RESERVOIR POTENTIAL OF A LACUSTRINE MIXED CARBONATE / SILICICLASTIC GAS RESERVOIR:
THE LOWER TRIASSIC ROGENSTEIN IN THE NETHERLANDS

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The Lower Triassic Rogenstein Member of the Buntsandstein Formation produces gas at the De Wijk and Wanneperveen fields, NE Netherlands and consists mainly of claystones with intercalated oolitic limestone beds. The excellent reservoir properties of the oolites ($\phi = 20-30\%$; $k = 5-4000$ mD) are predominantly controlled by depositional facies. Oolitic limestones are interpreted as the storm and wave deposits of a shallow, desert lake located in the Central European Buntsandstein Basin.

The vertical sequence of lithofacies in the Rogenstein Member indicates cyclic changes of relative lake level. The reservoir rock is vertically arranged in a three-fold hierarchy of cycles, recognised both in cores and wireline logs. These cycles are a key to understanding the distribution of reservoir facies, and are used as the basis for a high-resolution sequence stratigraphic correlation of the reservoir units.

Slight regional-scale thickness variations of the Rogenstein Member (in the order of tens of metres) are interpreted as the effects of differential subsidence associated with the inherited Palaeozoic structural framework. The depositional basin can be subdivided into subtle palaeo-highs and -lows which controlled facies distribution during Rogenstein deposition. Oolitic limestones show their greatest lateral extent and thickest development in the Middle Rogenstein during large-scale maximum flooding.

Potential reservoir rocks (decimetre to metres thick) are present in the NE Netherlands, in particular in the Lauwerszee Trough and the Lower Saxony Basin, where abundant gas shows of 200 - 4000 ppm CH$_4$ have been recorded. Preserved primary porosity is interpreted to be a result of rapid burial in subtle depositional palaeo-lows in this area. The thickest, amalgamated oolite intervals (tens of metres thick) occur in the eastern part of the Central Netherlands Basin. Because of poor reservoir properties, other areas appear to be less promising in terms of Rogenstein exploration potential.

INTRODUCTION

The Lower Triassic Rogenstein Member forms a reservoir for natural gas at the De Wijk and Wanneperveen fields, NE Netherlands (Fig.1). It is present over large parts of the Dutch on- and offshore (Mabillard et al., 1989; Geluk and Roehling, 1997), and may have potential as a secondary exploration target in a number of producing Buntsandstein fields in the Netherlands. The Rogenstein Member is a

Key words: Lower Triassic, Netherlands, Rogenstein, Epeiric, Desert Lake, Playa Lake, Lacustrine Reservoir, Bunter Shales, Oolites, Ooid, Carbonate-Siliciclastic.
mixed carbonate-siliciclastic succession and consists mainly of silty claystones with intercalated decimetre to metre-thick oolitic limestones and thin sand streaks. The best reservoir quality is associated with the oolitic limestone beds which are arranged in intervals a few metres thick which can be traced over hundreds of kilometres or more (Geluk and Roehling, 1997). The oolitic limestones have porosities of 20-30% and permeabilities of 5-4000 mD (Pipping, 2001). The main uncertainty of the Rogenstein play is associated with reservoir impairment, as observed in fields such as Roswinkel and Middelie field (Pipping, 2001; Kooper, 1998). An initial study by Palermo (2002) showed that the reservoir quality is predominantly controlled by depositional facies and stratigraphic position, and that effective porosity mainly results from the preservation of primary interparticle porosity.

The objective of this study is to a detail the distribution of the different reservoir facies types in the Rogenstein Member and to investigate the controls on reservoir quality. These objectives were best achieved by establishing a consistent high-resolution sequence stratigraphic framework and a refined sedimentological and diagenetic model. The results will hopefully contribute to an improved interpretation of reservoir development and potential risks, both for exploration and field development.

Rogenstein deposition took place in an exceptional setting which has no modern equivalent, and at the present day the Member forms a good example of a “layer-cake” reservoir system (Geluk and Roehling, 1997; Bormann, 2001). General aspects of this system relating to sedimentology, processes and controlling factors are discussed in this paper. The results may be applicable to reservoir prediction in similar epeiric systems, for example in the Middle East.
DEPOSITIONAL SETTING OF THE LOWER BUNTSANDSTEIN

The Central European Buntsandstein Basin, a successor to the Late Permian Rotliegend and Zechstein basins, extended from England to Poland and from Denmark to southern Germany (Fig. 2a). In general, the Induan-Olenekian Lower Germanic Triassic Group in central Europe marks a gradual transition from the restricted marine/evaporitic sediments of the underlying Permian Zechstein Formation to the continental deposits of the overlying Induan-Olenekian Lower Germanic Triassic Group. The Induan-Olenekian Lower Germanic Triassic Group is characterized by clastic sediments, including conglomerates, sandstones, and siltstones, as well as evaporites, particularly in the Röt Formation. The stratigraphic sequence includes the Lower Buntsandstein, the Middle Buntsandstein, and the Upper Buntsandstein, each with distinct sedimentary facies and facies relationships. The stratigraphic chart in Fig. 2b provides a detailed view of the stratigraphic sequence in the Netherlands, with specific members identified in the Röt Formation. The palaeogeography of the Central European Basin in Rogenstein times, as depicted in Fig. 2a, shows the extent of the basin and its relationship with surrounding regions.

Figure 2a (above, left). Palaeogeography of the Central European Basin in Rogenstein times, extending from England to Poland and from Denmark to southern Germany. Modified map from Ziegler (1990), supplemented with lake dimensions after Paul (2000).

Figure 2b (above, right). Stratigraphic chart for the Lower Triassic in the Netherlands (after Pipping et al., 2001).
in their rain shadow. Consequently, the study area was north of the Hercynian mountains and was therefore Tethys Ocean in the SE. The study area was located Zwan and Spaak, 1992) with wind coming from the source areas (Mabillard probably subjected to more arid conditions than the sedimentation pattern (Mabillard Induan-Olenekian period was characterised by a distance from the provenance area. Climatic variations the Roer Valley Graben and the Hessian depression. 1996; Ziegler, 1990). Clastics entered the basin through unconformity over large parts of the basin. Volpriehausen Formation is marked by a minor regional unconformity eroded down to the Rogenstein. However, a sedimentological and diagenetic review (Palermo, 2002) showed that reservoir quality may predominantly be controlled by sedimentary facies.

In Rogenstein times, the Central European Basin was fairly uniform with little record of differential subsidence, as indicated by the isochore pattern of the Buntsandstein and stratigraphic correlations across the basin (Geluk and Roehling, 1999; Fisher and Mudge, 1998). Accommodation space was partly filled by siliciclastic material sourced from Hercynian mountains to the south of the study area (Geluk et al., 1996; Ziegler, 1990). Clastics entered the basin through the Roer Valley Graben and the Hessian depression. Grain size decreases towards the basin centre with distance from the provenance area. Climatic variations are regarded as an important control on the sedimentation pattern (Mabillard et al., 1989). The Induan-Olenekian period was characterised by a strongly monsoonal climate (Parrish, 1993; Van der Zwan and Spaak, 1992) with wind coming from the Tethys Ocean in the SE. The study area was located north of the Hercynian mountains and was therefore in their rain shadow. Consequently, the study area was probably subjected to more arid conditions than the source areas (Mabillard et al., 1989).

Deposition in the Central European Basin during Rogenstein times took place in what has been interpreted as a shallow playa lake (Paul, 1982) with a very gentle depositional gradient. Three major facies belts can be distinguished: (1) red playa shales, sometimes associated with hypersaline interbeds, dominated the lake centre; (2) oolite limestone sheets occur in intermediate, more marginal parts of the lake, detached from the shoreline; (3) towards the basin margin, the oolites contain increasing amounts of quartz grains and are gradually replaced by sandy, ooid-poor sheet deposits (Geluk and Roehling, 1997; Mabillard et al., 1989; Voigt and Gauupp, 2000; Paul and Peryt, 2000). No indications of fully-marine conditions have been found in the central and western parts of the basin (Paul, 1982). Fossils in the Rogenstein member are restricted to a few species such as conchostracians in addition to stromatolites (Paul and Peryt, 1985; Kozur, 1980).

The oolite beds are thickest in the transitional zone between lake centre and lake margin. Single, decimetre- to metre-thick oolite beds may extend over several hundreds of metres (Pipping, 2001; Paul and Peryt, 2000). These beds are arranged in oolite intervals a few metres thick which can be traced for hundreds of kilometres or more in the Dutch on- and offshore areas (Geluk and Roehling, 1997; Paul, 1982).

METHODS AND DATABASE

Data compilation

The workflow began with the quantitative sedimentological description of 706 m of Rogenstein core-slabs from 28 wells (Fig. 1) in terms of lithology, sorting, grain size, sedimentary structures and associated components. The next step was the compilation and normalisation of wireline logs (gamma ray (GR), sonic log (SL), density (DENS), neutron (NEUT), deep resistivity (DRES), medium resistivity (MRES)) following Rider (1996), and a detailed core-to-log calibration. Based on direct comparison between cores, wireline logs and log measurements, distinct cut-offs and electro-facies types were defined, focusing on lithology and reservoir properties. In cases of uncertainties due to a lack of core material, cuttings were investigated.

In order to reconstruct the regional diagenetic history and the reservoir development, 126 thin-sections were investigated.

Core and wireline logs were investigated in terms of cyclicality and stacking patterns. Within the Rogenstein succession, accommodation cycles at three different scales were recognised. Large- and medium-scale cycles were used for the correlation of wireline logs using 49 wells in the Dutch on- and offshore area (Fig.1). Based on the stratigraphic cycles, the Rogenstein Member was divided into the three informal units (Lower, Middle and Upper), whose depositional conditions were similar.

Approximately 400 composite well-, gas-, litho-, mud-, and formation evaluation- logs from the NAM database were investigated for hydrocarbon gas shows and specific mud-weight. Wireline logs from 92 wells were used to construct a Rogenstein isopach map. Net thickness (m), gross thickness (m) and net:gross maps were produced for each unit and for
Fig. 3. Structural framework of The Netherlands (NAM).
Fig. 4. Flow-diagram for Rogenstein lithofacies classification. Based on sedimentological core descriptions, six lithofacies types were distinguished according to lithology, sedimentary structures, components and texture, and were interpreted in terms of depositional energy and sub-environment.
Fig. 5. Electrofacies classification of the Rogenstein focusing on reservoir qualities. Based on core-to-log calibrated shapes and cut-offs on normalised wireline logs, the lithofacies types (LFTs) were assembled into three electrofacies types which correspond to facies associations.
The Lower Triassic Rogenstein in The Netherlands

the entire member. Finally, facies maps were drawn for each unit by interpreting all the data which was available.

FACIES AND RESERVOIR PROPERTIES

Based on the sedimentological core descriptions, six lithofacies types were distinguished according to lithology, sedimentary structures, components and texture and were interpreted in terms of depositional energy and sub-environment (Fig. 4): The lithofacies types (LFTs) were combined in three facies associations which were resolvable in wireline logs.

Log shapes and cut-offs on normalised wireline logs (following Rider, 1996) were used to distinguish between these facies associations (which correspond to the electrofacies types) in uncored intervals (Fig. 5). Facies associations were:

Oolitic sheets
Oolite beds are in general a few decimetres thick and are arranged in intervals up to a few metres thick, which are either amalgamated or are separated by thin beds of clay. Individual oolite beds typically have a sharp erosional base followed by a fining-up succession with rip-up clasts, ooids and silt. Low-angle lamination and dewatering structures are common, together with wave ripples, and synaerisis and desiccation cracks in the bed tops.

The facies association can be subdivided in two lithofacies types, namely: (i) Oolitic Limestones, comprising centimetre to metre thick, light red to white oolitic grainstone intervals (oolid content > 50 vol %) with intercalated reddish-brown clay drapes; and (ii) Oolitic Sandstones, made up of centimetre to metre thick, light red to grey oolitic sandstone beds (oolid

Fig. 6a. Oolitic grainstone showing weak compaction and early circum-granular crust cementation. Note the resulting high primary intergranular porosity and the very well connected pores giving rise to high permeability (DeWijk field, Middle Rogenstein, parallel nichols; blue stain indicates porosity).

Fig. 6b. Oolitic sandstone with an oolitic grainstone intraclast showing poor compaction and round sparite-filled pores between darker brown meniscus cementation. A stromatolitic crust can be seen in (B,C,Y).

(DeWijk field, Middle Rogenstein, parallel nichols blue stain indicates porosity).

Fig. 6c. Oolitic grainstone, showing poor compaction and equant coarse crystalline, blocky sparite cementation. The sparite cement overgrows an earlier generation of calcite meniscus cements (C-X). Note the syntaxial overgrowth of ooid rims in (B-X). (Well Doornspijk, central Netherlands, cutting sample, Middle Rogenstein, parallel nichols; blue stain indicates porosity).

Fig. 6d. Oolitic sandstone with destroyed porosity, as an effect of compaction due to competence contrasts between carbonate and quartz grains. During deeper burial diagenesis the quartz components penetrate the less competent ooids and destroy the primary porosity. (Pernis-West field, southern Netherlands, Upper Rogenstein, parallel nichols; blue stain indicates porosity).
content < 50 vol %). Observed features in both lithofacies types can be interpreted in terms of storm deposition (c.f. Aigner, 1985) in a shallow playa lake with periods of subaerial exposure and changes in carbonate production, salinity and siliciclastic supply.

**Silty Claystones**

These comprised massive, up to several metre thick, reddish brown silty claystones, sometimes with rippled lenticular to flaser-like intercalations and graded laminae. This facies association can be subdivided into three lithofacies types: (i) **Oolitic Claystones**: silty claystones with wave-rippled to flaser-like oolitic intercalations, sometimes interrupted by bioturbation or desiccation cracks; (b) **Sandy Claystones**: silty claystones with lenticular to streaky sandstone intercalations often combined with desiccation cracks and anhydrite nodules; (c) **Destratified silty claystones**: massive silty claystones with anhydrite nodules, desiccation cracks, tepee structures and microbial lamination. Rootlets, brecciation, mottling and reduction spots are also common.

These observations point to deposition in a generally low energy playa lake with changing salinities and carbonate production. The presence of rootlets indicates periods when there was vegetation, while desiccation cracks and anhydrite nodules indicate periods of desiccation.

**Argillaceous Sandstones**

This facies association comprised graded, centimetre thick sandstone beds with erosive bases, claystone intraclasts often combined with wave ripples, desiccation cracks and anhydrite nodules. Decimetre thick hummocky beds with low angle lamination were rarely observed. These features indicate deposition in wave-dominated shallow water with periods of desiccation.

Reservoir properties were mainly derived from poro-perm measurements and from thin sections cut from plugs of Rogenstein cores. Palermo (2002) showed in an initial study that the excellent reservoir properties of the oolitic limestones in the De Wijk gasfield are predominantly due to the preservation of primary inter-particle porosity. The oolitic grainstones show porosities of 20-30% and permeabilities of 5-4000 mD. In contrast, oolitic sandstones show relatively poor reservoir properties as do the argillaceous sandstones and silty claystones.

**DIAGENESIS**

In order to understand reservoir development, the diagenetic history of the Rogenstein was reconstructed. A number of cement types in different geographic locations together with quartz content and leaching events contributed to the preservation of reservoir properties.

**Circum-granular cement**

Circum-granular calcite crusts (Moore, 1989) are the most common cements in the oolitic grainstones. These take the form of short columnar idiomorphic and brownish crystals, growing radially around ooids. In general, the cement does not completely fill the pore spaces and large amounts of primary porosity are preserved. Also, quartz-free oolitic grainstones do not show significant compaction (Fig.6a)

The intensity of cementation between the ooids decreases with higher quartz contents (Fig.7), and the quartz content of the oolitic limestones seems to have
had a major impact on reservoir quality. The lack of evidence for significant compaction within the clean oolitic limestones points to early cementation before burial (Goekdag, 1985). The idiomorphic habit of the calcite crystals suggests an early phreatic origin for the cement (c.f. Adams and McKenzie, 1998; Moore, 1989).

**Compaction**
Marked variations in the degree of compaction were observed within the different lithofacies types. Oolitic sandstones normally show strong grain-to-grain penetrations between quartz and calcite components. However, grain-to-grain penetrations were only observed between quartz and calcite grains, resulting in the destruction of porosity (Fig.7). A semi-quantitative investigation of 35 thin sections showed that grain mineralogy and the fraction of quartz grains are the main controls on the intensity of compaction and the preservation of primary porosity in the oolitic limestones. With an increasing content of quartz grains, the amount of grain-to-grain penetrations increases while the amount of circum-granular crust cement decreases. The quartz grains penetrate and destroy the less competent ooids by pressing them into pore spaces (Fig 6d). Primary porosity is generally completely destroyed at a composition of 50% ooids and 50% quartz grains (Fig.7).

Rarely, the ooids were completely micritised or sometimes slightly recrystallized to micro-sparite cement. This type of compaction is a pervasive diagenetic feature in the oolitic sandstone facies, especially in wells in the southern Netherlands towards the palaeo lake margin. A vertical trend has been observed, corresponding to vertical variations in quartz content within the oolitic limestones. The oolitic grainstones of the Upper and Lower Rogenstein show slightly higher quartz contents compared to the Middle Rogenstein. Therefore, grain-to-grain penetrations are more abundant in the upper and lower units compared to the middle part of the succession, where stylolites are a common feature.

Stylolites and grain-to-grain penetrations are evidence of compaction. Mechanical compaction between components is mainly related to the quartz and ooid content. Quartz-free oolites were protected from mechanical compaction between components by early circum-granular crust cements, hence no loss of primary porosity due to compaction was observed.

**Sparite and Meniscus cements**
Equant, coarsely crystalline and blocky calcite cement was only observed in thin sections of cutting samples from the area between the Central Netherlands and the Lower Saxony Basin (Fig.6c, locations in Fig.3) and in two thin sections of oolitic intraclasts from the De Wijk field (Fig. 6b). Sparite cementation sometimes formed syntaxial overgrowths on ooid rims. The clear, transparent sparite cement occludes the pore space between the more brownish meniscus cement which is concentrated at the grain contacts and forms characteristically rounded pore spaces (Figs.6b and 6c). Associated circum-granular crust cement was not observed in these samples. In addition, a very fine laminated crust was observed on some intraclasts, comparable to the “stromatolite roots” observed in the German Rogenstein described by Paul and Peryt (2000) (Fig.6b).

The fact that the ooid components are loosely packed implies that cementation occurred before significant compaction took place. Since the sparite cement overgrows the calcite meniscus cement, the meniscus cement must be an earlier cement type. Meniscus cements indicate exposure and the influence of meteoric waters originating in the vadose zone. Sparite cementation must have taken place after meniscus cementation but before deeper burial, since no significant compaction was observed. In other areas such as the De Wijk field, both sparite and meniscus cementation occur only within oolitic intraclasts, which points to a fairly early origin. Both cement types are confined to distinct geographic locations and may indicate structural highs which were relatively exposed to meteoric influences compared to other areas. The occurrence of stromatolite crusts on these intraclasts further support this model, since stromatolites are restricted to the Eichsfeld-Altmark swell (Fig.2a), a palaeohigh (Paul and Peryt, 2000) within the German Rogenstein equivalent. This assumption is also supported by regional correlations (see below).

**Leaching**
Strongly leached ooids were mainly observed in the sandy intervals overlying the oolitic sheets within the small-scale cycles. They were recognized in similar positions throughout the Rogenstein Member. The intensity of leaching appears to increase as the proportion of ooids decreases. Leaching varies between a few leached cortical layers, and major corrosion leaving only the relicts of ooid rims, usually replaced by haematite (Goekdag, 1985). Leached ooids with drusy cement inside the ooids were also observed. In contrast to data in Goekdag (1985), leached ooids were not only restricted to the De Wijk area but were also observed in other wells.

The cyclic appearance of leached ooids interpreted to be of very early diagenetic origin points to short periods of exposure to meteoric waters. It can be assumed that meteoric leaching was short-lived since underlying beds were not affected. Early circum-granular crust cement growing inside leached ooids
Fig. 8a. Facies model derived from log shapes and small-scale cycles during maximum flooding. The model assumes four facies belts within a very shallow desert lake. Massive silty claystones with thin oolitic intercalations were deposited towards the deeper basin. Landwards, ooid sheets up to several decimetres thick accumulated in "shoal"-like carbonate sand bodies, absorbing the energy of winds and waves far offshore. Behind the shoal, ooid sheets thinned out by grading into wave-rippled oolitic sand sheets, which covered rooted and bioturbated mudstones. Algal mats baffled the sediment in a supratidal setting.

Landwards, an adjacent mudflat was locally interrupted by alluvial fan deposits towards clastic point sources (Geluk et al., 1996) such as the Roer Valley Graben.

Fig. 8b. Facies model derived from log shapes and small-scale cycles during maximum regression. The study area was dominated by an extensive, mostly desiccated mudflat. Within the shallow, probably hypersaline lake, mostly mudstones with microbial lamination were deposited and the shoal bodies were replaced by decimetre-thick wave-rippled sand sheets.
indicates early diagenetic leaching which must have taken place before significant burial or cementation. The fact that leached ooids are found in many wells in the NE Netherlands, and as there is no correlation between leaching and the appearance of the Base-Rijnland unconformity, suggests that this kind of leaching is not a local unconformity-related phenomenon restricted to the De Wijk field, as was assumed by Goekdag (1985).

DEPOSITIONAL MODEL

The very uniform distribution of the oolite intervals, which extend for more than 100 km, and the distinct layer-cake characteristics which have been recognized in previous studies, probably reflect slow, regular subsidence of in a low-relief epeiric basin (Geluk and Roehling; 1997; Pipping, 2001). Epeiric basins are characterized by an almost negligible morphological gradient, which is responsible for absorbing wave energy far offshore (cf. Irwin, 1965). Interpretations of the depositional processes within epeiric successions are somewhat difficult, due to the fact that direct modern analogues do not exist. The formation of a uniform and uniform facies zones is not yet fully understood, and only relatively few basin-wide subsidence of epeiric basins characterized by an almost negligible morphological gradient, which is responsible for absorbing wave energy far offshore (cf. Irwin, 1965). Interpretations of the depositional processes within epeiric successions are somewhat difficult, due to the fact that direct modern analogues do not exist. The formation of a uniform and uniform facies zones is not yet fully understood, and only relatively few basin-wide subsidence studies have so far been undertaken (e.g. Poeppelreiter, 1998; Aigner and Dott, 1990; Poeppelreiter and Aigner, 2003).

Voigt and Gaupp (2000) developed a depositional model for the SE part of the Central European Basin which may be applied to the study area but with some modification. Extending this simple model, two alternating depositional models are proposed here in order to describe the fluctuating environmental conditions reflected in the pronounced transgressive-regressive cyclicity.

Depositional model during small-scale maximum transgressions (Fig. 8a)

Four facies belts can be differentiated within the shallow-water desert lake. Massive silty claystones with minor thin oolitic intercalations were deposited towards the deeper basin. Landwards, decimetre thick ooid sheets accumulated in “shoal”-like carbonate sand bodies, absorbing the energy of winds and waves. Sedimentary structures in these sheets (e.g. hummocky bedding, erosive bases, grading, intraclasts, dewatering structures) are evidence of rapid, event deposition, probably induced by storms. Behind this “barrier”, ooid sheets thinned and graded into wave-rippled oolitic sand sheets which covered rooted and bioturbated mudstones. Crinkly-laminated mudstones indicate microbial growth with sediment baffling in a supratidal setting, and are interpreted as lake-margin deposits. Landwards, adjacent mudflats were locally interrupted by alluvial fan deposits derived from clastic point sources (Geluk et al., 1996), such as the Roer Valley Graben. However, desiccation cracks within the oolitic intervals point to major lake level changes, even during times of overall maximum flooding.

Depositional model during small-scale maximum regressions (Fig. 8b)

During maximum regressions with lowest lake levels, the frequency of desiccation episodes in the playa lake increased. The study area was dominated by extensive, mostly desiccated mudflats. Within the shallow remnants of the lake, mudstones with microbial lamination were mostly deposited, and the oolitic shoal bodies were replaced by decimetre thick wave-rippled sand sheets.

Discussion

The model of Voigt and Gaupp (2000) assumed continuous migration of facies belts with uninterrupted carbonate production through time. However, previous correlations, consistent at local to regional scales, together with sedimentary structures and the fact that cycles can be traced over hundreds of kilometres with minor thickness changes, indicate phases of complete breakdown in carbonate production. Therefore, in addition to facies migration, facies replacement is assumed to be a controlling factor: During the lowest lake-level, it can be assumed that no oolitic carbonates were produced. Instead, they were replaced in shallow-water settings by thin argillaceous sand-sheets, with similar sedimentary structures to the oolitic sheets. For these reasons, two different depositional models for small-scale high and low lake levels are required to explain the facies distribution and the stratigraphic cycles (Fig. 8).

HIERARCHY OF DEPOSITIONAL CYCLES

Using the concepts of accommodation versus sediment supply (Cross et al., 1993; Homewood et al., 2000; Homewood and Eberli, 2000), the hierarchy of depositional cycles was analysed. The vertical arrangement of facies indicates a three-fold hierarchy of stratigraphic cycles at small, medium, and large scales. These cycles are traceable over hundreds of kilometres in the Dutch on- and offshore area (Geluk and Roehling, 1997).

Small-scale cycles

Oolitic limestone beds form prominent markers in wireline logs and cores which are generally dominated by massive claystones. In the southern Netherlands close to the palaeo lake margin, oolitic limestones are replaced by oolitic sandstones. Towards the basin...
Fig. 9. Macroscopic and microscopic observations on a fully developed small-scale cycle in the De Wijk area. Basal low-angle laminated oolitic limestone beds grade upwards into massive rooted claystones. The latter are occasionally interrupted by thin wave-rippled sandstone streaks showing a slight increase in frequency, thickness and maximum clastic grain-size towards the middle part of a small-scale cycle. They are often associated with abundant desiccation cracks which are sometimes filled with anhydrite. Above the sandy middle part, rooted silty claystones are again dominant, and pass up into oolite intervals.
centre in the northern part of the Dutch offshore area, oolitic limestone intervals grade into thin oolite streaks until they disappear. Only the most prominent oolite intervals can be traced in this area.

A fully developed small-scale cycle (Fig. 9) is typically between five and 15 m thick. Basal low-angle laminated oolitic limestones or oolitic sandstones grade up into rooted claystones. The middle parts of the cycles are mostly composed of massive, rooted metre-thick claystones, occasionally interrupted by thin wave-rippled sandstone streaks. These show a slight increase in frequency, thickness and maximum clast grain size towards the middle parts of small-scale cycles, and are often associated with abundant desiccation cracks, sometimes filled with anhydrite. However, in many cases the sandstones are missing, in particular towards the basin centre. Above the middle part, rooted silty claystones are again dominant and pass up into oolite intervals either gradually or abruptly, depending on palaeogeographic position.

Discussion
The vertical succession of lithofacies indicates cyclic changes of energy conditions, most probably controlled by lake-level changes. Basal oolitic storm sheets grade vertically into silty claystones, which were deposited in a generally low-energy environment with wave influence. The oolite intervals indicate the highest depositional energies and also the highest wave influence. The oolite intervals grade into thin oolite streaks. These show a slight increase in frequency, thickness and maximum clast grain size towards the middle parts of small-scale cycles, and are often associated with abundant desiccation cracks, sometimes filled with anhydrite. However, in many cases the sandstones are missing, in particular towards the basin centre. Above the middle part, rooted silty claystones are again dominant and pass up into oolite intervals either gradually or abruptly, depending on palaeogeographic position.

In the middle parts of the cycles, anhydrite nodules, a higher quantity of desiccation cracks and the fact that the cracks are sometimes filled with anhydrite together indicate a marked overall decrease of accommodation and a higher frequency of periods of desiccation.

The maximum clast grain-size within the thin sand streaks occurs around the middle part of the small-scale cycles, and may be explained by bypass of siliciclastics from the basin fringe area. A break in carbonate production is assumed to have occurred between the ooid-bearing intervals, since ooids are not observed in the argillaceous sandstones and silty claystones in the middle parts of the cycles. This interpretation is also supported by the fact that the ooids tend to become smaller and less complex internally with decreasing bed thickness. Haematite crusts on leached ooids at the top of the oolite intervals may also indicate periods of longer exposure. Since the thicker sand streaks sometimes show low-angle lamination which is similar to that of the oolitic limestones, equivalent depositional mechanisms can be assumed, but under lower accommodation conditions. Accommodation shows extreme variations due to marked lake-level changes and periods of extreme desiccation. Therefore, the major factor that controlled facies development is varying accommodation.

The pronounced small-scale cyclicity forms an important control on reservoir quality since in most cases macroscopic interparticle and oomouldic porosity is closely related to facies. This is also displayed in the variation of the reservoir properties which follow the small-scale cyclic trends (Fig. 10).

Medium-scale cycles
Medium-scale cycles form packages ten to 30 m thick that can be recognised in continuous cores and wireline logs. Medium-scale cycles comprise stacked small-scale cycles, in which the thickness of the associated oolitic intervals shows systematic upward variations. Maximum medium-scale regression is interpreted to occur around the sandier intervals within a claystone succession, while transgressive peak is marked by the thickest oolite interval in the package.

Medium-scale cycles can best be distinguished in wells in the northern offshore blocks and in the southern Netherlands towards the lake margin. In the latter area, they tend to become more amalgamated and cycle thickness decreases to 10 m; cycles are separated from each other by prominent claystone intervals. However, medium-scale cycles in the northern offshore blocks show a different trend. The thickness of the massive, claystone-dominated units increases to 30 m, while the oolite streaks occur only around the maximum transgression, forming clear markers for medium-scale transgressive maxima, and small-scale cycles become more difficult to distinguish. In some areas such as the NE Netherlands, it is relatively difficult to recognise medium-scale cycles, while small-scale cycles are well developed and easy to trace. When possible, several closely spaced wells in a particular field (e.g. De Wijk) were used to identify the cycles at a medium scale.

Discussion
The medium-scale cycles are interpreted to be controlled by the same mechanism as the small-scale cycles but operating over longer time-spans. Packages of stacked small-scale cycles, containing oolite intervals of comparable thickness, indicate generally similar base-level conditions. Intervals with thick oolite beds are assumed to have been deposited during periods of high accommodation and accompanying carbonate production. The claystone-dominated horizons between the oolite intervals are interpreted to represent times of low accommodation with little or no carbonate production. Consequently, the thickest oolite intervals are interpreted to represent transgressive maxima, and the claystone-dominated
Fig. 10. Subdivision, trends and interpretations within the Rogenstein Member. This composite calibration panel of a well from the De Wijk field shows that the different cycle hierarchies can also be recognized in the variations of the saturation curve. The calculated porosity does not show this trend clearly since the high but ineffective porosity of the claystones is included.
intervals between the packages to represent maximum regression.

**Large-scale cycles**
A single large-scale cycle covers the entire Rogenstein Member and is composed of 4-5 stacked medium-scale cycles and 16-19 small-scale cycles (Fig. 10). The large-scale trend is in general obvious and was recognised in all palaeogeographic locations in the study area. Oolite-bearing intervals and beds within the stacked medium-scale cycles thicken upwards towards the Middle Rogenstein (Fig.10) and become progressively thinner towards the top. The grain size of the ooids follow this trend. Accordingly, the cleanest and thickest oolite beds with the biggest ooids, which form the best reservoirs, are found in the middle part of the Rogenstein Member.

**Discussion**
Oolite intervals in the Middle Rogenstein Member (Fig.10) showing the greatest bed thickness and the largest ooid-size are interpreted to have been deposited during intervals of maximum lake levels. By contrast, the thinner oolite intervals in the Upper and Lower Rogenstein are interpreted to have been deposited during intervals of less pronounced lake-level highs. Therefore, the entire Rogenstein is interpreted to represent a single large-scale cycle, displaying an overall transgressive phase towards the Middle Rogenstein followed by overall regression towards the top. This large-scale trend is also displayed by a change of reservoir properties. The thickest and cleanest oolites with the best reservoir properties occur in the Middle Rogenstein around the transgressive maximum, while reservoir properties decrease towards the maximum regression.

Indicators for marine influence (e.g. fossils) have not been observed in the study area. This corresponds with observations in the western part of the basin (Voigt and Gaupp, 2000; Paul, 1982) and suggests climatic variations may have been a major control on the stratigraphic record. The lake-level variations were presumably the result of variable precipitation in the drainage area (Clemmensen, 1994; Geluk and Roehling, 1997).

Decreasing precipitation in the source area could cause lake regression, and combined with flash flooding (due to intermittent heavy rainfall) may have supplied more siliciclastic material by means of ephemeral sheet-floods bearing large amounts of suspended sediment. The accommodation potential for sediment deposition during the regressive phases is mostly concentrated in the shallow remnants of the lake.

In respect of the very gentle depositional gradient, the accommodation potential shifts strongly towards the basin fringe-area during the transgressive phases. Furthermore, a general increase in rainfall may correspond to more continuous discharge from the source areas with minor suspension transport. Clemmensen (1994) and Geluk and Roehling (1997) assumed climatic fluctuations as one of the main controlling factors of the stratigraphic record in the Lower Buntsandstein.

**CORRELATION**
Due to their remarkable lateral continuity, the cyclic patterns recognized form an excellent stratigraphic framework for regional correlation of the reservoir units. As in previous regional studies, the slightly angular sequence boundary at the base-Volprieuchen unconformity (Fig. 2b) was used as a datum (Mabillard et al., 1989; Bormann, 2001; Geluk and Roehling 1997). The correlation began at the De Wijk field (Pipping, 2001) where the greatest amount of data was available, and was enlarged stepwise. Firstly, the base-Volprieuchen unconformity and the large-scale cycle maximum were correlated, marked by the thickest and most widespread oolite-bearing interval. Smaller-scale cycles were correlated within this framework, followed by the reservoir units determined by the calibrated cut-offs (Figs.11, 12).

The general thickness trends of the Rogenstein are accompanied by systematic regional facies changes. In areas with reduced overall thickness, oolite intervals are normally more thickly developed, with a trend to amalgamation with thinner claystone beds. By contrast, areas with a thickly developed Rogenstein tend to have progressively thinner oolite intervals separated by thick claystone units.

**REGIONAL MAPPING**

**General thickness and gas shows during drilling** (Fig. 13)
A thickness map of the entire Rogenstein was created, by correlating the bases and the tops of 92 wells on- and offshore (see Fig.1). The isopach map was calculated with the GeoFrame module Basemap and manually corrected, incorporating the first-order structural framework. The Rogenstein reaches its maximum thickness in the following areas: (i) The offshore blocks around the Cleaver Bank High, Central Offshore Saddle, Winterton High and the Vlielton Basin; (ii) the NE Netherlands, around the Lauwerszee Trough and the Lower Saxony Basin; (iii) The West and Central Netherlands basins which also have a trend of slightly higher thickness compared to the surrounding areas. The Rogenstein is thinner around structural highs such as the Maasbommel High, Ameland Block and the Groningen Block.
Fig. 11. Representative SW-NE stratigraphic cross-section through the Dutch onshore area, showing subtle variations in thickness accompanied by systematic facies changes. A subtle palaeohigh around well Doornsijk-2 (DSP-2), characterised by reduced cycle- and overall thickness, separates the oolitic sandstones towards the southern lake margin from oolitic limestones in the NE (see Fig. 15 for a depositional model illustrating the interaction between sea level-changes and palaeo-topography).
Fig. 12. Representative SE-NW cross-section through the Dutch onshore and offshore. The relationship between overall thickness and facies distribution can be seen, as can the influence of medium-scale lake-level changes. The well AME-202a in the area of Ameland Block “filters” the oolitic limestones towards the NW offshore; only the thickest oolite intervals, often around medium-scale transgressions, can be traced over the entire area.
Fig. 13. Rogenstein thickness (m) and gas-show map. The Rogenstein is characterised by a relatively uniform subsidence pattern and was deposited on a mosaic of Variscan crustal blocks. The isopach pattern generally follows the Variscan structural framework, as is well documented in areas with high well densities such as the Permian Lauwerszee Trough. To help evaluate possible relationships between overall thickness, structural grain and the occurrence of gas, signatures for gas shows have been marked on the map.
A similar tendency is also assumed for the Texel-IJsselmeer-High, which is difficult to reconstruct since the Rogenstein is completely eroded in this area. However, another area with thinner Rogenstein separates a smaller sub-basin around the De Wijk area from the Lower Saxony Basin. In general, the thickness decreases towards the London-Brabant and the Rhenish Massifs in the SW. Furthermore, a decrease in overall thickness was also observed in the NE offshore blocks towards the German border around the Ameland Block and the Schill Grund High.

In order to evaluate a possible relationship between overall thickness, structural framework and the occurrence of gas, signatures for gas shows were added to the map (Fig. 13). Approximately 400 composite well logs were screened for gas shows and the density of the drilling fluid. A higher fluid-density increases the value of a gas show, since a higher mud-weight presses more gas back into the formation. The map was also to guide the detailed correlation, highlighting areas with abundant gas shows that were studied by a higher density of wells which were correlated in detail. In terms of exploration potential, most gas shows are concentrated in the NE Netherlands while smaller accumulations are found in the SW onshore area.

Discussion
The Lower Buntsandstein Formation is characterised by a relatively uniform subsidence pattern and was deposited above a mosaic of Variscan crustal blocks. As regards the general thickness of the Rogenstein, it is notable that the isopach patterns largely reflect the Variscan structural framework (Fig. 13). This is well documented in particular in areas with a high well density, such as the Permain Lauwerszee Trough, located between the Texel-IJsselmeer-High and the Groningen Block, where the Rogenstein is thick. These regular and marked thickness differences point to regional variations in accommodation, which may be strongly influenced by differential subsidence between tectonic elements mostly of Variscan age. This assumption is also supported by regional facies development (see below). Similar relationships between thickness, accommodation and differential subsidence within the Triassic of the Central European Basin have been observed in other epeiric successions such as the Muschelkalk (Braun, 2004; Borkhataria, 2005) and the Keuper (Poepelreiter, 1998).

Reservoir Distribution (Fig. 14a-c)
Gross and net: gross maps were directly derived from the cross-sections by measuring the gamma-ray, sonic and neutron/density cut-offs by hand. The maps highlight the thickness trends of oolite intervals. The calculations were not carried out with mapping software, since the cut-offs of the logs are variable and depend on geographic location. For example, the oolitic sandstones around the West Netherlands Basin show very high gamma-ray readings, probably due to high contents of radioactive minerals. Therefore the sonic log was used, as it showed a clear response. In the De Wijk field, the GR response is clear but the SL gives only a subtle response to oolitic limestones due to their very high porosities. The data quality was controlled by summarising all hand–picked net thickness values and comparing them with the computer-calculated overall thickness of the Rogenstein. The maximum error tolerance was 1%. The maps were drawn with Surfer using the radial basis function for interpolation.

Lower Rogenstein
The oolitic limestone intervals are thickest in the eastern part of the central Netherlands. By contrast, oolitic sandstones are thickest in the SE Netherlands around the Central Netherlands Basin. In the central and northern parts of the offshore area, the oolite-bearing intervals are generally thin and often reduced to barely traceable streaks. Only the thickest intervals of the medium-scale cycles can be traced while the cycle thickness and the claystone content increases. Major trends can best be seen in the thickness maps (Fig. 14a). Towards the basin margin in the South Netherlands, the oolite intervals grade into thin oolitic sandstone streaks in tandem with a decrease in cycle thickness. The area between Central Netherlands and Lower Saxony Basin (locations in Fig. 3) shows a marked reduction in cycle thickness and a reduction of the oolitic limestone intervals to thin streaks.

Middle Rogenstein
The oolitic limestone intervals in the study area are thickest in the Middle Rogenstein (Fig. 14b). However, the overall thickness trend of the oolite intervals in general remains the same — thick in the eastern Netherlands and thinner towards the NW. The oolitic limestones in the eastern part of the Central Netherlands form massive amalgamated intervals, tens of metres thick. Oolitic sandstones towards the southern basin margin are also generally arranged in amalgamated units. Oolite intervals are fairly thick in the middle of the area between Central Netherlands and Lower Saxony Basin. The thinning trend of the oolite intervals towards the northern offshore area is similar to that in the Lower Rogenstein, with the only difference being that there are a few more traceable beds and the oolite intervals are slightly thicker.

Upper Rogenstein
The regional trends in thickness and oolite proportions in the Upper Rogenstein are very similar to those in
Fig 14a. Lower Rogenstein thickness (m) and net : gross (%) ratio.
The Lower Triassic Rogenstein in The Netherlands

Fig. 14b. Middle Rogenstein thickness (m) and net : gross (%) ratio.
Fig 14c. Lower Rogenstein gross (m), net (m) thickness and net : gross (%) ratio.
the Lower Rogenstein (Fig. 14c). However, even some very thin intervals can be traced over hundreds of kilometres. Amalgamation generally occurs in the same areas as in the Middle Rogenstein but is less pronounced. Most importantly, the number of small-scale cycles increases towards the NE onshore and the northern offshore area. These uppermost cycle-defined correlation lines run over long distances almost parallel to the base-Volpriehausen unconformity. Towards the basin margin in the south, one-and-a-half medium-scale cycles are truncated.

**Discussion**

In general terms, the Rogenstein succession shows a relatively uniform subsidence pattern, marked by a balanced thickness distribution over the entire study area. However, the maps and the detailed correlations highlighting the thickness of the oolite intervals provide a key for the understanding of the depositional system. Differences in thickness are generally very subtle and the lateral variations amount just to a few metres over hundreds of kilometres within a small-scale cycle.

Nevertheless, there are areas, apart from the basin margin, with up to 40% reduction in cycle thickness. These are interpreted to represent zones of slightly lower subsidence and thus slightly lower accommodation (see Figs 11, 12). As indicated by isopachs and facies geometries, these areas are interpreted as “subtle palaeo-highs”. Areas with thicker cycles are interpreted to represent zones of slightly higher subsidence and thus slightly higher accommodation (“subtle palaeo-lows”).

Palaeo-lows are considered to represent sediment traps, in particular for coarser-grained material, both carbonate or quartz sand. The thickest and deepest part of the basin within the study area was located around the centre of the northern offshore sector. The palaeo-highs are interpreted to have influenced patterns of sediment distribution depending on their development and regional position. They probably acted as barriers for the transport of siliciclastic sediment towards the basin centre. In addition, they are interpreted to have formed the main zones of carbonate production and they were influenced by storms and waves where they were located above wave base. In addition, they were sheltered from clastic “poisoning”; both factors probably enhanced carbonate production.

The regional arrangement of the palaeo-highs and -lows is interpreted to be a major factors controlling sediment distribution, since they divided the study area into several more or less separate sub-basins with different properties which have a direct influence on reservoir quality. Within an extensive but very shallow desert lake, palaeo-highs are regarded as very sensitive indicators for accommodation changes (Fig. 15a-c). During times of overall low accommodation, only thin oolite streaks (or no carbonates at all) were preserved on top of the palaeo-highs. Oolite intervals are more thickly developed within the subtle depressions, pinching out towards the palaeo-highs. In contrast, during times of overall higher accommodation caused by an overall higher lake level, massive amalgamated oolite beds were preserved on the tops of the palaeo-highs, generating the highly continuous oolite intervals observed in the middle Rogenstein.

Within the thick oolite intervals of the subtle palaeo-lows, oolitic intraclasts with different cement types and stromatolite crusts indicate the allochthonous origin of the ooids. This implies that ooids were produced on top of the palaeo-highs and were later transported into the palaeo-ows.

**FACIES MAPS**

Facies maps (Fig 16 a,b,c) were compiled using the stratigraphic cross-sections, the thickness, net: gross maps and the log shapes, supplemented by thin-section studies. Since the overall accommodation changed during the Rogenstein, different facies maps for the Lower, Middle and Upper Rogenstein were compiled. The nomenclature of facies zones is descriptive, combining lithologies and thickness-trends. In addition, the supposed zones of ooid production and the directions of ooid distribution are highlighted. As described by several authors (e.g. Paul and Peryt, 2000), ooid production in the eastern German part of the basin is interpreted to have taken place on top of the subtle palaeo-highs. This is consistent with the thickness trends, distribution patterns and thin-section observations within the ooid-bearing intervals (regional facies trends are listed in Table 1).

**REGIONAL EVALUATION OF RESERVOIR PROPERTIES**

The regional evaluation of reservoir properties was the final step of data synthesis. The data were compiled in a Rogenstein play-map including producing fields, gas shows and reservoir properties (Fig. 17). In terms of exploration potential, the study area was divided into the following five provinces (Table 1):

**West Netherlands and western Central Netherlands Basin**

This area was situated in a zone of mixing of clastic sediments from the south and ooids from the north. Resulting oolitic sandstones show poor reservoir properties, mainly due to the effects of diagenetic compaction. A qualitative relationship between quartz grains, ooids and reservoir impairment due to
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| **West Netherlands-Central Netherlands Basin** | - sub-basin and a major sediment trap for siliciclastics  
- bordered by a palaeo-high extending from the Eastern Netherlands to the Broad Fourteens Basin in the north and the London Brabant Massif in the south  
- zone of mixing between clastic sediment derived from the south and ooids produced on the palaeo-high to the north  
- thickest in the eastern part of the sub-basin                                                                                       |
| **Roer Valley Graben- SW Basin fringe area** | - SW basin fringe area towards the London Brabant Massif, assumed to be relatively close to a clastic point source  
- amalgamated oolitic sandstones with a generally low ooid content  
- ooid content decreases progressively towards the ooid impoverished sandstones of the Amethyst Member in the SW                                                                 |
| **East Netherlands/ Texel IJsselmeer High / Broad Fourteens Basin** | - 'ridge' of palaeo-highs and main centre of ooid production  
- barrier to siliciclastic sediments delivered from the south  
- thick amalgamated oolitic limestones in the Middle Rogenstein  
- oolites are thickest in the eastern Netherlands, towards the German Border  
- eroded in most parts of the area around the Texel IJsselmeer High due to Jurassic and Cretaceous inversion |
| **NE Netherlands**            | - several sub-basins following the Permian structures of the Lauwerszee Trough and the Lower Saxony Basin  
- surrounded by ooid-producing palaeo-highs and therefore located near to the centres of ooid production  
- sediment trap for sand-free ooids around the transgressive maximum  
- mostly eroded around the Friesland platform but present in the very western part.  
- palaeo-high around the Ameland Block was too deep for ooid production and formed a barrier to the transport of ooids into the offshore area |
| **Northern Offshore and Terschelling Basin** | - depocentre of the eastern Rogenstein Basin  
- thick massive claysstones with a few thin oolite streaks, Rogenstein Member shows maximum thickness in this area  
- surrounded by deeper palaeo-highs which acted as barriers to the transport of ooids towards the basin centre  
- widespread erosion of the Rogenstein occurs around the Cleaver Bank High and the North Western Dutch offshore Blocks due to Jurassic and Cretaceous inversion |

Table 1. Regional facies and palaeogeographical trends in The Netherlands.
Fig. 15. Depositional model for the complex interaction between subtle palaeo-highs and palaeo-lows during maximum accommodation conditions of the Lower, Middle and Upper Rogenstein.
Fig. 16a. Lower Rogenstein facies map.
Fig. 16b. Middle Rogenstein facies map.
Fig. 16c. Upper Rogenstein facies map.
Fig. 17. Predictive Rogenstein play map displaying synthesis of the gas-show and facies maps.
Fig. 18. SW-NE cross-section through The Netherlands onshore, highlighting Rogenstein reservoir properties.
diagenetic compaction effects was observed. As mentioned above, these effects can be explained by the marked competence contrast between carbonate and quartz clasts, and the restriction of calcite circumgranular cements to carbonate grains. The tight oolitic sandstones are easily recognised in wireline logs by a positive DENS/NEUT separation and have even poorer reservoir properties than the silty claystones, as displayed on the porosity/permeability cross-plots (Fig. 19) Maximum values are 6.3% porosity and 17 mD permeability; average values are around 4% porosity and 0.1mD permeability (based on 51 plugs).

SW basin margin area
These areas were the most proximal to the clastic source areas. The ooid content of the oolitic sandstones decreases and they grade into ooid-poor sandstones with primary porosity. However, no gas shows were found within the Rogenstein Member in this area. The poro-perm values show a linear trend, indicating that grain size is a major controlling factor on reservoir properties.

Maximum values are 22.3% porosity and 226 mD permeability; average values are around 18% porosity and 20 mD permeability. However, this is based on only eight plugs, thin sections of this area were not available.

Eastern Netherlands, Texel IJsselmeer
High and K-Blocks
The thickest and most massive amalgamated oolite intervals (tens of metres in thickness) were localized in the East Netherlands, striking towards the Central Netherlands Swell where the Rogenstein Member is completely eroded. The region is assumed to have functioned as a source area for the ooids of the reservoir facies, and is interpreted to have formed a subtle high during Rogenstein times. Since the region was affected by Cretaceous inversion, the formation is not charged with gas. Hence only a limited amount of data exists. Thin sections showed that the Rogenstein reservoir in this area is mostly tight due to early sparite cementation.

NE Netherlands
Thick decimetre- to metre-scale oolitic limestone beds of the Middle Rogenstein, with the highest Rogenstein exploration potential of the Netherlands, are present in this area. In large parts of the Friesland Platform, the Rogenstein Member is completely eroded. The producing De Wijk and Wanneperveen gasfields are located in the easternmost part of the Friesland Platform. In Rogenstein times, the area is interpreted to have comprised several subtle sub-basins, comprising the Lauwerszee Trough, the Lower Saxony Basin and the area around the De Wijk field, separated by a subtle palaeo-high. Preserved primary porosity was preserved by early phreatic circumgranular cements, with permeabilities of several Darcies and porosities up to 28%. Two minor leaching events were observed in thin sections of cores from the De Wijk field, slightly enhancing the reservoir
properties. A linear grain-size trend in plug measurements (Fig. 20) confirms these observations. The De Wijk area provides the largest amount of data compared to the rest of the region, and was used for calibration between plug measurements and wireline logs. Excellent reservoir properties are displayed by a negative neutron/density separation in gas-bearing formations (“gas effect”). The local occurrence of patchy anhydrite cementation may constitute a potential risk.

Maximum values of the oolitic limestones’ porosity and permeability are 29% and 4 D, respectively. Average values are around 20% porosity and several hundred mD permeability (based on 323 plugs).

**Northern and central Dutch offshore area**

In this area, the Rogenstein Member has its maximum thickness (200 m: see Fig.13) and it is therefore interpreted as the deepest part of the Dutch Rogenstein basin. Since it is also the most distal part relative to clastic and carbonate source areas, only dm-thick oolite streaks are recent and are intercalated in massive claystones. Due to this lack of reservoir rock, the area is not expected to have exploration potential. In addition, anhydrite cements are abundant and plug the primary pore space completely. In Blocks A, E, and L, large parts of the Rogenstein are completely eroded.

**Discussion**

Various controlling factors have to be considered regarding the exploration potential of the Rogenstein Member. Destruction of primary porosity due to intense sparite cementation (e.g. eastern Netherlands), diagenetic compaction effects (e.g. West and Central Netherlands Basin) or simply the absence of reservoir rock (Northern and Central Dutch offshore areas) or gas shows (e.g. SW basin margin area) restrict the exploration potential of the Rogenstein to the NE Netherlands. However, even there, several uncertainties have to be considered. In areas were the Rogenstein Member is relatively deeply buried (e.g. towards the Groningen Block), more diagenetic compaction and possibly the destruction of primary porosity may be expected. Furthermore, reservoir prediction is difficult in these areas, since neither core material nor thin sections are available. Another critical point may be the potential occurrence of anhydrite cements, as in the northern offshore blocks where anhydrite-plugged oolitic grainstone streaks are a pervasive feature. Although patchy anhydrite cement was only observed in a few thin sections from cores samples in the NE Netherlands, it may constitute a risk because cores are limited to a few locations. Therefore, additional indicators (e.g. cuttings, well tests, density/ neutron log combination) need to be considered. Fig.18 shows a reservoir cross-section based on the density/ neutron log combination through the Netherlands onshore. The cross-section shows the two-dimensional arrangement of potential reservoir rocks and recorded gas-shows.
CONCLUSIONS

Sedimentary components, sedimentary structures and the lack of body fossils indicate that Rogenstein deposition took place in an epeiric desert lake. The lake was characterised by an almost negligible morphological gradient and wave energy was dispersed far from the shore line. Clastic sediments were mainly delivered from point sources along the basin margins.

- The vertical organisation of lithofacies indicates cyclic changes of energy conditions, controlled by lake-level changes. Oolite intervals form the bases of five to 15 m thick small-scale cycles. The oolitic limestones represent storm deposits and indicate relatively high energy. Small-scale cycles are a key to understanding the vertical distribution of reservoir properties.

- Small-scale cycles are stacked in intermediate-scale cycles, forming packages ten to 30 m thick. Medium-scale cycles are stacked to build a single large-scale cycle comprising the entire Rogenstein. The small-, medium- and large-scale cycles provide a sequence stratigraphic framework for regional correlation of the reservoir units.

- On a regional scale, the Rogenstein basin shows a relatively regular pattern of subsidence marked by a uniform thickness distribution. On a sub-regional scale, however, small thickness differences (excluding eroded portions) are apparent, and are interpreted to be a result of subtle differential subsidence. Depocentres in the Rogenstein basin are located in the offshore blocks around the Cleaver Bank High, Central offshore Saddle, Winterton High and the Vlieland Basin; and also in the NE Netherlands, around the Lauwerszee Trough and the Lower Saxony Basin. The West and Central Netherlands basins also show a trend of slightly higher subsidence.

- Areas with consistently reduced cycle thickness are interpreted as “subtle palaeo-highs”. These palaeo-highs influenced sediment distribution, depending on their development and regional location. Subtle palaeo-highs acted as barriers for the transport of clastic sediment towards the basin centre. They probably acted as the main zones of carbonate production. Areas with thick cycles are interpreted as “subtle palaeo-lows” acting as sediment traps. The regional arrangement of subtle palaeo-highs and palaeo-lows is regarded as one of the most important factors controlling the lateral distribution of facies and reservoir properties.

- Clean oolitic grainstones deposited in subtle palaeo-lows in general show significant amounts of primary porosity and well-connected pores. In contrast, clean oolitic grainstones deposited on top of the subtle palaeo-highs are characterised by sparite cementation and early vadose meniscus cement indicating exposure.

- The reservoir quality of the oolitic limestones is best displayed in the distinct separation of combined wireline logs (density/neutron, deep resistivity/medium resistivity).

- Thick oolitic limestone beds (decimetre to metre thick) with the highest Rogenstein exploration potential and the most important gas shows occur in the NE Netherlands. Preserved primary porosity is interpreted to be the result of rapid burial in subtle palaeo-lows in this area.

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