary. A clear acceleration, observed in subsidence (Zijerveld et al. 1992) as well as in uplift (Van den Berg 1994), is present, but not so evident as for the central part of the Roer Valley Graben. The hiatus observed from 650 to 100 ka, is due to an uplift phase known from the regional geomorphology (Van den Berg 1989), when the Meuse river terrace formation took place in the central part of the graben. The record strongly suggests that since the last 100 ka the region strongly subsided again.

Differences in sedimentation rates on both sides of the Beegden Fault are interpreted to reflect differences

in the rate of deformation between the Peel Boundary and the Feldbiss Fault systems. Different antithetic lineaments of both fault systems control the orientation of the river Meuse, and force the river in a more northeastern direction across the graben (Fig. 8).

Data from other wells reveal strong variations in sedimentation and erosion along the Peel Boundary Fault. The presence of Rhine deposits of Reuverian and Pre-Tiglian age in the Roer Valley Graben (well Herkenbosch) and on the Peel Block (Zagwijn 1960; Boenigk 1970; Urban 1978; P. Cleveringa pers. comm.) indicates that there was a passage across the northern graben boundary fault. A locally subsiding basin may allow the river to cross the Peel Boundary Fault at one place, synchronous with non-deposition elsewhere along strike (well Herten). This can be interpreted to indicate the temporary presence of a strong strike-slip motion along this fault. This fault is characterised by an anastomosing fault pattern (Van den Berg

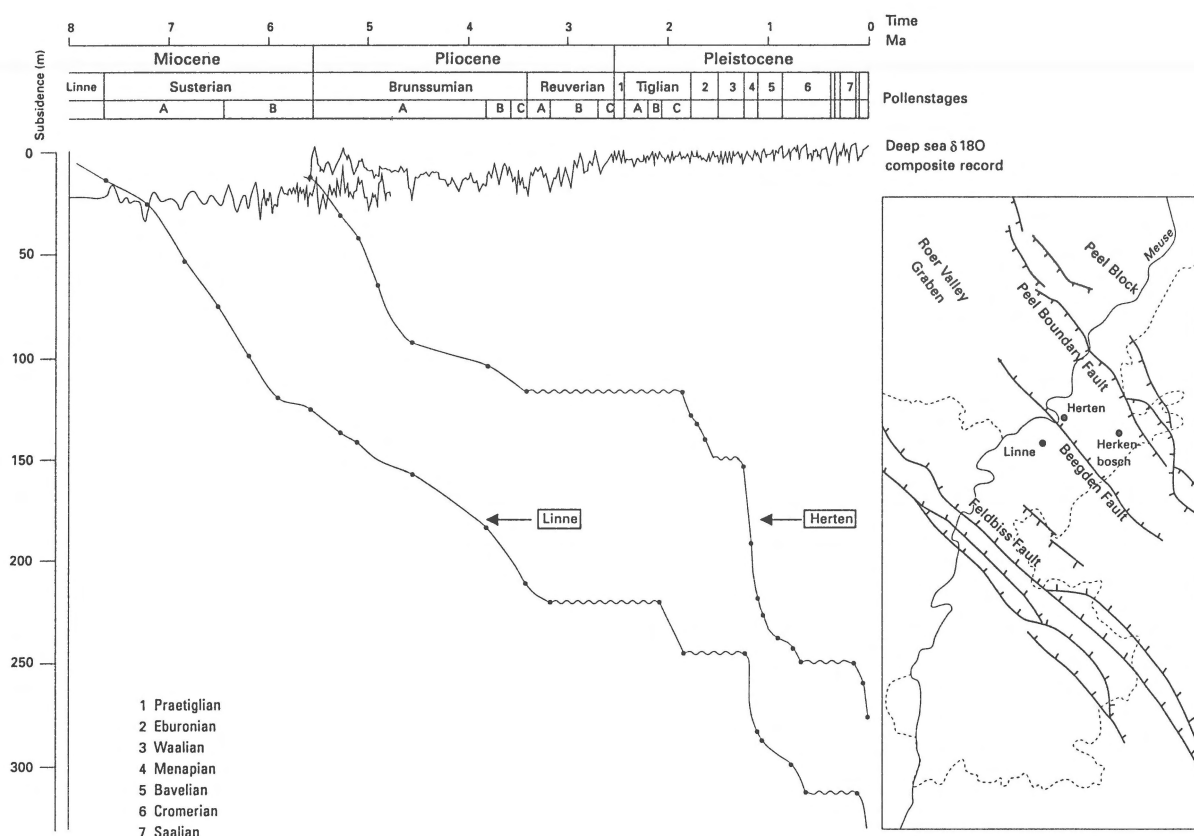


Fig. 8. Late Neogene and Quaternary subsidence of the Linne and Herten wells. The subsidence of the last 8 Ma suggests an increase in spasmodic dynamics with time. Pollen stages adapted from Zagwijn & Hager (1987) and Suc & Zagwijn (1983). Deep sea $\delta^{18}\text{O}$ curves adapted from Keigwin (1987), Krantz (1991), Shackleton et al. (1990) and Thunell et al. (1990).

et al. 1994). In such types of fault pattern, strike-slip motion produces an alternation of subsiding basins and compressional uplift blocks along the fault zone (Reading 1980). Such hiatuses in the Pleistocene record can be correlated over a wide area in Europe and are supposed to be of plate-tectonic importance (Van den Berg 1994).

Fault movements

An analysis of Cenozoic movements along the Peel Boundary Fault near the epicentre shows, that up to the Late Oligocene no substantial movements occurred along the Peel Boundary and Feldbiss Faults. The subsidence at first equally affected the Peel Block and the Roer Valley Graben. The Peel Boundary Fault was reactivated during the Late Oligocene. The initial fault movements on individual faults during the Late Oligocene were 0.01 mm a^{-1} , which is comparable with the calculated reversed movement during the

Late Cretaceous inversion phase (0.015 mm a^{-1}). The movements increased in the Miocene-Pliocene up to an average rate of 0.5 mm a^{-1} and during the Quaternary up to 0.8 mm a^{-1} .

Rates of fault movement along the southwestern margin of the graben can be deduced from the work by Rossa (1986). Average Tertiary (Oligocene to Pliocene) fault movements were 0.015 mm a^{-1} , much lower than recorded at the Peel Boundary Fault. Reversed fault movement during the Late Cretaceous inversion was calculated at less than 0.01 mm a^{-1} .

Conclusions

1. The Roer Valley Graben overlies older Paleozoic and Mesozoic sedimentary basins; its development is closely related to the Late Jurassic basinal development and the subsequent Late Cretaceous inver-

sion tectonics. In the course of geological history the depocentres of these basins shifted towards the northwest.

2. Differential subsidence of the Roer Valley Graben, forming part of the Northwest European rift system, started during the Late Oligocene; strong fault movements along the Peel Boundary Fault were initiated from the Miocene onwards.
3. During the Miocene, Pliocene and Quaternary an increase in differential subsidence can be observed in the area, accommodated in the northeast solely by the Peel Boundary Fault.
4. The spasmodic subsidence during the Late Neogene and Quaternary is thought to be the expression of intermittent strike-slip and dip-slip movements along the Peel Boundary Fault.

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References

- Ahorne, L., J.M. van Gils, J. Flick, G. Houtgast & A.R. Ritsema 1976 First draft of earthquake zoning map of NW Germany, Belgium, Luxembourg and the Netherlands – Kon. Ned. Met. Inst. De Bilt, Publ. 153: 39–41
- Bless, M.J.M. 1991 Eustatic sea level and depth of a Late Cretaceous epicontinental sea: an example from NW Europe – Geol. Mijnbouw 70: 339–346
- Bless, M.J.M., P.J. Felder & J.P.M.Th. Meessen 1987 Late Cretaceous sea level rise and inversion: their influence on the depositional environment between Aachen and Antwerp – Ann. Soc. Géol. Belgique 109: 333–356
- Bless, M.J.M., M. Dusaar, P.J. Felder & R. Swennen 1993 Lithology and biostratigraphy of Upper Cretaceous – Paleocene Carbonates in the Molenbeersel borehole (NE Belgium) – Geol. Mijnbouw 71: 239–257
- Boenigk, W. 1970 Zur Kenntniss des Altquartärs bei Brüggen (westlicher Niederrhein) – Sonderveröff. Geol. Inst. Univ. Köln, 17, Diss, 138 pp
- Bouckaert, J., M. Dusaar & E. van de Velde 1981 Exploration for coal in the Neeroeteren – Rotem area. Preliminary results of a seismic survey carried out in December 1980 – January 1981 – Ann. Soc. Géol. Belgique 104: 281–289
- Bouckaert, J., W. Fock & N. Vandenberghe 1988 First results of the Belgian geotraverse 1986 (Belcorp) – Ann. Soc. Géol. Belgique 111: 279–290
- Bouckaert, J. & M. Dusaar 1987 Arguments géophysiques pour une tectonique cassante en Campine (Belgique), active au Paléozoïque supérieur et réactivée depuis le Jurassique supérieur – Ann. Soc. Géol. Nord CVI: 201–208
- De Jong, J. 1982 Pollenanalytisch onderzoek van de boringen Linne (58D/313), Schinveld (60D/1025) en Nederweert (58A/89), alsmede een herinterpretatie van de boring Koningsbosch (60B/27) – Int. Rep. 919 Dept. Paleobot. Rijks Geol. Dienst, Haarlem, 5 pp
- Delmer, A. 1963. Mijnkaart van het Kempens kolenbekken – Annalen der Mijnen van België: 739–754
- Demyttenaere, R. 1989 The post-Paleozoic geological history of north-eastern Belgium – Meded. Kon. Akad. Wetensch. Lett. Schone Kunsten België 51: 51–81
- Demyttenaere, R. & P. Laga 1988 Breuken- en isohypsenkaarten van het Belgische gedeelte van de Roerdal Slenk – Belg. Geol. Dienst, Prof. Paper 1988/4 234, 20 pp
- Dusaar, M. & V. Langenaeker 1992 De ooststrand van het Massief van Brabant, met beschrijving van de geologische verkenningss boring te Martenslinde – Belg. Geol. Dienst, Prof. Paper 1992/5 255, 22 pp
- Geluk, M.C. 1990 The Cenozoic Roer Valley Graben, Southern Netherlands – Meded. Rijks Geol. Dienst 44-4: 66–72
- Geologisch Landesamt Nordrhein-Westfalen 1988 Geologie am Niederrhein, 60 pp
- Houtgast, G. 1992 Catalogus van aardbevingen in Nederland t/m 1990 – Kon. Ned. Met. Inst. De Bilt, Publ. 179, 166 pp
- Keigwin, L.D. 1987 Towards a high-resolution chronology for the latest Miocene paleoceanographic events – Paleoceanography 2: 639–660
- Klein, R.J. & M.V. Barr 1986 Regional state of stress in western Europe – In: O. Stephenson (ed.): Rock stress and stress measurement – Lulea, Sweden: 34–44
- Krantz, D.E. 1991 A chronology of Pliocene sealevel fluctuations, U.S. Atlantic Coastal Plain – Quat. Sci. Rev. 10: 163–174
- Langenaeker, V. & M. Dusaar 1992 Subsurface facies analysis of the Namurian and earliest Westphalian in the western part of the Campine Basin (N. Belgium) – Geol. Mijnbouw 71: 161–172
- Legrand, R. 1961 L'épéirogenèse, source de tectonique d'après des exemples choisis en Belgique – Mém. Inst. Géol. Univ. Louvain 22: 3–66
- Legrand, R. 1968 Le Massif du Brabant – Mémoires explicatives des Cartes géologiques et minières de Belgique 9, 148 pp
- Marret, R. & R.W. Allmendinger 1992 Amount of extension on 'small' faults: An example from the Viking graben – Geology 20: 47–50
- Patijn, R.J.H. 1963 Tektoniek von Limburg und Umgebung – Verh. Kon. Ned. Geol. Mijnb. Gen., Geol. Serie 21-2: 1–24
- Paulissen, E., J. Vandenberghe & F. Gullentops 1985 The Feldbiss fault in the Maas valley bottom (Limburg, Belgium) – Geol. Mijnbouw 64: 79–87
- Paulissen, H., B. Dost & T. van Eck 1992 The April 13, 1992 earthquake of Roermond (the Netherlands); first interpretations of the NARS seismograms – Geol. Mijnbouw 71: 91–99
- Peelcommissie 1963 Rapport van de Peelcommissie – Verh. Kon. Ned. Geol. Mijnb. Gen., Mijnbouwk. serie 5, 133 pp
- Reading, H.G. 1980 Characteristics and recognition of strike-slip fault systems. In: P.F. Ballance & H.G. Reading (eds): Sedimentation in Oblique-slip Mobile Zones – Int. Ass. Sed. Special publ. 4: 7–27

- Remmelts, G. & E.J.Th. Duin 1990 Results of a regional deep seismic survey in The Netherlands. In: B. Pinet & C. Bois (eds): The potential of deep seismic profiling for hydrocarbon exploration – Proc. Inst. François Petr. Expl. Res. Conf.: 335–343
- Rijkers, R., E.J.Th. Duin, M. Duser & V. Langenacker 1993 Crustal structure of the London-Brabant Massif, southern North Sea – Geol. Mag. 130: 569–574
- Rossa, H.G. 1986 Upper Cretaceous and Tertiary inversion tectonics in the western part of the Rhenish-Westphalian coal district (FRG) and in the Campine area (N. Belgium) – Ann. Soc. Geol. Belgique 109: 367–410
- Shackleton, N.J., A. Berger & W.R. Peltier 1990 An alternative astronomical calibration of the Lower Pleistocene timescale on ODP site 677 – Trans. R. Soc. Edinburgh, Earth Sci. 81: 251–261
- Suc, J.P. & W.H. Zagwijn 1983 Plio-Pleistocene correlations between the northwestern Mediterranean region and northwestern Europe according to recent biostratigraphical and palaeoclimatic data – Boreas 12: 153–166
- Thunell, R., D. Williams, E. Tappa, D. Rio & L. Raffi 1990 Plio-Pleistocene stable-isotope record for ODP site 653 – Proc. Ocean Drill. Program, Sci. Results 107: 387–399
- Urban, B. 1978 Vegetationsgeschichtliche Untersuchungen zur Gliederung des Altquartärs der Niederrheinischen Bucht – Sonderverf. Geol. Inst. Univ. Köln 34, 165 pp
- Van den Berg, M.W. 1989 Toelichting op kaartblad 59–62 – Geomorfologische kaart van Nederland, Staring Centrum/Rijks Geol. Dienst, Wageningen, 32 pp
- Van den Berg, M.W. 1993 River Maas terraces as a long continental record of climo-tectonic changes in north-west Europe. In: B. Yu & C.R. Fielding (eds): Proc. 5th Intern. Conf. Fluvial Sedimentology, Brisbane
- Van den Berg, M.W. 1994 Neo-tectonics of the Roer valley rift system. Style and rate of deformation inferred from syn-tectonic sedimentation – Geol. Mijnbouw, this issue
- Van den Berg, M.W., W. Groenewoud, G.K. Lorenz, P.J. Lubbers, D.J. Brus & S.B. Kroonenberg 1994 Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley rift system – Geol. Mijnbouw, this issue
- Vandenberghe, J. 1982 Geoelectric investigations of a fault system in Quaternary deposits – Geoph. Prosp. 30: 879–897
- Van den Haute, P. & C. Vercoutere 1990 Apatite fission track evidence for a Mesozoic uplift of the Brabant Massif: preliminary results – Ann. Soc. Géol. Belgique 112: 443–452
- Van Doorn, Th.H.M. & C.I. Leyzers Vis 1985 Tertiaire en Kwartaire reservoirzanden – In: Aardwarmtewinning en grootschalige warmteopslag in Tertiaire en Kwartaire afzettingen, Rijks Geol. Dienst rep. 85KAR02EX, Haarlem
- Van Wijhe, D.H. 1987 Structural evolution of inverted basins in the Dutch offshore – Tectonophysics 137: 171–219
- Zagwijn, W.H. 1960 Aspects of the Pliocene and Early Pleistocene vegetation in the Netherlands – Meded. Geol. Sticht. 111-1, 5, 78 pp
- Zagwijn, W.H. 1989 The Netherlands during the Tertiary and Quaternary: a case history of Coastal Lowlands evolution – Geol. Mijnbouw 68: 107–121
- Zagwijn, W.H. & H. Hager 1987 Correlation of continental and marine Neogene deposits in the southeastern Netherlands and the Lower Rhine district – Meded. Werkgroep Tertiair-Kwartair Geol. 24: 59–78
- Ziegler, P.A. 1982 Geological Atlas of Western and Central Europe – Shell Int. Petr. Mij/Elsevier Sci. Publ., 155 pp
- Ziegler, P.A. 1990 Geological Atlas of Western and Central Europe, second and completely revised edition – Shell Int. Petr. Mij, The Hague, 239 pp
- Zijerveld, L., R. Stephenson, S. Cloetingh, E. Duin & M.W. van den Berg 1992 Subsidence analysis and modelling of the Roer Valley Graben – Tectonophysics 208: 159–171