Geologie en Mijnbouw **73**: 157–168, 1994.

Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley rift system

M.W. van den Berg[1], W. Groenewoud[2], G.K. Lorenz[2], P.J. Lubbers[4], D.J. Brus[3] & S.B. Kroonenberg[4]
[1] *Geological Survey of the Netherlands, c/o DLO Winand Staring Centre, P.O. Box 125, 6700 AC Wageningen, Netherlands;* [2] *Ministry of Transport, Public Works and Water Management, Survey Department, P.O. Box 5023, 2600 GA Delft, Netherlands;* [3] *DLO Winand Staring Centre, P.O. Box 125, 6700 AC Wageningen, Netherlands;* [4] *Department Soil Science Geology, Agricultural University, P.O. Box 37, 6700 AA Wageningen, Netherlands*

Received 23 October 1993; accepted in revised form 15 April 1994

Key words: geomorphology, land subsidence, neotectonics, Roer Valley Graben.

Abstract

This article presents an integration of geomorphological and geodetic data from the area of the 1992 Roermond earthquake. A dense network of lineaments is evident from major and minor terrain features, and drainage patterns also show structural control on a kilometre scale. These discontinuous terrain lineaments, often of anastomosing character, match known fault patterns and suggest that the upper crust is subdivided into many, relatively small (up to 10 km scale) wedge-shaped blocks. The lineament distribution is consistent with patterns predicted by idealized strain ellipses. It shows a right-lateral component in the motion along major faults within the Lower Rhine Embayment. The wrenching component can be related to a left-lateral motion along the Variscan Front, and a subsequent right-lateral offset of the edge of the London-Brabant Massif. The analysis of a 117-years-long data set of vertical movements at 2922 geodetic bench-marks evidences significant differential movements, and corroborates the sense of relative motion given by the lineaments.

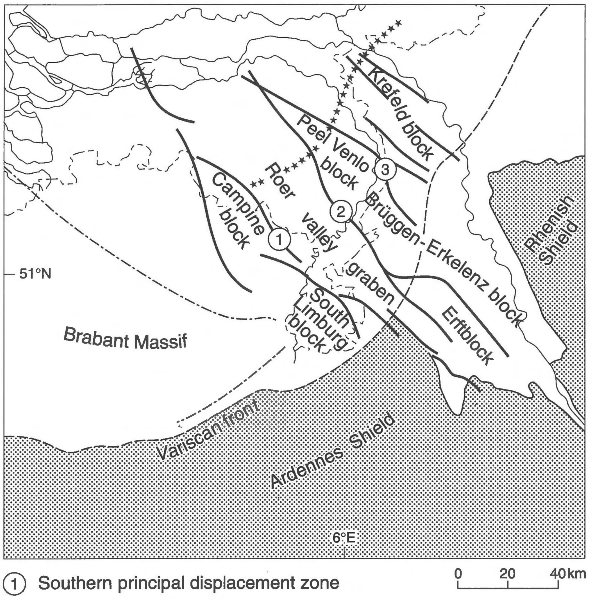
Introduction

In the south-eastern part of the Netherlands the NW-SE fractured zone of the Lower Rhine Embayment, an element of the western and central European rift system, is well expressed on the surface. The area was the scene of the Roermond earthquake on 13 April 1992. A combined analysis of geomorphological and vertical-velocity data for uplift and subsidence of this area will be presented.

The rationale for combined geomorphological and geodetic analysis in neotectonic research is that the former can give indications of the locations of lineaments and the sense of the movement. Geodetic research can give insight into the velocity of the movements, which otherwise can only be obtained as an average for long periods of geological time. This is important as recent research has shown that Quaternary velocities differ significantly from Late Neogene velocities and, that within the Quaternary significant accelerations and decelerations seem to have occurred (Van den Berg 1994).

Recently, rates of vertical movement for about 50 selected bench-marks located throughout the Netherlands were calculated from the extensive historical data base of the Dutch ordnance datum (NAP). This resulted in a map of regional vertical movements in the Netherlands, which shows a striking similarity with geological structures in the subsoil (Lorenz et al. 1991; Groenewoud et al. 1991).

This map has now been improved using levelling data of more than 20 000 surface bench-marks. From this analysis, a detailed and precise vertical-velocity map of the study area was obtained, enabling a first check on the neotectonic movements predicted by geomorphological studies. In interpreting the results one needs to be aware of other factors causing vertical



(1) Southern principal displacement zone
(2) Central principal displacement zone
(3) Northeastern principal displacement zone
** Hingeline of North Sea basin
–·– Subsurface outline of Brabant Massif

Fig. 1. Major structural elements in the study area and adjacent parts of the Lower Rhine Embayment.

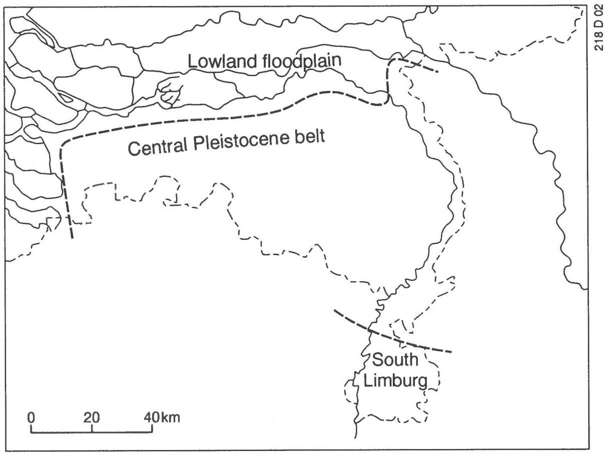


Fig. 2. Regional geomorphology of the southeastern Netherlands.

movements such as compaction, mining activities and glacial rebound.

Geological setting

The study area is situated in the transition zone between the southern North Sea Basin and the foreland of the Variscan Fold Belt. It borders the north-east of the London-Brabant Massif and is dominated by the extensional tectonics of the Lower Rhine Embayment (Fig. 1).

Three main landscapes have been distinguished, from south to north (Fig. 2):

1) the South Limburg area, characterized by strongly dissected loess-covered Pleistocene river terraces underlain by Cretaceous chalk or Tertiary sands;
2) the central area, characterized by flat Mid to Late Pleistocene (< 800 ka) braid plains covered by aeolian sand sheets. Local relief only rarely exceeds a few metres and slopes are less than 1°. Minor relief features stand out clearly in the flat terrain;
3) the northern area, comprising the Holocene flood plains of the rivers Meuse and Rhine. Lineaments are more difficult to trace here because of the young age and strong lithological contrasts; therefore, this part has not been included in the analysis.

The edge of the London-Brabant Massif strikes about N130°E. The Variscan Fold Belt forms a main structural element (thousands of km scale) in northwestern Europe (Ziegler 1990) with a regional orientation in the south-western part of the Lower Rhine Embayment of N60°E, turning to N35°E in the northeastern part. The embayment is dissected by a few (an order of magnitude shorter) NW-SE oriented fault zones. Their orientation with respect to the Variscan Front and the London-Brabant Massif suggests that they form an antithetic set with them (we use the terminology of Christie-Blick & Biddle 1985). Due to the bend in the Variscan Front, some of these fault zones dissect each other a hundred kilometres away in the foreland. This pattern determines the main structural grid, encompassing a number of blocks of which the Roer Valley Graben, the Peel-Venlo Block, the Erft Block, the Krefeld Block and the Campine High are the principal elements (Fig. 1).

Although the fault zones form secondary structures, we will refer to them hereafter as principal displacement zones (PDZ), because they form the main grid and we want to avoid local names for different sections. We recognize three PDZs: a southern, a central and a north-eastern. The southern PDZ separates the South Limburg Block and the Campine High from the Roer Valley Graben. The latter is separated by the central PDZ from the Peel-Venlo Block, which in turn is separated from the Krefeld Block by the northern PDZ.

The main trend of the central PDZ is N150°E, whereas the trend of the north-eastern PDZ is N120°E. The Peel-Venlo Block forms a wedge between the central and the northeastern PDZ and is bordered to the northeast by the Krefeld Block. The northern PDZ forms the continuation of a series of parallel main faults in adjacent Germany (Plein et al. 1982). There, these faults show well-developed flower structures on seismic reflection lines, indicative of wrenching (Christie-Blick & Biddle 1985). These main units are again subdivided into many subunits, some of which will be discussed below.

Morphostructural analysis

Due to their long-term behaviour, slow crustal movements along faults show up as surface features (e.g. smoothed terrain steps) of variable size. The study of these features provides valuable information on recent tectonics. Mapping and analysis of these surface features can be done in various ways, e.g. from satellite imagery and field documentation of geomorphic and stratigraphic relationships. A problem with satellite imagery is the discrimination between natural and artificial, man-induced, rectilinear features. However the resolution from satellite imagery is high.

The first step in the analysis was to prepare a contour map with 0.5 m intervals, drawn manually from point elevations on the 1 : 10 000 elevation map of the Topographical Survey of the Netherlands (not yet available in digitized form). The latter map is based on third-order levelling data points arranged in a more or less regular grid of 100 m × 100 m. The altitude information is given with 0.1 m accuracy. The next step was to identify discontinuities in the surface morphology. This was done by constructing long surface profiles parallel and perpendicular to the main strike of the contour lines. These profiles were drawn at regular distances of 5 km. Abrupt breaks in slope were mapped.

Using the regional geology and geomorphology we classified the identified surface discontinuities into man-made structures and natural features of aeolian, fluviatile and tectonic origin. Man-made structures are known from the topographic maps. Aeolian forms are divisible into two groups: (1) an undulating cover sand topography with local height differences less than 0.5 m; this type does not show up on the surface profiles; (2) large dune complexes (either with a strongly undulating relief or a whale-back shape), which appear to be situated on top of a continuous surface; therefore these features could easily be excluded. The subdivision of fluviatile forms into purely fluviatile and structurally controlled forms is less straightforward. Vandenberghe (1990) has shown that local drainage systems, as developed on the Campine Block, are strongly structurally controlled; braided or meandering channel patterns and incised valleys of the river Meuse also appear to line up with fault lines. So some of the river bends form a part of the lineaments.

The main criteria, applied by several observers, to distinguish tectonic lineaments (Fig. 3a) from each other or accidental alignments were:

- a minimum length of one kilometre or alternatively arrays of shorter discontinuous lineaments in line with each other;
- rectilinear jumps in altitude or slope breaks;
- rectilinear segments in the drainage pattern.

The striking difference in lineament-density between our study area and the area studied by Plein et al. (1982) is the result of different analysis techniques.

Determining land surface deformation

The Dutch ordnance datum NAP

All heights in the Netherlands are related to the Dutch ordnance datum NAP (Normaal Amsterdams Peil). This reference level was fixed in 1684 by nine stones in sluices in Amsterdam. Due to reconstruction works, these stones have all disappeared. The last stone, which was removed in 1953, was replaced by a 23 m-long foundation pile at the Dam square in Amsterdam. This pile now acts as the fundamental bench-mark of the NAP height datum.

For practical and theoretical reasons several bench-marks with very accurate heights are needed. These underground bench-marks, which serve as regional markers for the NAP, have been installed since the so-called Second Primary Levelling (1926–1940). At present there are more than 150 underground bench-marks all over the Netherlands.

For determining land surface deformation, the foundation of a bench-mark is of prime importance. In the so-called 'order' of a bench-mark an indication can be found of its foundation. For both first-order and second-order bench-marks the sites have been carefully selected, soil properties and geological

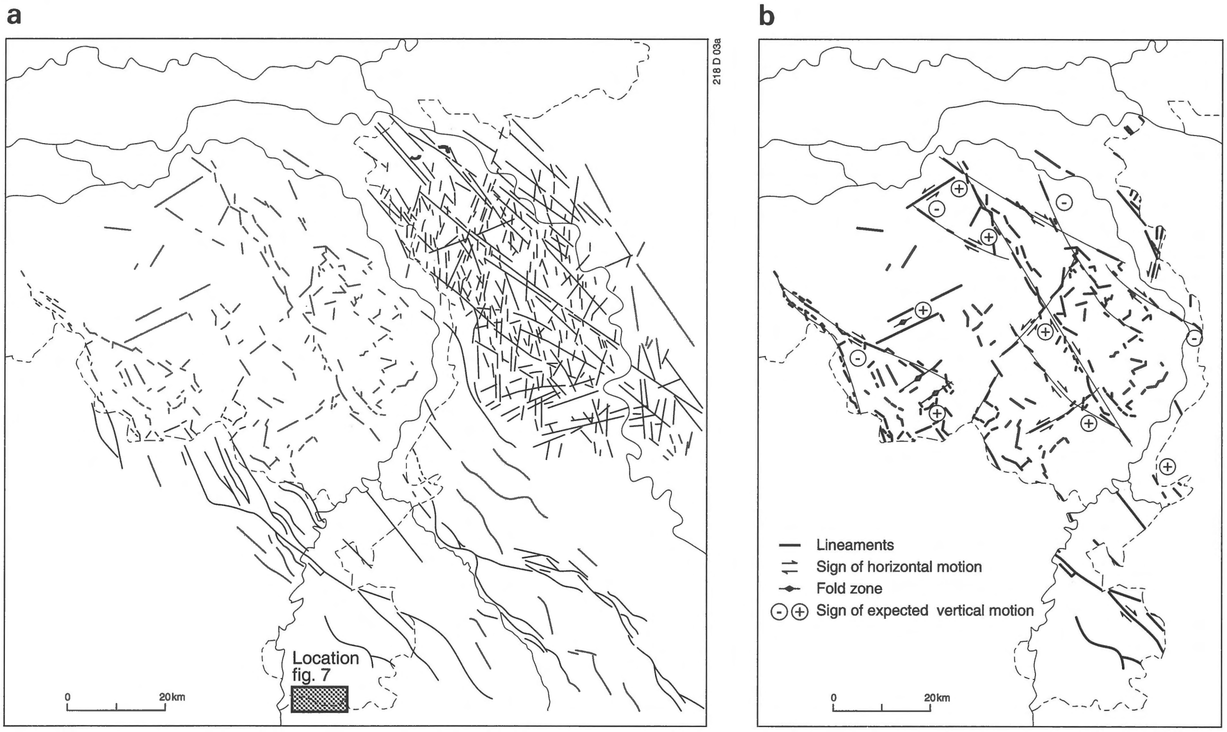


Fig. 3. a. Surface expressions of tectonic lineaments in the study area and its vicinity. Data in Germany from Plein et al. (1982; landsat images) and Ahorner (1962; geological study); in Belgium from Demyttenaere & Laga (1988; seismic) and Paulissen (1973; geomorphology). b. Main structural lines inferred from surface lineament arrays in Fig. 3a. The arrangement of structures indicates a right-lateral shear component within the general extensional setting.

conditions have been investigated, and all first-order and second-order underground bench-marks have been placed in the upper reaches of the Pleistocene sands. These sands were assumed to be stable. For third-order underground bench-marks, no geological research was carried out.

Since the stability of the underground bench-marks was of utmost importance, all of them were specially designed. This has resulted in a construction that protects the bench-mark from any vertical movements due to forces acting in the sediments above the foundation level (e.g. dragging from compacting Holocene sediments). Movements of the foundation level, however, cannot be ruled out. These movements have always been considered to be negligible. However, recent investigations have shown that significant movements do occur (Lorenz et al. 1991). This is an important observation, since the heights of the underground bench-marks have never been corrected for these movements.

Apart from the underground bench-marks, there is a dense network of 'surface bench-marks'. This network, which is much older than that of underground bench-marks, is available for practical purposes. The bench-marks predominantly consist of bolts that are placed in houses, churches, bridges, etc. The entire Dutch network consists of over 50 000 bench-marks, which means that, on average, there is one in every square kilometre.

In contrast to the underground bench-marks, surface bench-marks are 'free to move', i.e. it is accepted that, due to various mechanisms, vertical movement of the bench-marks is likely to occur. For this reason, the heights of all bench-marks are determined on a regular basis (at least once every ten years) using levelling techniques. Lithological and geological conditions must be taken into account when interpreting the movements of surface bench-marks. In the study area, the outcropping rocks include Cretaceous chalk in the extreme south, Pleistocene sands in the central part, and Holocene sands and clays in the north. Apart from the chalk, all the sediments are unlithified. Except for the Holocene sediments, all rocks are considered to be well consolidated.

Table 1. Precision requirements (in mm) as a function of the measuring distance l (in km) for 1st, 2nd and 3rd order levellings

	1st order	2nd order	3rd order
Section	$2.5\sqrt{l}$	$3.0\sqrt{l}$	$6.0\sqrt{l}$
Traject	$2.5\sqrt{l}$	$3.0\sqrt{l}$	$6.0\sqrt{l}$
Circle	$1.3\sqrt{l}$	$1.5\sqrt{l}$	$3.0\sqrt{l}$

(Example: for a 49 km circle of a 1st order levelling, the precision should be better than $1.3 \times \sqrt{49} =$ 9.1 mm)

Table 2. Input and output statistics of vertical movement analysis

Input statistics	
number of bench-marks:	11 207
number of measurements:	34 142
selected levellings:	1st, 2nd and 3rd order
first measurement:	1875
last measurement:	1992
minimum interval:	10 years
Output statistics	
vertical velocities	
calculated for:	2922 bench-marks
number of measurements:	171059
average vertical velocity:	-18 mm/100 yrs

Movement analysis

From repeated height determinations, an extensive data base on historical height data has been obtained. In spite of the yearly loss of about 3% of the bench-marks, long time series (up to 117 years) of changes in height are available for many of them. Various criteria have been applied for selecting the data. Of prime importance is the order of the selected levelling campaigns; first-order, second-order and third-order data are available for the movement analysis. These orders of levelling indicate the precision requirements for the levelling campaigns; a first-order levelling is the most precise. However, since the densities of the networks of second-order and third-order levellings are much higher than those of the first-order network, the redundancy of data results in height values with fairly comparable precision for all orders of levelling (Table 1).

From the selected data, rates of vertical movement or 'vertical velocities' can be determined quite easily. For this purpose, a regression analysis was conducted for each bench-mark record. In our study, we analysed data from first-, second- and third-order levelling campaigns. The statistics of movement analysis are given in Table 2.

One has to bear in mind that the heights of the surface bench-marks have always been determined relative to the underground bench-marks. This implies, that the recently observed height changes of the underground bench-marks are not incorporated in the records of height changes of surface bench-marks. Since the abrupt lateral changes (which obviously do not depend on absolute values) in the distribution of vertical velocities are the most important indicators for neotectonic activity, the research is not seriously hampered by this lack of absolute information.

Spatial interpolation

A regional map of vertical velocities has been constructed to compare these velocities at individual points with geological and geomorphological data. In principle, various techniques of interpolation can be adapted for this purpose, each with its own theoretical background and applications. We used the kriging technique to construct the maps shown in Fig. 4. An important advantage of this technique is that it provides estimates of the accuracy simultaneously with estimates of the spatial distribution of the velocity. For detailed information we refer to Journel & Huijbregts (1978), Isaaks & Srivastava (1989), and Webster & Oliver (1990). The kriging technique was slightly modified to account for the uncertainty of the vertical velocity at the bench-mark points estimated by regression analysis (Ahmed & De Marsily 1987). In this modified kriging technique the semivariogram based on errorless measurements of velocity is used. We approximated this semivariogram by the one based on regression estimates with small error (estimated variance < 0.01).

We assumed that the mean and variance of the vertical velocity will be different for the major tectonic units. Therefore we estimated semivariograms for these units separately and used these in stratified kriging (Stein et al. 1988). The vertical velocity at a new location was estimated by using the twenty nearest observation points in the same stratum. Figure 4a shows the result. The root of the kriging variance is shown on Fig. 4b. The kriging variance is strongly determined by the semivariogram, explaining the dif-

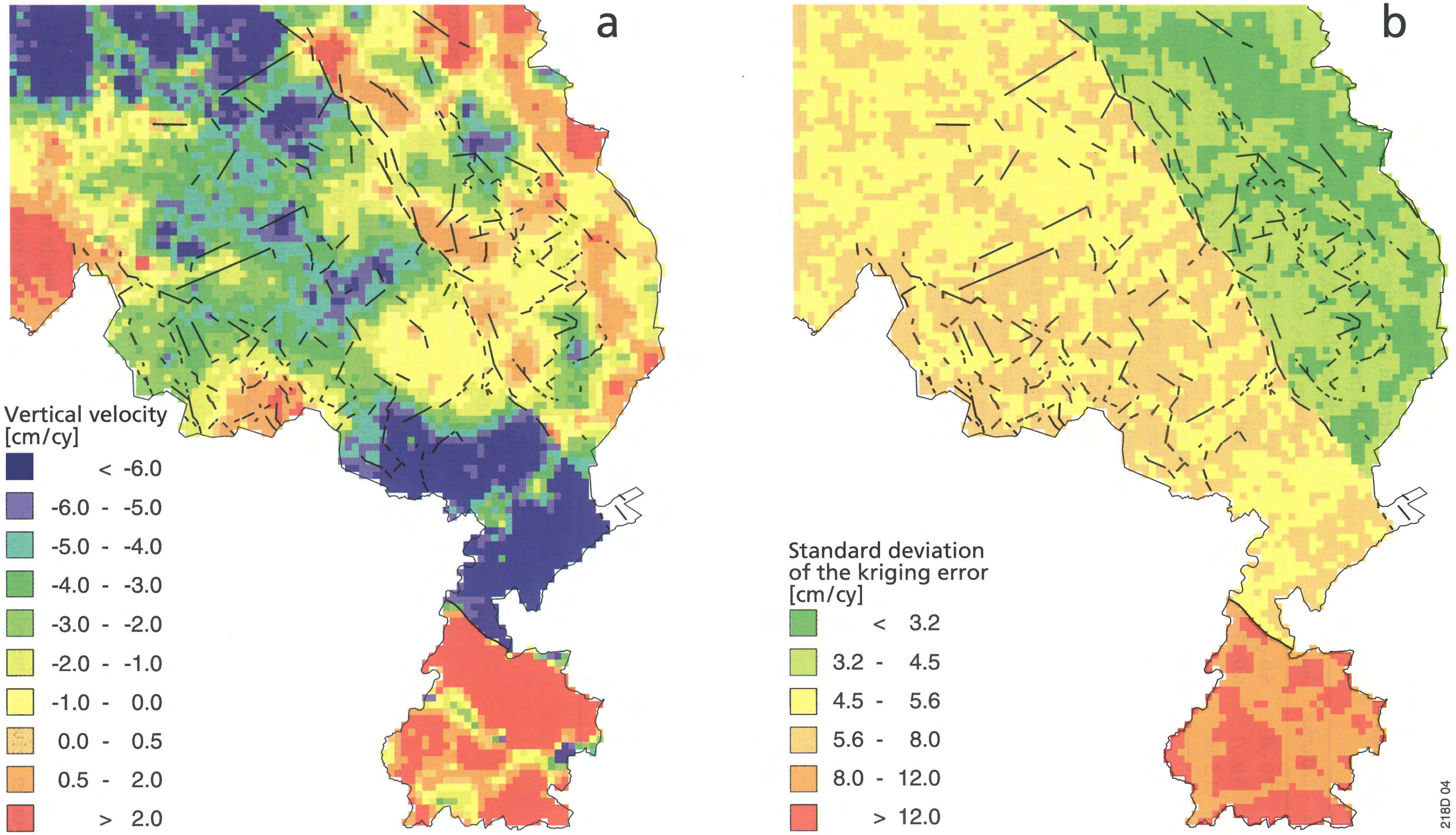


Fig. 4. a. Vertical velocities estimated in centimetres per century (cm/cy) by kriging. Scale 1:1 000 000. b. Kriging standard deviation in centimetres per century (cm/cy) of the estimated vertical velocities. Scale 1:1 000 000.

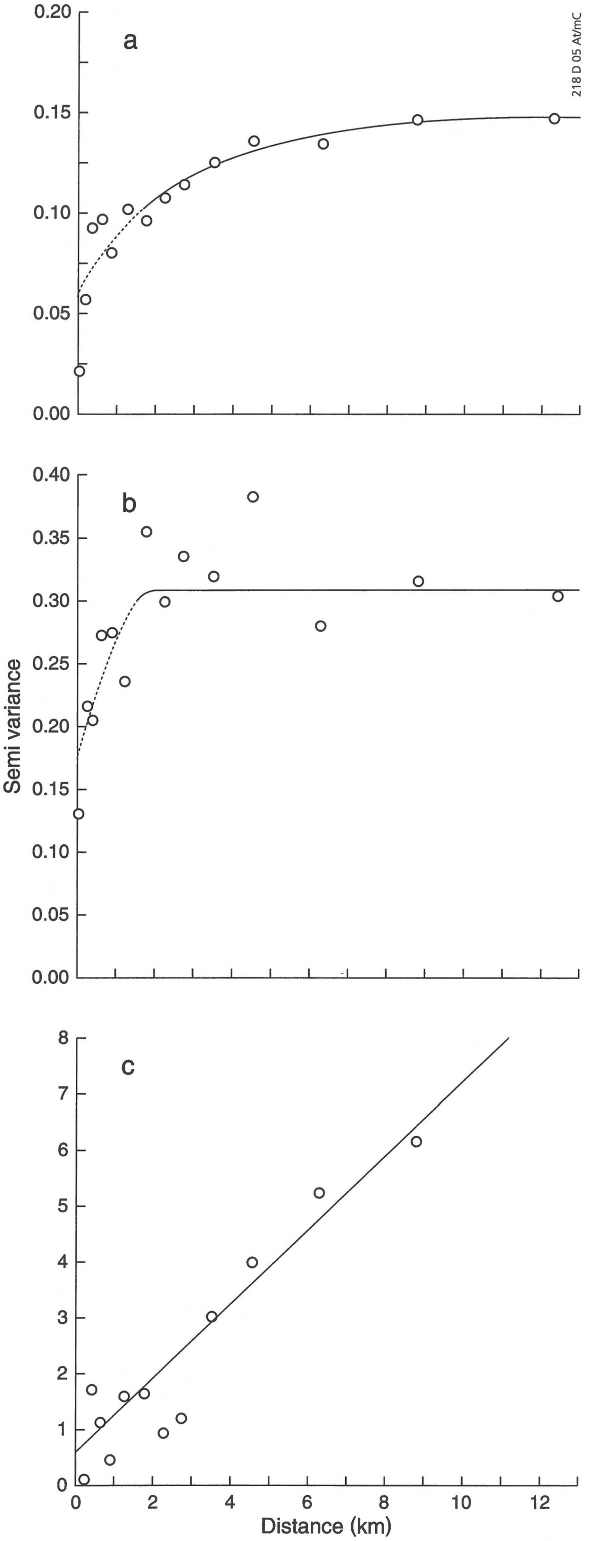


Fig. 5. Sample semivariograms and fitted models a: Peel-Venlo Block, b: Roer Valley Graben, c: Campine High together with South Limburg.

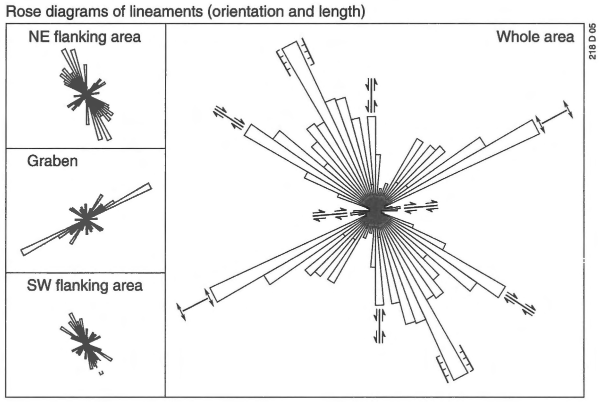


Fig. 6. Surface lineaments presented as rose diagrams (length × orientation) for the entire study area (whole area), the Peel-Venlo Block ('NE flanking area'), the Roer Valley Graben ('Graben'), and the Campine High ('SW flanking area').

ferent levels of the kriging variance for the strata. For example, the nugget and the sill of the semivariogram are much smaller for the Peel Horst (Fig. 5a) than for the Roer Valley Graben (Fig. 5b), which explains that the kriging variance is relatively small here.

Results and interpretation

Regional warping

To evaluate the pattern displayed by the lineaments, we first plotted the lineaments (cumulative length percentage × orientation-class) in a rose diagram for each major tectonic unit (Fig. 6). The different tectonic domains were then analysed.

The rose diagrams show strong concentrations around NW-SE (N140–160°E, N115–130°E) and NE-SW (N55–65°E), whereas a minor peak occurs around N40°E (Fig. 6). The diagrams for the NE flanking area (Peel-Venlo Block) and the SW flanking area (Campine High) are more or less similar, whereas NE-SW orientations predominate within the Roer Valley Graben.

The lineaments are clearly discontinuous, but show grouping of the individual lines into various long, spatially separated, arrays. In many cases, these composites coincide with known fault lines and line up with structures known from Belgium (Paulissen 1973; Demyttenaere & Laga, 1988) and Germany (Ahorner 1962; Plein et al. 1982; Fig. 3b). The angular relationships among the short lines as well as among the long composites are persistent at about 60°, 15° and 75°. This recalls the angles of shearing resistance in Riedel experiments (Tschalenko 1970). The central PDZ is a particularly clear example of a fault zone composed of a network of branching and rejoining elements. This pattern can also be recognized in the other composites.

All the above-mentioned features together emphasize the tectonic origin of the individual lineaments. The anastomosing appearance of the PDZs (with the 15° angle of the second-order lineations) is a strong indication that horizontal movements are in progress along these fault zones. This process of shear will lead to a structurally complex pattern of local uplifting and downwarping blocks. We established a hierarchy in the lineaments to predict the local movements from the lineament pattern.

The lineament pattern breaks up into associated elements that form arrays of different lengths. This length is taken as a key to the hierarchy. The highest level is formed by the longest continuous lines, i.e. the Variscan Front and the edge of the London-Brabant Massif. The second order is taken by the PDZs and the third and lower orders are taken by subsequently shorter elements. Using the mutual angular relationships between the hierarchic elements and an idealized strain ellipse (Harding et al. 1985) we determined the expected sense of movement on both sides of the shearing zones (Fig. 3b).

The distribution of vertical velocities roughly coincides with the principal structural elements (Fig. 4). Topographic highs, such as Netherlands South Limburg and the Peel-Venlo Block, are rising and topographic lows, such as the graben and the riverine area, are subsiding. But several apparent inconsistencies in this general picture are also evident. The smaller-scale patchy pattern within the blocks suggests that the main domains are divided into minor domains. This is especially striking within the graben. Furthermore, a conspicuous anomaly is that the river Meuse flows through an uplifting area for a considerable stretch of its course, whereas the Rhine is confined to an area of subsidence. Another striking feature is the subsiding north-eastern part of the Peel-Venlo Block. The relations of this general picture with the structural elements are discussed below.

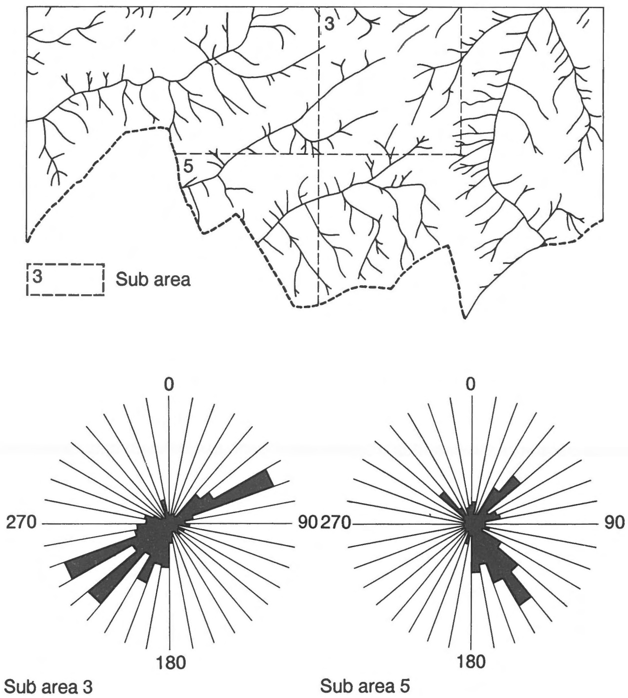


Fig. 7. An example of the structurally controlled valley orientation of the secondary drainage pattern in South Limburg (For location see Fig. 3). Rose diagrams (valley length × orientation) are shown for two subareas. Mapped area measures 10 km E-W.

Differential movements

South Limburg

The South Limburg Block forms a structural high, wedged between the Variscan Front (the Midi-Aachen Thrust) and the southern PDZ of the rift. Uplifting has been going on here since the Miocene, as evidenced by the river terraces (Van den Berg 1994). Although we know that the subsurface is strongly faulted (Felder & Bosch 1977), the fault system is expressed on the surface rather by the orientation of the secondary drainage pattern than by terrain steps (Fig. 7). For this reason the lineaments have not been indicated on the map of Fig. 3a.

Some strong lineaments emerge from the congruency of Meuse river terrace bluffs of different ages. This pattern probably reflects crustal buckling in the foreland of the Variscan Front during the Plio-Pleistocene (Fig. 2 in: Van den Berg 1994). Such movement is not apparent from the present-day vertical velocities.

Fault lines with a clear surface expression are almost all related to the southern PDZ. This zone itself is well expressed, both in the field by a smoothed scarp of 10–40 m height and on the velocity map by the opposite sense of vertical movements on both sides of the zone, i.e. subsidence at a rate of 0.7 mm.a-1 in the north and a general rapid uplift of 0.8 mm.a-1 in the south. The main direction of the Meuse river valley north of Maastricht is controlled by the conjugate faults associated with the PDZ. South of Maastricht the main orientation changes and becomes antithetic to the Variscan Front.

For a 10 km-wide area south-west of the southern PDZ we would expect some relative downthrow. However, extremely high uplift velocities (> 15 mm.a-1) are recorded here. They are interpreted as artefacts. This is the old coal-mining district; the observed uplift is calculated from measurements that have been collected over a period of about 20 years, and is caused by recharge of groundwater into the abandoned mines (Pöttgens 1990).

Campine Block

The Campine Block is one of the fractured structural highs wedged between two left-stepping fault elements of the southern PDZ (Geluk et al. 1994).

In map view, the southern PDZ splays 15°E in Belgium (Demyttenaere & Laga 1988) and forms a 'lazy S' before it rejoins with faults normal to the edge of the London-Brabant Massif. A pull-apart basin is encompassed. The NW-SE oriented short lineaments within this basin reflect normal and reverse extensional faults. This extension is in accordance with the observed subsidence. The registered uplift in the south-eastern part coincides with NE-SW oriented short lineaments. Their orientation is normal to the extensional features and, within a strike-slip setting, they may consequently reflect folding associated with a horizontal motion.

Roer Valley Graben area

The rose diagram drawn from the lineaments within the graben area is dominated by NE-SW orientations, which represent shearing structures antithetic to the PDZs. A subordinate orientation peaks at N120°E, interpreted to be formed by the associated P-shears. The latter occur preferentially along the central PDZ. Presumably this is determined by the structure of the main grid. These third-order structures delineate blocks, of which the corners experience local convergence or divergence depending on the relative sense of horizontal motion. The predicted movements at the fault junctions can in many cases explain the apparent inconsistencies mentioned above.

As indicated by Geluk et al. (1994), the Roer Valley Graben can be divided into two units with different structural styles: a south-eastern part and a north-western part. The Veldhoven Fault forms the boundary between the two units. Although its eastern continuation is not yet clear from the available seismic lines, it can be recognized on the surface as a pronounced, composite lineament with a general N40°E strike, right across the graben and continuing on to the Peel-Venlo Block. The surface elevation of both the graben and the Peel-Venlo Block is significantly higher south-east of this line than north-west of it.

In the south-eastern part of the graben area, between the river Meuse and the Dutch-German border, rapid subsidence can be observed (Fig. 4a). This contradicts the geophysical and geomorphological data, from which only minor subsidence, or even uplift is expected. The anticlinal structures in the subsurface, indicating a compressional regime (Van den Berg 1994), are believed to be responsible for this. Maybe the combined effects of increased regional groundwater extraction and of browncoal mining in the German part of the graben, overrule the expected movements.

A striking feature is the narrow uplifting zone along the Meuse amidst a wide subsiding area. In this area large-scale gravel extraction takes place, and possibly causes the relaxation.

Peel-Venlo Block

The Peel-Venlo Block continues south-eastward into the Brüggen-Erkelenz High. Together they form a north-eastward tilted, triangular block between the central and north-eastern PDZ. The Venlo Graben is a local sagged area in the northeastern corner of the block.

The stratigraphy in this Venlo Graben shows a discontinuous sedimentary record: sedimentation (= extension) alternates with non-deposition (= compression). The geodetic observations show that this subregion is currently experiencing strong uplift. We attribute this to a current clockwise block rotation (Fig. 8).

The Peel-Venlo Block is wedged between two right-lateral shear zones, with the central PDZ terminating much further south than the north-eastern one (Fig. 8, inset). This difference in length may cause block-torsion during an apparent anti-clockwise rotation of the Peel-Venlo Block. Such a torsion could

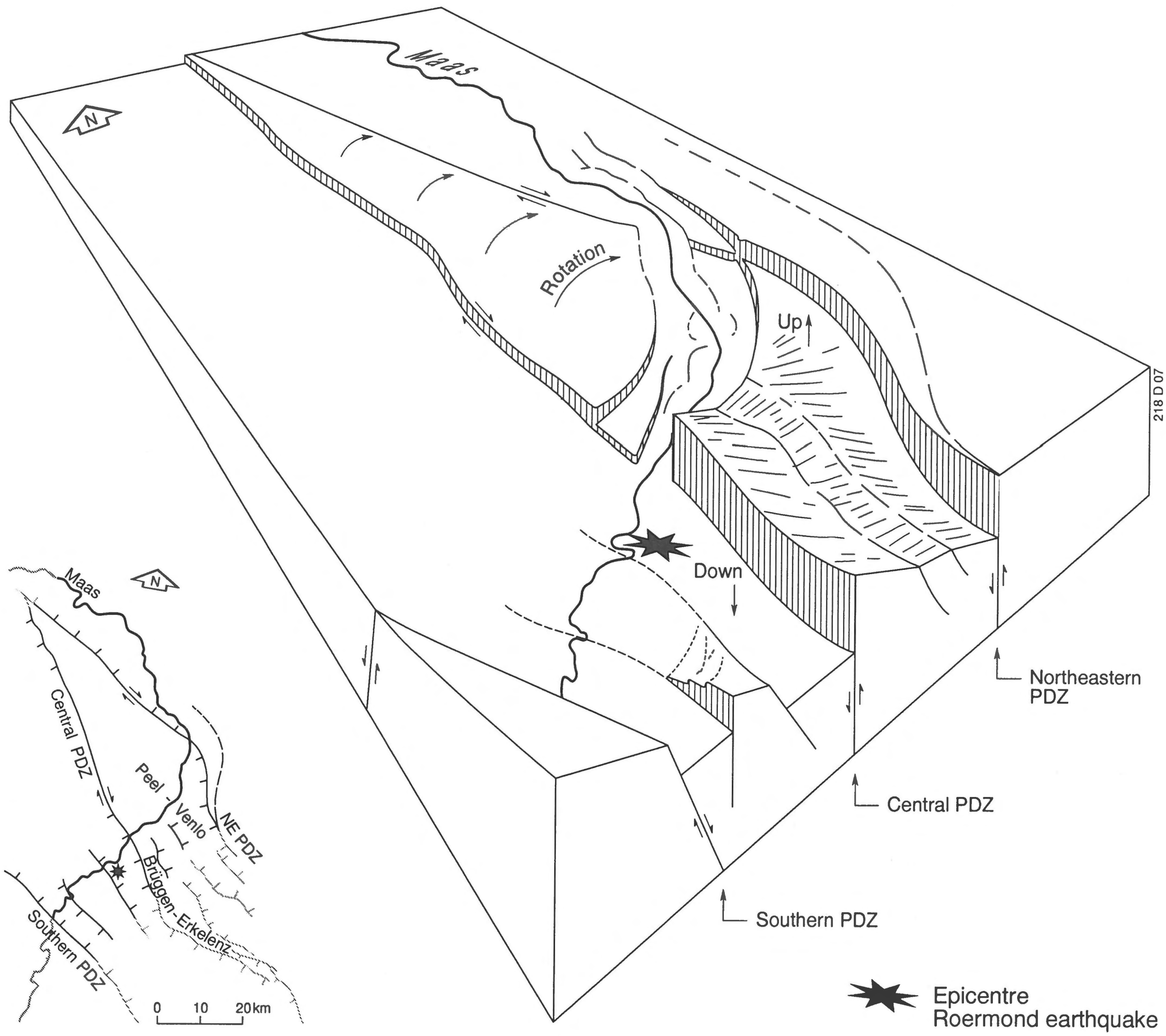


Fig. 8. A model for the relative motion of the Peel-Venlo Block. This block and its south-eastern continuation, the Brüggen-Erkelenz High, is wedged between two right-lateral, principal displacement zones (PDZ) causing a clockwise block rotation. This may generate compression in the north-east corner (the Venlo Graben) of the block and simultaneously extension along the central PDZ. This model matches the geodetic observations but disregards the overall geological trend of subsidence in the Venlo Graben. This apparent contradiction moreover stresses the periodic changes in styles of motion along the main fault lines. The blockdiagram is schematic and the mapped area measures approximately 60 × 80 km. The vertical throw at the surface along the central PDZ amounts to about 40m in the south-east and only a few metres in the north-west. The Maas valley is not shown to the south of the southern PDZ. To the north of the epicentre this valley is bounded by erosional scarps.

explain the relative uplift of the Brüggen-Erkelenz part and the consequent tilting to the north-east.

The course of the river Meuse (= Maas) in this area appears to be strongly controlled by lineaments within the block. Not only the general course but also most of the individual 'meander' bends line up with structural elements. Shortly after the Meuse crosses the north-eastern PDZ, the main direction of the river channel turns towards N145°E. This is the orientation of associated extensional structures expected under conditions of right-lateral shear. This extension is also reflected in the observed subsidence just north-west of the river.

The movements along the main faults cause stress, released by second-order shears in the blocks in between. The direction of a second-order trellis-like drainage pattern on the Peel-Venlo Block and the NE-SW oriented sets of lineaments reflect this stress. The second-order strain pattern is not evenly distributed over the wedge-shaped Peel-Venlo Block; it appears to be concentrated within the, topographically high, south-eastern half. The boundary between the two areas is formed by the earlier mentioned SW-NE oriented long composite lineament. Both the structural style and the surface altitude of the Roer Valley Graben also change across this lineament.

Hinge line of the North Sea Basin
The above-mentioned strong lineament separates both in the Roer Valley Graben and in the Peel-Venlo Block regions with different structural aspects. This lineament also marks an ancient structure in the subcropping Carboniferous, as already observed by Van Waterschoot van der Gracht (1918).

The difference in height of the land surface is also observed in the Meuse valley on the north-eastern side of the Peel-Venlo Block. As soon as the river crosses this lineament, older river terrace levels become buried under younger ones (terrace intersection zone). Outside the study area, the lineament lines up with the zone of outcropping Tertiary deposits in the east of the Netherlands. On the basis of these features, we assume that this marks the hinge zone of the North Sea Basin. This interpretation also explains that, generally, lineaments are less clear to the north-west of this structure.

Holocene riverine area
In the Holocene riverine area, lineaments are extremely difficult to trace at the land suface. There are at least three reasons for this:

1) The area is covered by subrecent Meuse-Rhine sediments, increasing in thickness towards the west (up to 10 m). This sediment cover obliterates Pleistocene surface deformations. Moreover, Holocene sedimentation rates (Törnquist 1993) balance the rate of present-day deformations.
2) Differential compaction of floodplain sediments complicates the interpretation of differences in land surface altitude.
3) The area lies basin-ward of the hinge line of the North Sea Basin. Here, the fault offsets are generally less than those south of this line; hence they are less likely to be traced on the surface.

Conclusions

This study demonstrates that the resolution of structural detail becomes far greater when subsurface analyses are complemented with land surface analysis.

The principal fault elements in the Lower Rhine Embayment show many characteristics of ongoing horizontal shear. They are expressed on the surface as well-defined, but discontinuous lineaments. The orientation and geometry of the composite lineaments correspond with structures predicted from the deformation of homogeneous isotropic materials.

The analysis of bench-mark records shows that the overall pattern of distribution of the vertical velocities fits the known main structural elements. Significant deviations from the general picture can be explained by adding a right-lateral shear component to the generally accepted regional extension. Such a motion is also documented instrumentally from earthquakes showing a dip-slip or strike-slip origin (Ahorner 1975). This suggests that for other areas with a low-frequency seismicity, the combined approach of morphostructural analysis and long geodetic time series can reveal the stress field.

Our study shows that also in areas of relatively low deformation rates, tectonic processes are fundamental to the understanding of supposedly climatically controlled land surfaces and drainage systems.

Acknowledgements

We are grateful to Rini Schuiling of the Department of Cartography and Visualization Techniques of the DLO Winand Staring Centre for his assistance in preparing the maps. We are also grateful to Anna-Maria Braun (stationed at the Survey Department, Rijkswaterstaat) and Ruben Dood (Survey Department, Rijkswaterstaat) for their contribution in the subsidence analysis and their patience in preparing the figures.

References

Ahmed, S. & G. de Marsily 1987 Comparison of geo-statistical methods for estimating transmissivity using data on transmissivity and specific capacity - Water Res. 23: 1717–1737

Ahorner, L. 1962 Untersuchungen zur quartären Bruchtektonik der Niederrheinischen Bucht - Eiszeitalter und Gegenwart 13: 24–105

Ahorner, L. 1975 Present-day stress field and seismotectonic block movements along major fault zones in Central Europe. In: Pavoni,

N. & R. Green (eds) Recent crustal movements - Tectonophysics 29: 233–249

Christie-Blick, N. & K.T. Biddle 1985 Deformation and basin formation along strike-slip faults. In: Strike-slip deformation, basin formation and sedimentation. Soc. Econ. Paleont. Mineral. Spec. Publ. 37: 1–34

Demyttenaere, R. & P. Laga 1988 Breuken- en isohypsenkaarten van het Belgische gedeelte van de Roerdal Slenk. Belgische Geol. Dienst Prof. paper 1988/4, 234 pp

Felder, W.M. & P.J. Bosch 1977 Geologische kaart van Zuid Limburg en omgeving: Pre-Kwartair, 1:50.000. Rijks Geol. Dienst, Haarlem

Geluk, M.C., E.J.T. Duin, M. Dusar, R.H.B. Rijkers, M.W. van den Berg & P. van Rooijen 1994 Stratigraphy and tectonics of the Roer Valley Graben - Geol. Mijnbouw, this issue

Groenewoud, W., G.K. Lorenz, F. Brouwer & R.E. Molendijk 1991 Geodetic determination of recent land subsidence in The Netherlands. In: A.I. Johnson (ed.) Landsubsidence: Proc. Fourth Int. Symp. Land Subsidence, Houston, Texas 12–17 May 1991: 463–471

Harding, T.P., R.C. Vierbruchen & N. Christie-Blick 1985 Structural styles, plate-tectonic settings, and hydrocarbon traps of divergent (transtensional) wrench faults. In: Strike-slip deformation, basin formation, and sedimentation. Soc. Econ. Paleont. Mineral. Spec. Publ. 37: 51–77

Isaaks, E.H. & R.M. Srivastava 1989 Applied Geo-statistics. Oxford University Press, 561 pp

Journel, A.G. & C.J. Huijbregts 1978 Mining geo-statistics. Academic Press, London, 600 pp

Lorenz, G.K., W. Groenewoud, F. Schokking, M.W. van den Berg, H. Wiersma, S. Jelgersma & F. Brouwer 1991 Heden en Verleden - Nederland naar Beneden ??? Interim rapport over het onderzoek naar bodembeweging in Nederland. Rijkswaterstaat Delft/Rijswijk, Rijks Geol. Dienst, Haarlem, 72 pp

Paulissen, E. 1973 De morfologie en de kwartairstratigrafie van de Maasvallei in Belgisch Limburg - Verh. Kon. Vlaamse Acad. Wet. etc. 35 (127), 266 pp

Plein, E., W. Dorholt & G. Greiner 1982 Das Krefelder Gewölbe in der Niederrheinischen Bucht - Teil einer groszen horizontalverschiebungszone? - Fortschr. Geol. Rheinl. Westf. 30: 15–29

Pöttgens, J.J.E. 1990 Bodembewegingen bij delfstoffenwinning in Nederland, van empirie tot fenomenologie. In: Bodemdaling in Nederland, Symposiumverslag. 8 nov. 1990, Faculteit Mijnbouw en Petroleumwinning, TU Delft: 13–34

Stein, A., M. Hoogerwerf & J. Bouma, 1988 Use of soil-map delinations to improve (co)-kriging of point data on moisture deficits - Geoderma 43: 163–177.

Tschalenko, J.S. 1970 Similarities between shear zones of different magnitude - Geol. Soc. Am. Bull. 81: 1625–1640

Törnquist, T.E. 1993 Fluvial sedimentary geology and chronology of the Holocene Rhine-Meuse delta, the Netherlands. PhD-Thesis Univ. Utrecht: 193 pp

Van den Berg, M.W. 1994 Neo-tectonics of the Roer Valley Graben. Style and rate of crustal deformation inferred from syn-tectonic sedimentation. Geol. Mijnbouw, this issue

Vandenberghe, J. 1990 Morphological effects of Pleistocene faulting in unconsolidated sediments (Central Graben) (id. Roer Valley Graben (authors)). Z. Geomorph. M.F. 34 (1)

Van Waterschoot van der Gracht, W.A.J.M. 1918 Eindverslag over de onderzoekingen en uitkomsten van den Dienst der Rijksopsporing van Delfstoffen in Nederland, 1903–1916. Drukkerij 't Kasteel van Aemstel, Amsterdam, 664 pp

Webster, R. & M.A. Oliver 1990 Statistical methods in soil and land resource survey. Oxford Univ. Press, 316 pp

Ziegler, P. 1990 Geological Atlas of Western and Central Europe. Shell Int. Petr. Mij. and Geol. Soc. London Publ., 2nd ed., 239 pp