Role of the Alpine belt in the Cenozoic lithospheric deformation of Europe:

sedimentologic/stratigraphic/tectonic synthesis

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North of the Upper Rhine Graben (URG), the Roer Valley Rift System (RVRS) corresponds to the northern segment of the European Cenozoic rift system described by Ziegler (1988) (Fig 1). The Cenozoic RVRS developed upon pre-existing basins of Carboniferous (Campine foreland basin) and Mesozoic (rift) age. It is structurally closely related to the Mesozoic basin. During the Mesozoic, the area was characterized by several periods of subsidence and inversion which have reactivated the Variscan structural trends (Ziegler, 1990; Zijerveld *et al.*, 1992; Winstanley, 1993). During the Cenozoic, the RVRS was affected by two periods of inversion named the Laramide phase (Earliest Tertiary) and the Pyrenean phase (Late Eocene-Early Oligocene) and by continuous subsidence since the beginning of the Oligocene (Geluk *et al.*, 1994). Preservation of Late Oligocene-Early Miocene marine sediments on the Rhenish Massif demonstrates that the Roer Valley Graben (RVG) was connected to the URG (Sissingh, 1998), indicating a common evolution during at least this period. A close relationship between these two grabens is also suggested by the distribution of the earthquake focal mechanisms in the northern part of the URG and the RVG which indicate a present day NE-SW extension in both areas (Plenefisch and Bonjer, 1997).

Structurally, the RVRS is the southwestern part of the Lower Rhine Embayment. Located in Belgium, Germany and the Netherlands, it consists of, from southwest to northeast, the Campine Block, the Roer Valley Graben and the Peel Block (the Campine and Peel Blocks corresponding to the RVG shoulders). The southeastern end of the RVRS is formed by the Erft Block which is not in the prolongation of the RVG but shifted towards the northeast. At a regional scale the RVRS is characterized by a NW-SE orientation which is regarded as parallel to the main Variscan inheritance (e.g., Ziegler, 1990; Geluk *et al.*, 1994). Fault distribution determined from the Triassic, Late Cretaceous and Miocene active faults reveals that most of the Triassic structures were reactivated during the Late Cretaceous and Miocene evolutions, whatever the type of deformation (inversion, thermal subsidence and rifting). This can be explained by reactivation of the inherited fault orientations, despite different stress fields responsible for the faulting activity.

Subsidence analysis has been carried out for 16 wells located in the Roer Valley Graben and the Peel Block. Calculated tectonic subsidence curves show a Cenozoic evolution marked by two periods of subsidence (Late Palaeocene and Oligocene-Quaternary) separated by a hiatus during the Eocene time, resulting from a period of erosion during the Late Eocene. This Late Eocene event was characterized by an uplift which cannot be quantified with the available data. Models from apatite-fission track analyses indicate that the uplift in the western part of the RVRS varies between 200 to 600 m (Van Balen *et al.*, 2002). Although subsidence analysis provides fundamental information concerning the quantification of tectonic subsidence, the spatial distribution is poorly constrained. To close this gap of information, we have studied 25 additional deep wells for which the stratigraphic data are not detailed enough for backstripping analyses, but can still help to define the dynamics of each block and the tectonic activity for each period (Late Cretaceous-Early Palaeocene, Late Palaeocene, Early Oligocene, Late Oligocene and Miocene-Quaternary). Thus, altogether 41 wells are used to constrain the spatio-temporal distribution of the subsidence during the Cenozoic.

Combination of information provided by the thickness maps for the Late Cretaceous-Early Palaeocene, Palaeogene and Neogene periods, with the thickness of the sediments observed in the wells at different periods (Late Cretaceous-Early Palaeocene, Late Palaeocene, Eocene, Early Oligocene, Late Oligocene and Miocene-Quaternary) allows to determine the plan view tectonic evolution of the RVRS. For the Late Cretaceous-Early Palaeocene period, the distribution of the Late Cretaceous Chalk formation clearly shows contrasted thicknesses with a minor thickness of sediments in the RVG and a strong subsidence on its

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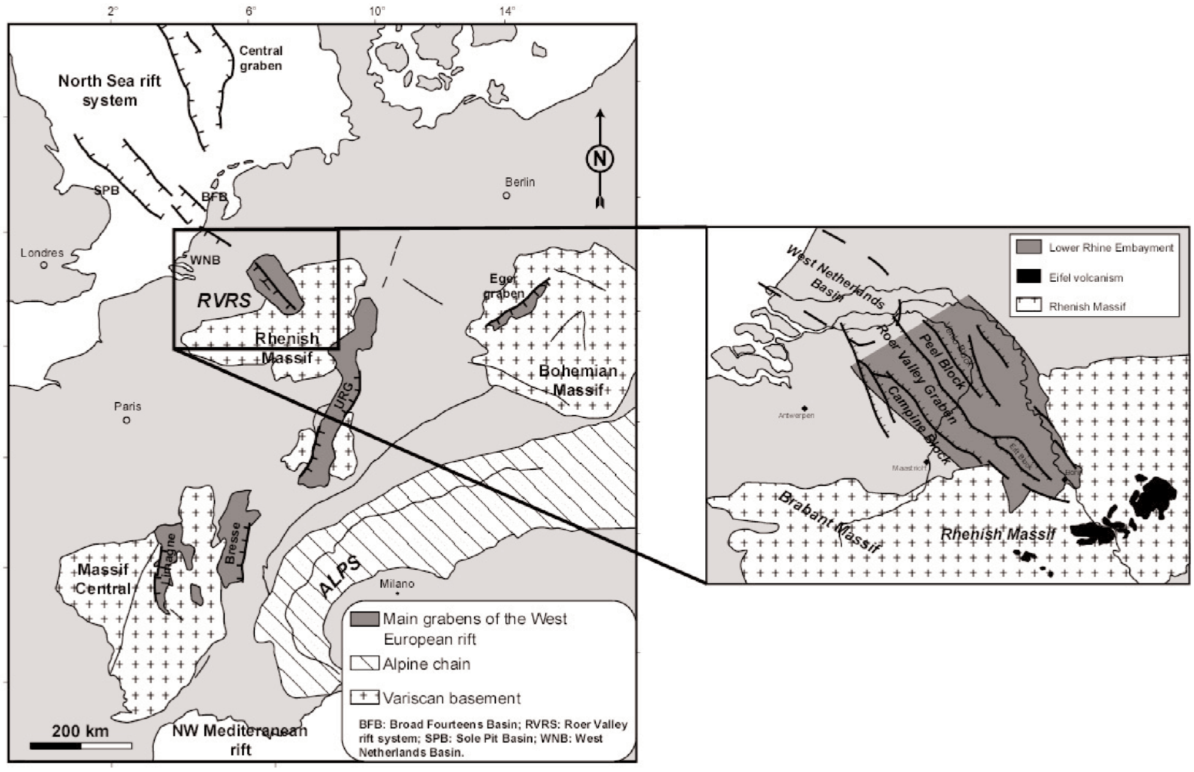

Fig. 1.- Simplified geological map of the European platform, the southern North See and the Roer Valley graben.

shoulders. The major uplift was mainly restricted to the graben and was controlled by the Peel Boundary fault zone, the Veldhoven fault zone and the Rijen fault zone (see figure 2 for fault location). We interpret the Late Cretaceous-Early Palaeocene final geometry as the result of a transpressional context with the greatest principal horizontal stress ($\sigma 1$) between NE-SW and N-S, comparable to the nearby West Netherlands Basin. Subsidence analysis for the Late Palaeocene period suggests a global subsidence in the studied area (RVG, Peel Block and Venlo Block). Quantification of the tectonic subsidence provides estimation of minor vertical displacements along the Peel Boundary fault zone ranging between 50 and 70 m during this period. It is unlikely that the Late Palaeocene subsidence of the Lower Rhine Embayment has resulted from a rifting event generated by far field stresses, because during a rifting process subsidence is generally controlled by a substantial fault activity and is restricted to a graben area. Then, the slight subsidence (<100 m) developed after a main compressive phase might result from a stress relaxation and a lithospheric sagging. Most of the information concerning the Eocene evolution has been partially destroyed by a strong erosion event during the Late Eocene. Well data indicate a progressive decrease of the thickness of the Dongen formation (Eocene) towards the East. This thinning could result from (1) a less active subsidence in the eastern part of the RVRS and/or (2) a doming of the central part of the Lower Rhine Embayment (i.e., eastern part of the RVRS). The Early Oligocene marked the onset of the rifting phase in the RVRS. The thickness of the sediments combined with subsidence analysis indicates that the Early Oligocene was affected by a general subsidence with a maximum of vertical displacement in the central part of the Lower Rhine Embayment. Similar sediment thicknesses on the Peel Block and the RVG suggest a minor or no fault activity of the Peel Boundary fault zone during this period. The Early Oligocene subsidence could result either from the elastic response of the lithosphere after the Late Eocene doming, or from a slight extension phase which would have affected the Lower Rhine Embayment during this period. During the Late Oligocene period, the tectonic subsidence has increased in the southeastern part of the RVG with the development of narrow depocentres close to the Peel Boundary fault zone, whereas it decreased in the northwestern half of the RVG and the Peel Block. The Peel Boundary fault zone was active in its southeastern part only with vertical offsets ranging between 250 m and 300 m. Secondary fault activity along the Peel Boundary fault zone antithetic faults has also controlled the development of the depocentres. We interpret the narrow deformation as the result of a WNW-ESE oblique extension which has only affected the southeastern part of the graben. After the regressive phase at the Oligocene-Miocene boundary,

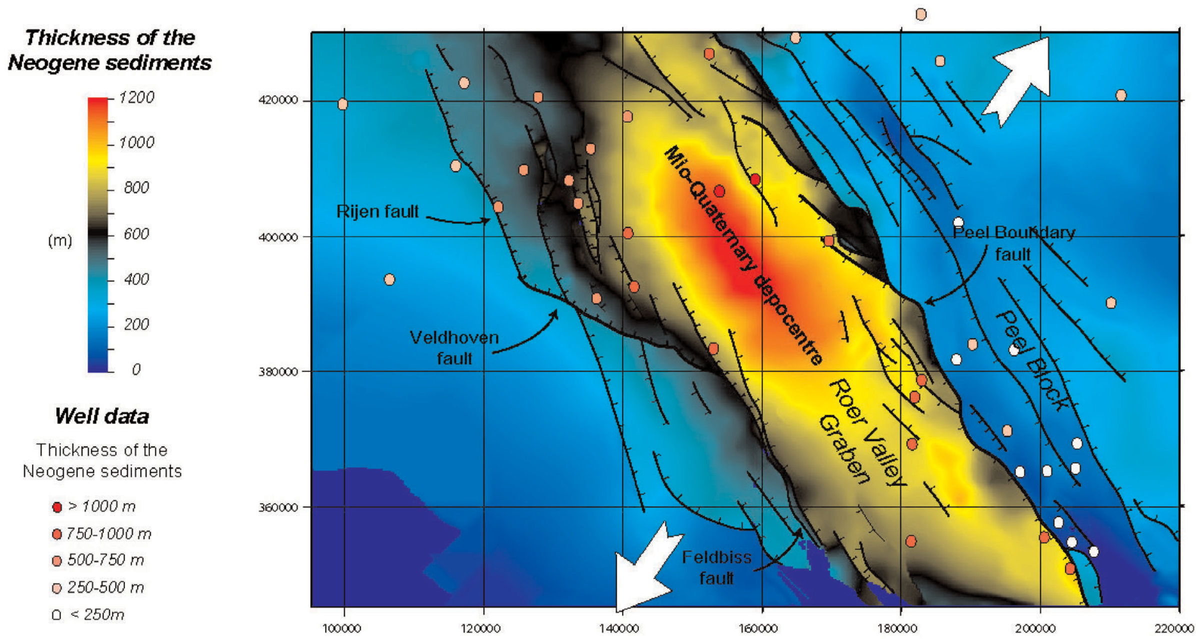

Fig. 2.- Thickness map of the Neogene sedimentation showing the development of the main depocentre in the northern part of the RVRS. The distribution of the active faults and the location of the main depocentre are explained by a NE-SW extension since the beginning of the Miocene.

deformation was extended to the northwestern part of the RVG where a main depocentre developed (Fig. 2). Contrary to the Late Oligocene evolution, the oblique orientation was strongly reactivated especially along the Veldhoven fault zone. Extension has induced the formation of two depocentres: a main depocentre in the northwestern part of the RVG and a minor one in the southeastern part. The orientation of the active faults and the development of the main depocentre at the intersection of two oblique main faults can be interpreted as the result of a NE-SW extension. For the Quaternary period, analysis of high precision Digital Elevation Model with a 5 m resolution step reveals a continuous activity of the Miocene faults. The displacement rate values determined along the graben border faults (i.e., the Peel Boundary fault zone and the Feldbiss fault zone) indicate the continuous development of the depocentres formed during the Miocene and highlight the major role of the large-scale tectonics in the evolution of the RVRS. Analysis of the earthquake focal mechanism data shows that the RVRS is affected by a present-day NE-SW extension related to a nearly vertical greatest principal stress ($\sigma 1$) (Plenefisch and Bonjer, 1997).

We integrate now the Cenozoic evolution of the Southern North Sea basins and the West European rift (WER) in order to characterize the global evolution of the European Alpine foreland. During the Early Palaeocene evolution, the southern North Sea basins were affected by an inversion phase regarded as the result of a main N-S compression (e.g., Ziegler, 1992a). South of the RVRS, evidences of doming and graben inversion (Malkovsky, 1987; Le Griel, 1988; Barbarand *et al.*, 2002) suggest that the deformation was induced by a N-S compression, like in the southern North Sea. For the Late Palaeocene period, the lack of precise information, mainly due to the continental paleogeography of western Europe, renders a determination of Late Palaeocene deformation south to the RVRS difficult. In the North Sea basins, the subsidence has been attributed to the continuous late-rifting process in the northern Atlantic (Ziegler, 1992a) or a lithospheric relaxation after the Early Palaeocene inversion (de Lugt *et al.,* 2003). During this period, the RVRS then corresponded to the southern end of the North Sea rift system. The Early Eocene sedimentation in the southern North Sea is related to a general subsidence with minor fault activity, suggesting a thermal subsidence after the late-rifting stage which ended at the end of the Palaeocene (Ziegler, 1992a). In southwestern Europe, the spatial distribution of the Lutetian sedimentation suggests that it did not result from a period of subsidence linked to the Late Eocene-Oligocene rifting phase but rather from the development of local lakes in a peneplain domain. The Early Eocene period then corresponds to a tectonically quiet period in the North Sea and the WER. Compared to the Early Eocene evolution, the Late Eocene period was characterized by intensive and opposite deformation in the southern North Sea and the WER. The southern North Sea basins were affected by a second phase of inversion, whereas this period corresponds to the onset of the rifting event in the WER. In the southern North Sea and the Channel area, reactivation of the Mesozoic and Cenozoic faults in a reverse faulting mode has been interpreted as resulting from a nearly N-S compression related to the Pyrenees formation (Ziegler, 1990). In contrast, the Late Eocene sedimentation in the Massif Central graben, the central part of the Upper Rhine graben and the Eger graben proves that the WER was affected by extension during this period (Michon, 2001). In the WER, the direction of extension inferred from strongly constrained data suggests a clockwise rotation of the direction of extension towards the East (*i.e.*, E-W in the Massif Central and N-S in the Eger graben) and a direction of extension perpendicular to the Alpine front. At a European scale, the Oligocene evolution corresponds to a propagation of the extension related to the WER towards the North and a stop of the inversion phase in the southern North Sea basins. The superposition and the similar shape of the Late Eocene and Oligocene main depocentres in the Massif Central grabens and the central part of URG indicate a continuation of the direction of extension during the Late Eocene and the Oligocene. North to the URG, the RVRS subsidence resumed in the Early Oligocene and accelerated in the Late Oligocene. In the southern North Sea, the Oligocene corresponds to a phase of subsidence due to thermal relaxation of the lithosphere and sedimentary load, without or with minor fault activity (Ziegler, 1990; de Lugt *et al*., 2003). Although the RVRS, the Eger graben and the URG subsided more or less continuously during the Oligocene-Quaternary evolution, the Oligocene-Miocene transition was marked by a radical change in the European geodynamics. In the RVRS, the URG and the Eger graben, the depocentre shapes and the fault orientation suggest a change of the stress field at the Oligocene-Miocene transition and a NW-SE trending extension since the Early Miocene. In the Massif Central, the Miocene-Quaternary evolution was characterized by a strong uplift of the whole province which makes a determination of the regional stress field in this province difficult. In the Bresse graben, although sedimentation developed during the Miocene-Quaternary evolution, a westward propagation of the Alpine flexural basin was proposed to explain this subsidence (Merle *et al*., 1998). Finally, the displacement along the Rhône-Saône transfer zone which was a left lateral fault zone during the Late Eocene and the Oligocene, has changed at the Oligocene-Miocene transition and became right lateral (Laubscher, 2001). In the North, the southern North Sea basins continued to subside with minor fault activity during this period. In the Channel area, inversion was maximum during Early Miocene but is still ongoing during the Quaternary (Ziegler, 1990).

This work shows that the Cenozoic evolution of the southern North Sea and the European platform was characterized by a succession of several phases of inversion, quiescence and subsidence. Given the location of the geological structures and the timing of the deformation, we propose to interpret the Cenozoic evolution of the studied area taking into account the formation of the Alpine mountain chain. First, at the European scale, the Early Palaeocene N-S compression is contemporaneous with the closure of the oceanic Piemont (Ziegler and Roure, 1996) and the Eo-Alpine compressive phase (Michon and Merle, 2001). The contemporaneity between the beginning of the continental collision events and the inversion phases in the European Platform and the southern North Sea basins could suggest that during the first step of a continent-continent collision the stress is directly propagated in the adjacent plate. Second, data show that the Late Eocene-Oligocene period was mainly characterized by the formation of the WER which is interpreted in terms of passive rifting (Ziegler, 1992b; Merle *et al*., 1998). Geological data also indicate that the directions of extension were perpendicular to the Alpine mountain chain. The Late Eocene-Oligocene period corresponds to a phase of strong deformation in the Alpine chain with the formation of the eclogitic rocks of highest pressure. Thus, the phase of extension in the Alpine foreland which has induced the formation of the WER, is coeval with a phase of main compressive deformation in the Alps. If the propagation of the main compressive stress into the European lithosphere during the collision is a generally admitted mechanism to explain graben inversion in the North Sea, the Channel area and the Bohemian Massif (Ziegler, 1992a), it can not explain the formation of the WER in the neighbourhood of the Alpine mountain chain. The origin of the WER is then poorly understood and the consequence of the formation of a mountain chain with a deep lithospheric root could probably be taken into account (Merle and Michon, 2001). Third, geological and geophysical data indicate that the present day stress field in western Europe is characterized by a NW-SE to NNW-SSE maximum compressive stress (Müller *et al*., 1992). Analysis of the earthquake focal mechanism data in the UGR and the RVRS shows that this maximum compressive stress induces left lateral displacement in the southern and central URG, whereas it causes NE-SW extension in the northern end of the URG and in the RVRS (Plenefisch and Bonjer, 1997). In consequence, we interpret the general evolution of western Europe during the Miocene-Quaternary period as the result of the NW-SE collision between Europe and Africa. In this model, the URG and the RVRS concentrate the main deformation and limit two separated blocks. One fundamental feature is the change of the global deformation of the European lithosphere at the Oligocene-Miocene transition. Assuming that the Late Eocene-Oligocene extension was induced by the formation of a deep Alpine lithospheric root (Merle and Michon, 2001), we postulate that the slab break-off of the Alpine chain already proposed by several authors occurred at the Oligocene-Miocene transition. Such a slab break-off could explain the stop of the Late Eocene-Oligocene perpendicular extension and the development of the NW-SE maximum compressional stress which controls the European deformation since the beginning of the Miocene.

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