Rifting systems and its significance for hydrocarbon exploration in the Netherlands

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Abstract

Rifting has shaped the Dutch subsurface in a significant way. A brief summary of general knowledge regarding this topic is given as a background to the symposium on rifting systems and its significance for hydrocarbon exploration in the Netherlands. This symposium coincides with increased interest in hydrocarbon exploration in the Netherlands. New data becoming available is creating new insights into mature exploration areas. The improved subsurface imaging of geological structures, with better 3D acquisition and computer aided imaging tools, makes it increasingly clear that trapping and accumulation of hydrocarbons in the Netherlands can be much more complex than earlier realized. The North Sea rifting phenomena are connected in a complicated way to the Upper Rhine Graben via the Netherlands. Also the non-geologist in the country is periodically reminded of the rifting process because of minor earthquakes.

Basins related to rifting play a significant role in the spectrum of basin types. Rifting is widely recognized as an important factor shaping our oil and gas fields. It has been the subject of numerous papers describing rift phenomena in the country and the wider Southern North Sea area. The importance of structuration caused by the rifting process for oil and gas exploration is well documented for selected cases, but the subject is somewhat neglected compared to the numerous papers available in the Northern North Sea area of the UK and Norway.

In the following a short anthology of topics associated with rifting and related structuration is given and its relevance for exploration in the Netherlands is briefly reviewed.

1.0 Introduction

The North Sea is generally seen as an example of a rifted basin. The Netherlands is an integral part of this basin and forms the complex transition of the North Sea rift system to the Cenozoic Rhine Graben system, part of the European Cenozoic rift system (Sissingh, 2006a). Rifting was already described decennia before continental drift was accepted but the new global tectonics theory including major plate movements after 1967 gave rifting a different meaning. Present day examples of active rifts are the East African Rift and the mainly German Cenozoic Rhine Graben rift. The Dutch Roer Valley Graben, the active present day rift basin of the Netherlands, is the northern extension of the latter. The first description of these areas goes back to the first part of the twentieth century but the full knowledge of all rifting processes and associated structuration is still developing and subject of this workshop.

Dr. P.A. Ziegler became very well known promoting the rift concept in the Netherlands but he is modest about his important role and in a mail to the conveners of this conference he writes: "*….rifting was invented much before my active time. Just think of Hans Cloos (1936) as an early rifter! My personal work was much later and centered on understanding the evolution of the Arctic-North Atlantic and Tethys rift systems and also the evolution of the European Cenozoic rift system. That the Permian Oslo, the Mesozoic North Sea and the Cenozoic Rhine-Rhône rift systems have nothing to do with each other should by now be clear to anybody who had freed himself from Stille's misbegotten Mittelmeer-Miöse rift concept and read my publications.* "

2.0 Rifting definition

Rifting is a fundamental geological process and many descriptions can be found. A widely used handbook like Kearey & Vine (1990) has proposed the following definition:

Rifts are defined as elongate depressions where the entire thickness of the lithosphere has deformed under the influence of tensional forces.

When this description is compared to current internet definitions one can see an increasing emphasis on continental plate processes.

Wikipedia:
In geology, a **rift** is a place where the Earth's crust and lithosphere are being pulled apart. Typical features are a central linear down dropped fault segment, called a graben, with parallel normal faulting and rift-flank uplifts on either side forming a rift valley. The axis of the rift area commonly contains volcanic rocks and active volcanism is a part of many but not all active rift systems. Rifts are distinct from Mid-ocean ridges, where new oceanic crust and lithosphere is created by seafloor spreading. In rifts, no crust or lithosphere is produced. If rifting continues, eventually a mid-ocean ridge may form, marking a divergent boundary between two tectonic plates.

Indopedia:
In geology, a **rift** is a place where the Earth's lithosphere is expanding. Typical features are a central linear down dropped fault segment, called a graben, with parallel normal faulting on either side. The central portion of the rift area commonly contains volcanic rocks and active volcanism is a part of active rift systems. Rifts are located at **divergent boundaries** between two tectonic plates. Between oceanic plates the rifts occur as oceanic ridges and where these oceanic ridges intersect continental crust rift valleys result as the continent begins to split.

Rifting is presently not only restricted to the depression as suggested by Ziegler (2001) when describing the process as a combination of far-field plate boundary stresses and frictional forces exerted on the base of the lithosphere by the convecting upper mantle. This implies the rifting process involves a wider (plate) area and the process is important beyond the extensional phase. Such an approach has been used recently for the area south of the Netherlands (Sissingh, 2006a, 2006b) giving better explanation between the relation of changes in Atlantic and Mediterranean plate movements and rifting, uplift and subsidence of various terranes in NW Europe.

2.1 Some general characteristics of rifting

Keary & Vine (1990) give a listing of a number of characteristics of rifting that give clear insight:

- The term rift applies to major lithospheric features and does not encompass small scale structures.
- Geological studies demonstrate that the bounding faults of rift valleys are of normal type. Rifts consequently develop in response to tensional stresses but there are theories noting compression plays a role.
- The location of rifts is often controlled by crustal weakness
- The lithosphere underlying rifts is generally abnormally thin and invaded by low velocity, low density and high temperature material
- Horizontal displacement is relatively small [8-10 km for the Rhine Graben]
- Rifts are spatially associated with **domal uplifts**.
- Rifts may form an interlinked network dividing a continental plate
- Rifts often contain extensive **volcanic rocks**. Where present these rocks are mildly to strongly alkaline and the alkalinity decrease with time and increases with distance to the rift axis.

2.2 Classification of rifting

It is customary to classify rifts. *One of the questions we would like to pose at this workshop is whether we are in an active or paleo rift area.*

- Rifting associated with “Break Up” is **active rifting**
  - Precursor of a new ocean
    - Splitting creates a number of not utilized rifts (Aulacogens).
- Continental collision creates compression and areas distant from the suture can develop a tensional regime (Rhine Graben).
- Distinction is sometimes made between rifts generated by continental rupture (mantle activated rifts) vs. rifts generated during collision (lithosphere activated rifts or ‘passive’).
- Mantle activated rifts are characterized by large volumes of extrusive rocks.

2.3 Structure of continental rifts

Continental rifts are bounded by normal faults. Rifts develop in response to tensional stresses.

Mega structures related to rifts are:

- Transcurrent faults
- Strike slip faults
- Pull apart basins
- Triple junctions
- Aulacogens [Central Graben is an example (Kearey & Vine, 1990)]

2.3.1 Crust and rifting

Deep seismic refraction indicates that crust underneath rifts is significantly thinner than beneath adjacent areas. This has also been noted in the Netherlands. Deep seismic shows a thinner crust in the Roer Valley Graben area (Rijkers & Duin, 1994).
Typical thickness of the continental crust is on average 35 km (Kearey & Vine, 1990), less than 20 km in active (rifting) areas and up to 80 km beneath young fold belts. Observations in the Netherlands confirm this with a thickness of about 38 km underneath the massifs (London Brabant Massif). In the rifted areas the thickness is less. Over a limited area underneath the Roer Valley Graben the depth of the Moho is 28 km. The location of the earthquake of 1992 observed at a depth of about 18 km is in line with the observation of the deep seismic (Duin et al., 1994) and is traced back to one of the boundary faults.

It is interesting to note that a large part of the northern offshore also has a thinner crust (Duin et al., 1994; Abramovitz & Thybo, 2000). Danish deep seismic lines (MONA LISA -1,-2) suggest a subdivision in the Avalonian basement rock into a northern area with thinner crust and a southern area (in the Netherlands a line parallel to the Frisian islands), that displays a thicker crust with a good developed middle crustal part (Abramovitz et al., 1999). The northern thinner crust is possibly oceanic crust (including meta-sedimentary cover), with a relatively low (5.8-5.9 km/s) basement velocity compared to the southern area with blocks that share cratonic properties. The lithosphere in the northern offshore is therefore possibly weaker and more prone to rifting vs. the southern part of the Netherlands. The southern area including paleo highs like Texel IJsselmeer High and the Zandvoort-Maasbommel-Kreveld High, consist of an amalgation of different terranes during the Caledonian orogeny (Abramovitz et al., 1999). It seems such suspected Caledonian blocks have a higher lithospheric strength (*In this workshop Beekman will discuss strength and cooling*).

Gravity surveys (Visser et al., 1987) have shown present day uplifted regions are in isostatic equilibrium; however negative Bouguer anomalies are locally present over the rifted Roer Valley Graben structure. This presently active graben, is characterized by a narrow 30 km wide and over 100 km wide anomaly. Over other parts of the Dutch onshore an anomaly is also noticeable over the Lauwerszee Trough.

3.0 Rifting in the Netherlands

As a good introduction to the structural history of the Netherlands, reference is made to Heybroek (1974) and van Wijhe (1987). Recently an update was published by De Jager (2007). Regional structure maps of the Netherlands can be found in Duin et al. (2006).

3.1 Hydrocarbon discoveries in rift areas of the Netherlands

Geological description of graben tectonics in the Netherlands started in the Roer Valley Graben area and was used for the coal exploration and exploitation in the first part of the twentieth century in the southern part of the country. For example reverse movements were already noted by W.C. Klein in 1910 in South Limburg (Heybroek, 1967).

The location of this rift valley as well as the description and definition of other tectonic elements in time can be found in Adrichem Boogaert & Kouwe (1997). The predecessor of this graben to the west, in what is called the West Netherlands Basin, yielded several oil and gas discoveries starting in 1938 (the first oil) or 1944 (the first field). See for the oil and gas fields of the West Netherlands Basin Bodenhausen & Ott (1981), De Jager et al. 1996 and Alvaro Racero-Baena & Drake (1996). Exploration in the onshore part of the basin was at its peak in the 1950 s and 1960s, but continues till today. The first oil offshore was discovered by Tenneco in 1970 in F18 in the Dutch Central Graben. A flow of 325 m3 of light/medium (31 API°) oil was measured during flow tests from Jurassic sandstones at a depth of 2,500 m but was not commercial. Later a number of significant commercial oil and gas finds were made in the Dutch Central Graben. The major discovery F3-FB Jurassic condensate/oil discovery in 1974 was one of the highlights. The southern rift basins yielded several oil fields: Kotter (De Jong & Laker, 1992), Logger (Goh, 1996), Helm (Hastings et al., 1991), Helder/Hoorn (Roelofsen & de Boer, 1991) and the Rijn (Alberts et al., 2003) oil field in P15.

Rifting processes not only affected the basin areas only but are of importance to a much larger area including the Lower Saxony Basin, the Lauwerszee Trough. Of particular interest are the Broad Fourteens Basin and the adjacent area because many of the Dutch offshore Rotliegend gas fields can be found at its northern edge (*This area is discussed in three presentations this workshop*).

3.2 Geological history and rifting in the Netherlands

Rifts play a significant role in the development of sedimentary basins in the Netherlands. Several rift cycles have been described in the country in a number of different megatectonic settings. The duration of the rifting is highly variable.

3.2.1 The earliest rifting

The geological history of the Netherlands more or less starts with rifting. De Jager, (2007) states that in the late Ordovician the Avalonia micro plate rifted away from Gondwana and joined Baltica in the late Ordovician with the closure of the Tornquist Ocean. The resulting collage with blocks like the London Brabant Massif and the Texel IJsselmeer High influence the development of rifting. The rupturing due to the Jurassic rifting seems to halt against these Caledonian blocks (*Deep seated faults possibly originating in this period are discussed by Lichtenberg this workshop*).

The next period where rifting may be a structural factor of importance is during the Devonian into the Mississippian. Fraser and Gawthorpe (1990) suggest (back arc) rifting initiated a series of half grabens. The Campine Basin in the Southern Netherlands is one of these half grabens. Also Ziegler (1982) already noted before the late Carboniferous (Variscan) compressional events started, Dinantian half grabens can be explained by Carboniferous rifting (Arctic – north Atlantic rift system). Kockel (2002) suggests a similar explanation and adds that part of this rifting has been obscured by the later Variscan events.

After the Variscan events there is little evidence for rifting in the Netherlands contrary to reports from Germany (Ziegler, 1990; Gast, 1988). Kockel (2002) also notes that for block faulting, older than Upper Rotliegend, no clear major faults or grabens can be outlined. In the Upper Rotliegend, the Schneverdingen sands are deposited in block faulted grabens. In the Netherlands thickness differences of deposits of Rotliegend and Zechstein age do not indicate rifting grabens. The nature of the depocenters of the Permian basin (Geluk, 2005), so clearly expressed in their facies patterns, is explained as a result of the decay of the thermal anomaly introduced during the Permo-Carboniferous (Van Wees et al., 2000).

3.2.2 The breaking up of Pangea

In the Mesozoic a number of rifting events can be distinguished related to the break up of Pangea. The opening of the Atlantic continues in the Tertiary. Because of the Alpine collision, partly due to the opening of the Southern Atlantic, a number of compressional events change the stress field over large areas and periods with significant inversion are more dominant than periods with extension (Ziegler, 1982; Ziegler, 1990).

3.2.2.1 Triassic rifting

The late Triassic rifting is also known as Early Kimmerian tectonic phase (see Van Adrichem Boogaert & Kouwe, 1997; De Jager, 2007)

Outside the Netherlands in Britain, Late Permian or Early Triassic rifting have been proposed. In the Netherlands significant tectonic movements during the Triassic are concluded from three unconformities. The Hardegsen unconformity (also called Solling unconformity) is found over large parts of the Netherlands separating the Upper and the Lower Germanic Trias groups. In the upper Germanic Trias group one can find the early Kimmerian unconformities in the Keuper. These unconformities are associated with rifting.

In this workshop examples of the evolution of an hydrocarbon habitat system in Early Triassic sediments of the Vlieland Basin is given by Van Oijk.

In the North Sea four rift grabens can be observed located in the Netherlands, Germany and Denmark. They are called the Dutch Central Graben, Horn Graben and the Glückstad Graben. The thickness of Upper Triassic and Lower Jurassic section can exceed 1500m. There is an increased thickness of the same section in the Broad Fourteens basin. This may be related to the overall stress regime of the area but is not interpreted as rifting.

3.2.2.2 Mid and late Kimmerian tectonic phase

The major tectonic elements of the Netherlands form in the Mid and late Kimmerian tectonic phase in the second half of the Jurassic.

Early in the Middle Jurassic (Aalenian-Bathonian) a large area in the middle of the North Sea, the Central North Sea Dome, was uplifted by the mid Kimmerian tectonic movements (Ziegler, 1990, Underhill & Partington, 1993). Regional uplift and erosion over most of the Netherlands occurred during the Late Jurassic lasting in some areas till the Early Cretaceous. The doming is generally associated with a new phase in the Mesozoic break-up of the Pangea supercontinent between Greenland and Scandinavia. After the doming the well-known trilete rift system

developed in the northern North Sea, over 200 km north of the Dutch offshore. The southern branch called the Central Graben, is via Tail End and Feda half-grabens connected to the Dutch part of the North Sea via the German and Danish offshore (see: Wride, 1995).
The rough outlines of this Central North Sea rift dome are described by the erosional edge of the Early Jurassic series (Underhill & Partington, 1993). Similar large radius arches are associated with currently active volcanic rifts as the more recent Rhine Graben rift system. The Central Graben transects the crest of this dome. At the triple junction of the Central Graben, the Viking Graben and the Moray Firth fault, a large volcanic center was initiated. The presence of Permian salt complicates the structural interpretation. The Dutch Central Graben was probably the southernmost extension of a major N-S oriented depocenter, which extended from the Viking Graben into the Central North Sea Graben. Contrary to some of the other Jurassic graben structures, the Dutch Central Graben is a reactivated Triassic rift structure (Geluk, 2005). At the end of the Jurassic the rupturing of the Jurassic Dutch Central Graben reached the southern part of the Graben and was active in the Vlieland Basin (Herngreen et al., 1991). The marine incursions started in the Middle to Late Callovian (Clark-Lowes et al., 1987; Wong et al., 2007; -, 1989; Adrichem Boogaert & Kouwe, 1997). The Vlieland basin was flooded during the Portlandian. Rupturing started in the Broad Fourteens, West Netherlands, Central Netherlands and Roer Valley Graben during the Lower Cretaceous (see for general outline and stratigraphy: Adrichem Boogaert & Kouwe,1997).
The structural development of the Dutch Central Graben area has been illustrated in more detail at the workshop.

Towards the end of the Early Cretaceous, crustal separation was in the north Atlantic and rifting began to concentrate on the area between Norway and Greenland (Ziegler, 1990). During the Early Cretaceous the continued rifting in the North Atlantic resulted in the formation of oceanic crust and Africa started to rotate anticlockwise towards the European plate. The South Atlantic started to open.
Consequently, rifting in the Netherlands ceased and inversion started in the Jurassic basins perhaps as early as the Albian (Oudmayer & De Jager, 1993)
It is interesting to note that the Mid and Late Kimmerian rifting did not cut through the old Caledonian and Lower Carboniferous highs and rejuvenated old basin areas like the Campine Basin.

3.2.3 The Alpine collision

The Alpine collision adds a compressional element to the rifting tectonics. Sissingh (2006) describes the repeatedly occurring changes in the plate collision stress regime between Europe, Africa, Iberia and Apulia, as well as the stepwise opening of the North Atlantic and accompanying plate reorganization of the Mid-Atlantic Ridge. Old structural massifs like the Ardennes and the Rhenisch blocks are little affected. The basin areas show periodical deformation uplift and erosion (Sissingh, 2006),

Three major, mainly compressive tectonic phases have been recognized and named in the North Sea rift system (De Jager, 2003; Ziegler, 1987).

These phases have been named:

- Sub Hercynean (Late Cretaceous)
- Laramide (Early Paleocene)
- Pyrenean (Eocene-Oligocene)

3.2.3.1 Subhercynian and Laramide late Cretaceous tectonic phases

In the late Cretaceous, subsidence patterns are completely reorganized. The previous stable highs started to subside rapidly, accumulating thick sequences of Chalk. Eventually even the long-lived London-Brabant Massif and the Mid North Sea and Ringkøbing-Fyn Highs were inundated.

Tectonic inversion affected many of the Late Jurassic-Early Cretaceous rift basins in Late Cretaceous and Early Tertiary time. The sediments in the rift basins are more sensitive to compression and an inverted relief develops whereby graben areas are transformed into relative highs. See for inversion in the Netherlands (De Jager, 2007; De Jager, 2003; Gras & Geluk, 1999; Nalpas et al., 1995; Hooper et al., 1995; Gras, 1995; Baldschuhn et al., 1991; Dronkers & Mrozek, 1991). This change is governed by the progressive opening of the North Atlantic and the onset of the Alpine collision in the south, in the realm of the western Tethys. The opening of the southern Atlantic causing an anticlockwise rotation and northwards movement of Africa changed the European stress pattern from extension to compression at the beginning of the late Cretaceous (Sissingh, 2006).

Locally, inversion, as a result of sub-Hercynean compression tectonics, lead to significant erosion of the rift sequence. This erosion introduces considerable uncertainties in tracing the Late Cretaceous coastline corresponding to the maximum transgression.
Major erosion occurred during the various tectonic pulses. The hiatus in the Late Santonian to Early Campanian is called the sub-Hercynean unconformity. It can be found over several basins in the Netherlands and basins in the surrounding areas in Northwest Europe, like the Sole Pit, the West Netherlands Basin, the Lower Saxony Basin and the Dutch Central Graben Basin. The West Netherlands and the Broad Fourteens Basin display more inversion than the Dutch Central Graben.

The Laramide phase has been placed in the Mid-Paleocene (De Lugt, 2007) and terminated in the Late Paleocene. Further movements during the African-European collision result in compression of the whole European platform (Sissingh, 2006a) and are the formative stress source. The west-directed motion of Apulia characterizes this phase. Laramide compression caused inversion of the Dutch Central Graben, the Broad Fourteens Basin, the West Netherlands Basin and the UK Sole Pit Basin (De Jager, 2003; Ziegler, 1998; van Wijhe 1998). The Laramide phase was probably the most severe inversion (De Jager, 2003). Subsequent subsidence and rise of the area outside the North Sea basin caused a sedimentation pulse. Regional uplift caused massive erosion and peneplenation of complete areas.
Reactivation of faults after cessation of the Laramide phase resulted in the formation of local depocenters for example above the inverted Broad Fourteens Basin. It has been observed that tectonic movement in the Paleocene was without exception accommodated by reactivation of Mesozoic and older faults. A dextral strike slip is suggested from structural geometries (Broad Fourteens Basin: Nalpas et al., 1995; Dutch Central Graben: Schroot, 1991).

3.2.3.2 Pyrenean and Savian tectonic phases

At the end of the Eocene the Pyrenean pulse caused broad uplift of the West and Central Netherlands basins. The Eocene-Early Oligocene Pyrenean orogenic phase resulted in renewed uplift (Ziegler, 1990; Van Wijhe, 1987). Sissingh (2006a) relates the movement to the slow northern directed movement of Apulia inducing Alpine thrusting.
During this phase inversion in the Netherlands occurred and basin boundaries became overstepped and a large area compared to previous inversion pulses was severely uplifted. The aerial exposure of large parts of the basin results in serious erosion. The sediments are transported to the deeper parts of the basin. In the Pyrenean compressional phase strong

variations occurred in accommodation space and erosion. The main stress orientation during the Pyrenean phase was at an oblique angle to the pre-existing structural grain, resulting in reactivation of faults with a strike slip component. This stress regime (Kooi & Cloetingh, 1989) is probably comparable to the earlier inversion phases, but this is often obscured by the Pyrenean events. After the uplift almost comparable to the Laramide uplift, local subsidence was evident by Oligocene deposits indicating differential subsidence.

A late tectonic pulse is called the Savian erosion. It is also believed to be caused by the regional stress regime induced by the Alpine orogeny (De Jager, 2007), but also sea-level changes may have played a role. The erosion terminates the Oligocene sedimentation. The event is clearly visible on seismic as the Mid-Miocene unconformity. This mappable seismic marker is widely recognized in the southern North Sea (Oudmayer & De Jager, 1993). Almost the whole southern North Sea has emerged above sea level. In the late Oligocene Apulia moves slowly north resulting in crustal shortening in the Alpine areas. That continues till the late Miocene when thrusting ended and a re-organization of the North Atlantic sea floor spreading changed the stress regime.

After the Savian phase, regional subsidence resumed and delta sediments filled up the basin. No major tectonic movements can bee seen in the sediment record. Present day activity makes it likely there was continuous movement in areas like the Roer valley Graben. The sediment thickness in these Grabens exceeds 2000m. Based also on observations of Dronkers & Mrozek (1991) and Nalpas et al. (1995) for Late Cretaceous-Early Tertiary movements, Dirkzwager et al. (2000) concludes that older faults in rifted basins have been reactivated numerous times. Basin boundaries have been reactivated in particular and seismicity along these boundaries and illustrate rifting structures form a zone of structural weakness (Dirkzwager et al., 2000). *The reactivated faults can act as a conduit for migrating hydrocarbons (Verweij this workshop). These faults can sometimes also act as regional seals.*

4.0 Fault patterns

To understand the hydrocarbon trapping it is very important to understand the fault patterns. The most widely studied structural horizon in the Netherlands, the Base Zechstein, shows a typical rhomboid pattern of intersecting fault patterns (Oudmayer and De Jager, 1993; De Jager, 2007) with a dominant family of fault trends NW-SE, intersected by NNE-SSW faults. In the northern offshore a more N-S trend is found.

Interesting to note is that no significant difference is found in the rift basin area, compared to the platform areas. Because the faults predate the rifting, it leads to the conclusion that many faults are reactivated and few faults were newly formed with the exception of some pop up structures (De Jager, 2007; Glennie, 1998). Many faults at Rotliegend level were inherited from the Late Carboniferous fault patterns originating from the movements originating from the Variscan orogeny or earlier (*The deap seated faults discussed by Lichtenberg*). Reactivation of faults can explain compartmentalized reservoir behavior during production because sand to sand fault seal (*see Geiss, Lichtenberg and Rijkers, this conference*).

Reactivation of faults makes it more difficult to reconstruct paleo stress from present day fault patterns.

Shallower fault patterns are affected by salt movements because of the presence of Zechstein salts of large parts of the Netherlands. Salt walls have been found at the edges of the rift basins (Remmelts, 1996).

Inversion structures in the broad fourteens basin are more complex, with sorter wavelength, than in the Dutch Central graben, because the inversion was stronger (De Jager, 2003). The area of inversion is characterized by major reverse-faults.

5.0 Sedimentation and erosion in the Netherlands

Sedimentation in the Netherlands has been summarized by Ziegler (1982), Ziegler 1990 and Adrichem Boogaert & Kouwe (1997) and several chapters of Wong et al. (2007). For the sedimentation in the Permian and Triassic see also Geluk (2005). Detailed studies of the Tertiary (De Lugt, 2007) give a clearer explanation of the Tertiary events.

Because of significant erosion during the Jurassic uplift, extrapolation of sediment thickness of Triassic and Lower Jurassic section outside the rift basins is often speculative.
Erosion in inversion periods is also difficult to estimate. A summary of the magnitude of inversion is given by De Jager (2003). In the Broad Fourteens crustal shortening has been estimated at 10-12%, whereas estimates for the Dutch Central Graben only reach 1-2%. Nowhere does the amount of uplift exceed 2 km, contrary to 3.5 km sometimes quoted.

5.1 Source rock and erosion

In order to understand erosion an estimate sediment loading is of importance. Estimates of erosion help the timing and quantification of hydrocarbon generation. Good estimates of uplift and erosion can be critical for the outlining of prospective areas (Alberts & Underhill, 1991). The extend and quantification of erosion estimates are often very uncertain and sometimes controversial (De Jager & Geluk 2007) and is one of the least documented and understood subjects surrounding the rifting process.
For the Westphalian Limburg Formation coals, the most dominant gas generating source rock, the gas generation is closely interlinked with the Dutch rift basins. In the rifting phase gas generation accelerated in the subsiding rift basins and halted during inversion. Present day charge is limited to selected areas less affected by inversion (De Jager & Geluk 2007).

6.0 Magmatism related to rifting in the Netherlands

Rifting is closely linked to magmatism. The intensity of magmatism varies in the various rifting phases in the Netherlands.

- Extensive Permian Rotliegend volcanism in Germany, also to be found in the Netherlands (Van Bergen & Sissingh, 2007; Ziegler, 1992) may be linked to rifting.
- Evidence for Triassic magmatic activity is limited. Interesting are vulcanoclastics in the Central Graben well F3-7. Low level of Triassic volcanism has also been noted outside the Netherlands (Ziegler, 1982).
- More evidence for Jurassic magmatic activity can be found. The most significant feature is the Zuidwal Volcano (Cottençon et al., 1975; Herngreen et al. 1991). The Zuidwal volcanics may represent one or more cycles of trachite-phonolite eruptions (Van Bergen & Sissingh, 2007).

  Other Jurassic magmatic rocks are present at the rim of the Dutch Central Graben (E6-1). These occurrences are considered the southernmost expression of Jurassic magmatism associated with rifting in the Northern North Sea with a centre in the Forties basaltic province.
- From the Cretaceous many magmatic occurrences have been described farther to the south in the West Netherlands Basin, illustrating the igneous activity becoming increasingly younger in southward direction.
- Ash layers in the Tertiary Dongen Formation and volcanic material in Oligocene strata illustrate that volcanic activity in the Tertiary is significant. This is most likely linked to the development of the Rhine rift system (Van Bergen & Sissingh, 2007).

7.0 Heat flow in Graben areas

For the analysis of hydrocarbon generation, heat flow is an influential parameter. In rift areas the heat flow is higher than in the surrounding areas. Based on 65 wells the average temperature gradient in the Netherlands is 31 degree C/km. Based on the subsurface values only, the trend is approximately 29.5 degree C/km (Verweij, 2003). The Roer valley Graben shows a higher gradient. In the Central Graben area from tests and logs a gradient of 31.7 – 35.5 degree C/km has been computed (Crepieux et al., 1996). Temperatures below the gradient are observed in northern blocks like A12, E17, F3, F18, L2, L8, L11, L12). In blocks P3, P5, P12, Q1, Q4 Q10 temperatures have been observed exceeding the trend. *Heat flow is discussed this workshop by Van Wees.*

8.0 Summary of the workshop

Structuration related to the rifting process affects large areas of the Dutch subsurface. The underlying rift processes are important to understand structural style of hydrocarbon traps and the generation of hydrocarbons in the Netherlands.

This summary shows that despite the vast increase of structural knowledge, because of increased coverage of the on and offshore area by commercial seismic, the number of papers that discuss the Dutch rifted basis and its related structural processes is limited. This overview shows that besides structural interpretation more work can be done on estimates of erosion and this literature survey outlines a few areas of special interest, like the interpretation of deep seismic lines in the Netherlands.

We hope that this workshop will initiate more integrated studies of the rifting processes in the Netherlands.

9.0 Acknowlegments

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