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Subsidence analysis and modelling of the Roer Valley Graben (SE Netherlands)

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ABSTRACT

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The Roer Valley Graben (southeastern Netherlands) forms the most northern branch of the European Cenozoic Rift System. Sedimentary backstripping of exploration wells provides control on vertical tectonic motions during the complex post-Paleozoic geodynamic evolution of the area.

The Roer Valley Graben evolved by repeated reactivation of Permo-Carboniferous fracture systems. At least three episodes of extension-related subsidence are recorded. These occurred during the Late Permian–Early Triassic (> 255–240 Ma), the Middle Jurassic (168–165 Ma) and the late Cenozoic (36–0 Ma). A Late Jurassic–Early Cretaceous stretching phase is weakly inferred from incomplete data.

Crustal stretching values calculated from the tectonic subsidence curves can account for the reflection seismic controlled crustal configuration of the Roer Valley Graben area. Results demonstrate a close relationship between the Roer Valley Graben and the basins in the North Sea during the Mesozoic. In contrast, the Cenozoic evolution of the Roer Valley Graben is independent from that of the North Sea and is related to the development of the Rhine Graben.

Introduction

The Roer Valley Graben in the southeastern Netherlands forms the northwestern branch of the European Cenozoic Rift System (Fig. 1), the regional tectonic setting and geological history of which is outlined by Ziegler (1992, this volume). The Mesozoic and Cenozoic evolution of the Roer Valley Graben is summarized in Fig. 2: (1) Mesozoic extensional reactivation of pre-Variscan structural trends (e.g. Ziegler, 1978, 1988; Geluk, 1990) in concert with the break-up of Pangea and opening of the present Atlantic Ocean and with rifting and thermal subsidence in

the North Sea Central Graben (e.g. Kooi et al., 1989); (2) Late Cretaceous and earliest Tertiary transpressional adjustments, related to Alpine and Pyrenean collisions (Ziegler, 1988, 1990), resulting in inversion and the development of an erosional hiatus; and (3) a spatially and temporally complex pattern of vertical displacements, rotations, and inversions during the Tertiary, culminating with renewed rift formation which, in the Roer Valley Graben, appears to remain active at the present-day. The record of this tectonic history is reflected by the complexity of the Mesozoic and Cenozoic stratigraphy of southeastern Netherlands, as summarized in cross-sections derived from seismic lines, in Fig. 3.

In this paper the history of vertical tectonic motions of the crust in the Roer Valley Graben is quantified by a backstripping and tectonic subsi-

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Fig. 1. Tectonic setting of the Roer Valley Graben (RVG), southeastern Netherlands, from Ziegler (1982). CG = Central Graben; SPB = Sole Pit Basin; WNB = West Netherlands Basin; RM = Rhenish Massif; RG = Rhine Graben; BG = Bresse Graben. A indicates the location of Amsterdam.

dence modelling analysis of a number of wells and shallow boreholes from the graben and surrounding areas (Fig. 4). The results elucidate the timing and character of thermo-extensional events in the Roer Valley Graben and thus help to establish possible tectonic links between the North Sea and Cenozoic European rift systems.

Subsidence analysis

Stratigraphy records the vertical motions of the crust during the development of sedimentary basins. The *backstripping method* (or geohistory analysis) separates isostatic effects of sediment and water loading from those of tectonic subsidence (Steckler and Watts, 1978; Van Hinte, 1978). Mathematical procedures to calculate tec-

tonic subsidence through time from stratigraphic columns have been discussed, for instance, by Steckler and Watts (1978), Sclater and Christie (1980) and Bond and Kominz (1984). The necessary input consists of stratigraphic time–depth information (thicknesses and ages, lithology, compaction/porosity, and depositional waterdepths).

The present study is based on the analysis of the logs of 22 exploration wells and two shallow boreholes in the Roer Valley Graben and surrounding areas. The wells are listed in Table 1; their locations are given in Fig. 4. Eight wells located in the Netherlands offshore, previously analyzed by Kooi et al. (1989), are included. The relative and absolute ages of the chosen stratigraphic horizons in exploration wells were derived from the “Stratigraphic nomenclature of the Netherlands” (Nederlandse Aardolie Maatschappij BV and Rijks Geologische Dienst, 1980) and the timescale of Haq et al. (1987). In the shallow boreholes, detailed knowledge on the continental sedimentation record of the Roer Valley Graben since 3 Ma was derived from litho-, morpho-, pollen- and magnetostratigraphy. The timing of these relies upon the demonstrated excellent match between paleo-temperature curves for the Late Neogene from deep-sea cores (Shackleton et al., 1990; Ruddiman et al., 1989; Thunell et al., 1990) and from the pollen record (Zagwijn, 1985) which has allowed the deep-sea derived timescale to be applied to the continental sedimentation record (Van den Berg, 1990).

Porosity–depth corrections were calculated on the basis of the observed average lithologies using standard exponential relations and material parameters (cf. Sclater and Christie, 1980). Porosity data available from the Roer Valley Graben (Van Doorn and Leyzers Vis, 1985) are insufficient for the construction of local porosity–depth curves.

No specific paleobathymetric data are available for the study wells. Published paleogeographic studies suggest that the area was located during much of the Mesozoic near the margins of basins; thus, waterdepths presumably never exceeded 100 m (Ziegler, 1978, 1988, 1990). Cenozoic paleogeographic interpretations (Letsch and Sissingh, 1983; Zagwijn, 1989) indicate similar paleobathymetries; shallow marine conditions

Fig. 2. Summary of post-Variscan tectonic history of the Roer Valley Graben.

Fig. 3. (a) Tertiary stratigraphy as observed in seismic profile 8119; boxed numbers are inferred numerical ages of seismic horizons (*Rijks Geologische Dienst* interpretation) and (b) interpreted Mesozoic and younger stratigraphy from The Netherlands deep seismic reflection profile 8601 (after Remmelts and Duin, 1990). Locations of the seismic lines are shown in Fig. 4.

were interrupted by minor periods of continental sedimentation.

A major erosional hiatus straddling the Cretaceous/earliest Tertiary boundary, truncating most Cretaceous strata, is common to all wells. In calculating the tectonic subsidence curves, no estimate of the thickness of the missing strata was made. This compares to basins in the southern North Sea where the removal of up to 1500 m of section has been deduced from compaction studies of sediments underlying the unconformity (Bulat and Stoker, 1987). In the present backstripping calculations, this has introduced a mi-

nor underestimate of decompaction and, consequently, of the tectonic subsidence.

Calculated *tectonic subsidence curves* for the selected wells in the the Roer Valley Graben area are given in Fig. 5. The estimated depth error bars for one of the wells are shown in Fig. 6; the error bars are derived from possible extreme variations in adopted porosity–depth relationships (cf. Bond and Komintz, 1984; Gallagher, 1989). For the older strata, absolute ages used may include uncertainties of several millions of years. Breaks in sedimentation, implying a loss of subsidence information, are indicated in Fig. 5

Fig. 4. Major basinal deeps and highs in the southern part of The Netherlands and locations of wells used in the backstripping analysis (cf. Table 1 for well names); also shown are the locations of the seismic profiles shown in Fig. 3 and the area (stippled) of neotectonic uplift used in constructing Fig. 11. IJMH = IJmuiden High; ZVR = Zandvoort Ridge.

TABLE 1

Wells used in the backstripping analyses; locations are given in Fig. 4

Number	Well name	Total depth (m)
<i>Peel Horst, northeast of Roer Valley Graben (Fig. 5)</i>		
1	Belfeld BFD-01	1179
2	America ACA-11	1079
3	Liessel LIE-22	1302
4	Oploo OPL-16	1131
5	Nijmegen NVG-01	1262
6	Altforst ALT-01	647
7	Maasbommel MSB-01	1705
8	Maasbommel MSB-02	1269
<i>Roer Valley Graben (Fig. 5)</i>		
9	Nederweert NDW-01	2908
10	Asten AST-01	2633
11	Veldhoven VEH-01	2098
12	St. Michielsgestel SMG-01	3327
13	Oisterwijk OIW-01	2480
14	Loon op Zand LOZ-01	2990
15	Dongen DON-01	1532
16	Waspik WAP-01	2594
17	Wijk en Aalburg WAA-01	2946
18	Almkerk ALM-01	2365
19	Werkendam WED-01	2266
20	Molenaarsgraaf MOL-01	1438
21	Boeikop BKP-01	998
22	Everdingen EVD-01	2191
<i>Netherlands offshore (Kooi et al., 1989)</i>		
23	P12-1	3554
24	P15-1	3224
25	S2-1	1766
26	Q1-2	3072
27	Q4-1	3105
28	Q7-1	2573
29	Q8-2	2535
30	Q10-2	2337

by dashed horizontal lines joining data points at equivalent depths but with unconformable ages (the ages of the strata immediately above and below the hiatal surface). In fact, an erosional hiatus is probably associated with a reversal of subsidence, not quantifiable in the computed tectonic subsidence curves because of the absence of the corresponding data.

The tectonic subsidence curves display a step-wise pattern with periods of rapid subsidence followed by phases of slower subsidence. Many of the rapid subsidence episodes are temporally

consistent throughout the study area suggesting a common origin related to regional tectonic processes. The observed patterns can be interpreted in terms of distinct episodes of crustal "stretching", resulting in phases of rapid "syn-rift" subsidence followed by phases of slower, exponentially decaying, thermal "post-rift" subsidence during which the extensional mechanism is inactive. The recognition of "syn-rift" and "post-rift" subsidence patterns allows establishment of a semi-quantitative time-frame for the post-Paleozoic tectonic history of the Roer Valley Graben area, as illustrated in Fig. 6.

In general, two major regional rifting episodes can be identified in the calculated subsidence curves. The first spans Late Permian–Early Triassic times ($\sim 255 - \pm 240$ Ma); it is associated with the resumption of sedimentation after the late Hercynian orogenic events. The second regional rifting stage began around 36 Ma and affected the entire Roer Valley area but is not evident in the southern North Sea (Kooi et al., 1989). In most wells located within the Roer Valley Graben rifting appears to have persisted until the present. Syn-rift subsidence of its flanking regions, in contrast, has apparently terminated at about 24–30 Ma (cf. Fig. 5).

Apart from these regional rifting events, there is limited control on intra-Jurassic–Early Cretaceous intervals of rapid subsidence in the Roer Valley Graben area. For instance, wells 12 and 17 record an Early Jurassic extensional event that may or may not have regional significance (Fig. 7). Secondly, a short duration event of accelerated subsidence straddles the Bajocian/Bathonian boundary (approximately 168–165 Ma) in wells where strata of these ages are preserved (Fig. 8). Subsequently, increased rifting activity in the North Sea during the Late Jurassic and Early Cretaceous was accompanied by transtensional movements governing the rapid subsidence of the West and Central Netherlands and Broad Fourteens basin (Ziegler, 1990; Kooi et al., 1989). To what extent this tectonic pulse also affected the Roer Valley Graben is uncertain given the scarcity of preserved section of these ages.

Wells in the northwestern part the Roer Valley Graben provide evidence for an acceleration

of tectonic subsidence during the Pliocene and Quaternary (Fig. 9a), seen also throughout the southern and central North Sea (Kooi et al., 1989; Geluk, 1990). This event is further illustrated by the inset in Fig. 9a which gives backstripped subsidence curves since 3 Ma for two shallow boreholes drilled in the graben.

The shapes of the observed tectonic subsidence curves are interpreted as reflecting repeated thermo-extensional, rifting events in the Roer Valley Graben area. These occur during the

Late Permian–Early Triassic, Middle Jurassic, and latest Eocene–Oligocene; an additional event is inferred for the Late Jurassic–Early Cretaceous.

In this section, *theoretical syn-rift* and *post-rift thermal subsidence curves* are compared with the observed tectonic subsidence curves. The modelling approach is based on the lithospheric stretching assumption (McKenzie, 1978; Royden and Keen, 1980), whereby the lithosphere is heated during rifting and subsequently cools

Fig. 5. Calculated tectonic subsidence curves for wells 1–22 listed in Table 1. Horizontal dashed lines represent hiatus breaks.

Fig. 6. Qualitative interpretation of tectonic subsidence curve for well 9; error bars on depth estimates are included.

through vertical heat conduction. The implementation of the model allows incorporation of finite (e.g. Jarvis and McKenzie, 1980) and multiple stretching phases (Kooi et al., 1989).

The modelling depends upon the initial crustal thickness and, based on preliminary models, a value of 37.5 km was adopted to provide the best overall results. The model assumes Airy isostatic compensation and disregards the potential effects of lateral heat flow.

Figure 7 compares the observed tectonic subsidence of wells located in the Roer Valley Graben with the theoretical subsidence curves for a Late Permian–Early Triassic rifting event. The comparison indicates stretching factors, β , for these wells in the range 1.06–1.17 (~6–15% thinning of the crust with commensurate heat input). Wells located outside the Roer Valley Graben in which this event is observed (not shown in Fig. 7) suggest β s of 1.04–1.07. The observed versus mod-

Fig. 7. Tectonic subsidence of selected wells during and after the Late Permian–Early Triassic rifting event (255–240 Ma), compared to synthetic subsidence curves constructed with a model for one-layered lithospheric stretching with various stretching factors.

Fig. 8. Tectonic subsidence of selected wells during and immediately after the Middle Jurassic rifting event (168–165 Ma), compared to model subsidence curves. The modelled subsidence incorporates the ongoing effects of the Late Permian–Early Triassic event.

elled subsidence for the Middle Jurassic rifting event is given in Fig. 8. Crustal extension less than 6% ($\beta < 1.06$) is indicated. Figure 9 give the results for the Oligocene to recent rifting cycle of the Roer Valley Graben area. Figure 9a shows results for wells located within the graben; the linear subsidence patterns suggest that rifting commenced at 36 Ma and continues until the present. The cumulative crustal thinning during this period is in the range 6–10% (β of 1.06–1.11). For wells located on the flanks of the Roer Valley Graben the model results are given in Fig. 9b. They indicate that the syn-rift phase of subsidence ended by around 30 Ma with β factors ranging between 1.02 and 1.05. Where Pliocene and Quaternary acceleration of tectonic subsidence is evident (most noticeably in the northwesternmost part of the graben; Fig. 9a), the observed rates could be interpreted in terms of an additional crustal extension of up to 4%.

Discussion and conclusions

The sedimentary columns penetrated by wells drilled in the southeastern Netherlands provide a regionally consistent, although incomplete, record of Mesozoic and Cenozoic vertical crustal motions of the European lithosphere between the North Sea and the Rhine Graben. Episodes of

rapid, syn-rift style subsidence are recognized during the latest Permian–Early Triassic, the Middle Jurassic and during the Oligocene to Recent. These rifting cycles are interrupted by periods of smoother, thermally-controlled, post-rift subsidence and by phases of inversion tectonics in the Late Cretaceous and Eocene. Anomalous, or internally inconsistent, subsidence patterns are also observed, as would be expected in a limited study area in which a number of long-lived faults are subject to repeated reactivations. An example is the apparent cessation of Oligocene syn-rift subsidence in wells in the northwestern part of the Roer Valley Graben (Fig. 9b) contrasting with wells in the axial parts the graben that continue to subside rapidly until the present (Fig. 9a). This is likely an effect related to differential movements of fault blocks within an essentially uniform regional tectonic setting.

The faults and fault zones controlling the development of the Cenozoic Roer Valley Graben appear to have been active also during the Late Permian–Early Triassic rifting event. This event can be recognized throughout the study area, but the subsidence modelling indicates higher Permo-Triassic stretching factors for wells located within the Cenozoic graben ($1.06 < \beta < 1.17$) than for those located on its flanks ($\beta <$

1.07). A similar pattern is expected for the minor Middle Jurassic rifting event though sedimentary control is restricted to the graben only.

Figure 10 gives a schematic regional crustal section through the southeastern Netherlands, based on a deep seismic reflection profile (Rem-

Fig. 9. Tectonic subsidence of selected wells, compared to model subsidence curves, for (a) rifting beginning at 36 Ma and continuing until the present and (b) rifting beginning at 36 Ma and ending at 30 Ma. The modelled subsidence incorporates the residual effects of earlier events. Inset in (a) shows tectonic subsidence calculated for two RGD (*Rijks Geologische Dienst*) shallow boreholes in the Roer Valley Graben; boreholes "Ospel" and "Eindhoven" are located nearby wells 10 and 11, respectively.

Fig. 10. Schematic compilation of the results of part of The Netherlands deep seismic reflection profile 8601 (after Remmelts and Duin, 1990) crossing the Roer Valley Graben; location is given in Fig. 4.

Fig. 11. Record of Miocene to recent uplift of the southern flank of the Roer Valley Graben (located in Fig. 4) from dating of river terraces (after Van den Berg, 1990; Veldkamp and Van den Berg, in prep.).

melts and Duin, 1990). It indicates that the Moho discontinuity rises from 30–31 km under the flanks of the Roer Valley Graben to about 28 km beneath the graben axis. Taking into account the post-Carboniferous sedimentary succession, the crustal layer beneath the graben is 24–25 km thick. This can be interpreted to be the cumulative effect of all the Mesozoic and Cenozoic crustal stretching. The subsidence modelling determined an initial crustal thickness of about 37.5 km. Using this value, the crustal thicknesses observed in the reflection profile imply β s of about 1.50 for the graben and 1.30 elsewhere. The combined effects of the stretching events documented in the tectonic subsidence curves result in β s up to 1.30–1.34 and about 1.12 respectively. The “missing” amount of stretching (about 15%) may be attributed to an earlier Permo-Carboniferous phase of wrench tectonics (Ziegler, 1990) and to the inferred extensional and transtensional tectonics during the Late Jurassic and Early Cretaceous.

The Mesozoic extensional events observed or inferred in the Roer Valley Graben can also be documented in the southern North Sea (Kooi et al., 1989, 1991), although the pattern of intermittent subsidence and inversion episodes is more complex, for instance in the Broad Fourteens (Van Wijhe, 1987) and Sole Pit basins (Van Hoorn, 1987). In contrast, the important Cenozoic rifting phase of the Roer Valley Graben, commencing in the Oligocene, does not find its equivalent in the southern North Sea. At this time, the Roer Valley Graben appears to have greater affinity with the slightly earlier and contemporaneous Rhine Graben system (Illies, 1981).

However, by Pliocene time, and continuing until the present, the situation is changed: a rapid phase of subsidence evident in the region offshore the Netherlands (e.g. Kooi et al., 1991) parallels a similar tectonic reactivation seen in some of the Roer Valley Graben wells and shallow boreholes (Fig. 9a). Recent tectonism in the Roer Valley Graben is further evidenced by thickness variations of Quaternary deposits over the main bounding faults, morphological observations (Vandenberghe, 1990), geodetic measurements (Waalewijn, 1966; Bisschops, 1973), and

the pattern of historical seismicity in northwestern Europe (Ahorner, 1983).

An illustration of the Plio-Pleistocene tectonism of southeastern Netherlands is given in Fig. 11 which shows the uplift of the southern flank of the Roer Valley Graben (cf. Fig. 4) since 15 Ma based on detailed analysis of fluvial terraces of the Maas (Meuse) River. Precise dating methodologies were similar to those cited earlier for the dating of continental sediments within the graben (Van den Berg, 1990, in prep.); they were used in conjunction with climatic change models of terrace development (Veldkamp and Vermeulen, 1989; Veldkamp and Van den Berg, in prep.) to determine the terrace heights and ages, indicated in the figure by solid dots. The onset of the fluvial system in this area corresponds with the Haq et al. (1987) longterm sealevel fall at about 14 Ma (cf. Fig. 11). The low uplift rate observed thereafter dramatically changes at about 3 Ma when a sudden increase in rate occurs. At the same time a hiatus is seen in the sedimentation record of the graben (Fig. 9a, inset); the sedimentation record otherwise indicates an acceleration of tectonic subsidence.

Thus, at present, the Roer Valley Graben displays tectonic affinity with the Rhine Rift system but is also influenced, in its northwestern part, by a Plio-Pleistocene North Sea downwarp. Acceleration of Plio-Pleistocene subsidence of the North Sea Basin can be related (Ziegler, 1990; Kooi et al., 1989, 1991) to the build-up of the present-day NW–SE oriented compressional stress field of northwestern Europe (Klein and Barr, 1986). This ambient intraplate stress regime plays an important role in the present tectonic activity of the Roer Valley Graben. The NW–SE trending fault systems of the Roer Valley Graben appear to be related to Permo-Carboniferous structural trends controlling the subcrop of Carboniferous strata beneath Permian and younger sediments. This structural predilection, and the absence of a heat flow anomaly (Geluk, 1990; Remmelts and Duin, 1990; Ramaekers, in press), can be interpreted as evidence for a “passive” rifting mechanism, controlled by changes in the lithospheric stress regime rather than by “active” asthenospheric thermal activity.

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