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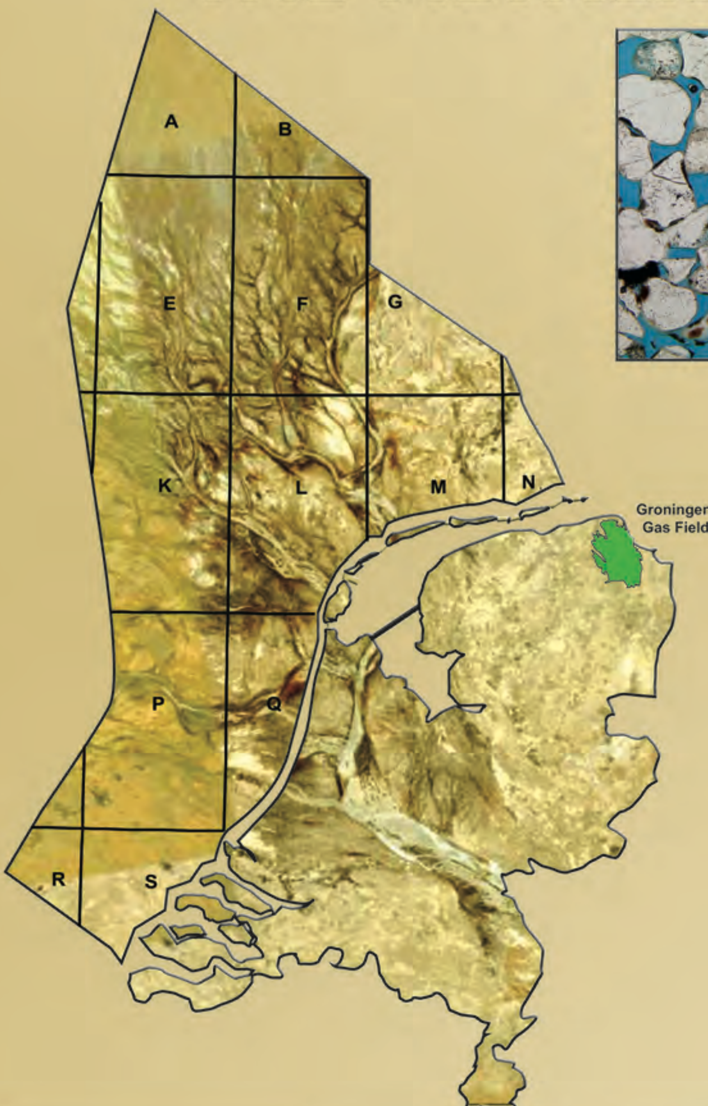
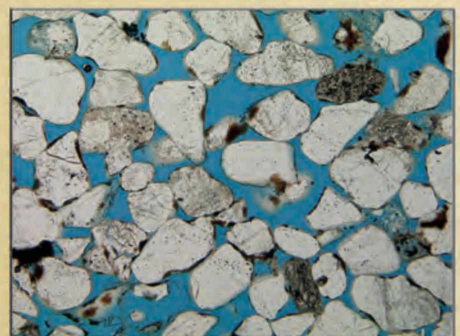
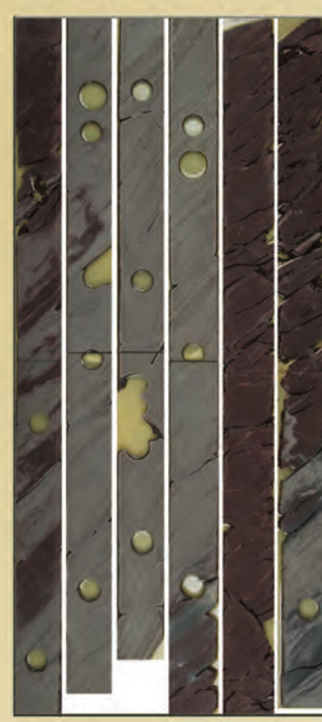
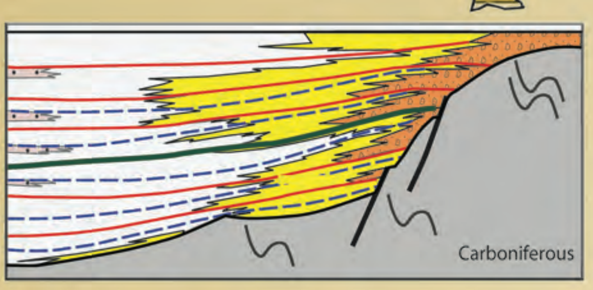
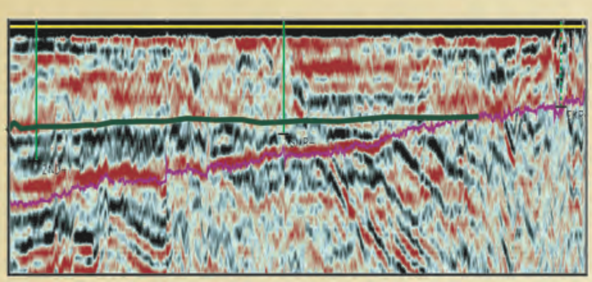
THE PERMIAN ROTLIEGEND OF THE NETHERLANDS











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The Permian Rotliegend of the Netherlands

Jürgen Grötsch and Reinhard Gaupp, Editors

CONTENTS

Introduction

Groningen: A Review

Stratigraphy

Depositional Environments

Diagenesis

Structure and Tectonics

Pressures and Fluids

Appendix A

Appendix B

THE GRONINGEN GAS FIELD: FIFTY YEARS OF EXPLORATION AND GAS PRODUCTION FROM A PERMIAN DRYLAND RESERVOIR

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ABSTRACT: The Permian Rotliegend sandstone reservoir in the Groningen Field forms the largest onshore gas accumulation in Europe (2,900 x 109 m3 or 100 Tcf Gas Initially In Place). The gas is contained in a high-quality dryland sandstone reservoir at approximately 2,900 m below sea level. The Groningen Field was discovered in 1959 by well Slochteren-1 with production starting in 1963.

In this paper, the different phases of field development are discussed, illustrating the improved understanding of the subsurface over the past five decades through continued data acquisition like coring and advancements in technology, particularly of 3D seismic. The initial field development phase took some fifteen years, during which 29 well cluster locations were built and a total of over 300 wells were drilled for production and observation purposes. Integration of acquired data from the field together with state-of-the-art static and dynamic modelling technology now allow operating the Groningen system as a smart field, which requires only a few operators to produce up to 255 x 106 m3/d (9 x 109 scf/d) of gas on peak days during winter.

Interestingly, the main focus of early exploration drilling was on oil prospects in Zechstein carbonates, and only with well Slochteren-1 did the focus change to gas prospects in the underlying Rotliegend Group. As is well established now, this gas petroleum system of Palaeozoic origin is the most important one in the Netherlands and is responsible for the generation of the Groningen Field gas predominantly during the Jurassic and, less importantly, during the Tertiary.

Furthermore, a characterisation of the Rotliegend reservoir is provided. Its complex reservoir architecture is, firstly, a function of the sedimentary facies distribution, ranging from proximal alluvial-fan deposits in the south to playa-lake deposits in the north and, secondly, of the multiphase structural deformation of the Groningen High in the northern Netherlands. Diagenetic impairment of reservoir quality plays only a minor role in the field, which is related to the relatively early gas charge in the field. Gas retention over such a long time is attributed to the perfect top seal formed by the Zechstein evaporites.

Fifty years after discovery, the Groningen Gas Field is still the most important gas supplier in Europe, with the end of field life expected in some fifty years from now. A review of this history to date is presented in this paper.

THE RATIONALE FOR AN INTEGRATED STRATIGRAPHIC FRAMEWORK OF THE UPPER ROTLIEGEND II DEPOSITIONAL SYSTEM IN THE NETHERLANDS

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ABSTRACT: Due to the nature of the depositional environment and most importantly the lack of (bio) stratigraphic control, it remains difficult to establish a robust and reliable stratigraphic framework for the Upper Rotliegend which can be used as a guideline to better understand the internal architecture. The most important challenges encountered are the identification of the large-scale basin architecture and basin fill, the identification of a sequence stratigraphic model for (semi-) arid continental deposits, and the relationship between the distribution of Upper Rotliegend sediments and the underlying Variscan structural framework.

Based on the present-day knowledge and status of particular stratigraphic aspects, it can be concluded that a single “silver bullet” solution does not exist for providing a more profound understanding of the depositional model. It is evident that none of the methods available should be used in isolation but rather integrated in the framework of sequence stratigraphy providing the petroleum geologist a genetic and predictive geological model.

ROTLIEGEND FACIES, SEDIMENTARY PROVINCES, AND STRATIGRAPHY, SOUTHERN PERMIAN BASIN UK AND THE NETHERLANDS: A REVIEW WITH NEW OBSERVATIONS

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ABSTRACT: The environments of deposition of the Upper Rotliegend in the Southern Permian Basin have been of continuing interest since the discovery of the Groningen Gas Field in 1959. This is because the quality of the porosity and permeability of the sands is in most places dependent upon the original depositional environments. In the earliest years, the emphasis of much work was on mapping broad depositional realms of aeolian, fluvial, and playa environments. As new discoveries came under development, the geometry of small-scale features such as dune (good reservoir) and interdune (poor reservoir) became important, informed in part by studies of modern deserts. As the Rotliegend play matured, the emphasis of studies shifted to approaches that recognised rock units below the level of the known members of the Rotliegend that were tied into process framework elements such as climate change.

The present study uses modern analogues for the Rotliegend at Bristol Dry Lake and Cadiz Dry Lake, in the California desert, U.S.A., as a basis for the discussion of ancient Rotliegend depositional environments. At these sites active aeolian, fluvial, and playa depositional environments have produced a sedimentary record similar to that in the Rotliegend.

Additionally, there exists at Bristol Dry Lake a sand-flat sedimentary domain that constitutes a transition zone between the playa and surrounding fluvial and aeolian sedimentation, where the processes associated with all three major environments are roughly in balance. A sand flat also exists in the ancient Rotliegend, although it is more commonly referred to as the “transition zone” in North Sea literature. At Cadiz Dry Lake the geographical resemblance to the Rotliegend is impressive, with winds blowing parallel to the elongation of the playa and ephemeral streams entering from the margins in a manner analogous to the

Rotliegend of the Southern North Sea, where fluvial and wind transport directions are at roughly right angles in much of the basin. Our work suggests that in our study area the Silverpit Formation has the qualities of a desert playa lake that was episodically flooded.

We illustrate here with core examples the major lithofacies of the Rotliegend, including aeolian, fluvial, and playa sediments. These are tied to a stratigraphic scheme that is based on the major formations of Upper and Lower Slochteren, and a new, if minor, member known as the Hyde Sandstone, representing the last "regression" of the playa in the UK. Isopach and palaeogeographic maps of the major sedimentary domains that are dominated by aeolian, fluvial, or playa processes illustrate the evolution of the Rotliegend. The maps show the irregularity of the Sand Flat and its lateral shifts through time, as well as the distribution of the other domains due to dominance of wind or fluvial sedimentation locally. They also illustrate the dependence of much of the facies distribution on the palaeotopography of the Carboniferous. The development of dune fields that became the best reservoir rock was dependent upon the location of fluvial systems that supplied sand to the wind, and upon topographic slope. Much of the best dune reservoir was deposited not in the basin centres, where it became deeply buried and compacted, but on the flanks of major structures as windward and leeward sand seas and dune fields.

A COMPARISON OF MODERN DRYLAND DEPOSITIONAL SYSTEMS WITH THE ROTLIEGEND GROUP IN THE NETHERLANDS

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ABSTRACT: The Rotliegend Group in the Netherlands provides a depositional record of fluvial, aeolian, and playa interaction within a major Permian dryland basin. Ephemeral fluvial systems drained off the London–Brabant and Rhenish Massifs and flowed northwards towards the Silverpit Formation desert lake, whilst marginal dune fields expanded and contracted in response to changing aridity and fluvial runoff. There are few modern parallels to the scale of the Southern Permian Basin depositional system as a whole, but recent dryland analogues provide a valuable means to understand the depositional processes which locally operated across the basin during the Late Permian. A variety of modern analogues is required to adequately sample the range of climatic conditions that the Rotliegend depositional systems encountered, with examples selected from modern ergs, fluvial and alluvial fans, playa, lacustrine, and saline-lake settings. However, although the longterm allocyclic controls on deposition and preservation of the Rotliegend have long been recognized, the contrast between the diversity of surficial facies seen in modern dryland settings and that preserved in the ancient record suggests that the Rotliegend also failed to preserve much of the expected facies diversity through aeolian deflation and sustained, polycyclic reworking of interacting fluvial, lacustrine, and aeolian systems. Widespread fluvial activity and lacustrine shoreline facies, which form a visible record of relatively recent pluvial episodes in modern basins, have limited preservation potential, and maps of gross facies belts in the Rotliegend are not true palaeogeographic facies arrangements but time-averaged associations of those facies which ultimately entered the stratigraphic record.

MAPPING OF FLUVIAL FAIRWAYS IN THE TEN BOER MEMBER, SOUTHERN PERMIAN BASIN

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ABSTRACT: The Ten Boer Member (ROCLT; Upper Rotliegend, Southern Permian Basin) is a claystone-dominated succession with thin sandstone beds, deposited on the margin of a large saline lake. The sandstone beds were deposited by fluvial channels and associated unconfined sheet floods in the distal part of a fluvial system. A recent re-perforation test in a depleted Rotliegend well successfully produced 30 Mm3 gas from a thin ROCLT sandstone bed at only 50K Euro re-perforation costs.
This success triggered a detailed study to map the fluvial fairways and assess the lithofacies associations of the ROCLT.

Based on log and core analysis the ROCLT succession is subdivided into five cycles, each characterised by a high-to-low-to-high gamma-ray succession and an associated mudstone–sandstone–mudstone sediment sequence. The cyclic succession is interpreted as a wet–dry–wet climatic change. Log correlation panels and gamma-ray-log-derived net sand maps show that the sandstone deposits are concentrated in SSW–NNE-oriented belts 15–30 km wide. The belts are fairways for fluvial transport from the Variscan Mountain Range in the south to the basin centre in the north. The shape of the fluvial fairways changes from elongate belts to lobe shapes across a narrow east–west-oriented transition zone. Net-to-gross drops drastically north of the transition, and the sandy lithofacies changes accordingly from stacked sandstone in the elongate belts to thin sheet sandstone embedded in claystone in the lobe-shaped part. Over time the fluvial fairways show a lateral shift, and the entire fluvial system gradually progrades northward.

The net sand maps assist to further constrain the locus of isolated sheet-sandstone reservoir units, and thus aid in future reservoir architecture modeling.

CYCLICITY AND FACIES RELATIONSHIPS AT THE INTERACTION BETWEEN AEOLIAN, FLUVIAL, AND PLAYA DEPOSITIONAL ENVIRONMENTS IN THE UPPER ROTLIEGEND: REGIONAL CORRELATION ACROSS UK (SOLE PIT BASIN), THE NETHERLANDS, AND GERMANY

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ABSTRACT: The Permian Upper Rotliegend Group in the UKCS Quads 48-49 was deposited in a mixed aeolian–fluvial–playa–lacustrine environment which displays different orders of internal cyclicity.

A low-frequency backstepping–forestepping depositional sequence, which encompasses the whole Rotliegend succession in the study area, was probably influenced by a long-term tectonic control. This depositional sequence can be subdivided into five cycle sets, 30–70 m thick, designated Unit U1 to Unit U5. These units are defined by the recognition of marked shifts in the evolution of depositional systems. The cycle sets are in turn subdivided into 16 elementary cycles (15–20 m thick), bounded by regionally widespread surfaces picked at the point of lower aridity. These high-frequency cycles show drying-upward and and drying-wetting-upward trends.

The Base Permian Unconformity shows a consistent topographic relief, and it represents a major sequence boundary. The lower part of the sedimentary succession, dominated by the deposits of semipermanent braided streams and catastrophic floods, was deposited in relatively confined sub-basins controlled by extensional WNW–ESE-trending faults. The fluvial system merged basinward into playa and lacustrine facies associations (U1).

Vertically, the succession records a climatic change from more humid conditions (U1) to a first aridity peak (U2) marked by erg expansion and a change in fluvial style, with ephemeral streams between the erg and the inherited structural highs. The aridity peak was combined with a smoother palaeotopography.

The middle to upper (U3–U5) part of the succession was deposited during a phase of tectonic quiescence in which the initial pronounced palaeotopography was almost completely leveled. Following a dramatic climatic shift toward more humid conditions, an erosional surface cut deeply into the underlying erg complex. This wetting phase was responsible for sudden deactivation of erg expansion between U2 and U3, abrupt reorganisation of depositional environments, and overall backstepping of facies belts (U3).

As a consequence of the maximum Silverpit Lake expansion, the depositional setting was characterised by strong lateral uniformity in the study area. Relatively confined fluvial systems fed thin and isolated sandstone lobes interbedded with lacustrine mudstones, which alternated with anhydrite-rich mudstones. These latter deposits, testifying to dry maxima, were correlative toward the margin of the basin with aeolian sandstones, highlighting the contraction of the playa lake (U4).

Following this prolonged stage, the sedimentary environment was characterised by deposition of gravity-flow-dominated delta-front lobes in the study area. This depositional change suggests active progradation under relatively humid conditions which characterised the uppermost interval of the Upper Rotliegend Group (U5).

The proposed hierarchy of the sedimentary succession, located at the interaction between fluvio–aeolian and playa–lacustrine depositional environments, provides a tool for the understanding of their mutual relationships in the UK sector (Rotliegend feather edge) as well as in the Dutch and German regions.

PALAEOTOPOGRAPHY-GOVERNED SEDIMENT DISTRIBUTION—A NEW PREDICTIVE MODEL FOR THE PERMIAN UPPER ROTLIEGEND IN THE DUTCH SECTOR OF THE SOUTHERN PERMIAN BASIN

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ABSTRACT: The Southern Permian Basin (SPB) formed a large, elongated saucer-shaped inland depression extending from the UK to Poland and from Belgium to Denmark. During the Middle to early Late Permian the SPB was filled progressively by playa sediments from its centre in northwestern Germany before it was flooded at the onset of the Zechstein. The Netherlands were situated at the southern part of the saline playa lake.

The sediment fill has an onlap configuration upon the underlying Carboniferous and Lower Rotliegend strata. Although regional contour maps suggest a fairly gradual thinning of the Upper Rotliegend interval towards the basin edge, more careful examination reveals that there are prominent steps in thickness and facies. It can be concluded that these steps are defined by steps in the palaeotopography of the basin.

These topographic steps are related to pre-Variscan and Variscan structural elements. During deposition of the Upper Rotliegend these large-scale topographic steps defined the location of the main fluvial fairways towards the basin centre, extensive (mud)flat areas, and the relative highs on which the dune fields developed. Next to these large topographic elements relief inversion, differential erosion, and faults caused smaller-scale topographic relief elements. This relief exerted prominent influence on the sediment dispersal patterns and sediment type both laterally and vertically. This holds especially true for the basal Rotliegend sandstones and in the pinch-out area near the playa margin.

SEDIMENTARY ARCHITECTURE AND PALAEOGEOGRAPHY OF LOWER SLOCHTEREN AEOLIAN CYCLES FROM THE ROTLIEGEND DESERT-LAKE MARGIN (PERMIAN), THE MARKHAM AREA, SOUTHERN NORTH SEA

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ABSTRACT: The Rotliegend gas play in the Southern Permian Basin has yielded over 200 gas fields in the Netherlands; they are found in an E–W fairway along the southern flank of the basin. Sandstones generally pinch out basinward, but localized, isolated sands are present north of the main fairway. The Rotliegend of the Markham gas field and a number of smaller fields in its vicinity ("Markham area") provides a good example of such an isolated sand occurrence, and it may serve as a model for exploration in the "feather edge" of the Rotliegend desert lake.

The reservoir interval (Lower Slochteren Member) is a diachronous sequence, 20–50 m thick, from aeolian-dune sandstones to desert-lake mudstones. Periodic fluctuations of lake level, probably controlled by short-period Milankovitch rhythms (precession or obliquity) resulted in the formation of desert-lake mudstone drapes that compartmentalize the reservoir over kilometers. The Lower Slochteren interval consists of four aeolian cycles, 5–15 m thick, which are retrogradational from sharpbased aeolian sandstone, via sandflat and mudflat deposits to desert-lake mudstone. Toward the south the clay-bearing facies pinch out and aeolian sandstones merge into a compound aeolian sandstone body 20 m thick. The aeolian cycles accumulated in an eastward-dipping, 10-km-wide palaeovalley in the Base Permian Unconformity. The cycles onlapped onto the valley margins until the entire valley was filled and a depositional plain came into place. The plain was flooded by the Rotliegend desert lake, followed by the formation of progradational cycles about 5 m thick, each consisting of a basal desert-lake mudstone grading upward into mudflat and sandflat deposits.

The change from retrogradational (fining-upward) cycles to progradational (coarsening-upward) cycles seems controlled by the rate of formation of accommodation space during lake-level rise. Initially palaeotopography restricted the creation of accommodation space, thus allowing sediment supply to keep up with rising lake level and forcing dune sands to stack up against rising palaeogeography, resulting in aggradational to retrogradational sequences. However, lake-level rise across the depositional plain caused regional flooding and rapid and far retreat of the lake-margin depositional system, causing accommodation space to be filled after the flooding and resulting in progradational sequences.

The Markham case shows that the presence of isolated Rotliegend sandstones is related to palaeotopography and that their internal architecture is controlled by periodic expansion and contraction of the desert lake. It emphasizes the importance of accurate seismic definition of the Base Permian Unconformity and detailed, sedimentology-driven correlation for future exploration at the fringes of the Rotliegend-play fairway.

SEDIMENTARY FACIES, CORRELATION, AND ARCHITECTURE OF ROTLIEGEND RESERVOIRS AT THE SOUTHERN PERMIAN BASIN MARGIN: THE P01-FA CASE STUDY AND THE CHALLENGED MYTH OF LAYER-CAKE STRATIGRAPHY

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ABSTRACT: Sedimentology, log analysis, and high-resolution seismic data of the P01-FA structure, located in the western part of the Netherlands sector of the North Sea, were used to assess the correlatability and connectivity of the sand bodies, to unravel the complex internal reservoir architecture, and to demonstrate the impact that different conceptual geological models driven by different correlation methods can have on the correct understanding of the subsurface.

Heterogeneity of reservoir architecture and internal reservoir facies was first assessed based on a well-to-well log-based correlation, and the results were compared with a correlation based on detailed examination of an inverted seismic cube.

The overall resulting reservoir architecture based on detailed seismic-supported geological and stratigraphical analysis is significantly different from the one based only on well-to-well correlation, which may, at first glance, suggest a simple layercake architecture. The new model highlights how both, the internal structural and stratigraphical framework and the distribution of reservoir facies are most likely the result of a complex interplay of erosion, sedimentation, and tectonics. Tectonics was especially active during the lower and middle part of the Upper Rotliegend Group accumulation, thus influencing the lateral continuity of individual stratigraphic units.

This study also demonstrates how unravelling the internal composition of mixed aeolian–fluvial reservoirs, by detailed seismic examination, is critical to describe the reservoir heterogeneity in order to assess and predict connectivity. This is especially important in sandy reservoir containing minor reservoir elements which can create large permeability contrasts (e.g., baffles and barriers) and ultimately influence hydrocarbon flow.

This study demonstrates that an integrated evaluation using detailed sedimentary facies analysis and examination of seismic inversion data can allow a better understanding of reservoir geology by reducing the subsurface uncertainties and thus the risk associated with future appraisal and development activities.

DIAGENESIS AND RESERVOIR QUALITY OF ROTLIEGEND SANDSTONES IN THE NORTHERN NETHERLANDS—A REVIEW

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ABSTRACT: The Permian Rotliegend clastic reservoirs form the main gas-bearing intervals in the Netherlands, Northwest Germany, and the Southern North Sea. We review and summarise the results of more than thirty years of diagenesis and reservoir-quality studies in Rotliegend sandstones of the Netherlands and adjacent areas.

The Rotliegend sediments were deposited in an alluvial–wadi–aeolian dune–sandflat–playa lake depositional setting, marked by an arid to semiarid climate, in which drier and wetter climatic cyclicity drove sedimentary processes. Present depths of Rotliegend reservoirs in the range of 2 to ca. 4.5 km, are often referred to as maximum burial depths. Rotliegend clastics were exposed to temperatures between 60°C and180°C. Structural uplift during Late Jurassic and Cretaceous times influenced the Rotliegend pressure and fluid-flow regime.

The paragenetic sequence is spatially variable and comprises a wide variety of authigenic minerals, with several early cements typical of continental red-bed sequences. Characteristic of semiarid (to arid) environments is reddening and the presence of grain-coating metal (Fe, Al, Mn, and Ti) oxides as well as smectitic, illitic, and chloritic grain-coating clays. Early blocky and often pore-filling cements include dolomite, gypsum, anhydrite, and halite, but also quartz and K- and Na-feldspar overgrowths. Burial-related authigenic precipitates are Fe-dolomite, calcite, siderite, and quartz cements, kaolinite, dickite, chlorite, and mainly fibrous illitic clay.

Dissolution of feldspar and volcanic rock fragments, of soluble pore-filling carbonate, sulphate, and halite cements, and the formation and destruction of secondary porosity are important factors in determining current reservoir properties. Most of the variance in porosity and permeability can be explained by a small number of significant variables: carbonate (and anhydrite) cementation, initial mineralogy, grain size, clay matrix content, diagenetic clay association, diagenetic quartz, and feldspar dissolution. Pore-blocking anhydrite and carbonate cements are the most pronounced phases that impacted on porosity. Impairment of permeability is due mainly to authigenic clays (illite, kaolinite, chlorite).

Even after pronounced diagenetic alteration the depositional setting remains as an important control on overall reservoir quality. Aeolian dunes and dry aeolian sandflat deposits remain the best potential reservoirs even under deep burial. However, pore-occluding blocky cements, mechanical compaction, or clay growth can heavily impair reservoir quality in optimum depositional facies, particularly under extende d exposure times to high temperatures. Long-term or continuous gas fills preserve favourable reservoir properties. The spatial proximity of Carboniferous source rocks to Rotliegend reservoirs in the Netherlands is considered to be a smaller risk for reservoir quality compared to northern German subsurface analogues.

Reservoir characterisation studies spanning more than three decades clarified the mechanisms, controlling factors, and relative timing of many diagenetic processes, but uncertainties about the quantities of resulting products remain. The multitude of interfering factors that control Rotliegend reservoir properties and the geological heterogeneity in the area does not favour conceptual models of regional applicability. Evaluation of the existing concepts on Rotliegend reservoir quality indicates the necessity of combining all available data to constrain the complexities of depositional facies, diagenesis, structuration, and charge history in the specific cases.

FRACTURES IN THE DUTCH ROTLIEGEND—AN OVERVIEW

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ABSTRACT: The Permian Upper Rotliegend sandstones from the Upper and Lower Slochteren formations form the main gas reservoir of the Netherlands and are the host for the giant Groningen gas field. Fractures in the Rotliegend are quite rare in the Dutch subsurface, based on the very large core and log database that has been acquired over half a century. The fractures therefore are not considered to be a major control on the reservoir response and gas recovery in most of these areas. The Rotliegend can have tight reservoir properties due to the combined effects of more pronounced mechanical compaction and diagenesis. In these situations the presence of natural fractures and creation of hydraulic fractures can assist in improving the vertical and lateral connectivity. The impact of fracture presence depends on the types of natural fractures and their orientation, which define preferred well paths and steer the selection of the optimal hydraulic fraccing methods to deploy in the tight gas reservoirs.

Many Rotliegend fields are compartmentalised by faults, creating baffles and barriers to fluid flow on a production timescale and more rarely on a geological timescale. Hydrocarbon columns in certain Rotliegend fields are longer than can be expected based on mapped structural closure, because of fault seal. Understanding fractures—their origin, orientation, and properties—assisted in improving the understanding of the properties of faults and the different potential fault-seal mechanisms that are observed in the Rotliegend. Fractures are in a way smaller representations of the larger faults in the subsurface.

The various Upper Rotliegend fracture types include cataclastic, cemented, shale smear, phyllosilicate framework, and open fractures. The most common types in the Upper Rotliegend are cataclastic and cemented fractures. Detailed laboratory analysis of fractures in cores has shown that both cemented and cataclastic fractures can hold significant pressure differences. However, cemented fractures and faults are not continuous and therefore likely leak through weaker, poorly cemented windows along the fault and fracture surfaces. Cataclasis may be continuous along the entire fault and fracture surfaces and may form a sealing mechanism in the high-net-to-gross Upper Rotliegend sandstones.

The Rotliegend fracture types and their properties are defined by the conditions of temperature, pressure, and stress during the deformation phase during which these fractures developed and by possible additional effects of conditions at subsequent tectonic phases. Knowledge of the geotectonic history of the Rotliegend is therefore of relevance to improve the understanding of the presence and properties of fractures.

This paper provides an overview of the tectonic history of the Rotliegend, describes fracture origin and propagation, addresses the various Rotliegend fractures in detail, and discusses implications for Rotliegend field development and exploration prospectivity. The purpose of this overview paper is to

contribute to Rotliegend structural characterisation, primarily by providing a catalogue of Rotliegend fractures. Reference is made in some places to fields and pressure and fluid data, but the intent is not to provide detailed field cases or fault-seal examples.

PRESSURE AND FLUID FLOW SYSTEMS IN THE PERMIAN ROTLIEGEND IN THE NETHERLANDS ONSHORE AND OFFSHORE

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ABSTRACT: Hydrodynamics-based approaches were used to characterise and analyse the present-day pressure and fluid-flow conditions in the Permian Rotliegend reservoirs in the Netherlands. These approaches involve the use of multi-well pressure–depth plots, regional all fluid overpressure maps, salinity maps, and hydraulic-head maps. The maps and plots revealed a general regional trend of, often stepwise, decreasing fluid overpressures from northeast towards the south. Values of fluid overpressure vary between hard geopressures (Pexcess > 40 MPa in block L2) and near-hydrostatic pressures (Pexcess < 1 MPa in southern offshore). The highest overpressures occur in a zone following the northern limit of the Permian Rotliegend reservoirs. The width of the zone of high overpressures extends southward into the onshore Netherlands in the area of the Lauwerszee Trough. The hydraulic-head map of the Rotliegend reservoir demonstrates the potential for a general southward dewatering direction.

The hydrodynamic evaluation identified that there are distinct regional differences between the southern and the northern part of the area with respect to important factors influencing both pressure generation (such as sedimentary loading and gas generation) and dissipation (by fluid flow) in the Rotliegend reservoir. The distribution of observed overpressures and hydraulic heads reflect these regional differences. We show that because the vertical and lateral dewatering of the Rotliegend reservoirs is controlled by the permeability framework, the regional variations therein exert a major influence on the observed distribution of fluid overpressure. Relatively high fluid overpressures are maintained in zones where dewatering of the Rotliegend is severely restricted. This is especially apparent in the southern part of the Dutch Central Graben and also in the northern part of the Lauwerszee Trough.