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Inverted basins in the Netherlands, similarities and differences

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Abstract

All Dutch rift basins that formed during Jurassic and Early Cretaceous extension have been inverted during the Late Cretaceous and Early Tertiary. Several inversion pulses occurred more or less simultaneously in all basins. Analysis of vitrinite reflectance data, in combination with fission track and fluid inclusion data show that the magnitude of uplift and erosion generally did not exceed 2 km. Inversion was strongest in the Broad Fourteens, Central Netherlands and West Netherlands basins. The direction of maximum compressive stress was generally not at right angles to the pre-existing fault trends, and resulted in transpressional movements. Within the NW-SE striking basins, dextral strike-slip movements can often be interpreted, which is consistent with a general N-S to NNW-SSE direction of maximum compression related to Alpine structural events. Where no Zechstein salt is present, trends of flower structures formed through reverse reactivation of pre-existing faults. Where the Zechstein salt is thick, re-activated faults could not breach the salt, and a broad uplift of the post-salt succession resulted, while faulting below the salt caused acceleration of halokinesis. In areas where the Zechstein salt was thin, and where the offsets of reverse faults exceeded the thickness of the salt, impressive thrusts with the Zechstein salt as detachment horizon developed. The later Tertiary inversion pulses did not affect all basins, and caused broad basin uplift in the West and Central Netherlands basins while individual faults were no longer reactivated. It appears that due to crustal thickening during the first inversion pulses the crust could become stabilised such that further compression could only be accommodated by broad basin uplift.

Keywords: West Netherlands basin, Central Netherlands Basin, Broad Fourteens Basin, Dutch Central Graben, Lower Saxony basin, Roer Valley Graben, Sole Pit Basin, Sub-Hercynian, Laramide, Pyrenean, Savian

Introduction

Basin inversion is the reversal of the subsidence of a sedimentary basin in response to compressional or transpressional stress (Ziegler, 1987a). As a consequence of inversion, basins are transformed into relative highs, and their thick basin fill sequences are uplifted to shallower depth than their, generally thin, time-equivalent deposits adjacent to the basins (Dronkers & Mrozek, 1991). In the Netherlands, tectonic inversion has affected the rift basins that formed during Jurassic and Early Cretaceous extension. The most strongly inverted basins are the West Netherlands, Central Netherlands and Broad Fourteens basins. Less inverted are the Dutch Central Graben and the Roer Valley Graben, while the Vlieland Basin and Dutch part of the Lower Saxony Basin are only very mildly inverted (Fig. 1). Structural inversion occurred during the Late Cretaceous and the Early Tertiary, and several pulses of accelerated inversion can be identified. In detail there are notable differences in the way that structural inversion affected these basins, in particular with respect to timing, magnitude of uplift and structural style.

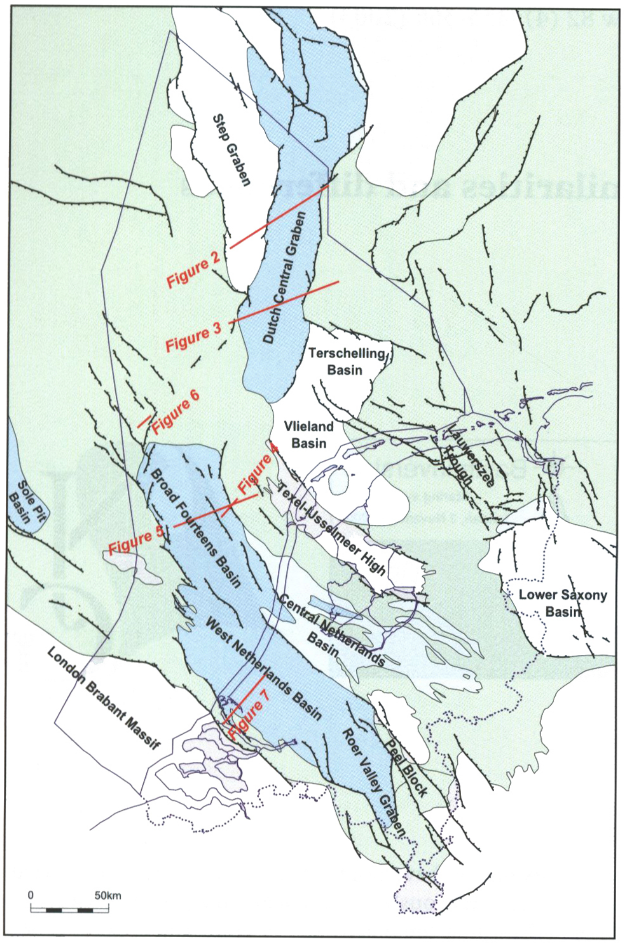

Fig. 1a. Structural elements map of the Netherlands showing main and minor Mid and Late Kimmerian Jurassic to Early Cretaceous rift basins (dark and light blue respectively), highs (grey) and platforms (green).

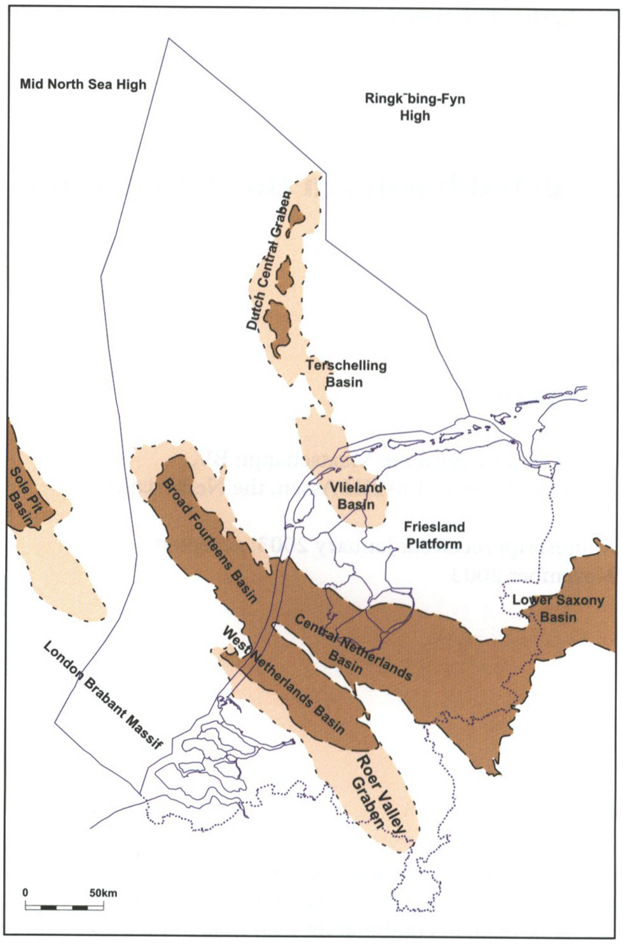

Fig. 1b. Alpine basin inversion. Light shading shows mildly inverted areas, where the Upper Cretaceous chalk is thin as a result of erosion and/or no to limited deposition; dark shading shows strongly inverted areas, where no chalk has been preserved

Structural setting

The dominant NW-SE structural trend that can be seen on structural maps of the Dutch subsurface was probably already established during the Silurian to Early Devonian Caledonian orogeny. An important period of uplift occurred at the end of Carboniferous and into the Early Permian, when the thick Westphalian clastics, deposited in a Variscan foredeep, became deeply eroded. The NW-SE Caledonian fault trend was reactivated at that time, and a conjugate NE-SW fault trend developed (Ziegler, 1990a, 1990b). Subsequent thermal subsidence led to the development of the Southern Permian Basin, which extends from the UK to Poland. North of an east-west trending line running from approximately south of the Lower Saxony Basin to the centre of the Broad Fourteens Basin, the Zechstein salt was deposited above the clastics of the Permian Upper Rotliegend Group. To the north, the thickness of the salt increases to about one kilometre. Where the Zechstein salt is present, it acted as a detachment level during subsequent tectonic deformation. As a result, the structural style in the post-Permian sequences differs markedly between areas with and without salt. During the Jurassic, and preceding continental break-up between north-west Europe and North America, tectonic extension strongly accelerated, affecting a wide area. During this Late Kimmerian rifting, the main tectonic elements in the subsurface of the Netherlands were formed. From Norway to the northern Dutch offshore, most extension was accommodated within the roughly north-south trending North Sea rift system, of which the Dutch Central Graben, the Step Graben and the Terschelling Basin form the southernmost extension. To the south of this, the NW-SE trending Broad Fourteens, West Netherlands, Central Netherlands and Vlieland basins and the Roer Valley Graben formed through reactivation of pre-existing NW-SE fault trends. Also the UK Sole Pit Basin and the essentially German Lower Saxony Basin formed during this phase of extension. Platform areas adjacent to

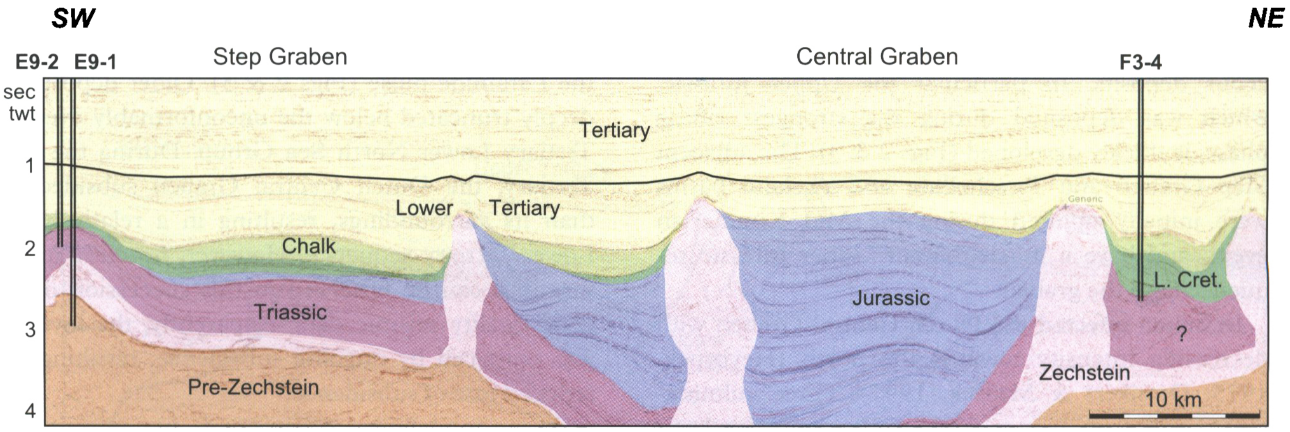

Fig. 2. NW-SE Seismic section across the northern sector of the Dutch Central Graben. For location see figure 1a. Within the graben, post-Campanian chalk locally overlies inverted and eroded syn-rift deposits, and Tertiary deposits overly the truncated chalk and older sequences, indicating that two phases of inversion occurred: the Campanian Sub-Hercynian phase and the Paleocene Laramide phase. During the Early Tertiary, subsidence of the graben was less then outside the graben, but no reversal of the subsidence (i.e. uplift) occurred.

these developing rift basins were at the same time uplifted and deeply truncated. The opening of the North Atlantic brought an end to extension in the southern North Sea area. The widely recognised Late Kimmerian Unconformity of Early Cretaceous age separates the syn-rift deposits from overlying Early Cretaceous post-rift sediments (Ziegler, 1990).

During the Late Cretaceous, the Alpine foldbelt formed when Africa, including Italy, collided with Europe. Further compression continued into the Tertiary. The effects of these forces were felt in the southern North Sea, where thermal subsidence was interrupted and rift basins from the British Isles to Poland were inverted to a greater or lesser extent (Ziegler, 1987b, 1988, 1990a, 1990b; Ziegler et al., 1995; Dronkers & Mrozek, 1991). Inversion-related uplift resulted in thinning and erosion of the Upper Cretaceous chalk and Lower Tertiary clastics over the rift basins and in local truncation of older sediments. Four inversion phases can be recognised: (1) the Sub-Hercynian phase, peaking during the Campanian; (2) the Laramide phase, peaking during the mid to late Paleaocene; (3) the Pyrenean pulse at the end of the Eocene, and (4) the Savian pulse at the end of the Oligocene (Fig. 8). After this period of inversion, regional subsidence took over again.

Inverted Basins

Dutch Central Graben and adjacent areas

The Dutch Central Graben is the southernmost extension of the Mesozoic North Sea rift system and is flanked by the shallower Step Graben and Ter-

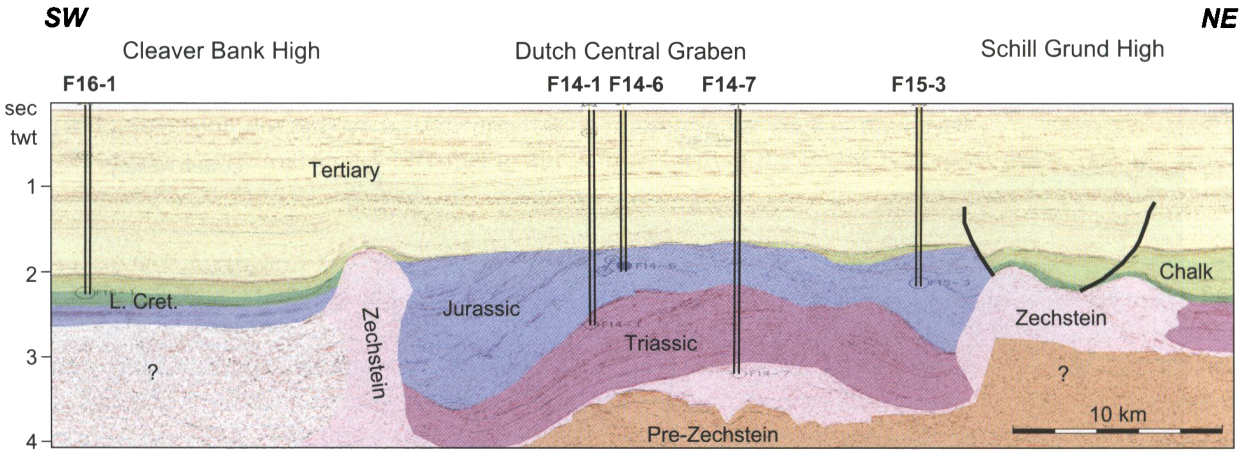

Fig. 3. NW-SE Seismic section across the southern sector of the Dutch Central Graben. For location see figure 1a. Post Campanian chalk overlies eroded syn-rift deposits, and Tertiary deposits overly truncated chalk and older sequences. Inversion in the south of the Dutch Central Graben was stronger than in the north. Note that the thickness of Lower Tertiary above the graben is less than elsewhere, indicating a reduced rate of subsidence during the Early Tertiary. However, no unconformities can be seen, so no uplift and erosion occurred during the Early Tertiary.

schelling and Vlieland basins (Fig. 1a). It displays increased thicknesses of the Triassic to Lower Cretaceous deposits. In particular the Upper Jurassic, which was deposited during the strongest rifting phase, is thickly developed (Figs 2 & 3). The adjacent Step Graben and Terschelling and Vlieland basins were initially uplifted during the Mid Kimmerian event, and have a much thinner Upper Jurassic sequence than the graben.

Inversion affected the Dutch Central Graben with decreasing intensity towards the north (Heybroek, 1975; Dronkers & Mrozek, 1991). Three culminations, where no Upper Cretaceous chalk has been preserved, can be recognised (Fig. 1b). From seismic sections it can be seen that uplift created broad anticlinal highs (Figs 2 & 3), and that the Zechstein salt prevented transmission of inversion related faulting into the overlying strata (Dronkers & Mrozek, 1991). The inversion pulses did cause an acceleration of the growth of salt domes and walls.

The Sub-Hercynian pulse resulted in significant erosion of pre-Campanian deposits within the most strongly inverted areas, probably already down to the Early Cretaceous Vlieland Formation. In various locations post-Campanian Chalk overlies the Campanian unconformity (Heybroek, 1975; Dronkers & Mrozek, 1991). In well F17-4, near the southern inversion high, a locally developed intra-chalk sandstone occurs at the level of the Campanian. This is interpreted as indicating that in the most strongly inverted axis of the central Graben, already during this phase of inversion erosion had cut down to the lowermost Cretaceous or even the Jurassic. For those are the only sandy sections of which the erosion products could be the source of the sand in this intra-Chalk sand lens.

From seismic cross sections it is clear that a second strong inversion pulse occurred during the Paleocene: the Laramide pulse (Figs 2 & 3). Older deposits are deeply truncated below the unconformably overlying Tertiary Lower North Sea Group. During the Early Tertiary, the Dutch Central Graben subsided less than its surroundings, resulting in a relatively thin Lower Tertiary sequence. However, no clear unconformities can be observed in this succession on the good-quality seismic data. Apparently, the inversion was outpaced by ongoing subsidence, resulting in a reduced rate of subsidence.

Basin modelling, constrained by vitrinite reflectance data, indicates that the maximum amount of uplift and erosion in the Dutch Central Graben is some 600 to 700 m. This is in good agreement with maximum uplift of circa 500 m estimated by Huyghe & Mugnier (1994), and uplift of 750 m of Heybroek (1975) and Dronkers & Mrozek (1991).

Broad Fourteens Basin

The Zechstein salt is only present in the northern half of the Broad Fourteens Basin, causing striking differences in structural style between its northern and southern sectors (Dronkers & Mrozek, 1991; Hooper at al,. 1995; Huyghe & Mugnier, 1995; Nalpas et al., 1995). In the southern part of this basin, Late Kimmerian rifting created a series of tilted halfgrabens with expanded sections of the Upper Jurassic to Lower Cretaceous syn-rift deposits of the Delfland Group. In the northern part, structuration above the salt was decoupled from sub-salt faulting, and halfgrabens with syn-rift deposits are less clearly developed.

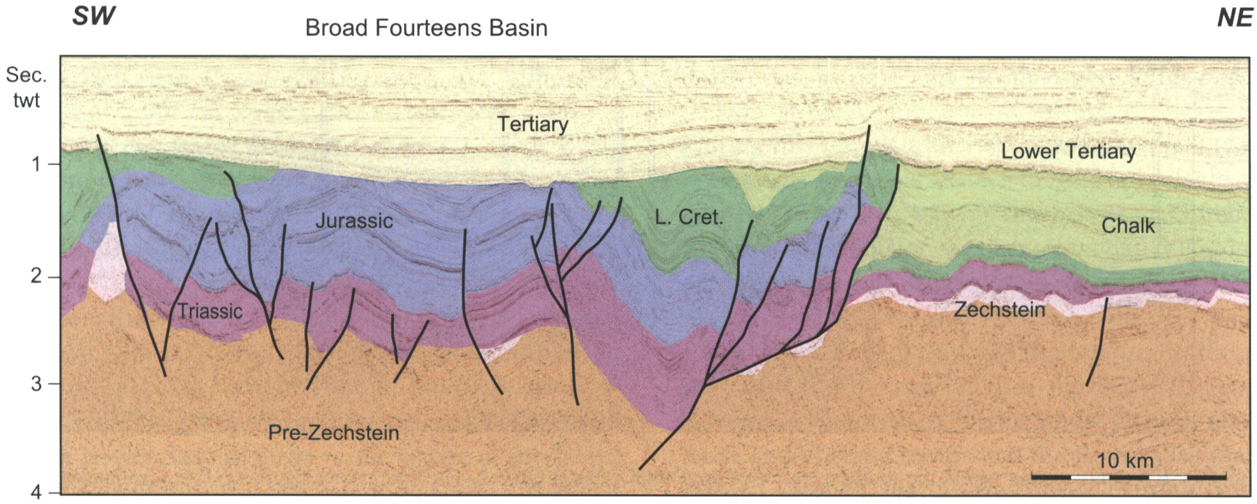

Fig. 4. Seismic section across the northern sector of the Broad Fourteens Basin. For location see Figure 1a. Inversion resulted in an impressive thrust fault along the north-east flank of the basin, which is seen in more detail on figure 5. Contrary to the West Netherlands Basin, the Pyrenean phase of inversion hardly affected this part of the Broad Fourteens Basin.

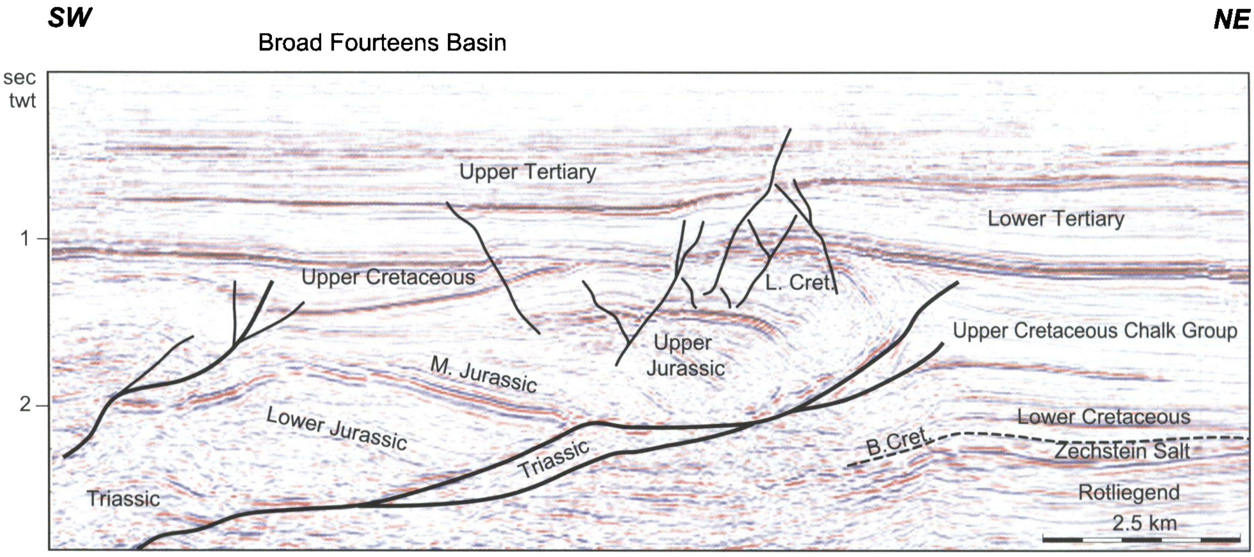

Fig. 5. Seismic section across showing the thrust along the north-east flank of the Broad Fourteens Basin. It can be seen how the fill of the basin has been thrust onto the platform during the Late Cretaceous, and prior to deposition of the post-Danian Tertiary sequence. Minor further inversion occurred during the Pyrenean phase of inversion at the end of the Oligocene. Note also the expansion of the Upper Jurassic and Lower Cretaceous deposits into the thrust-fault, indicating that this was an extensional fault bounding a half-graben during Kimmerian rifting.

Inversion in the Broad Fourteens basin, was stronger than in the Dutch Central Graben, and resulted in more complex structures with a much shorter wavelength (Fig. 4). The area of inversion of the Broad Fourteens Basin is sharply defined by major reverse faults. Figure 5 shows one of these on the NE margin of the basin. The main thrust-fault is a reversely reactivated Kimmerian extensional fault, bounding a wedge of Jurassic and Lower Cretaceous syn-rift deposits. The complex nature of the thrust is demonstrated by nearby well (L16-8), which penetrated the same Triassic interval three times, with the shallowest occurrence of the top Triassic being about 1500 m shallower than the deepest. Also on the SW flank of the basin reverse thrust faults are seen on seismic, and also in a Mobil well, which encountered the top of the Triassic four times (Dronkers & Mrozek, 1991). Inversion not only created thrusts but also NW-SE trending anticlinal arches (Hooper at al., 1995). In the southern part of the basin, where no Zechstein salt is present, inversion resulted in steep reversely reactivated faults and flower structures. Total shortening is estimated to be 10 to 12% (Hayward & Graham, 1989).

Inversion started sometime during the Turonian to Santonian, and possibly locally already during the Albian (Hooper at al., 1995). The first important inversion pulse is the Campanian Sub-Hercynian pulse. In several sectors of the basin post-Campanian Chalk was deposited on an eroded older section. The main *inversion phase was, however, the Paleocene* Laramide pulse (Huyghe & Mugnier, 1995), when the basin fill was deeply eroded, locally down to the Triassic (Nalpas et al., 1995). It is generally assumed that faults were reactivated with a strike-slip component (Huyghe & Mugnier, 1994). A dextral sense of strike-slip is suggested from structural geometries (Nalpas et al., 1995), which would be in agreement with a general N-S sense of (Alpine) compression. On a regional scale, the Tertiary Pyrenean phase only caused basin inversion of the south-eastern sector, where the Broad Fourteens Basin merges with the Central and West Netherlands basins. Locally, however, also further north some effects of this phase can be seen. For example on figure 5, where above the toe of the main inversion thrust the Lower North Sea Group is truncated below the base of the Oligocene Middle North Sea Group. Following this, tectonic relaxation occurred with south-west dipping normal faults on the back of the thrust.

North of the Broad Fourteens Basin, pop-up structures at the level of the Rotliegend, below the thick Zechstein salt, are a clear indication of compression, which must be related to these phases of basin inversion, which were the only times when compression occurred since the Permian (Fig. 6). These pop-up structures occur along NW-SE, NE-SW and WNW-ESE fault trends that apparently were all reactivated more or less simultaneously. In the same general area, a Chalk graben is present following a reactivated NNE-SSW trending fault at pre-Zechstein salt levels (Oudmayer & De Jager, 1993). Apparently, depend*ing on the direction of pre-existing faults, reactivation* during the Late Cretaceous resulted in transpression

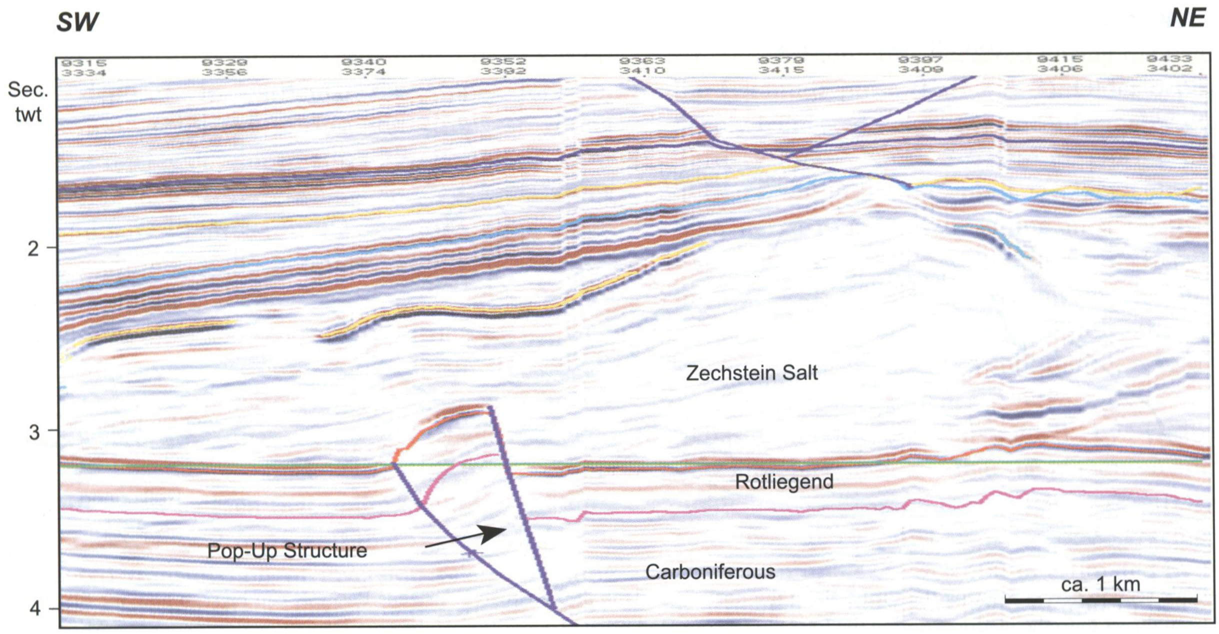

Fig. 6. Seismic section on the Cleaver Bank High, north of the Broad Fourteens Basin, showing a NW-SE trending pop-up structure bounded by a reverse fault. The compressional nature of this structure indicates that it must have formed during Alpine inversion. For location see Fig. 16.

or transtension. Locally, subtle Riedel structures at the base of the Tertiary indicate that minor dextral wrenching occurred during the Tertiary Pyrenean phase. (Oudmayer & De Jager, 1993).

Estimates of the maximum inversion in the Broad Fourteens Basin in the literature are 2200 to 2500 m (Hooper at al., 1995), 2000 to 3000 m (Oele et al., 1981; Nalpas et al., 1995) and 3000 to 3500 m (Van Wijhe, 1987a, 1987b; Dronkers & Mrozek, 1991; Huyghe & Mugnier, 1995). Independent modelling of the burial history in the Broad Fourteens basin in NAM, well constrained by vitrinite reflectance, fission track and fluid inclusion data suggests that not more than 1500 to 2000 m of uplift and erosion occurred. The possible reasons for these differences are discussed later.

West Netherlands Basin

In the West Netherlands Basin no Zechstein salt is present, and Late Kimmerian rifting resulted in the development of a series of halfgrabens filled with synrift deposits of the Upper Jurassic to Lower Cretaceous Delfland Group. Overlying Cretaceous post-rift deposits can be seen to onlap the basin margins (Fig. 7; Bodenhausen & Ott, 1981; De Jager et al., 1996).

During the Late Cretaceous inversion, pre-existing rift faults were reactivated. Along individual faults the reversed sense of movements can often still clearly be deduced: normal offsets at the deeper, and reverse offsets at the shallower stratigraphic levels. Several NW-SE trends of impressive flower structures formed under a transpressional regime. Thinning of the Upper Cretaceous chalk from the south-east towards the inverted basin, with internal unconformities visible on seismic data, clearly shows that the flower structures started forming during the Late Cretaceous Sub-Hercynian inversion phase (Fig. 7).

During the Paleocene Laramide inversion phase, the West and Central Netherlands basins were together further inverted and deeply eroded, locally down to the Triassic. During the Early Tertiary, The Pyrenean inversion pulse affected the basin. Along its southwest margin the Lower Tertiary thins towards the inverted basin, and above the basin, as well as in the Central Netherlands Basin, erosion of the Lower Tertiary occurred (Fig. 7). Noteworthy is that while the Sub-Hercynian and Laramide inversions resulted in reverse reactivation of pre-existing faults, the Pyrenean inversion caused broad basin uplift without significant fault reactivation. At the end of inversion, relaxation of the stress regime resulted locally in minor normal reactivation of faults. Due to the late inversion of the West and Central Netherlands basins, the Tertiary cover is very thin, locally not more than circa 500 m (Bodenhausen & Ott, 1981). Maximum inversion, as indicated by basin modelling constrained by vitrinite reflectance data and sonic velocities of Triassic claystones is circa 1500 m.

Central Netherlands Basin

The Sub-Hercynian inversion in the Central Netherlands Basin is not well documented, as due to deep erosion hardly any Upper Cretaceous deposits have been preserved. As in the West Netherlands Basin, the Tertiary cover is very thin as a result of uplift during Pyrenean inversion. It is likely that similar to the adjacent Broad Fourteens and West Netherlands basins, also the Sub-Hercynian and Laramide phases had a strong effect here. Maximum inversion, as indicated by basin modelling is circa 1500 m.

Roer Valley Graben

The Roer Valley Graben forms the south-eastern extension of the Late Kimmerian West Netherlands Basin, and was reactivated during the Cenozoic as the north-western branch of the Rhine Graben rift system (Ziegler, 1994). The effects of inversion were strongest in the NW sector of the graben. Inversion commenced during, or possible before, the Early Campanian, and ceased during the Maastrichtian (Geluk et al., 1994). Upper Cretaceous clastics deposited on the Peel Block are considered to represent the erosional products from the inverted Roer Valley Graben, while the adjacent Maasbommel High and Peel Block incurred strong subsidence (Gras, 1995; Gras & Geluk, 1999; Geluk et al., 1994). During this Sub-Hercynian phase the north-eastern boundary fault, the Peel Boundary Fault, was reactivated by transpressional strike-slip movements, and positive flower structures formed in the western part of the Peel Block. The presence of Maastrichtian and Early Paleocene chalk deposits within the graben indicates that no Laramide inversion occurred (Gras & Geluk, 1999). The Tertiary is very thick, reaching up to 2000 m, and shows no evidence for Pyrenean inversion (Van den Berg, 1994; Van den Berg et al., 1994).

Lower Saxony Basin

The Lower Saxony Basin is largely located within Germany. Only its westernmost part extends just into the Netherlands. The Dutch sector of the basin has only been mildly inverted. Towards the east, in Germany, the central sectors of the basin are strongly inverted, particularly its southern part. Inversion started in the Turonian and peaked during the Santonian and Campanian Sub-Hercynian phase, and during the Paleocene Laramide phase (Betz, et al., 1987; Baldschuhn et al., 1991). Only minor inversion occurred locally during the Oligocene (Betz et al., 1987). Estimates of total maximum inversion uplift range from 2 km (Betz et al, 1987) to 4 or 5 km (Baldschuhn et al., 1991) or locally even 8 km (Kockel, this volume). Inversion created thrusts along the basin margins and trends of flower structures. En-echelon fault geometries are suggestive of strike-slip movements, although major horizontal displacements cannot be proven. Crustal shortening is estimated to be some 8 km (Kockel, this volume)

Sole Pit Basin

The Sole Pit Basin is entirely located in the UK sector of the Southern North Sea. The Sub-Hercynian phase of inversion started during the Turonian, and

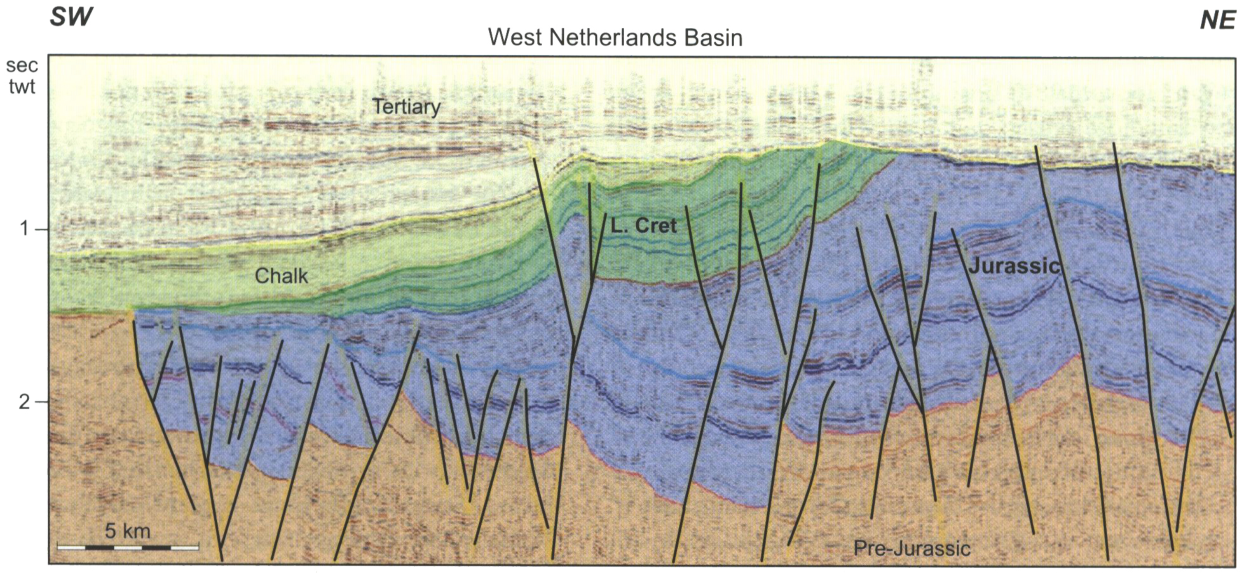

Fig. 7. Seismic section running from the south-west flank of the West Netherlands Basin into the inverted basin. For location see Figure 1a. Three phases of inversion occurred. The Sub-Hercynian phase caused thinning of the Upper Cretaceous chalk sequences towards the basin while flower structures started forming. During the Laramide phase flower structures developed further, and major uplift caused significant erosion below the base of the Tertiary. During the Pyrenean phase of inversion, broad basin uplift occurred, without significant reactivation of faults.

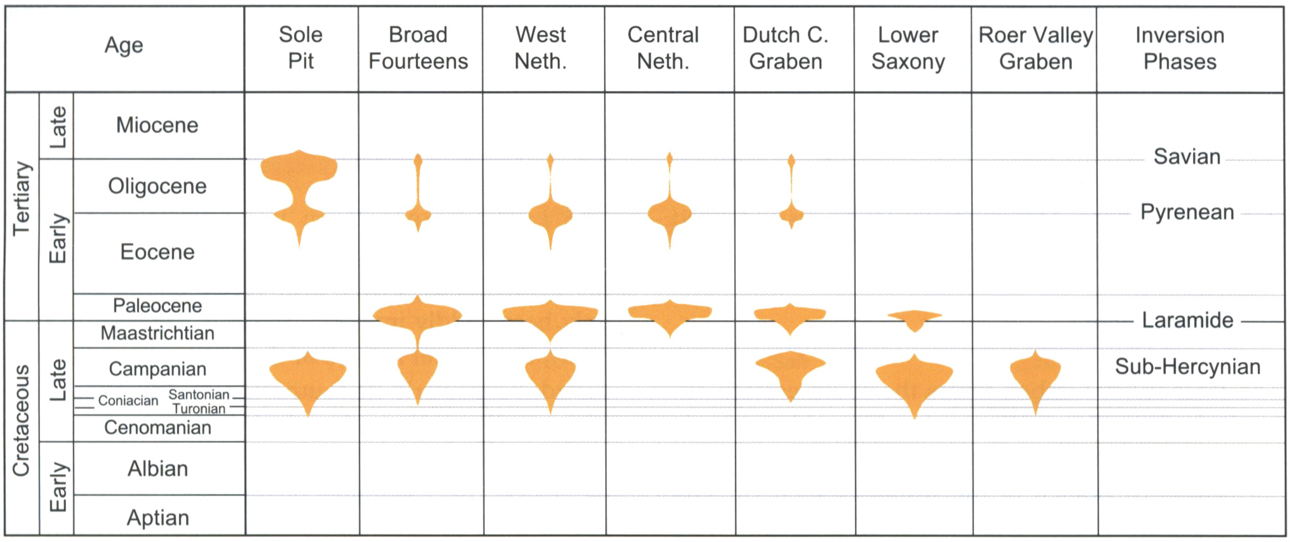

Fig. 8. Timing of inversion: four phases on inversion occurred more or less simultaneously in different basins, but with different magnitudes. Some inversion phases, in particular the later ones, left some of the basins unaffected.

lasted until the Campanian. Turonian to Lower Campanian chalk thins and onlaps onto the centre of inversion, where Upper Campanian to Maastrichtian chalk unconformably overlies the Jurassic (Van Hoorn, 1987). The Laramide phase of inversion has not been documented in this basin. Fission track analyses suggest that there were two inversion pulses in the Tertiary, at 40-30 Ma (Pyrenean) and at 30-20 Ma (Savian). Inversion was probably associated with dextral strike-slip movements and resulted in Riedel shears and flower structures at Pre-Zechstein salt levels. Due to the decoupling effect of the Zechstein salt, inversion resulted at shallow levels in a simple domal uplift. Total maximum uplift is estimated at about 1500 m, based on Lower Triassic claystone velocities and vitrinite reflectance data from the Carboniferous (Van Hoorn, 1987).

Similarities and differences

Timing of inversion events

The timing of inversion phases in the various basins is summarised below and on Fig. 8. The following main phases of inversion can be recognised:

1. The Sub-Hercynian inversion pulse started in the Turonian and peaked during the Campanian. Thinning of chalk sequences can be seen towards the inversion highs, and post-Campanian chalk is deposited on Campanian unconformities in all main Late Kimmerian rift basins.
2. In most Dutch basins the strongest inversion occurred during the Paleocene Laramide pulse, with significant erosion down to Jurassic strata in the West Netherlands, Central Netherlands and Broad Fourteens basins and in the Dutch Central Graben. Only the Roer Valley Graben was not affected by this inversion phase. The Laramide phase was relatively weak in the German Lower Saxony Basin, and apparently did not affect the Sole Pit Basin.
3. At the end of the Eocene, the Pyrenean pulse caused broad uplift of the West Netherlands and Central Netherlands basins. The uplift rapidly diminishes towards the north-west into the Broad Fourteens Basin. Other Dutch basins were not inverted during this phase. During the Early Tertiary, subsidence of the inverted Dutch Central Graben was clearly less than areas flanking the graben, showing that the effects of inversion also affected this basin. However, no uplift and erosion occurred.
4. At the end of the Oligocene, the Savian pulse caused significant uplift in the UK Sole Pit Basin (Van Hoorn, 1987), but no significant inversion can be attributed to this pulse in the Netherlands.

The magnitude of these four pulses varies per basin, and not all pulses can be recognised in all inverted basins. In some cases this is because erosion following a later phase of inversion obscured the effects of an older inversion. In other cases there is little doubt that an inversion pulse had left a basin unaffected. Surprisingly, there is good evidence that the Roer Valley Graben was not inverted during the Laramide phase, even though this graben forms the direct continuation with the West Netherlands Basin, which was strongly inverted during this phase.

The clear similarities in timing of the different pulses strongly suggest a common cause for inversion.

The main driving force for basin inversion in NW Europe is generally assumed to be related to collisional coupling between the Alpine foreland and the Alpine orogen, with early compressive movements becoming dominant during the Late Cretaceous (Ziegler, 1987b, 1990a, 1990b; Ziegler et al., 1995). Ziegler assumes that basins in which the crust was most attenuated, and hence weakest, were prone to be inverted first. Furthermore, modelling indicates that during inversion the crust of inverted areas can increase in thickness and becomes stronger to the degree that later on only minor further deformation was possible (Ziegler et al., 1995). An argument in favour of such a stabilisation of inverted areas may be that the last inversion phase in the West Netherlands Basin resulted in a broad uplift of the area, while individual faults, which were reactivated in earlier phases, seemed to have effectively 'locked'. Also the observation that later inversion phases affected fewer basins may be considered as an indication that some form of 'stabilisation' made some of the basins and/or faults less susceptible for further inversion. The UK Sole Pit Basin is, however, an exception to this. This basin was inverted during the early and late inversion phases, but not during the Laramide phase. An alternate explanation for why not all inversion phases affected all basins may be related to the differences in their structural trend and differences in the direction of the compressional stress through time. Some basins were more favourably oriented for inversion during one phase of inversion and other basins during another phase of inversion.

Structural styles of inversion

The most striking differences in the structural style of inverted basins are related to the absence or presence of Zechstein salt. Where salt is present and sufficiently thick, an effective decoupling of faulting below and above the salt occurred. In the West Netherlands Basin, where Zechstein salt is missing, faults were reactivated by transpressional movements, and flower structures formed at Jurassic and Cretaceous levels. Flower structures are also observed in the Roer Valley Graben and in the southern sector of the Broad Fourteens Basin, but not in areas where Zechstein salt is present. In the Dutch Central Graben, with very thick Zechstein salt, faults above and below the salt are entirely detached. There, inversion caused the post-salt deposits to be uplifted in a broad anticline, while the build-up of compressional stresses resulted in sub-salt fault reactivation and acceleration of halokinesis. Where only thin Zechstein salt was present and fault throws exceeded the thickness of the salt, such as in parts of the Broad Fourteens Basin, the salt acted as a detachment surface along which the basin-fill was thrust onto the adjacent platforms. The same relationship is also observed in the lower Saxony Basin (Kockel, this volume)

Most authors observe indications of dextral strike-slip movements during inversion. In the Broad Fourteens Basin, folds above thrust faults bordering the basin display an en-echelon pattern indicative of dextral strike-slip component (Nalpas, et al., 1995). Huyghe and Mugnier (1995) conclude that geometries of inversion-related thrusts are consistent with either sinistral strike-slip along N160° trending basement faults or with dextral strike-slip along N140° trending basement faults. NE of the Broad Fourteens Basin, subtle Riedel structures at the base of the Tertiary indicate that minor dextral wrenching occurred during the Tertiary Pyrenean phase as well. (Oudmayer & De Jager, 1993). In the West Netherlands Basin, a dextral displacement along NW-SE faults of the Pijnacker field is interpreted (Racero-Baena & Drake, 1996). No clear indications of the sense of oblique transpressional movements have been reported from the Dutch Central Graben. In the Sole Pit Basin, the alignment of faults below the Zechstein salt, as well as en-echelon patterns of shears above the salt, indicate right-lateral strike-slip movements on NW-SE trending basement faults (Van Hoorn, 1987). The observed dextral sense of transpressional movements along NW-SE trending faults is in agreement with a N-S to NNW-SSE directed Alpine compression.

Magnitude of inversion

Measures for the magnitude of inversion are the amount of crustal shortening and the amount of uplift and erosion. Only for a few basins estimates of crustal shortening have been reported in the literature. For the Broad Fourteens Basin, shortening has been reconstructed to be 10% (Hooper et al., 1995) or 10 to 12% (Hayward & Graham, 1989), and for the Dutch Central Graben 1 to 2% (Huyghe & Mugnier, 1994). For the German Lower Saxony Basin, approximately 8 km of shortening has been estimated (Kockel, this volume), which would equate to some 10%. No quantitative estimates of amount of shortening have been reported for the other basins.

The amount of uplift and erosion is best established through detailed reconstruction of burial histories, constrained and calibrated by analyses of vitrinite reflectance, fission track and fluid inclusion data, and analysis of sonic velocities in shales. Analyses carried out in NAM indicate that the maximum inversion of the Dutch basins nowhere exceeded 2 km, and in most places amounted to not more than 1 to 1.5 km. In the literature, estimates for maximum amounts of inversion of the same basins are generally significantly higher: up to 3500 m for the Broad Fourteens Basin. It appears that these higher estimates do not fully account for thinning of Late Cretaceous chalk sequences onto the inverted basins. Adjacent to the inverted basins up to 1500 m of Upper Cretaceous Chalk sequence has been laid down, for a significant part coeval with basin inversion. Schematic palinspastic reconstructions shown in some papers advocating the higher estimates for inversion, suggest that a similar thickness of chalk was originally deposited above the inverted basin (Oele et al., 1981; Van Wijhe, 1987a; Dronkers & Mrozek, 1991). However, as a result of the Late Cretaceous Sub-Hercynian inversion phase, the upper section of the Upper Cretaceous chalk thins depositionally towards the inversion axis. In the inverted basins only up to a few hundreds of metres of Upper Cretaceous chalk has been deposited and locally probably less. The result of the difference in rate of subsidence within and outside the inverted basins during the Late Cretaceous, and in some basins also during the Early Tertiary, means that if palinspastic reconstructions down to a pre-inversion horizon are used, the amount of uplift and erosion can easily be overestimated. For example, a palinspastic reconstruction of a section in the Broad Fourteens Basin by Hooper et al. (1995) shows that the top of the Holland Formation (mid Cretaceous) within the basin is circa 1600 m shallower than adjacent to the basin. This does not imply that there has been 1600 m of uplift. At least 500 m of this total difference, and probably more, was the result of the differential rate of subsidence during the Late Cretaceous. This may be more clearly demonstrated by examining the seismic sections across the Dutch Central Graben (Figs 4 & 5), where the base of the Tertiary North Sea Group is several hundreds meters shallower within the graben than outside it. However, this is not the result of uplift. Seismic data clearly shows it to be the result of a higher rate of subsidence outside the inverted graben, and not of its continued uplift and erosion. Inversion was outpaced by regional subsidence.

Summary and conclusions

Differences in the structural expression of inversion of the Dutch Late Kimmerian rift basins can be related to a large extend to the presence and thickness of the Permian Zechstein salt, which acted as an important zone of detachment during structural deformation. Different inversion pulses affected most basins more or less at the same time. Reverse faults and in some cases impressive thrusts developed as a result of crustal shortening.

During the inversion, pre-existing NW-SE trending faults were reactivated obliquely, and in several cases a dextral sense of lateral movement can be established. This is consistent with a general N-S direction of maximum Alpine compression related to the collision of Africa and Europe. Noteworthy is that the later Tertiary inversion phases affected less basins. While in the West Netherlands Basin early inversion pulses resulted in reverse reactivation of pre-existing faults, during the Tertiary Pyrenean phase only broad basin uplift occurred without significant fault reactivation. It appears that early inversion had resulted in a thickening and stabilisation of the crust such that individual faults became effectively locked. Further crustal shortening could only be accommodated by broad basin uplift.

The amount of inversion established through palinspastic reconstructions to a pre-inversion horizon, is generally higher than when established through reconstruction of the burial history, constrained by vitrinite reflectance, fission track and fluid inclusion data, and analysis of sonic shale velocities. The first method results in estimates for the Dutch basins of up to 3.5 km of inversion, the second in estimates of up 2 km. The difference is due to the fact that at some times inversion-related uplift was less than ongoing regional subsidence, resulting in thinning of syn-inversion deposits above the inverted basins, but not in uplift and erosion.

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