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Neotectonics of the Roer Valley rift system. Style and rate of crustal deformation inferred from syn-tectonic sedimentation

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Abstract

The Roer Valley rift system emerged since the Middle Miocene and fluvial sediments were supplied to it by the Rhine, Maas (Meuse) and local Belgian rivers. Ever since the emergence, thirty fluvial terraces of the lower Maas river have been formed due to regional uplift. Their age–altitude record shows strong evidence for an important acceleration of the tectonic activity at the end of the Pliocene (around 3 Ma), and for high-frequency oscillations superimposed on a general continuous trend. Three relaxation periods during the Quaternary were identified, the first from 1.5 to 1.2 Ma and two short ones around 5 ka BP and after 2 ka BP, respectively. The reactivations, following these relaxation periods, appear to be of plate-tectonic importance. The observed accelerations in tectonic activity since the Late Pliocene through the Pleistocene to the present day, raise the question: are we at present living in a period of extremely high crustal dynamics? Floodplain positions of the rivers Rhine and Maas repeatedly changed in space and time. Strike-slip movements along the graben bounding faults explain this behaviour. The events point to punctuated changes in the stress field orientation, probably related to the interplay between Alpine and Ardennes-Rhenish Shield stress generators within the regional stress field.

Introduction

Recent work on subsidence (Zijerveld et al. 1992) and stratigraphic modelling (Kooi & Cloetingh 1989; Kooi 1991; Kooi et al. 1991; Cloetingh & Kooi 1992) of the southern North Sea region provides evidence of a phase of accelerated subsidence in the Late Neogene. This phase has been recognised all around the North Atlantic (Cloetingh et al. 1990).

These observations stress the importance of the study of the time frame of the Late Cenozoic geodynamics (neo-tectonics), more so because similar observations have been made in other parts of the world (Kaldova 1988; Ruddimann et al. 1989). Whether the observed events are synchronous, however, is still uncertain.

Integrated studies of fluvial geomorphology, fluvial sedimentology and stratigraphy can improve the time resolution of regional neotectonics. This is demonstrated in the present case study of the Roer Valley rift system.

Earlier work in this tectonic domain (Van den Berg 1989) has shown a strong matching of independently mapped fluvial and structural patterns. This observation has led to the basic assumption that crustal block movements, even if they operate at extremely low rates, due to their persistence steer the long-term position of the fluvial system. If so, the analyses of the fluvial record in space and time may reveal the ongoing crustal deformations.

This paper focuses on the uplifting south flank and subsiding central part of the rift system. The interpretation of their dynamics will be followed by some reflections on the plate-tectonic implications.

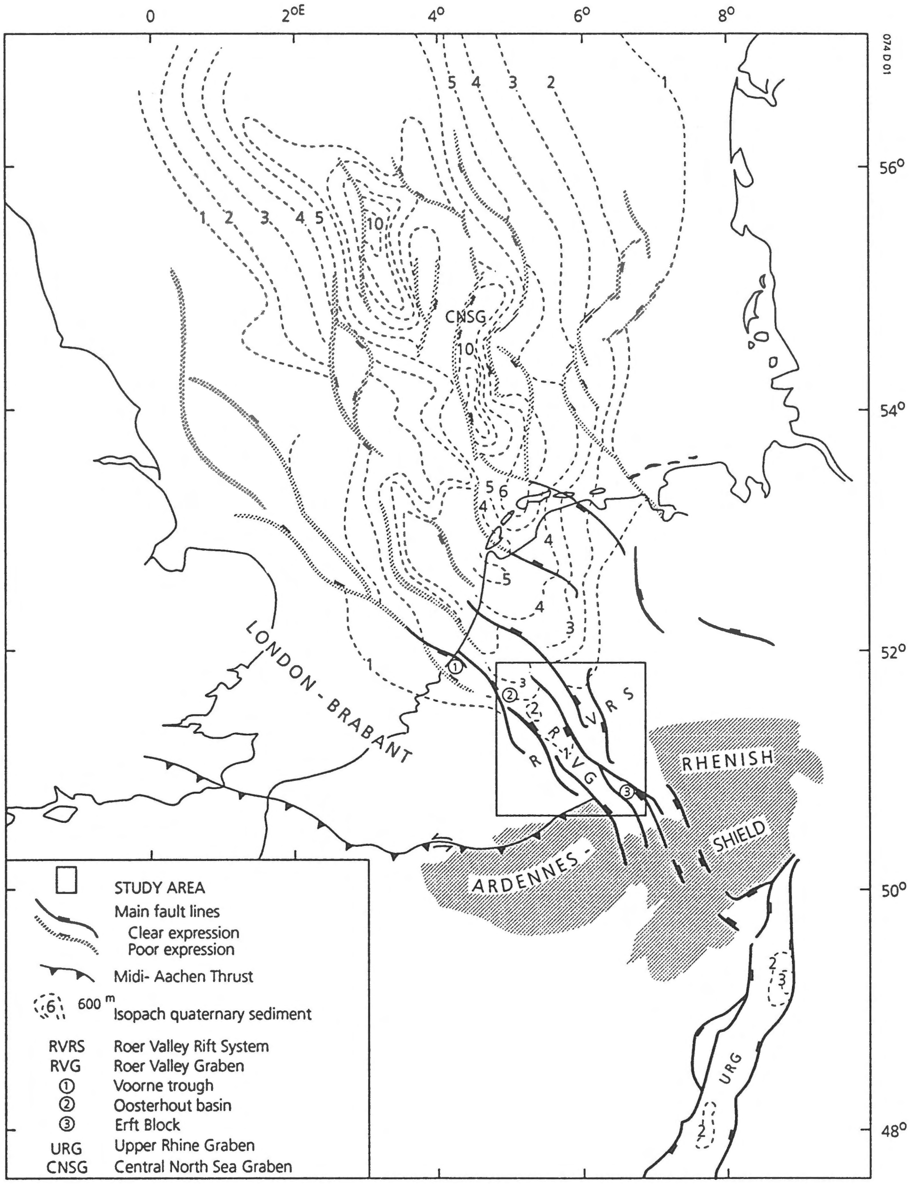

Fig. 1. The study area (indicated by the box) within its tectonic setting. Quaternary isopach lines at intervals of 100 m (after Caston 1977; Illies 1975). (Partly after: Illies 1975 and GECO Exploration Services & Alastair Beach Associates 1989.)

Structural setting

Tectonic units

The Roer Valley rift system forms the main structural-physiographic unit of the Lower Rhine Embayment. The system forms the southernmost extension of the North Sea Basin (Fig. 1). As such it forms part of the western and central European rift system, a chain of depocentres that connects the Mediterranean with the North Sea (Ziegler 1987). Owing to its hydrocarbon prospects, the geohistory of the North Sea Basin and the basin's structural setting are quite well known (Van Doorn & Leyzers Vis 1985; Van Hoorn 1987; Van Wijhe 1987; Demyttenaere 1988; GECO Exploration Services & Alaistair Beach Associates 1989; Remmelts & Duin 1990; Geluk 1990).

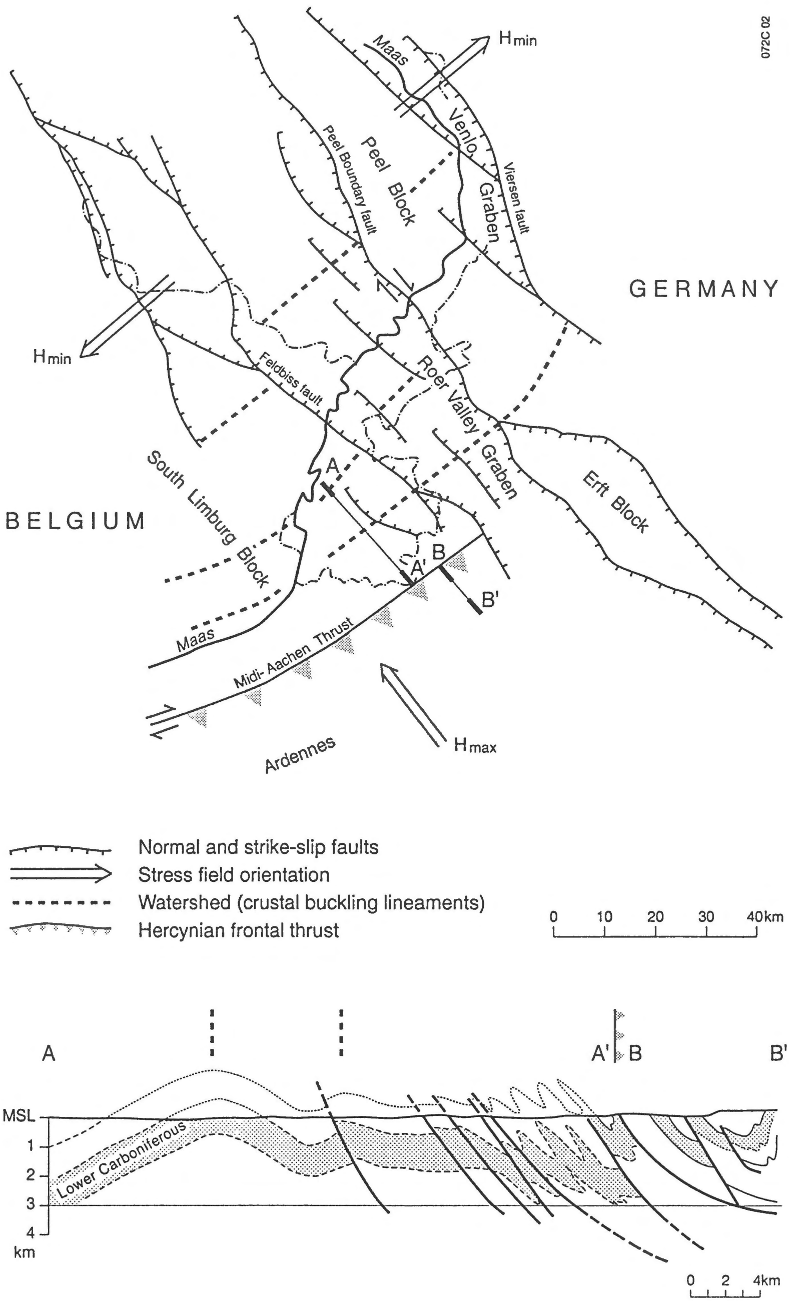

Fig. 2. Regional (palaeo) watersheds developed parallel to the Midi-Aachen Thrust in the course of the Late Neogene. They coincide with subsurface structural highs of Hercynian age and therefore are interpreted to reflect crustal buckling caused by neotectonic foreland compression.

The Roer Valley rift system forms a NW-oriented fault-bounded element between the sub-parallel Upper Rhine and Central North Sea Grabens. Together these grabens form a dogleg-like structure within the extensional setting of the NW European plate. The local North Sea depocentres are aligned with the ancient fault patterns at Triassic and Jurassic levels. Although the fault expression in the Cenozoic sediments is poor, the matching between the sediment distribution and the structural pattern suggests a strong control by the latter (Fig. 1).

The study area is divided into two asymmetrical segments, both having their deepest part along the northeast side:

(i) The southern segment, showing the strongest subsidence, is referred to as the Roer Valley Graben (formerly named Central Graben (Remmelts & Duin 1990; Geluk 1990) or Ru(h)r Graben (Ziegler (1992)).
(ii) The northern segment is the Peel-Venlo Block (Van Rooijen et al. 1984), the deepest part of which is referred to as the Venlo Graben. Three NW-oriented, principal displacement zones (PDZs) bound the segments: the left-stepping Sandgewand-Feldbiss-Rauw-Rijen faults in the southwest; the Peel-Roer Boundary Fault forming the central element, and the Viersen Fault in the northeast. To the south the area is flanked by the rising South Limburg Block. The northern flanking region (the Krefeld High) will not be considered.

The two main segments have been faulted. These segments display subtle to strong differences in vertical movements, both expressed in the sedimentary record as well as in their geomorphology. Analysis of their dynamics in space and time is important for a comprehensive view on the detailed evolution of the rift system dynamics, as discussed below.

State of stress

The regional crustal motions are controlled by the interplay of at least three intraplate stress fields.
(i) The subsiding North Sea Basin generates a flexural marginal bulge. The Pleistocene highs in the southern and eastern Netherlands may be an expression of this bulge which forms waterdivides: to the south with the W-E running 'Flemish Valley' in Belgium and to the east with the S-N running Ems valley. The PDZs dissect this bulge. The forming of a bulge may explain while fault zones in this region have a pronounced character in comparison with the poorer expressions more basinward (Fig. 1).
(ii) The horizontal principal stresses in western Europe indicate deep-seated stresses away from the Alpine collision front in a northwest direction (Klein & Barr 1986; Philip 1987; Mueller et al. 1992). This stress field (H_{max}) opens up the rift system by tensional forces (H_{min}) as is indicated by stress measurements (Ahorner et al. 1983; Illies & Greiner 1978).
(iii) The Midi-Aachen Thrust (Meissner et al. 1983) separates the study area from the Ardennes and Rhenish Shield to the southeast. Mapping of the main (palaeo-)water divides indicates a pattern of alignments oriented parallel to this thrust (Fig. 2). The divides correspond with positive tectonic structures, and are therefore interpreted to reflect (reactivated) crustal buckling lineaments generated by foreland compression by the Ardennes.

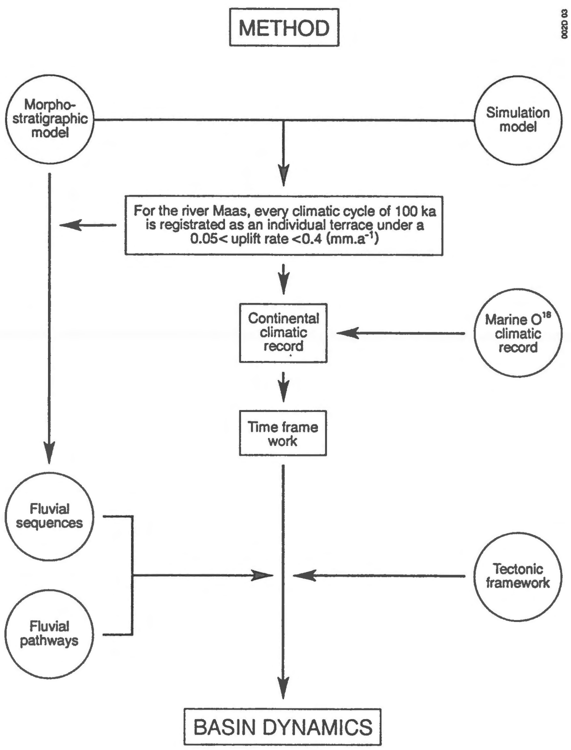

Fig. 3. Flow chart of the method used in the present approach to unravel the Plio-Pleistocene morpho-tectonics of the Roer Valley Graben.

The time frame

In order to obtain a time frame for the basin dynamics, an integrated approach was used including geomorphology, modelling and stratigraphic correlation (Fig. 3)

Morpho-stratigraphic studies of sediments of the river Maas in the south flank of the graben revealed a long flight of terraces (Fig. 4; Van den Berg 1989; Van den Berg et al. in prep.).

Veldkamp & Vermeulen (1989) and Veldkamp (1992) developed a model to simulate river-terrace formation. The model operates in large-scale analogies of real processes acting in conceptual 2000-year time-steps on a macro-scale (100 km^2) setting.

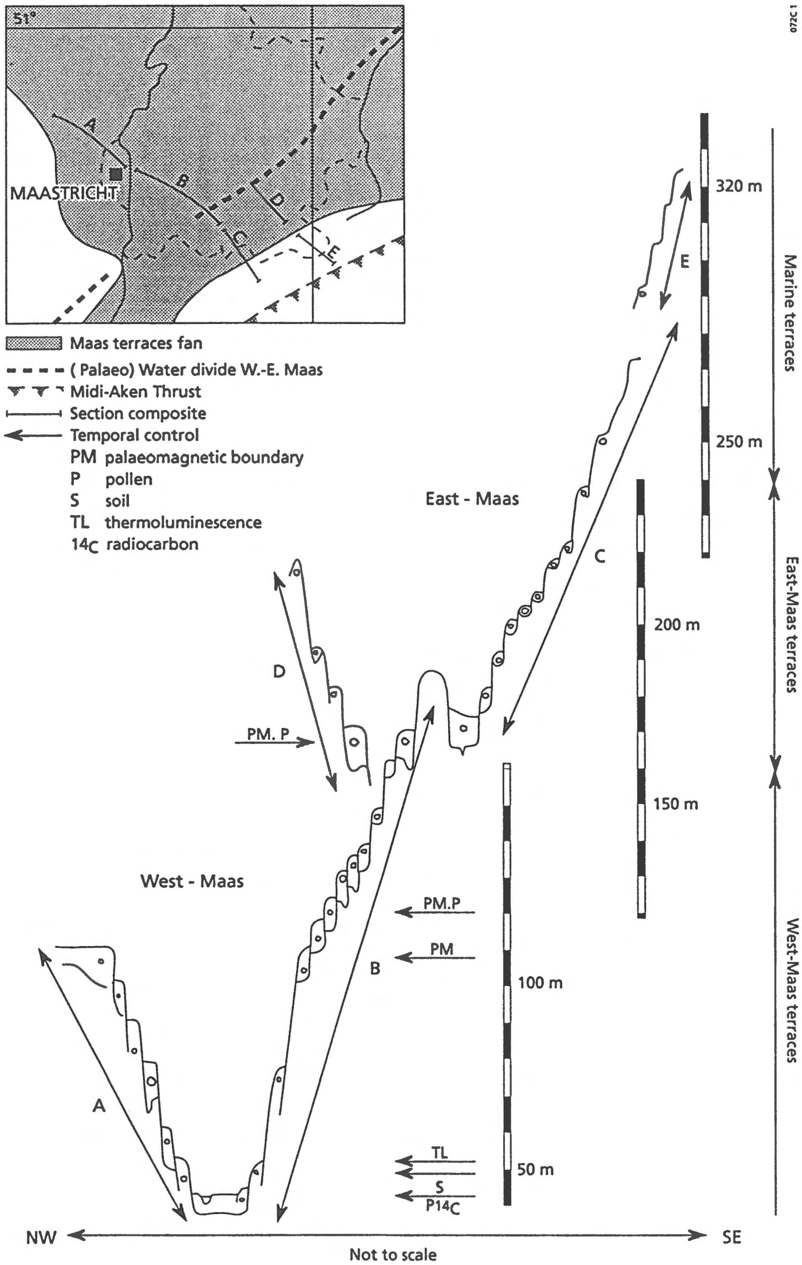

Fig. 4. Composite section of the Maas river terrace flight in South Limburg. For an indication of ages: the transition from marine terraces to fluvial (East-Maas) terraces occurred in the Mid Serravallian at about 13 Ma; the transition from East to West- Maas terraces occurred at around 2.1 Ma.

The first step in Fig. 3 combines these two approaches (Veldkamp & Van den Berg 1993). This led to the conclusion that the interplay between the tectonics and the macro-climatic variability (ruled by the eccentricity of the earth rotation) closely determined the long-term terrace formation and preservation. Under a tectonic uplift regime ranging from 0.05 to 0.4 $mm.a^{-1}$, every eccentricity-related climatic cycle is represented by a terrace in a rain-fed system such as the river Maas. Terrace sediments represent the cold periods and as such they are valuable counterparts of the palynological record registering the warm episodes (erosive periods). Therefore, the combined terrace and pollen record serves as a long continental climatic record.

This allows the correlation of that record with the deep sea oxygen isotope climatic record. For this correlation we used oscillation-pattern matching, supported by palaeomagnetic data. Shackleton et al. (1990) tuned the oxygen isotope record to the astronomical timescale. Thus our correlation of the marine with the continental record transmits this absolute timescale to the latter record (Fig. 5). The time resolution obtained in this way reaches the 20 000 years level. This is much better than a solely biostratigraphically based level.

In subsiding parts of the Roer Valley rift, sediment packages of different source areas interfinger or are superimposed (Edelman 1933; Zonneveld 1949; Kasse 1990; Boenigk 1978). The related fluvial systems have been distinguished by means of heavy-mineral provenance studies. Their ages come from associated pollen assemblages, palaeomagnetic data and correlative terraces (Zagwijn 1960; Zagwijn et al. 1971; Zagwijn & Zonneveld 1956; Van Montfrans 1971; Zagwijn 1989). The basin dynamics in space and time has been inferred from the combination of the morpho-(litho)stratigraphic model with the time frame within the given tectonic framework. We used the terraces in uplifting parts (time–altitude position). In the subsiding part we used map-pattern correlation of the changing fluvial pathways (palaeogeography) with the known structural units.

Regional Late Miocene emergence

The study area slowly changed from a shallow marine environment to a fluvial plain since the Mid-Miocene, around 13 Ma (Quitzow 1974; Zagwijn & Hager 1987; Zagwijn 1989). This regressive coastal plain is bounded in the southeast by a palaeo-coastline . This line is either marked as a sub-aerial, low fossil cliff with residual beach-pebbles (Van den Berg 1989, Felder & Bosch 1989, De Jong & Van der Waals 1971), or as a buried beach (Hager 1981; Boersma 1992). The cliff forms an important morpho-stratigraphic marker in the regional uplift history, because the onset of the regression is well correlated with Vail's cycle boundary TB 2.4/2.5 (13 Ma; Herngreen 1987)

The emerging coastal plain was fed by three feeder systems: the (Early-)Rhine, the Maas, and a number of relatively small 'Belgian' streams draining the north flank of the Brabant Massif. The uplifting south flank of the rift system together with the Ardennes-Rhenish Shield were important sediment suppliers. Net upstream erosion leaves a terrace flight. The erosion record of the Maas system is the longest and best dated of the three and can be used separately to reconstruct the uplift history of the southeast flank of the system. This record will be discussed first, followed by a discussion focusing on the sedimentation area: the subsiding grabens.

Uplift of the south flank region

The record

In the southeast part of the area, below the last Mid-Miocene marine cliff a flight of 30 fluvial terraces has been formed (Fig.4). The flight is spread in a terraced 'fan'. Its formation is strongly tectonically controlled in space and time. In mapview the 'fan' is divided by two buckling lineaments parallel to the Midi-Aachen Thrust (Fig. 2); the southernmost lineament separates the (palaeo) East-Maas from the (present) West-Maas, the other one separates the Main Terrace group from the Middle Terrace group. The 'fan' is bounded to the west by a series of along-strike overstepping faults (the Rauw, Hooge Mierde and Rijen faults). The time is expressed by the height difference between the individual terrace steps. The vertical distance between the last marine cliff (age about 13 Ma) and the first Maas terrace, that witnesses cold-climate conditions of the Latest Pliocene to earliest Pleistocene (age about 2.7–2.4 Ma), amounts to only 30 m. This distance is bridged by three terrace levels of late Tertiary age. The 30 m corresponds to an average uplift rate of around 3.10^{-6} $m.a^{-1}$. On the other hand the remaining Pleistocene through Holocene record covers 160 m, giving an average uplift rate of 6.10^{-5} $m.a^{-1}$. The major difference between these two long-term averages in uplift rates, in conjunction with the results obtained from the subsidence analysis published elsewhere (Zijerveld et al. 1992), highlights the importance of the discontinuity in the rates of the vertical motions. This break may be used to define more precisely the timing of the onset of the regional neotectonics (Fig. 5).

Figure 6 shows in more detail the regional neotectonic uplift record. The record is based on the height and age of various individual fluvial terrace surfaces. These surfaces have been reconstructed by finding best-fit plains through the tops of the respective fluvial sediments (Van den Berg 1989). In this way we were

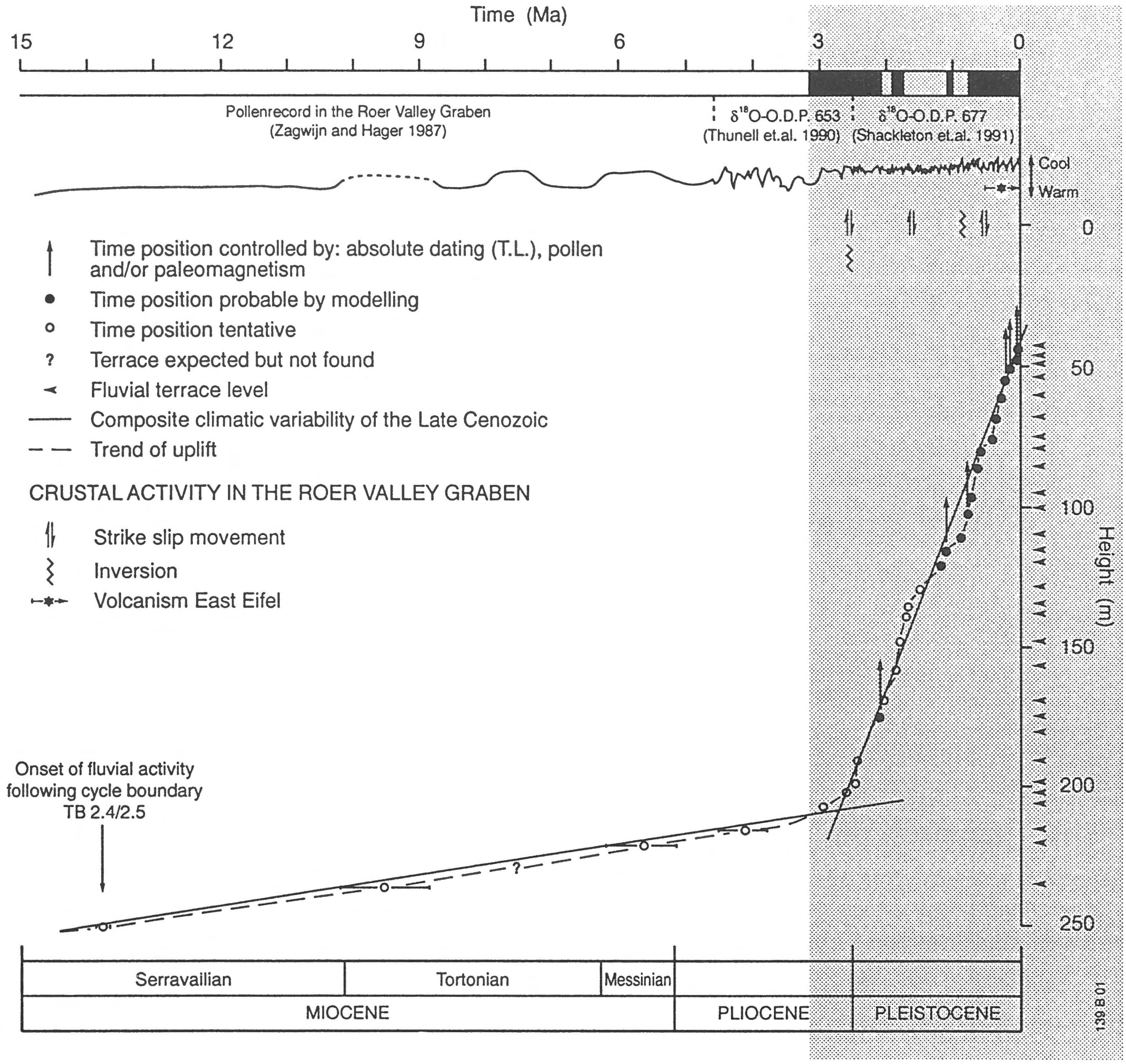

Fig. 5. Miocene to recent uplift record at the southern shoulder of the Roer Valley Graben from dating of the terrace flight in Fig. 4. The major break in the uplift witnesses the onset of the regional neotectonics at around 3 Ma.

able to ignore the effects of post-depositional erosion or accumulation affecting the height of the terraces. The obtained accuracy is estimated to be in the order of about +/- 1 m.

The positions of the reconstructed terrace surfaces on the time axis were chosen at the very end of glacial periods around the transition to the next interglacial. Due to this climatic shift, floodplain aggradation is replaced by a rapid fluvial incision into the old floodplain (Van den Berg 1993). This is the response to an important change in the bedload/discharge ratio. Such a cold–warm shift lasts only a few thousand years. So within the scale proportions of Fig. 6, time-error bars can not be indicated.

Interpretation

The Pleistocene terrace record shows some clear departures from the average uplift rate of 0.06 $mm.a^{-1}$. These are interpreted to reflect the waxing and waning of the regional stress field. The most important reactivation occurred between 3 and 2.7 Ma, a second one around 1 Ma, and a third one just after 500 ka BP. Precision levelling indicates that the area is presently

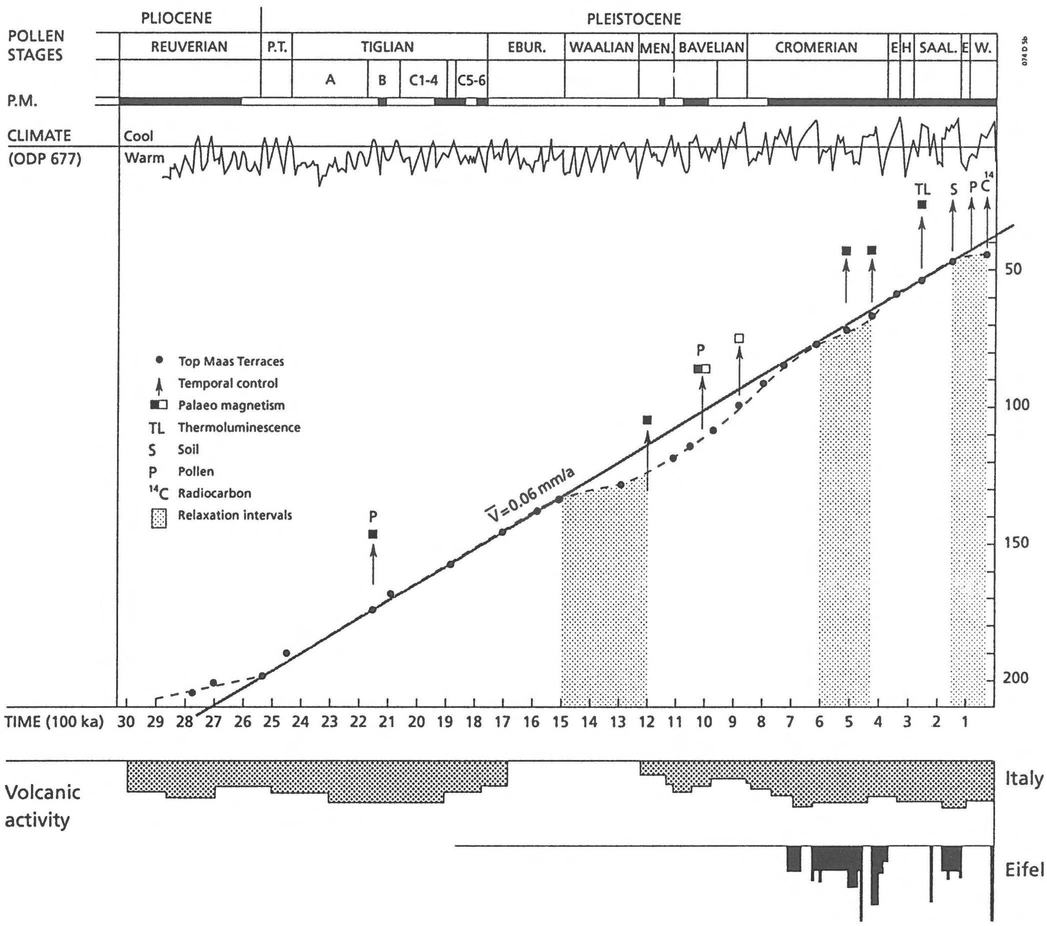

Fig. 6. Enlargement of part of Fig. 5. Superimposed on the longterm uplift trend (timescales of 10^6 years), high-frequency oscillations (in the range of 10^5-10^4 years) reflect fluctuations in the stress regime. Italian volcanic activity drawn after Scheepers (1994); Eifel volcanics after Van den Bogaard & Schmincke (1990).

being uplifted at a rate of 8 (+/-3). 10^{-4} m.a^{-1} (Lorenz et al. 1991; Groenewoud et al. 1991). This rate is in accordance with results obtained for other parts of the Rhenish Shield (Malzer et al. 1983; Ziegler 1992). It is an order of magnitude higher than the long-term average. It suggests a sub-recent strong reactivation, particularly if this value is considered in relation to the low values obtained for the last 200 ka.

The subsiding graben

The record

The Plio-Pleistocene sedimentary succession within the Roer Valley Graben is summarised as a composite section (Fig. 7). This section runs perpendicular to the fault systems and is consequently perpendicular or oblique to the trend of the Maas and Rhine feeder systems. The stratigraphic record shows that the river Rhine periodically flowed outside the main graben. During these periods the river was located to the east, like in the present situation. The tectonic controls on these changing palaeogeographic configurations will be exemplified for the period around the latest W-E

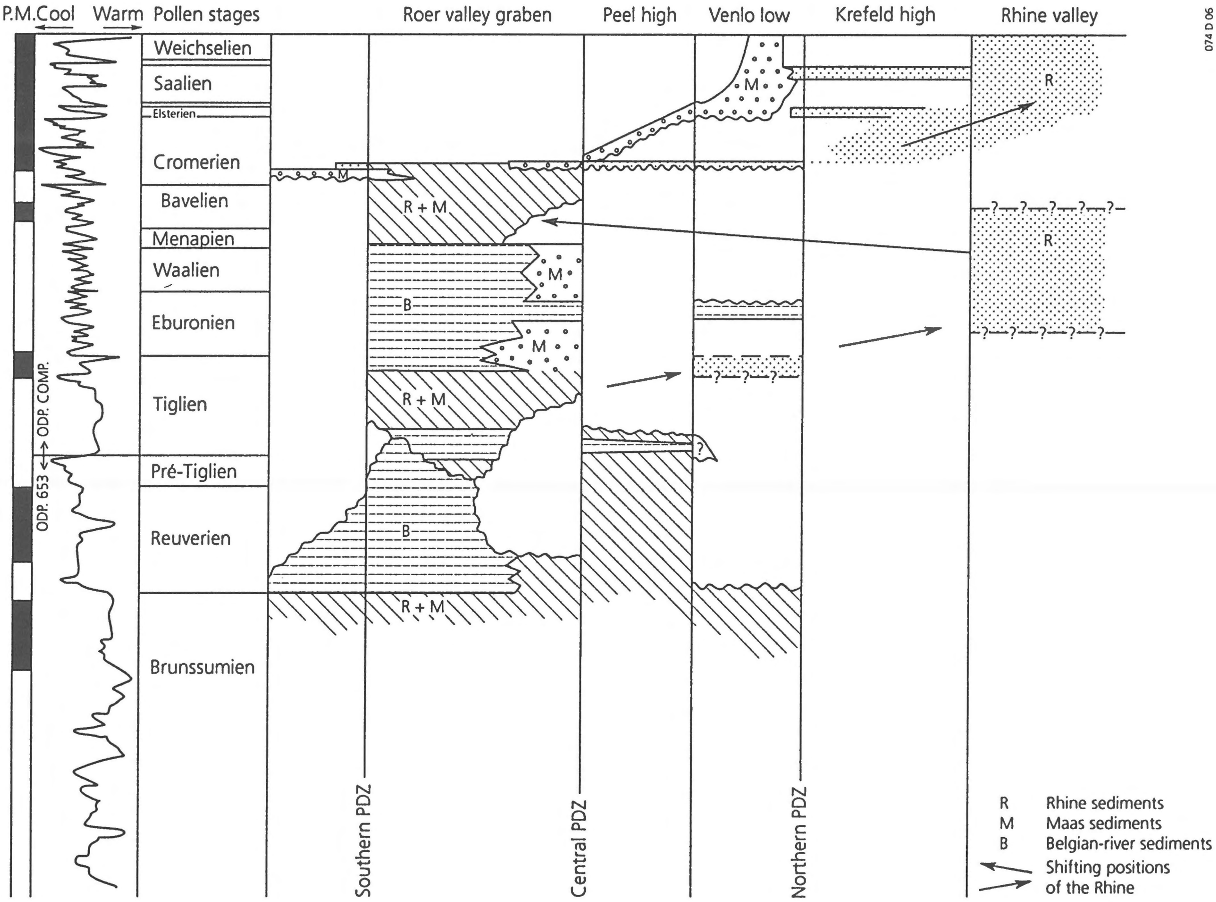

Fig. 7. Stratigraphic chart showing the sedimentary infill of the Roer Valley rift system by the Plio-Pleistocene Rhine, Maas and Belgian rivers. Indicated by arrows is the shifting position of the Rhine (and Maas) across the principal displacement zones (PDZ). This behaviour is tectonically controlled by strike-slip motion along the central PDZ; see also Fig. 8a-c. (Sediment record compiled partly after Zagwijn 1960; Van der Toorn 1967; Bisschops 1973; Bisschops et al. 1982; Zagwijn & De Jong 1983).

shift of the Rhine (Fig. 8a-c). This level was selected because it lies at relatively shallow depth in the graben and its palaeogeography is controlled by many borings.

Rhine sediments show a characteristic mineral zoning over time (Zonneveld 1949). The youngest Rhine sediments in the graben are characterised by the 'Weert' mineral zone. The areal distribution of this mineralogy (Fig. 8a) shows that the system occupied a wide depositional plain with a mid-graben area of non-deposition. The river Maas formed a tributary river. In the course of the next cold stage, the Rhine sediments disappear from the graben and only Maas sediments (the Rosmalen mineral zone; Zonneveld 1964) are found in a pattern that is strongly confined by faults in the middle part of the central PDZ where there is a strong curvature on its fault trace (Fig. 8b).

Interpretation

Palaeogeography

If we assume right-lateral strike-slip motion along the central PDZ, deformation adjacent to this zone relies on its shape (Christie-Blick & Biddle 1985). The major bends in the fault trace either act as a releasing or as a restraining bend. The first opens up a local pull apart basin (confining the Maas floodplain), while the latter simultaneously forces the encompassed block (the Erft Block) to emerge. As this block is tilted towards the northeast, the river Rhine is forced into that direction.

To meet the optimal angular relationships between stress orientation and the fault line in a strike-slip setting, an additional stress component is required as normal faulting dominates the regional structural style

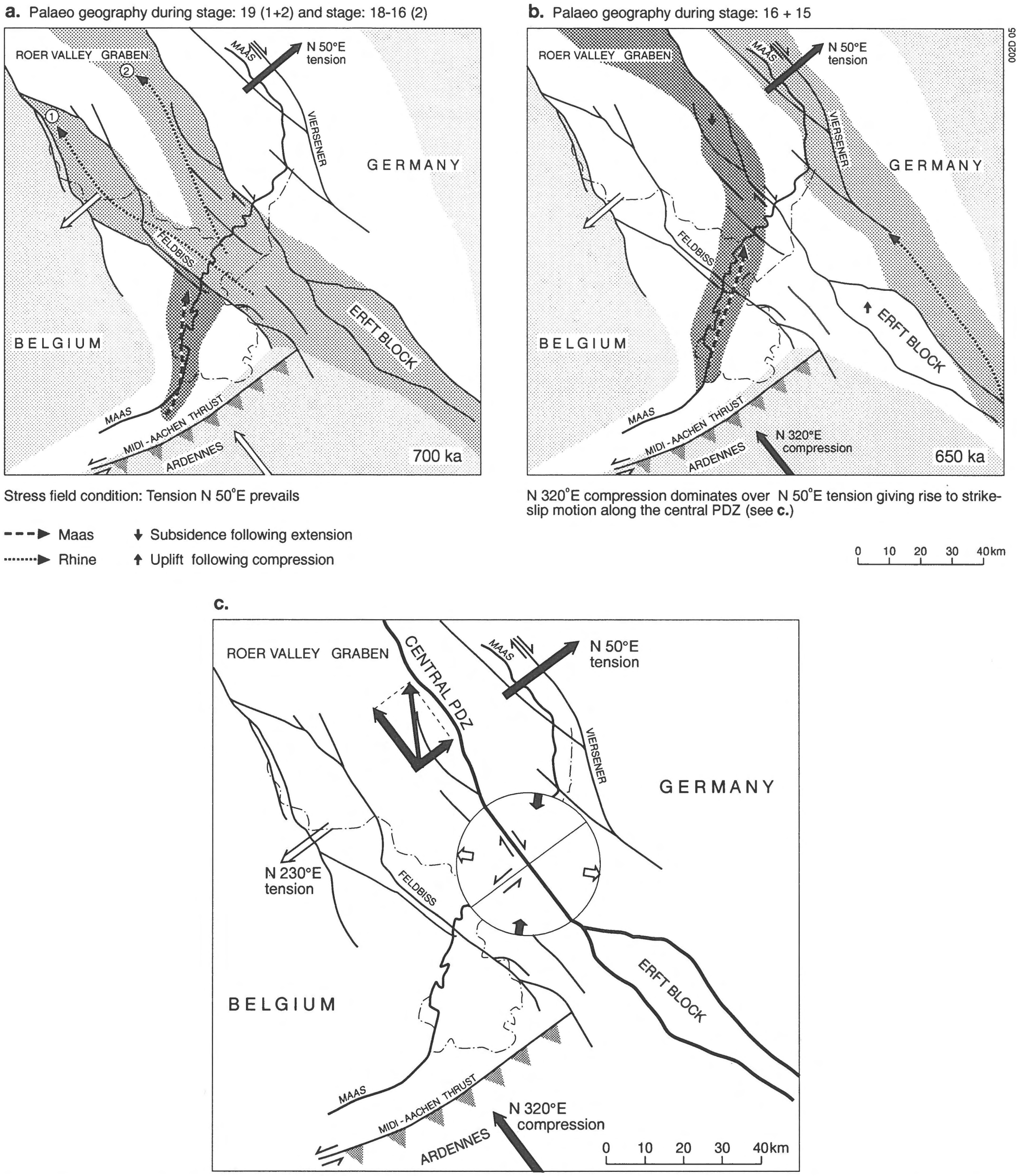

Fig. 8. Palaeogeographic evolution around 700 ka BP showing the last eastward shift of the Rhine. The present-day course of the Maas is shown for orientation purposes. *a*) Over the period equivalent to deep sea stages 19 through 16, normal faulting and tension dominates in the Roer Valley Graben. *b*) In the course of stage 16, transtensional and transpressive movements along the central principal displacement zone (PDZ) cause a palaeo-geographic reorganisation in and separation of the positions of the Rhine and Maas floodplains by uplift and tilting towards the northeast of the Erft Block. *c*) The change from normal faulting to strike-slip faulting along the central PDZ is interpreted to result from an increase in foreland compression by the Ardennes Massif along the reactivated Midi-Aachen Thrust.

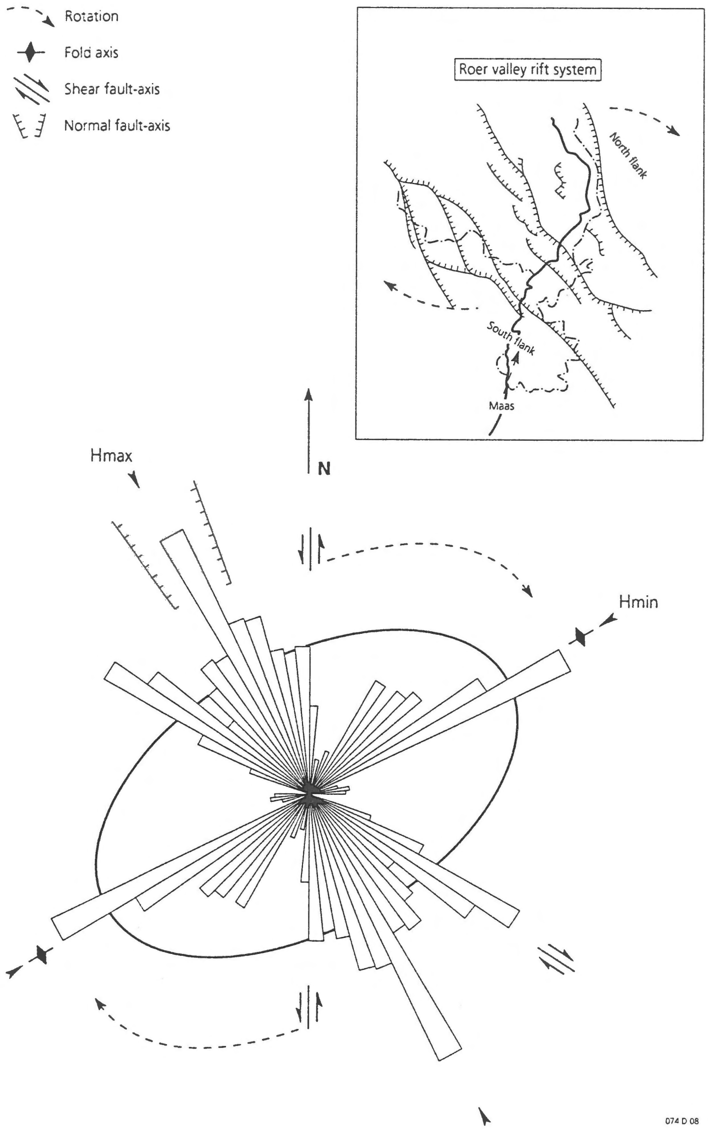

Fig. 9. Morphologically identified lineaments in the study area formed since around 600 ka represented in a rose diagram (orientation class × cumulative-length percentage, after: Van den Berg et al. 1994). The diagram is consistent with a right-lateral rotation following the horizontal stress components H_{max} N150-160° E and H_{min} N50–65° E.

(Fig. 8c). It is suggested that the interplay between the regional SW-NE oriented tension and the NW-oriented compression generated by the Ardennes (see above) periodically may lead to such optimal conditions (Fig. 8c).

Temporarily active depocentres along the three principal displacement zones are assumed to be likewise indicative for periods when the Ardennes stress field overrules the general tension. For example, within the Voorne Trough, a depocentre arranged along the southern PDZ, about 200 m-thick deltaic deposits of Pre-Tiglian age are encountered. The Pre-Tiglian lasted only 100 000 years and represents a cold stage with low sea-levels. The unusually thick and lithologically uniform deposits suggest therefore an extremely high accomodation rate in the marginal trough during this time interval. This is consistent with the coeval strong reactivation of the uplift of the Ardennes as registered by the Maas river terrace record. Along the northern PDZ (the Viersen Fault), periodic preservation in the

Venlo marginal graben also indicates periods with local extension in the releasing bend. Such simultaneously operating processes in basin extension and flank uplift are important markers in the neotectonic evolution of the stress regime.

Stress-controlled geomorphology
In Fig. 8a, the floodplain splits around a mid-graben non-deposition area within the graben. This floodplain separation is interpreted to represent a mid-graben relative high, bounded by flanking lows. In the Roermond area, the Roer Valley Graben is also morphologically characterised by a persistent central high (with terraces = uplift) and two flanking fault-bounded lows. Both from the seismic lines and from the morphology we know that such a tectonic low in itself repeats such a relief pattern. This tectonically defined morphology shows a sequence of scales: the fractal-alike pattern that emerges shows a strong similarity with the stress-responding differential flexural crustal motions at basin-wide scales in a tensional setting (Cloetingh et al. 1985). This sequence may suggest that the crustal mechanics of a divergent strike-slip setting operate at a local, a regional and a basin-wide scale. The scale determines the nature of the bounding structures: faults or flexures.

Shortly after the Rhine shifted to the east, the Maas also shifted out of the graben and slipped off the tilted Peel Block towards its present position. The present-day surface of this series of abandoned floodplains shows a well-defined deformation pattern, expressed as a low relief (1 to 2 m scale) of structural lineaments (Van den Berg et al. 1994). Figure 9 shows the rose-diagram (cumulative length × orientation-class) of the lineaments in the area. The orientations are consistent with the results obtained in an area east of the Viersen Fault (Plein et al. 1982).

In accordance with the palaeogeography, the geomorphology indicates the ongoing right-lateral divergent strike-slip faulting due to block rotation over the last 600 ka. This is the most recent pulse in a series.

Plate-tectonic implications and discussion

We identified a number of accelerations and decelerations (pulses) superimposed on a generally high-rate tectonic phase since the last 3 Ma. There are indications from other parts of Europe that important physiographic changes tend to cluster around these pulses.

For example, near the Gauss-Matuyama magneto-boundary a thrusting pulse of the Jura mountains causes the connection of the Upper Rhine with the Swiss Alps. This has been identified in the heavy-mineral composition of the Rhine sediments (Boenigk 1982; Tebbens et al. 1995).

The Alpine geodynamics are thought to be the mechanical consequence of the Africa-Europe collision. The presence of intra-plate stresses provides a possibility to understand a coupling between the inter-plate dynamics of the two plates and the pulses observed in our study area. It is suggested here that the relaxation interval between 1.5–1.2 Ma (Fig. 6) may be the consequence of an observed change in direction of the relative motion of the African plate. During a part of the Early Pleistocene this direction temporarily changed from northwest towards northeast; this is extensively studied in the Tyrrhenian arc system by e.g. Van Dijk & Scheepers (1994) and summarised by Scheepers (1994). From the same area Brogan et al.(1975) report a profound change in the activity of the Tyrrhenian arc about 1.1 Ma.

Contemporaneously with this last event, uplift and consequent terrace formation begin in the central Appenines, Italy (Coltorti 1993), the Limagne, France (Allier river, Veldkamp 1991), on the north flank of the Paris Basin (Somme river, Antoine 1993), and in the Bohemian Massif (W.H. Zagwijn, pers. comm. 1993).

The relaxation phase found between 600 and 430 ka shows a strong synchronism with phase 2 of the Eastern Eifel volcanic activity (Van den Bogaard & Schmincke 1990). The other recognised phases in the Eastern Eifel volcanism are relatively short with respect to the resolution of the changes in uplift rate registered by the Maas river record, although there is synchronism between the last recorded relaxation phase and phase 5 in the volcanic activity.

Although this list of records is far from systematic and complete, they suggest that the Maas terrace flight identifies a lithospheric signal of plate-tectonic importance.

The coincidence of regional uplift of ancient structural domes and sinking basins, together with the formation of pull-apart basins due to divergent strike-slip motions in response to foreland compression by the Alps and the Rhenish Shield, may suggest that these processes are controlled by important phases in the plate reorganisation (Cloetingh & Kooi 1992).

The observed accelerations in uplift from the Tertiary to the Pleistocene, in conjunction with the acceleration of global volcanism throughout the Quaternary (Kennet & Thunell 1975) and the present-day high velocities of crustal movements with respect to the Pleistocene long-term average, raise the intriguing question: Do we live at present in a period of extreme crustal dynamics?

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