Reservoir quality distribution as tool for better exploration prospect evaluation and estimation of the resource base in the Netherlands

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Remaining exploration potential in the Netherlands has been stable over the last decennium but there are a number of gas prospects that are less attractive because of poor reservoir quality and they obscure the future potential of the Dutch resource base. New insights how to develop such accumulations, and also the aging infrastructure in the Netherlands, make it important to consider the development of such gas reservoirs. Therefore, a quantification of their volumes is important. At this moment no clear estimate is available on how many of these prospects or even the existing stranded fields have a risk for impaired reservoir. There is limited published data on low permeability reservoir fields. In order to estimate existing and exploration potential in tight reservoirs of the Netherlands, a number of areas with a high risk for reservoir impairment have been defined. These areas are used in combination with TNO's prospect data base and stranded field list. An estimate is proposed of remaining tight reservoir gas potential in the most important gas bearing formations of the Netherlands: the Permian Rotliegend Slochteren and the Triassic Buntsandstein. A review of the diagenetic history of these formations is given in order to understand the selection of the five or six risk areas.

INTRODUCTION

Of the more than 250 gas fields found in the Netherlands, only a limited number can be classified as tight reservoir. Despite the significant depth of many Dutch gas reservoirs, serious reservoir quality problems are limited. There are a number of areas that have fields with poor reservoir quality. Poor reservoirs can be defined with an Initial Well Productivity (IWP = 1.4 * Q_{50}) lower than 400,000 m^3/d (up to 600,000 m^3/d is moderate, higher is good and over 1,200,000 m^3/d is called excellent [This workshop]). About twenty fields are known to initially display (very) low flow rates and have flow rates much lower than a IWP of 400,000 m^3/d, they are often sometimes informally called tight. Tight gas accumulations in the Netherlands that comply with the definition [this workshop] with a permeability lower than 0.1 Milledarcies (mD), are rare in the country [P6 Rotliegend this workshop]. Low flow rates with a Q_{50} lower than 100,000 m^3/d have been observed in Dutch fields with permeabilities of 5 mD or lower and can not produce by conventional means. The term "Tight gas reservoir" is only used twice in a title of a Dutch petroleum geology paper (Crouch et al. 1996, on the Ameland field; Peters et al. 2003, on Zechstein carbonates) and certainly is not restricted to fields with 0.1 mD. For example Crouch et al. refer in Ameland to reservoirs with a Q_{50} of about 50,000 m^3/d. The "tight" reservoir in the Netherlands [see definition this workshop] "that can not be produced with conventional means" starts therefore realistically somewhere below a Q_{50} of 100,000 m^3/d. The total amount of gas in producing and stranded fields with poor or tight production behavior is not

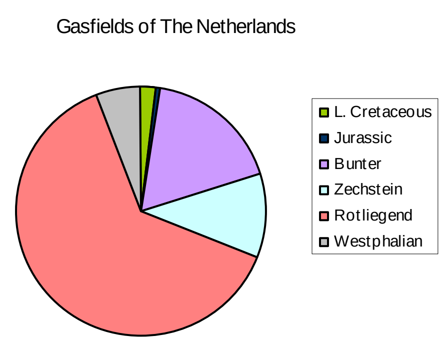

Fig. 1 Gas fields of the Netherlands by number, see for a volumetric comparison on time axis: Breunese et al..

exactly administered. The quantification of the gas futures, categorized by flow properties, is part of an ongoing study of TNO. The numbers in this paper represent a preliminary estimate, made for this workshop based on sorting the TNO/AGE stranded field database, by area. About 75 % of the discovered gas fields have been found in the Permian Rotliegend and the Triassic Buntsandstein (fig.1) and it is assumed that most tight gas exploration potential will be present in those two units. Remaining exploration potential in proven play concepts of the Netherlands has been analyzed (Breunese et al., 2005). The exploration potential has remained fairly constant over the last 10 years, yet it is not clear, what percentage of these prospects, has a risk for poor reservoir quality. In the current study the prospects of the TNO confidential database have been grouped in areas in order to come to an estimate of how much of this potential can be expected in tight gas reservoirs.
Reservoir quality can not be extrapolated on maps without an understanding of the diagenetic evolution of the reservoir. A brief review of the literature has been given in the next paragraphs, with the emphasis on the diagenetic history.

Tight gas reservoirs may not have been a central issue in the Dutch gas exploration and production, it was never far away. The first offshore exploration well in the Netherlands K17-1 hit 275 m tight gas-bearing Rotliegend reservoir (Oele et al. 1981), with a porosity of 7% and a permeability of less than 0.1 mD. The close by field K17-FA will now start production in 2006. The delayed start of K17-FA illustrates the tight gas reservoir problem in the Netherlands. Development of fields with very low production rates has often been put on the backburner or considered not feasible. Because of the aging infrastructure timely development of poorly producing fields becomes increasingly critical.

LOW PERMEABILITY GAS FIELDS

The most important gas producing formations, the Rotliegend and the Buntsandstein (fig.1) share a comparable arid depositional setting and there are also some general factors that impair the permeability of both formations: facies, early diagenesis and mechanical and chemical changes caused by increased burial. Deep burial is quite common, but poses not necessarily the most important problem for the reservoir quality down to about 3000 – 4000 m. The most serious reservoir damage is found in the inverted basins like the Broad Fourteen’s Basin. The damage is caused by the depth in combination with occasional fluid flow from the Zechstein. It is in this area that most low permeability fields are found.

The Rotliegend Slochteren Formation is the most important gas bearing formation in the Netherlands. Most literature with respect to reservoir quality is related to this Permian age reservoir. Below a short summary is given of the findings in a selection of these papers. It should be noted that the nature of the diagenetic minerals may be relatively simple, however that the diagenetic histories proposed by the various authors remains controversial (Lanson et al. 1996).

The reservoir quality of the Buntsandstein fields has received less attention compared to the Rotliegend. There are not that many papers on the reservoir quality of the Buntsandstein in the Netherlands and they cover areas that are far apart and the sands are deposited in separate basins. Because the Buntsandstein shares a number of facies with the Rotliegend, they have some general observations on reservoir quality in common. There are marked differences that can be explained by the different geological history and behavior of the under and overlying formations in particular the Zechstein and the Carboniferous.

The Zechstein carbonates rank third as Dutch gas reservoir. Zechstein carbonates can have very low porosity nevertheless these reservoirs have often good fracture permeability. Some Zechstein fields are known to be tight, still they are not reviewed here, because mapping of risk factors in these carbonates requires a more detailed study and the number of prospects are limited. Quantatively less important is gas from sands of the Westphalian and the lower Cretaceous age. There are numerous gas accumulations in the Westphalian sand layers with tight intervals and tight layers. More regional work has to be done before a good assessment of the productivity of Westphalian strata can be made. Often the Westphalian age sands show a very heterogeneous permeability. The combination of very high and very low permeability creates a very special type of production problems, like cusping. Poor drainage area and compartmentalization poses a more serious risk than tight reservoir. A number of stranded fields have poor productivity (volumes amount to about 7×10^9 m^3). The known future Westphalian tight reservoir gas potential is currently not estimated as high, judging from the number of prospects. Future studies can change this.
A number of gas fields are known in the Lower Cretaceous age Vlieland Formation. Generally the Vlieland does not come to mind as a tight formation, however the permeability is not very good (0.9 - 3.5 mD) in the Leeuwarden field (Cottençon et al. 1975). Not enough is published on the Vlieland Formation to give a review of its regional reservoir quality. Also the expected volume of the known prospects in the Vlieland is small.
Gas occurs in a number of other Triassic, Jurassic, Cretaceous and Tertiary age formations known in the country (van der Weerd, 2004). Tight gas reservoir potential of these formations is hard to quantify because there is little or no production information. A formation that may have noticeable tight reservoir potential is the Jurassic Scruff Formation (more than 30×10^9 m^3?). Not much on its reservoir quality is published.

ROTLIEGEND

The Permian Rotliegend Slochteren Formation is the main gas-producing horizon of the Netherlands and many detailed descriptions are available in the literature (see Adrichem and Kouwe, 1997). The producing, often 100 -300 m thick, Rotliegend sandstones in the country, have been deposited on the southern margin of the Southern Permian Basin.
There are a number of factors, which contribute to the reservoir quality of the Rotliegend sandstones. In an analysis of the various factors, Walzebuck (1993) found that the overriding factor was the textural characteristics of the sand determined by facies. This determines also the response of the rock to burial diagenesis.

The Rotliegend sandstones are dominantly fine to medium mature to sub mature sandstones (see de Booy, 1968; Almon, 1981; Gaupp et al, 1993). Notably are the well rounded quartz grains indicating long aeolian transport (Almon, 1981). Besides the aeolian facies, fluvial/wadi facies and sabkha sediments are distinguished.
The composition of the primary sandstones is on average quartz (85%), feldspars (4-6%), rock fragments (4-7%) and matrix (Almon, 1981; Nagtegaal, 1997). Monocrystalline quartz grains is the dominant grain type, about 20% is polycrystalline. The polycrystalline grains generally contain many crystallites per grain and are elongate and parallel, suggesting that they may be derived from metamorphic quartzites (Almon, 1981). Plagioclase is the most dominant feldspar. Several varieties of potash feldspar are present. Larger datasets in Germany show a wider spread (0-15%) of the feldspar (Gaupp, 1993; McCann, 1998) and a higher K-feldspar content. The Upper Slochteren contains more feldspar than the Lower Slochteren (de Booy, 1968). It has been

noted that the original composition may have been different, by breakdown of chemically–unstable components such as calcic plagioclases, amphiboles, pyroxenes and biotite.

Regional mapping of the main facies in the Rotliegend goes back to Lutz et al. (1975). An up to date discussion, of the distribution of the different facies of the Rotliegend sandstone belt, can be found in Verdier (1996). Better sorted aeolian facies suffered least from diagenesis, whereas the immature often fluviatile lithology loses much of their porosity and permeability. Sabkha deposits are characterized by poor reservoir properties.
Based on such facies, distribution maps of the various facies of the Rotliegend sandstones can be made. Facies distribution is not enough, to get a full understanding of the regional permeability. This already is recognized by Marie (1975) who uses facies for reservoir quality distribution, but makes an exception for the inverted basins. There may be two or three additional factors added: depth, insulation of Zechstein fluids and effects of meteoric water.

Depth

Almon (1981) noted that modern desert sand has a porosity of 40% and a permeability of several tens of Darcies. Because of (burial) diagenesis typical diagenesis Rotliegend porosity ranges from 5.5 to 26.9 percent and permeabilities ranges from 0.3 to 2,500 mD.
A number of factors play a role in this reduction of the reservoir quality. The early diagenesis (see for an overview Amthor and Okkerman, 1998) and depth of burial are two important factors. The effect of fluid flow, from the underlying Carboniferous and overlying Zechstein, is not easy to quantify, yet plays an important role.

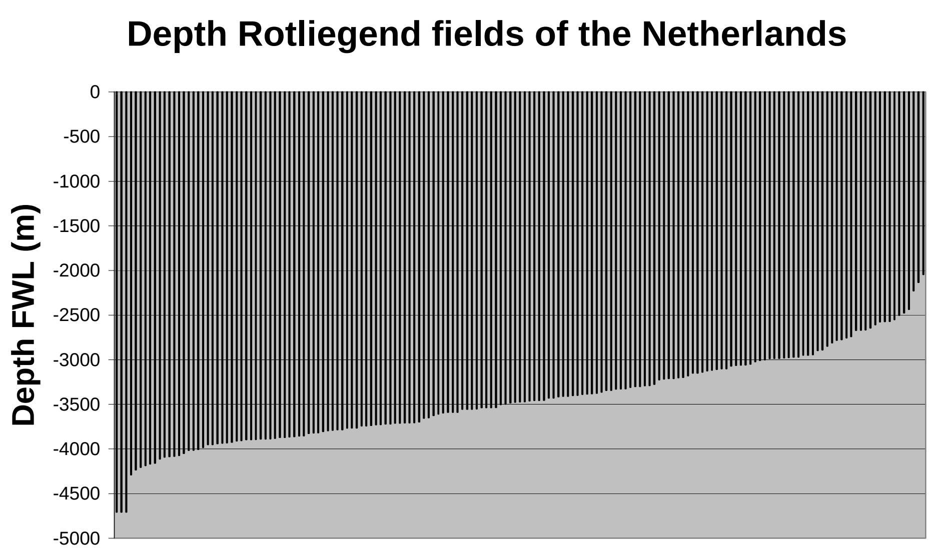

Fig. 2 Depth of FWL Rotliegend gas fields (n = 180) in the Netherlands (m).

In the early diagenetic processes, dolomite, anhydrite and authigenic quarts are precipitated. The mechanism that can explain these minerals and the isotopic composition is shallow groundwater diagenesis (Amthor and Okkerman, 1998) caused by evaporation and CO_2 degassing. These authors noted, in their Ameland field example, abundance of cements in sediments close to ground water tables vs. sediments in dry settings. Areas with high chance of groundwater presence have a higher risk for reservoir impairment. In particular areas were the Upper Slochteren is present, in facies deposited close to the desert lake, a risk for impaired reservoir is present. This is of importance because a significant number of known prospects could be affected.

Burial related diagenesis has received more attention than early diagenetic processes. Many papers have been written on the effect of burial on reservoir quality. Some of that information is summarized below.

The depth of a typical Rotliegend field is considerable with a depth between 2000-4700 m (see fig 2). Ironically the good dune facies will be more affected by compaction than the early cemented sabkha facies (Amthor and Okkerman, 1998).
The Rotliegend sandstones of the Netherlands were gradually buried during Triassic to present. Some parts reached a maximum depth already in the Cretaceous and were uplifted later. A typical reservoir underwent extensive diagenesis not just by the increased pressure but also by the increased temperature. Fluid inclusion studies give a feel for the minimum temperatures in the non inverted areas of 60° to 126° C (McNeil et al. 1998). Various petrographic and diagenetic studies showed that kaolinite and illite are the most frequent occurring authigenic clay minerals in Rotliegend sandstones under normal burial (Seemann, 1979; Rossel, 1982).

With increased depth of burial, compaction causes reduced porosity. Pressure solution and growth of authigenic minerals is another important factor plugging pore space. The influence of pressure solution is the strongest for the finest grain sizes (Nagtegaal, 1997).
Authigenic kaolinite, in the form of the well known clumps of booklets of pseudo-hexagonal flakes, is well known in Rotliegend sandstones, not buried deeper than 2500-3000m. The main source of the authigenic kaolinite lies in the decomposition of feldspar. Feldspar dissolution may also enhance porosity (Gaupp, 1993). At higher temperature the kaolinite evolves into dickite that displays more blocky crystals (Lanson et al., 1996). Authigenic quartz cementation, typical for intermediate burial, is a major factor in reducing reservoir quality. It can prevent kaolinization of feldspar grains. Illite pore linings are relatively rare in the quartz-cemented area (Almon, 1981). An important factor, that favors the crystallization of kaolinite, is acid fluid flow coming from the underlying Carboniferous coal measures (Lanson et al., 1996).

Of importance for the reservoir quality is the forming of illite. Two forms of illite can be found; the pore lining illite and the pore filling, bridging fibrous type (Seemann, 1979)
In particular the growth of fibrous illite is of importance because its negative impact on permeability. The larger surface and the finer network of bridging clay creates lower permeability. Illitization of kaolinite is favored by the increased temperatures and fluid flow from the Zechstein (Almon, 1979, Lanson and al. 1996). The Zechstein can provide the potassium/sodium required for the illite growth.
Increased temperature also induces the growth of chlorite. There is also evidence for late forming of dolomite and anhydrite (Marie, 1975). The late formed sulfates are likely sourced from the Zechstein.
Chemical conditions during diagenesis are directly linked to the geological history of the basin.

It is interesting that illite growth has been linked to high Ph values that can be explained by waters expelled from the compacting Zechstein related to the moment that faulting creates a contact between the Rotliegend and the Zechstein (Lanson and al. 1996). This illustrates their point that illite percentages are not directly related to depth, but varies from well to well. Lee (1989) dated based on K/Ar ages the forming of the illite and concluded that the illite formed in a relative short period and that its forming is related to major phases of tectonic activity, the Jurassic Kimmerian and Late Cretaceous- early Tertiary Laramide inversion movement. Lee's findings were confirmed in the Southern North Sea in the UK (Robinson et al, 1993) suggesting illite growth during a relative short period in the Jurassic related to a regional pore water movement. It is therefore questionable if present day illite growth takes place in deeply buried reservoirs that are still within range of many rigs (6-7 km).

It is clear that the very acid water of the underlying coal layers are very important for the diagenetic characteristics of the Rotliegend and probably explain part of the difference with the Buntsandstein diagenesis.

Feldspar dissolution, the growth of kaolinite and illite are consistent with low pH. Barite precipitation is occasional mentioned and may be sourced from the Carboniferous.

Gaupp (1993) summarizes the main fluid types for the Rotliegend:

a) Meteoric Rotliegend water
b) Alkaline fluids from Rotliegend shales
c) Acidic fluids form the Carboniferous
d) Brines from the Zechstein evaporites.

It is not easy to translate these fluid flows into maps.
There may be an exception for the Texel IJsselmeer High area. To the previous listing of fluids, meteoric water of periods after the Triassic can be added. In the Netherlands in most areas fluid flow from shallower formations is difficult or almost impossible because of the sealing Zechstein evaporites. In areas like the Texel IJsselmeer High this Zechstein cover has been eroded. Meteoric water during the Jurassic or Cretaceous, could have reached the Rotliegend.

Paleoburial can be used as a mapable risk factor. From the information above it is clear that reservoir impairment is more complicated than just temperature. Illite growth is also related to fluid flow from the Zechstein. Unfortunately such a flow is not easy to quantify. A simple risk outline with the inverted areas is at least reproducible and is used to outline prospects. Such maps are similar to the approach already used by Lutz et al. (1975) and Marie (1975).

Weissliegend

One factor that effects the Rotliegend can easily be related to a map. This is related to the poor reservoir called Weissliegend. The top 20-50 m part of the Rotliegend displays very poor reservoir quality in the Southern North Sea area (P and Q blocks, Bergen concession, lower K and L blocks like K17, extending in the UK). At many locations a sequence of uncolored (Weissliegend) structureless sands alternate with the original beds. Different causes for the Weissliegend alteration have been proposed. The most common explanation is reworking of the Rotliegend sands during the subsequent Zechstein transgression (Nagtegaal, 1979). The variable Weissliegend thickness is explained by the Rotliegend (dune) topography. Reworking had also a negative effect on the grain packing affecting permeability.

An other explanation for the Weissliegend suggests a relationship between the Rotliegend diagenesis and the overlying Zechstein. This has been suggested by Almon (1979). He suggests differences between areas overlain by thick evaporites compared to areas overlain by carbonates. It is generally observed that the reservoir quality of the Rotliegend sands is destroyed by anhydrite or dolomite cement in the areas where the Kupfershiefer directly overlies the Rotliegend sands and no clay (Ten Boer) is present between the Zechstein and the Rotliegend sands that can act as a seal for the various fluids from the Zechstein.
A map can be constructed that shows the Ten Boer absence as a risk factor. Geographically this risk area shows an overlap with the Broad Fourteen's basin. The Weissliegend area is larger (it includes areas like the Bergen Concession).

Permeability Rotliegend

The reservoir quality in the Rotliegend reservoirs is still good considering the average depth of burial. Rotliegend gas fields with porosities over 9-12 % combined with permeabilities of over 5 mD have generally initial well productivity of more than 300.000 m^3/d and are considered of moderate or better quality.

The kaolinite has a more profound effect on porosity than on permeability. Illite affects permeability more than porosity. The bridging illite, and in particular the fibrous, hairy type, reduces strongly the permeability (Stalder, 1973; Seemann, 1979).
Areas with serious porosity and permeability destruction in good primary reservoirs by diagenetic processes are confined to a few areas like the basins with a history of increased temperature (up to 165° C (Lanson et al. 1996) because of more than 4000 - 6000 m burial and exposure to relative short events related to tectonic activity.

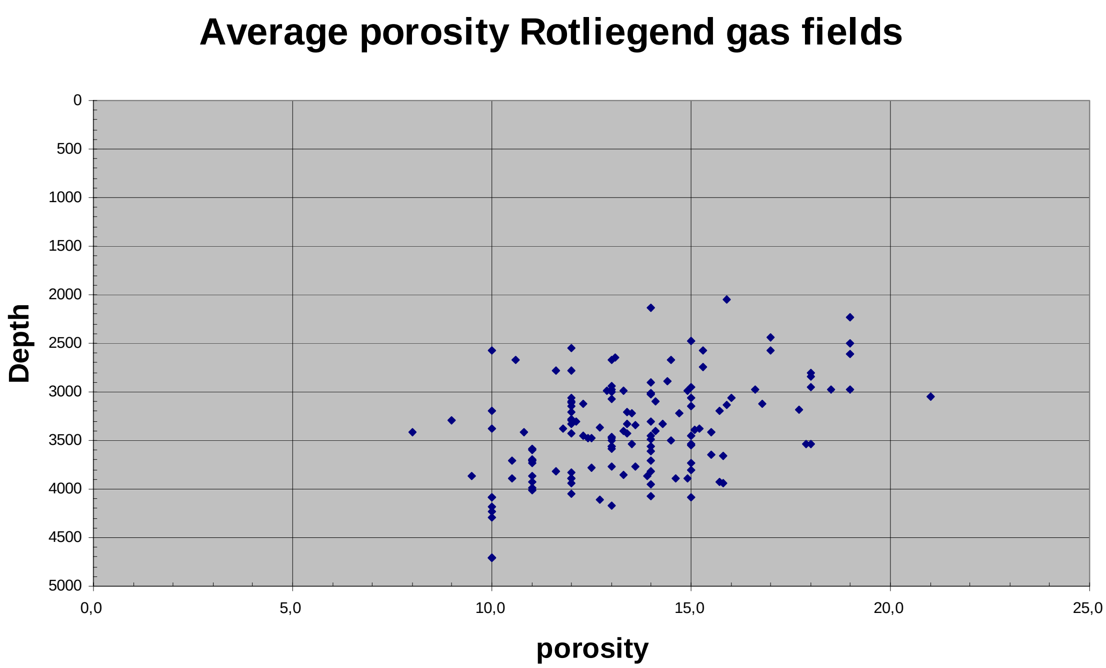

Fig. 3 Average porosity of Rotliegend gas fields (n = 180) in the Netherlands vs. depth (m.)

Figure 3 shows the spread of the porosity over depth of most Rotliegend fields in the Netherlands. It is clear that no simple relation with depth exists. This is the reason why only selected areas like the Broad Fourteens Basin have been used to flag increased reservoir risk and not all deep areas. Beside the basins, there are a few more areas, where impairment trends can be mapped. This will be described in the next paragraphs.

For a number of fields good reservoir performance of low permeability Rotliegend sands were explained by open fractures (Frikken and Stark, 1993; Gauthier et al., 2000). Based on the current knowledge this is difficult to map.

Areas with serious Rotliegend diagenetic problems

Based on the information discussed above a number of areas have been assigned. Poorly producing fields in these areas can be used to calibrate such areas.

Impaired areas based on Facies

The first map area is called fringe area and is based on facies. In the Rotliegend, the better sorted dune facies, are more promising than wadi facies. Wadi facies pose higher risk for diagenetic minerals, ergo lower permeability. There is an increased risk for compartmentalization (Frikken and Stark, 1993). In this exercise tight gas risk is defined by mapping wadi facies only.

Areas with dominant sabkha facies present have a higher risk for impaired reservoir. Poor porosity and permeability can be expected and has been mapped for the Upper Slochteren. A number of stranded fields and prospects with risk for low permeability reservoirs can be found in this area. From the known prospects it is estimated that more than 15 x 10^9 m^3 gas is present in such prospects. A number of prospects may have good permeability. A conservative estimate for the expected tight gas volume in this area would be 10 x 10^9 m^3.

Inverted basins

The second outline is related to deep burial. Because the relation of porosity and permeability with depth is not very clear, it is more meaningful to outline the areas with serious inversion like the Broad Fourteen's Basin in order to show the increased risk for reservoir impairment. There are a number of fields that can be used to calibrate the permeability reduction like K17-FA and Halfweg [This workshop]. It has to be noted that in many fields in this area part of the reservoir impairment is also related to the Weissliegend. The Weissliegend risk can be indicated on an additional map. This has not been done in this exercise. Small Rotliegend prospects have been eliminated in the Weissliegend area.

About 20 x 10^9 m^3 expected gas volume is known from prospects in the Broad Fourteen's Basin. This estimate could be higher because reservoir impairment is generally known and many prospects will never be matured.

Eroded Zechstein

A number of Rotliegend fields, like one finds in the wider area of block L13 (Frikken, 1996), have a strongly reduced permeability in areas outside fringe area or the inverted basin. This area does clearly not fit in the previous groups. It happens to be an area close to the Texel-IJsselmeer High, an area with no salt cover in the Zechstein and impairment by meteoric water from shallower horizons is possible. Meteoric water could reach the Rotliegend during the Triassic or Jurassic age, creating reservoir damage in the Rotliegend. Another explanation for the reservoir impairment is hydrothermal flow from the Jurassic Zuidwal volcano (Adrichem and Kouwe, 1997) close by.

The expected volumes of prospects from this area are estimated to be about 8 x 10^9 m^3, yet this number could be larger when this phenomenon is better understood. Several stranded fields can be found in this area (15 x 10^9 m^3).

BUNTSANDSTEIN

The Lower Triassic Buntsandstein is the second major gas producing horizon of the Netherlands. Contrary to the Rotliegend, the Buntsandstein is present, in a number of distinct basins (Adrichem and Kouwe, 1997). Compared to the Rotliegend, only a few papers are available on reservoir quality of the Buntsandstein. However it is recognized, as an important exploration risk (Purvis and Okkerman, 1996).
The Triassic sandstones are deposited, in a similar setting compared to the Rotliegend. Fluvial facies are more dominantly present, also aeolian facies are common.

A number of distinct units (Volpriehausen, Dethfurth, Hardegsen and Solling) can be distinguished each with its own paleogeography. The sandstone is also dominantly fine to medium grained, however often coarser grained sandstones and even conglomerates are described. The composition is dominantly quartz (53%, mainly monocrystalline), rock fragments (12%, often mud and schistose clasts), K- feldspar (5,6%) and plagioclase (1.7%). Much higher percentages of 9-26% feldspar have also been reported (Muchez, 1992).
The Aeolian facies are dominantly composed of well-rounded quartz grains. The wadi facies show a higher percentage of lithic components. Notable is the dolomite and anhydrite cement, that is very frequently reported (Fontaine et al., 1993; Purvis and Okkermans, 1996; Spain and Conrad, 1997). Halite plugging is noted particularly in the Central Graben area.

Compared to the Rotliegend, less is reported from the Buntsandstein, on diagenetic changes related to depth. Such reservoir impairment is certainly present. The same kaolinite, illite and chlorite growth can be expected, comparable with the Rotliegend. The reservoir quality reduction because of dolomite and anhydrite has received more attention in the literature.
The dolomite and anhydrite are explained as early cement (because of ^{18}O signature: Purvis and Okkermans, 1996 near surface in Central Graben area, Muchez et al., 1992, shallow depth in Campine basin area). The anhydrite is explained by inflow from Zechstein derived ground water. The dolomite was observed to be fabric selective and occurred predominantly in finer grained laminae (Purvis and Okkermans, 1996). They noticed also that dolomite often is enclosed by anhydrite and halite.
Halite cementation in Triassic sandstones can locally be a serious reservoir risk. The halite cementation appears texturally selective and occurs in the facies with the best porosity and permeability. The source of halite is poorly constrained. The Zechstein is the most likely source for the salt, yet Triassic Röt salt can not be ruled out. (Purvis and Okkermans, 1996).

Secondary porosity by dissolution of feldspar can play an important role. Dissolution took place after the dolomite and anhydrite cementation.

Permeability Buntsandstein

Were the dolomite and anhydrite cements are well developed, porosity is limited to secondary intergranular pore space (Spain and Conrad, 1997). Localized dissolution of anhydrite, rather than feldspar, can create good reservoir rock. Important is intergranular cementation and Purvis an Okkerman (1996) note that such porosity in dune and fluvial sandstones can be completely obliterated by anhydrite and halite. Permeability can also be reduced by these cements, but also by grain coating and authigenic clays. The permeability in the facies with the best initial reservoir properties can have now the lowest permeability because of anhydrite and halite cement. Intergranular dissolution can be stopped by grain coating. Illite coating can inhibit subsequent quartz and feldspar overgrowth. As in the Rotliegend authigenic illite reduces the permeability through the increased tortuosity of the flow path.

Areas with serious Buntsandstein diagenetic problems

In the West Netherlands basin and the area to the north called Off Holland Low, the sands of the various Bunter units become thinner to the north. Also the reservoir quality decreases. In the inverted basins also the Bunter displays serous permeability reduction as can be seen in a number of fields like in block P12.
In the general area of the Broad Fourteen's Basin, were serious reservoir impairment can be expected, the total expected volumes in the Buntsandstein come to 7.5 x 10^9 m^3. About 12.5 10^9 m^3 can be added from undeveloped fields in the area.

In the northern area, in the larger Central Graben area, the presence of salt precipitation in the pore space is a serious risk. Numerous exploration wells were dry because of salt impairment. The salt risk is hard to quantify, compared with other risks like charge, trap failure or illite impairment.
Illite growth in reservoirs of some blocks is probably related to depth. The total expected volumes of prospects in the Buntsandstein exceed 14 x 10^9 m^3 in this area and it is estimated that 15% of these prospects may have poor productivity due to salt or illite problems.

QUANTIFICATION OF TIGHT GAS RESERVOIR POTENTIAL IN THE NETHERLANDS

In the table below, estimates are given of the expected volumes from prospects and what is known of estimates for stranded accumulations (source: database TNO/AGE).

Area	**Formation**	**Undiscovered ('Prospects')** (risked expected vol.) 10^9 m^3	**Discovered ('Stranded fields')** (In Place volume) 10^9 m^3
Fringe area	Rotliegend	10-15	20
Broad Fourteen's	Rotliegend	20	20
IJsselmeer high	Rotliegend	8	15
Broad Fourteen's	Bunter	7.5	12.5
Central Graben	Bunter	2	2.5
Other formations		2-10	10-40

High low estimates

Not all volumes shown here in the various areas will be tight. For a conservative estimate of volumes that realistically can be called "tight" a discount is applied of the tabled numbers. Therefore, a low value of 100 x 10^9 m^3 is proposed for the lowest estimate of the undeveloped tight gas resource base. For an estimate of the maximum volumes it has to be noted that serious underreporting of tight prospects creates an underestimation of the true tight gas potential. From the data analyzed an upper limit of 200 x 10^9 m^3 is proposed, however this number can be significantly higher.

Upside potential

It should be emphasized that the above estimates are based on an analysis of known volumes. Part of these stranded fields and prospects will not be attractive to develop for other reasons than tight reservoir. Yet, there may be a large exploration potential that is not yet showing up in the data base used because a number of prospects in areas with tight reservoir problems are considered leads or are even unmapped. Moreover there may be a significant potential in play areas that as yet are considered "unproven" as far as their commercial potential is concerned.

The significance of tight gas volumes

The total number of prospects that fall in the serious risk areas can be compared to the remaining exploration potential in the Netherlands (Breunese et al., 2005). They report a mean of 330 x 10^9 m^3 with a range between 200 x 10^9 m^3 (P90) and 500 x 10^9 m^3 (P10). This means that the amount of gas in tight gas prospects would be in the order of 15-20% of the remaining exploration potential. This is much higher than expected from the now known volumes in tight gas fields compared with the total known reserves and can be explained by selective exploration in the past.
Compared to the total amount of gas reserves of the country (over 4,000 x 10^9 m^3 including the Groningen field), the 100 - 200 x 10^9 m^3 volume range is low, however this is a significant number compared to the remaining reserves of some 380 x 10^9 m^3 (excluding the Groningen field, see internet: EZ jaarboek, January 2006: offshore 232 x 10^9 m^3; onshore 158 x 10^9 m^3).
In addition to the volumes of 100 – 200 x 10^9 m^3, a number of existing fields have low permeability. Depending on the definition, the in place volume of gas in poor-tight reservoir is approximately 50 x 10^9 m^3.

CONCLUSIONS

An estimate of the undeveloped tight gas resource potential in the Netherlands is estimated between 100 and 200 x 10^9 m^3. Because of the aging infrastructure offshore timely development of low permeability fields becomes increasingly important. Therefore it is important to estimate the remaining exploration potential in tight reservoirs. With the mapping of a number of risk areas the prospect data can be filtered and a risk factor can be assigned to a number of prospects. The expected amount of gas in low permeability prospects is higher than 50 x 10^9 m^3 and poses a real challenge for exploration the coming years because this is a significant part of the exploration portfolio. Remaining prospects with a risk for poor productivity, is a larger share of the total expected volume, than can expected from the known discoveries in the past, because of selective prospecting. More work has to be done to classify the risks of the prospect database in order to come with a more accurate estimate of volumes in the future.
A significant part of the stranded gas fields of the Netherlands display poor reservoir characteristics. A conservative estimate of their gas volumes exceeds 50 x 10^9 m^3. The largest gas volumes in tight gas reservoirs are expected to exist in the Rotliegend, in particular in the upper Slochteren fringe area and the Broad Fourteen's Basin area. Tight gas reservoir potential in other formations may increase when more study work has been done.

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