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Reservoir modelling of the Vlieland Sandstone of the Kotter Field (Block K18b), offshore, The Netherlands

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Abstract

The Vlieland Sandstone reservoir of the Kotter Field has significantly outperformed the original production forecast. In view of an anticipated decline of the oil production, a geological re-evaluation was carried out in 1989–1990, with the aims of contributing to increasing productivity and improving sweep efficiency.

Three closely related models have been developed. The Idealised Vertical Facies Association is a sedimentological model based on core material and represents an idealised vertical sequence of genetically related sedimentary facies. The model describes an overall regressive trend, produced by the progradation of a barred shoreface sequence, which is bounded top and bottom by transgression-related erosional surfaces. Within the reservoir interval, the trend described by the Idealised Vertical Facies Association is cyclically repeated.

The Field Geological Layer Model forms the synthesis of the geological knowledge to-date and presents a three-dimensional description of the reservoir resulting from the integration of core, wireline log and seismic data. It is characterized by a minimum of four stacked regressive-transgressive cycles (each representing partial development of the Vertical Facies Association) and comprises a total of thirteen, geologically distinct layers.

The Field Engineering Layer Model has been developed by modification of the Geological Layer Model in order to meet the specific input requirements of a reservoir performance simulation study and to improve cost-effectiveness. Up to the end of the geological modelling study (Dec. 1990), the results of the simulation study were satisfactory.

Introduction

Field history

The Kotter Field is located in Block K18b in the Dutch offshore sector (Fig. 1). Continental Netherlands Oil Company (CNOC) operates the block on behalf of Canadian Occidental Netherlands Petroleum Company, L.L. & E. Netherlands Petroleum Company, Elf Petroland B.V., Nederlandse

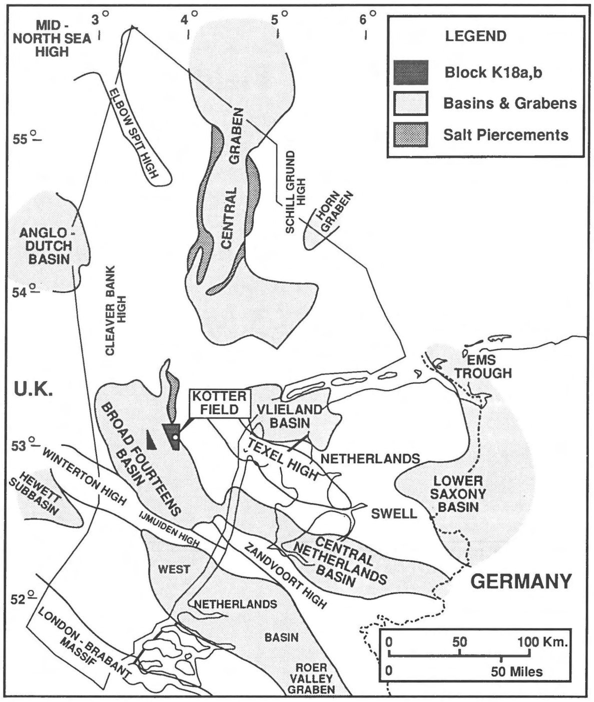

Fig. 1. Location map of Kotter Field (with major Mesozoic structural features). Based mainly on CNOC in-house studies and Ziegler (1982).

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Oil is produced from the Upper Delfland Sandstone 'Member' reservoir, discovered in 1980 by well K18-1, and from the Vlieland Sandstone Member reservoir (Fig. 2), discovered by well K18-2a in 1981. Well K18-3, drilled in 1982 and located approximately 0.6 km north-northeast of the field, was plugged and abandoned as a dry hole. The Vlieland Sandstone is the main Kotter Field reservoir and is the subject of this study.

Development of the field started in 1984, with first oil produced in September 1984. Up to December 1990, thirteen development wells (including sidetracks) have been drilled from the Kotter Platform. Six of these produce from the Vlieland Sandstone: K18-Kotter-1, -2, -3, -4, -8a, and -10 (Fig. 4). K18-Kotter-8a is a horizontal well which was recently drilled as a Vlieland Sandstone sidetrack from the K18-Kotter-8 Upper Delfland producer, which was shut-in for economic reasons. Note the dramatic increase in field production after this well was brought on-stream (Fig. 3). K18-Kotter-6 and K18-Kotter-9 are Vlieland Sandstone injectors (Fig. 4). The other wells are either Delfland producers/injectors or not-completed/suspended.

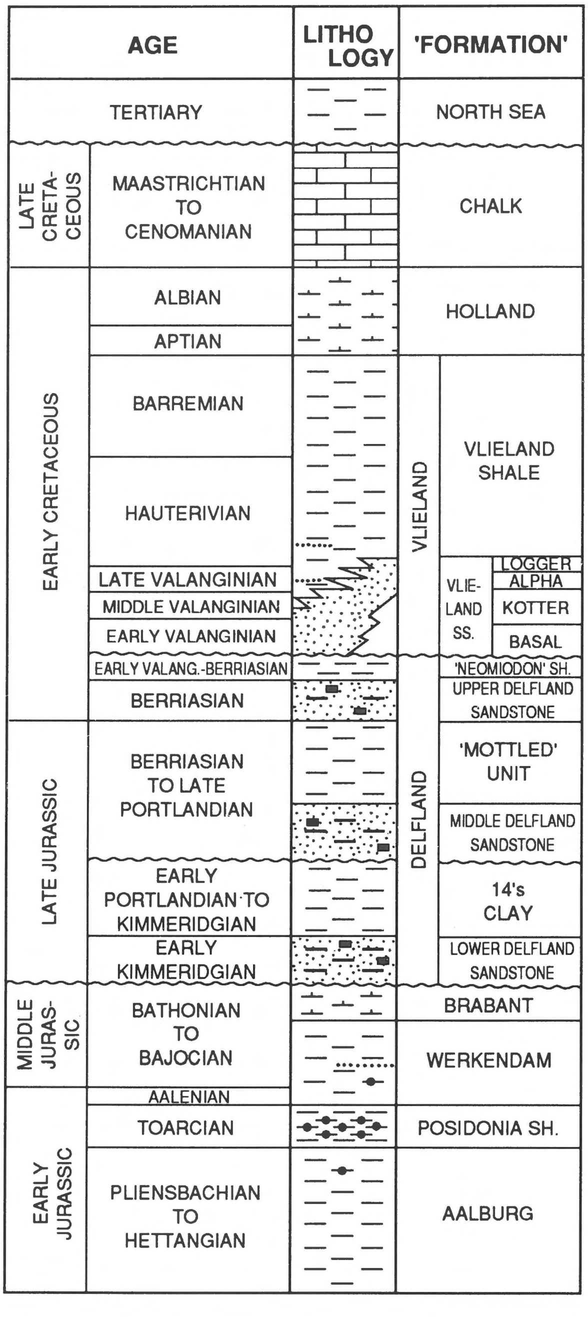

Fig. 2. Stratigraphic table for the Kotter Field area. Based mainly on CNOC in-house studies and NAM & RGD (1980).

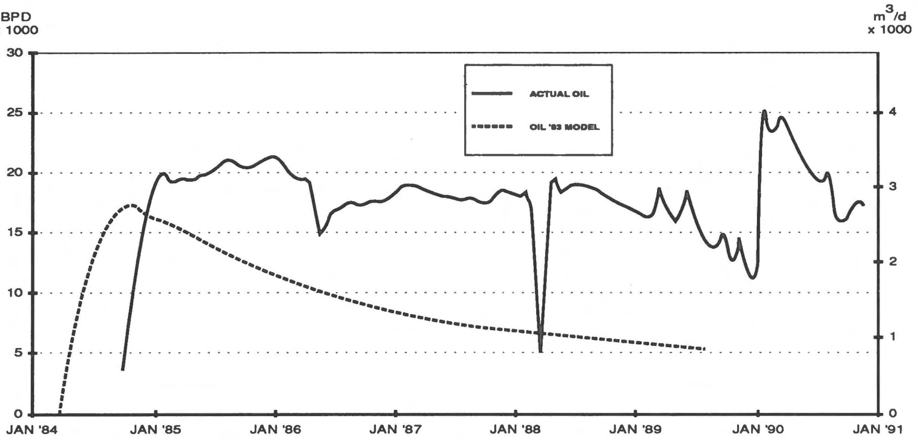

Fig. 3. Oil production data for the Kotter Field up to December 1990. The dashed line shows the predicted production rate based upon the previous (1983) model. The solid line shows the actual production to have far exceeded expectations. Note that the large jump in production after January 1990 is due to the drilling of a horizontal well (K18-Kotter-8a) in the reservoir. BPD: barrels per day.

Main production is from the Vlieland Sandstone reservoir, with a cumulative oil production, up to December 1990, of approximately 41 million barrels (MMBO), i.e. 6.5 million m^3. Total production from the field, up to December 1990, is approximately 44.5 MMBO or 7 million m^3.

Goals and objectives of the project

The Vlieland Sandstone reservoir has significantly outperformed the original production forecast (Fig. 3). In view of an anticipated decline in production, a major geological re-evaluation of the reservoir was undertaken in 1989–90 with the goal of contributing to a continuing high level of productivity and to improving the sweep efficiency of the field.

The following specific objectives were defined:

- to make a geological/depositional model for the Vlieland Sandstone and provide detailed geological input to reservoir modelling and production history matching efforts in the form of layer parameter maps and grids;
- to quantify reservoir heterogeneity at various scales;
- to prepare the data for a detailed calculation of the volume of oil originally in place in the reservoir.

The present paper describes the approach that was undertaken to meet the objectives, and presents some of the project's results.

Detailed geological analysis has been restricted to the uppermost two-thirds of the Vlieland Sandstone, representing the oil-leg and the upper part of the water-leg. The restriction of the study to this interval was governed both by the availability of core (maximum 92 metres below formation top) and by the needs of the reservoir-engineering model, which did not require a detailed analysis of the water-leg.

General geology

Structural setting

Block K18b is situated in the northeastern margin of the Jurassic-Cretaceous Broad Fourteens Basin, which is an inverted wrench-rift basin. Rift-related rotation and growth faulting occurred along northwest-southeast oriented Hercynian structures, with peak subsidence occurring in Late Jurassic times. Inversion took place during the Late Cretaceous (-Early Tertiary) Laramide tectonic phase, in reaction to compression in the Broad Fourteens Basin (Ziegler 1982).

The Kotter structure (Fig. 4) is situated on a

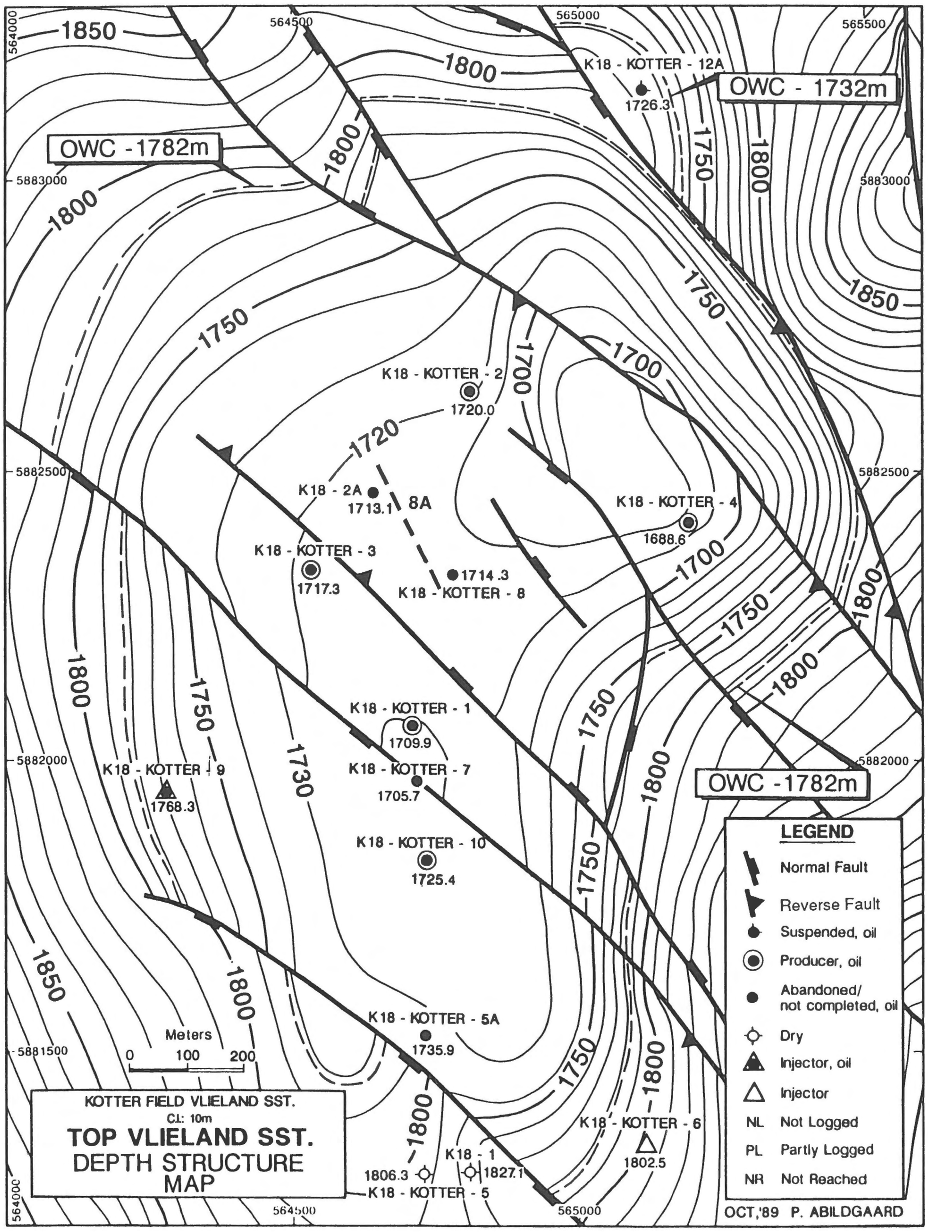

Fig. 4. Top Vlieland Sst. depth structure map showing well locations and the main structural features. Note the presence of a small dip & fault closure to the north of the main field. The normal faults grading laterally into reverse faults in the northeastern part of the field reflect the inversion of old normal faults. K18-3 is located approximately 0.6 km NNE of the field.

north-northwest trending, compressional, faulted anticline formed during the Laramide tectonic phase along rejuvenated growth faults. Maximum net horizontal movement along the major faults in the Kotter Field area is estimated to be about 3000 m. The Kotter Field structure shows four-way dip closure at Vlieland Sandstone level, with an original oil-water contact (OWC) at −1782 m True Vertical Depth Sub Sea (TVDSS). A small, separate accumulation of oil with an OWC at −1732.1 m TVDSS occurs in a fault block north-northeast of the main accumulation.

Stratigraphic setting

The Vlieland Sandstone Member represents the transgressive basal section of the Vlieland Formation (Cottençon et al. 1975, NAM & RGD 1980, Crittenden 1982). It overlies the 'Late Kimmerian Unconformity' (Rawson & Riley 1982) and represents the onset of the major Early Cretaceous transgression. Regional geological and seismic-stratigraphic studies by CNOC of the Late Jurassic to Early Cretaceous geology of blocks K18a and b and adjacent areas have identified four sand units within the Valanginian-Hauterivian (Fig. 2), which show a step by step transgression over the east-northeast flank of the Broad Fourteens Basin. They are termed (from base upwards) the Basal, Kotter, Alpha and Logger sand units. In the Kotter Field, the Basal sand and Kotter sand have been merged into one unit, termed the Kotter Field Vlieland Sandstone in the present study. Some evidence exists that the interface between both sands occurs in the basal section of the sandstone, which is beyond the scope of this study.

Biostratigraphy suggests a 'Middle'-Late Valanginian age for the upper two-thirds of the Kotter Field Vlieland Sandstone.

The transgressive marine shales of the Vlieland Shale Member, of Valanginian-Barremian age, form the seal for the Vlieland Sandstone reservoir.

The Toarcian Posidonia Shale is generally considered the oil source rock in the area. CNOC in-house studies show that the onset of kerogen maturation and migration took place in Early Cretaceous times in the deepest part of the Broad Fourteens Basin. In some areas, because of the Late Cretaceous inversion and subsequent Tertiary re-burial, maturation and migration may be continuing presently.

Depositional setting of the Kotter Field Vlieland Sandstone

The Vlieland Sandstone Member is described by NAM & RGD (1980) as the transgressive basal section of the Vlieland Formation, often consisting of one or more coarsening-upward sequences interpreted to be barrier sands, partly reworked into transgressive sheet sands (see also Cottençon et al. 1975). CNOC in-house studies have identified the Vlieland Sandstone in the K18b block as littoral sands.

A stacking of paralic deposits at the base of an overall transgressive series similar to the one presented here is not uncommon in the geological record and has been reported from various areas (see Franks 1980, McCubbin 1982, Reinson 1984). The main factors controlling such a pattern are the rate of sediment supply and relative sea level changes, the latter being a function of uplift, subsidence and eustatic sea level changes.

Palynofacies analyses of the Kotter Field cores indicate a littoral environment with depositional settings ranging from upper offshore to upper shoreface, with a possible minor lagoonal intercalation. Lower Cretaceous sands equivalent to the Kotter Field Vlieland Sandstone in Block Q/1 have been interpreted to be littoral deposits (Roelofsen & De Boer 1989).

Within this framework, a sedimentological model of the field has been constructed. The main diagnostic features of the facies identified in this model are displayed in Fig. 6.

Geological and engineering reservoir models

General

Three closely related models (see also Slatt & Hopkins 1990) have been constructed which each describe different aspects of the geology of the Vlieland Sandstone reservoir.

The first model, the Idealised Vertical Facies Association, is a two-dimensional sedimentological description of the reservoir. It is the synthesis of the sedimentological facies described in core and represents an upward coarsening and cleaning trend of genetically related facies formed by the progradation of a barred shoreface sequence. The top of this regressive association of facies is marked by a sharp or erosive junction formed by the transgressive drowning of the deposit. Within the reser-

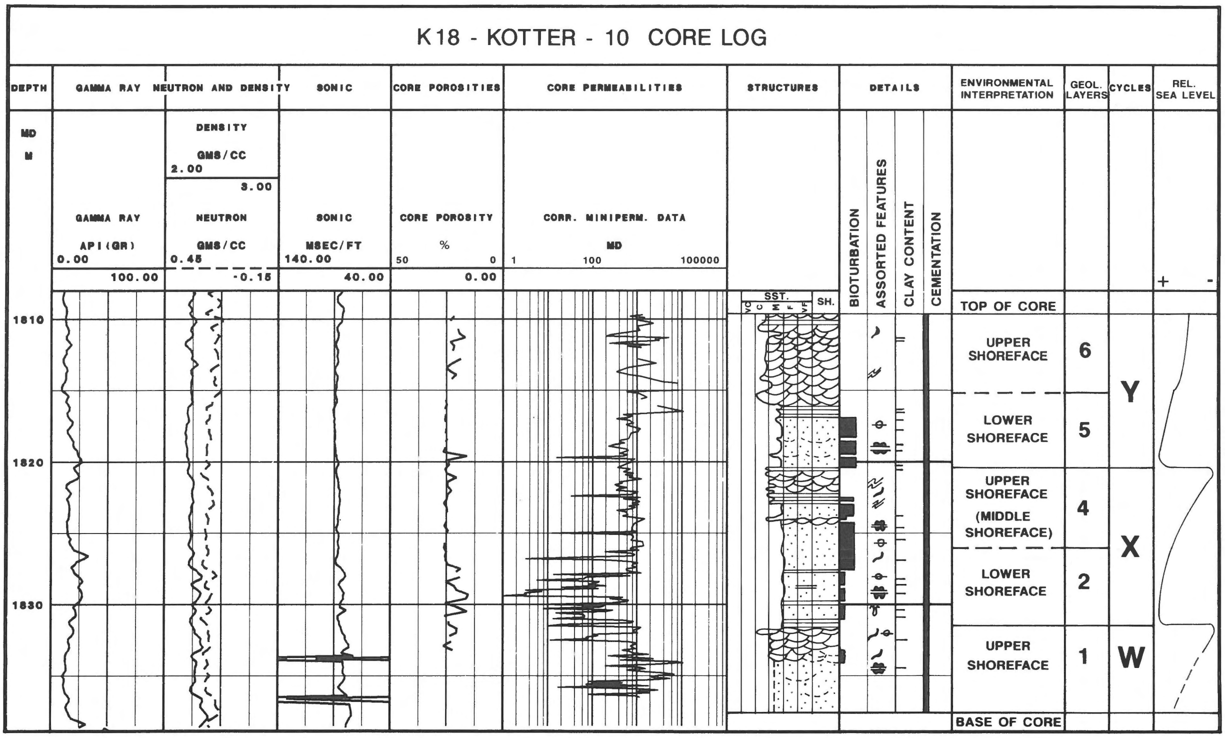

Fig. 5. K18-Kotter-10 core log showing typical wireline log responses, core analytical data and sedimentary features for the major sedimentological facies. Minipermeameter profile (calibrated to routine plug data) shows effect of thin clay laminae upon permeabilities (MD: millidarcy). Degree of bioturbation, clay content and degree of cementation are indicated on a 0–100% scale from left to right. Assorted features are mainly types of bioturbation and small-scale deformation structures. MD in depth column: measured depth along borehole.

voir interval the trend described by the Idealised Vertical Facies Association is cyclically repeated.

The Field Geological Layer Model is a three-dimensional geological description of the reservoir, with cycles and layers as key components. A cycle consists of a complete or partial development of the Idealised Vertical Facies Association. Each cycle is subdivided into a number of layers based upon correlatable geological parameters. A layer comprises either a single facies or a combination of facies, each displaying distinct reservoir characteristics. Between wells the facies and layers may vary within the genetic units. Wireline logs are essential for correlations in the construction of the Field Geological Layer Model.

The Field Engineering Layer Model is a transformation of the Field Geological Layer Model to meet specific input requirements of the reservoir performance modelling. The latter is carried out on a computer and requires a cellular description of the reservoir. Geological layers are either combined or subdivided into units, termed engineering layers, which form the basis of the cellular description.

Idealised Vertical Facies Association

Sedimentological logs at scale 1: 50 have been made for cores from wells K18-2a (91 m), K18-3 (23 m), K18-Kotter-9 (49 m) and K18-Kotter-10 (28 m). The sedimentological descriptions have been integrated with wireline logs and core analytical data.

Figure 5 presents a scaled-down version of the K18-Kotter-10 core log. It illustrates the regular stacking of facies which was observed in all cores. The Idealised Vertical Facies Association (Fig. 6)

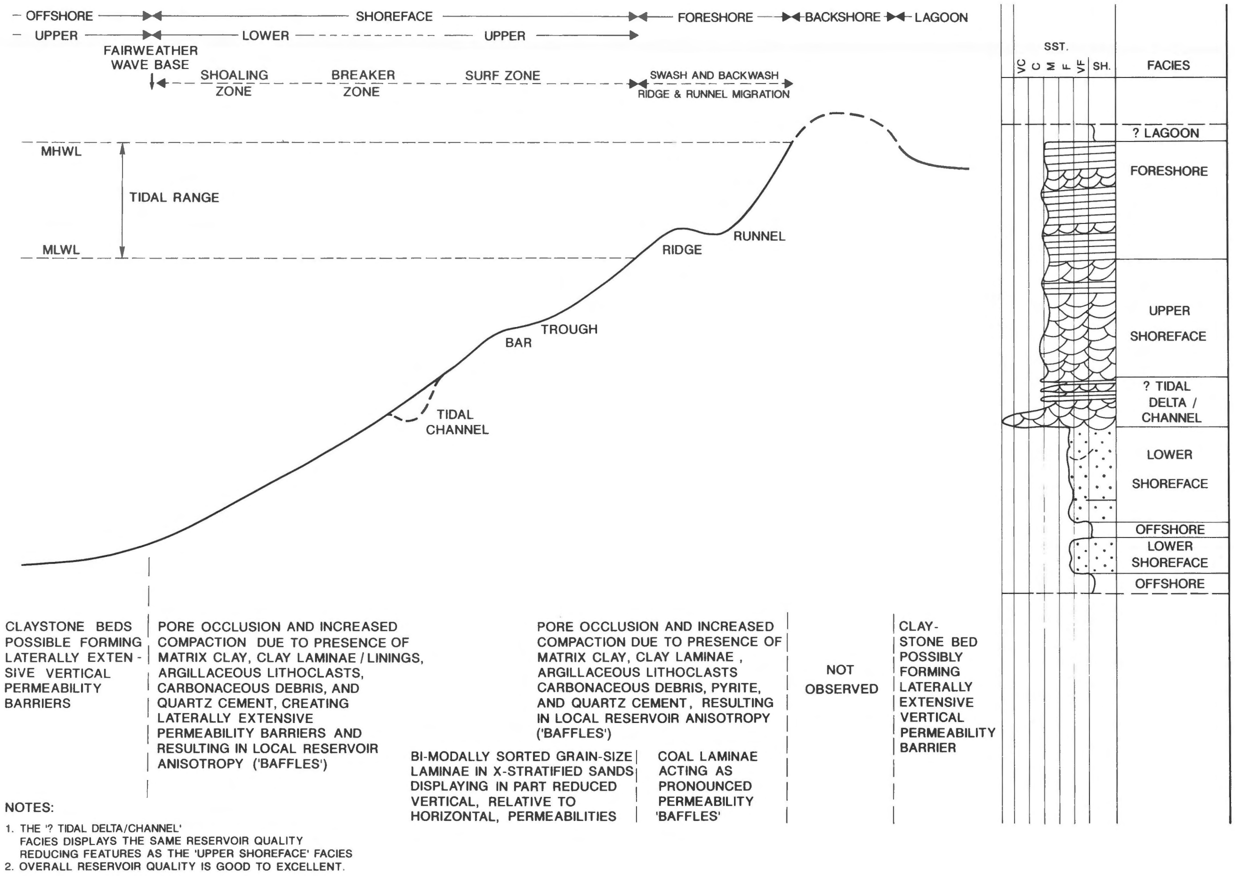

Fig. 6. Idealised Vertical Facies Association, with main reservoir quality reducing factors. Tidal delta or tidal channel facies is often absent, but where present may cut down into the lower shoreface. The model has a distinctive coarsening and cleaning upwards profile reflected in an upward increase in permeability.

has been derived by combining the individual sedimentological facies recognised in core and through the development of a depositional model for the Kotter Field Vlieland Sandstone. The sequence described by the Idealised Vertical Facies Association starts with argillaceous upper offshore sediments and passes upward to lower shoreface, upper shoreface and foreshore facies. It may be capped by a lagoonal claystone. This vertical facies association is thought to result from the progradation of a barred shoreface. A sharp, possibly erosive boundary, due to transgression, forms the top of this regressive association of facies. Intercalated sediments, possibly deposited in a tidal delta or tidal channel environment, form a locally occurring facies type.

The Idealised Vertical Facies Association is a hypothetical model and is incompletely developed in the study wells. This incomplete development reflects both the level of accommodation (i.e. the space available for sediment accumulation) and the degree of truncation that occurred during transgression.

The next paragraphs briefly describe the most important sedimentological and wireline-log characteristics of the various facies encountered. Diagnostic criteria for the interpretation of such facies in general and information on their depositional setting have been presented by De Graaff (1977), McCubbin (1982), Reinson (1984), and Walker (1985). The results of the palynofacies analysis are presented as an integral part of the sedimentological interpretations.

Offshore facies

The offshore facies consists of thin, strongly bioturbated claystone beds with nodular concentrations of secondary dolomite and/or siderite, which are at or below the resolution of wireline logs. It is not possible to systematically differentiate between offshore clayey and lower shoreface clayey sandstones, due to strong bioturbation having obliterated diagnostic features. The offshore facies does not possess reservoir quality.

Lower shoreface facies

The lower shoreface facies is characterized by variably argillaceous, strongly bioturbated, fine-grained sandstones. Clay occurs both as remnant patches of thin laminae and as admixed matrix (Figs 10A, 10B). Dispersed coaly debris and sand-sized ductile argillaceous lithoclasts/faecal pellets are common. Stratification is generally obliterated by bioturbation. The facies commonly shows a varying, relatively high gamma ray response. Reservoir quality is considered to be reasonable though variable grain packing and matrix clay distribution have introduced significant permeability anisotropy and zones of poor permeability occur, notably in Geological Layer 2 (Fig. 5). Thin discontinuous clay streaks and laminae are interpreted to reduce vertical permeability.

Upper shoreface facies

The upper shoreface facies is characterized by medium- to coarse-grained sandstones (Fig. 11B) with minor amounts of detrital clay. Trough cross-stratification is predominant with subordinate low-angle stratification. Bioturbation is virtually absent. Dispersed coaly debris is common. Rare coaly flasers and laminae are interpreted to have been deposited in interbar troughs, located between shoreface bars. The upper shoreface facies shows low gamma ray readings. Reservoir quality is typically good with little permeability anisotropy (cf. Fig. 5). Core plug values for vertical permeability in the beds with trough cross-stratification are typically lower than those for horizontal permeability.

Foreshore facies

Relatively thick sections of medium- to coarse-grained sandstones (Fig. 11B) displaying sub-horizontal to low-angle stratification, are interpreted to be beachface deposits. Trough cross-stratified, medium- to coarse-grained sandstones with coaly flasers showing pronounced responses on the neutron-density wireline logs, are interpreted as foreshore deposits. These coaly accumulations are interpreted to result from storm deposition on the foreshore.

A combined low gamma ray response and 'coal' response on the neutron-density logs is considered indicative of the foreshore facies. It is noted, however, that carbonaceous debris is in fact fairly rare in this facies.

Reservoir quality of the foreshore facies is good to excellent provided the carbonaceous content is low. High concentrations of carbonaceous debris are often associated with increased levels of compaction and pyrite cementation and thus severely reduce reservoir quality.

Lagoonal facies

Lagoonal sediments only occur in the K18-2a cores as a single thin (approx. 15 cm) claystone bed. This claystone contains a kerogen suite suggestive of deposition in a low-energy, possibly lagoonal setting. It does not have a distinctive wireline log character.

Tidal delta/channel facies

Sharply, usually erosionally based, upward fining, cross-stratified sandstone sequences up to 9 metres in thickness are thought to represent tidal channel deposits. Similar sandstones which do not display this well-developed upward fining trend may represent tidal delta developments, or poorly developed tidal channels. These deposits usually sharply and erosively overlie lower shoreface deposits.

Evidence for tidal currents is not conclusive. However, the presence of well-developed re-activation surfaces, of rhythmically alternating, bimodally-sorted foreset laminae (Fig. 11A), and of medium- to coarse-grained, trough cross-stratified sandstones regularly interbedded with fine-grained, laminated beds showing sub-horizontal to low-angle stratification, all suggest some degree of tidal influence.

Such tidal deltas and channels are typically oriented (sub)perpendicularly to the shoreline. This preferred orientation of the sandbody in turn gives rise to a permeability trend and hence to a preferred direction of fluid movement (sub)perpendicularly to the paleoshoreline.

The tidal delta or tidal channel facies shows a low gamma ray response, but this is not unique to this facies. The facies is very poorly defined on the other wireline logs.

Reservoir quality is generally good to excellent in these sandstones. Core plug values for vertical permeability are typically lower than those for horizontal permeability reflecting the strongly bimodal sorting of many of the beds and laminae.

Field Geological Layer Model

Introduction

The Field Geological Layer Model is a three-dimensional geological description of the reservoir resulting from the integration of core, wireline log and seismic data. There are three aspects to the description. Firstly, the Idealised Vertical Facies Association has been used to identify the presence of a number of regressive-transgressive cycles within the cored intervals. These have then been correlated across to the uncored intervals, using wireline logs. The product is the three-dimensional geological layer framework consisting of a series of vertically stacked regressive-transgressive cycles (labelled W, X, Y and Z from bottom to top) and a sequence of layers (1 through 13 from bottom to top; Figs 7, 8). Secondly, core-based petrophysical and petrological data has been used to characterize the reservoir properties of the layers. Thirdly, field-wide layer maps have been generated for individual layers or combinations of layers, portraying features such as isochore thickness and porosity distribution.

Geological layer framework

The geological layer framework which resulted from the integration of core sedimentological data and wireline logs is schematically presented in two-dimensional form in Fig. 8. Four, stacked, cycles and thirteen layers have been distinguished. Geological layers have been principally defined on the basis of correlatable sedimentary facies. In addition, porosity and permeability variations have been taken into account as the objective was to identify layers with distinct reservoir character (flow units). Consequently, the geological layers do not necessarily coincide with sedimentary facies, although they do broadly correspond to them.

			GEOLOGICAL LAYER MODEL		ENGINEERING LAYER MODEL
KOTTER FIELD VLIELAND SANDSTONE	CYCLE Z	Z 2	Layer 13	Upper Shoreface / Foreshore	Layer 13b
			Layer 12	Lower Shoreface	Layer 12+13a
		Z 1	Layer 11	Upper Shoreface	Layer 11
			Layer 10	? Tidal Delta / Channel	Layer 10
			Layer 9	Lower Shoreface	Layer 7+8+9
			Layer 8	? Tidal Delta / Channel	
			Layer 7	Lower Shoreface	
	CYCLE Y		Layer 6	? Lagoon Upper Shoreface /Foreshore	Layer 6
			Layer 5	Lower Shoreface / Offshore	Layer 5
	CYCLE X		Layer 4	(Middle Shoreface) Upper Shoreface	Layer 4
			Layer 3	Lower Shoreface / Offshore	Layer 3
			Layer 2	Lower Shoreface / Offshore	Layer 2
	'CYCLE' W		Layer 1	Upper Shoreface	Layer 1
			NOT ANALYSED		

Fig. 7. Geological and Engineering Layer Schemes, showing the amalgamation of Geological Layers 7 + 8 + 9 and the modification of Layers 12 + 13 to Engineering Layers 12 + 13a and 13b.

The large thickness of the Vlieland Sandstone in and around the Kotter Field indicates that the area was a local depocenter for a prolonged period of time, suggesting that subsidence occurred during deposition. Isochore mapping of the various reservoir units also suggests synsedimentary fault movement.

The cycle boundaries are interpreted to be laterally extensive, erosional or non-depositional surfaces, based on vertical facies contrasts. Readily correlatable features such as erosional lag deposits or root horizons have not been observed at the interfaces.

The possibly lagoonal claystone bed at the top of Cycle Y directly overlies an upper shoreface/fore-

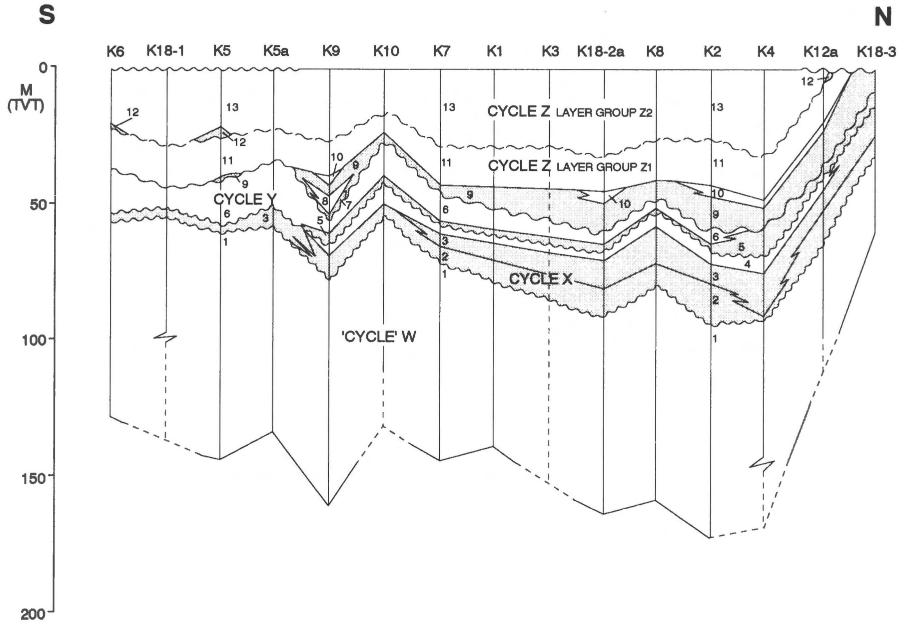

Fig. 8. Schematic well to well correlation diagram. The restricted development of some layers (i.e. 7, 8, 10, 12) reflects the localised development/preservation of sedimentological facies. Some layers (e.g. 2, 3 and 4) show lateral facies transitions within individual, unconformity-bounded, cycles. The section is oriented south to north across the field. The shaded layers are composed of lower shoreface and offshore facies. TVT: true vertical thickness.

shore unit. This suggests that a backshore-dune facies that formed the physical barrier between the lagoon and the open sea (cf. Bridges 1976) existed prior to falling victim to erosion. The presence of possible tidal channel/delta deposits in Cycle Z also suggests the presence of a barrier.

Paleogeographical reconstructions have been made for Cycle X, Cycle Y, Layer Group Z1 and Layer Group Z2 (Fig. 9). Partial fault control has been assumed in the reconstructions. Three main environments are distinguished:

- An environment dominated by high-energy wave action in relatively shallow water, generally characterized by upper shoreface and foreshore facies.
- An environment which through time changed from being dominated by low-energy wave action in relatively deep water, to being dominated by high-energy wave action in relatively shallow water, thus reflecting a prograding shoreline.
- An environment dominated by low-energy wave action in relatively deep water, generally characterized by lower shoreface and offshore facies.

The lower part of Cycle W has not been investigated because most of the sediments of this cycle occur within the water leg. The upper part consists of an upper shoreface unit (Fig. 7).

Vertical and lateral trends within cycles and layers

Increased truncation and reduced accommodation are thought to have resulted in reduced thickness of Cycle X in the southern part of the field (Fig. 8), with only a thin and indistinctly developed Layer 3 being preserved. Water depth is interpreted to have been relatively shallow and energy relatively high. Thicker preserved sediment sequences, with a predominance of lower shoreface facies, occur in the central and northern parts of the field. These features are interpreted to reflect a progressive increase in water depth and decrease in wave energy towards the north, during most of Cycle X's lifetime.

The overall paleogeographical picture for Cycle Y is fairly similar to that of Cycle X. The different

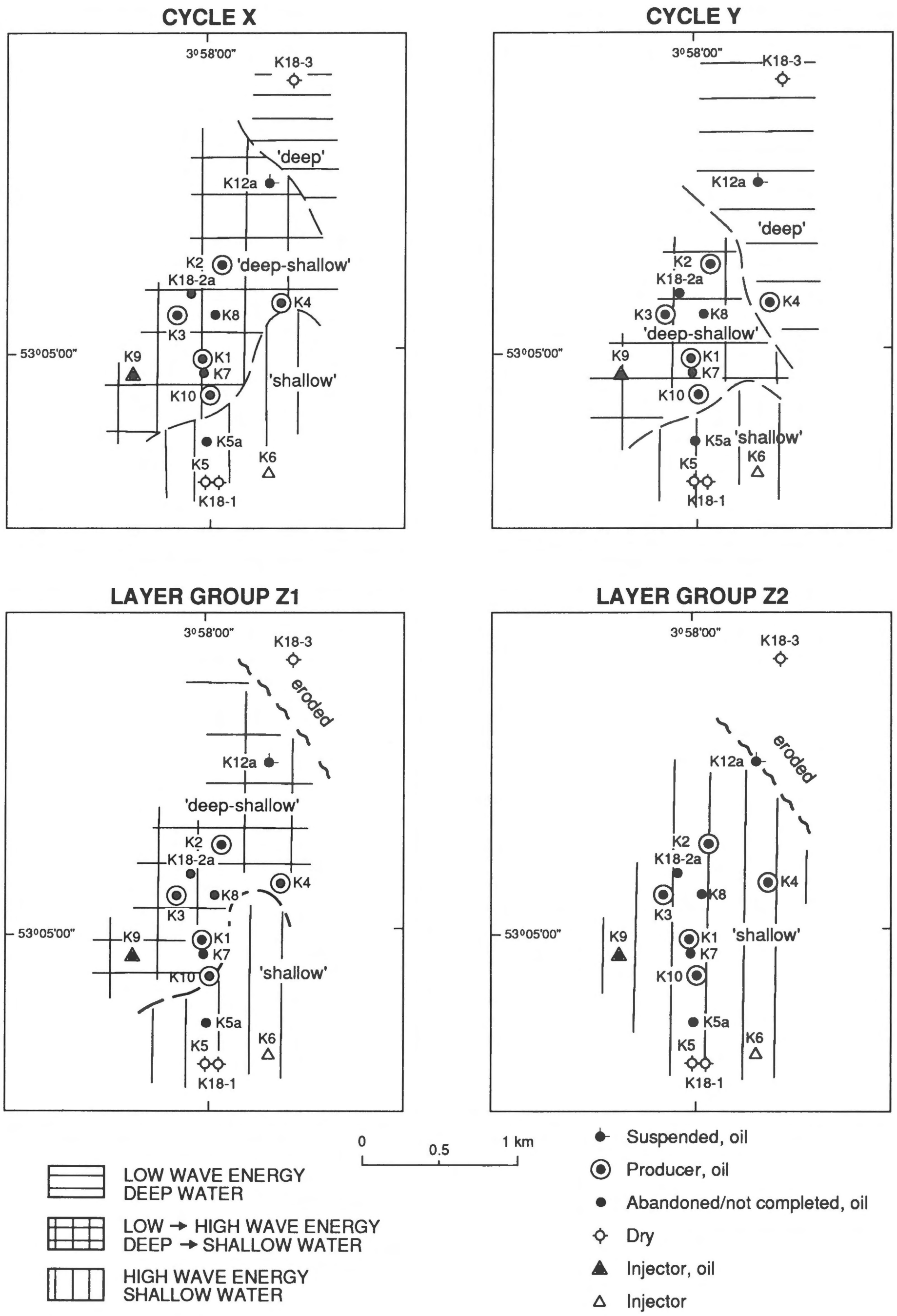

Fig. 9. Schematic paleogeographical reconstructions showing the interpreted lateral transition of sedimentological facies within the Kotter Field for Cycles X and Y and Layer Groups Z1 and Z2. Note how facies development is assumed to have been influenced by faulting north of K12a and southeast of K4 (see also Fig. 4).

pattern of total preserved sediment thickness and the presence of the possibly lagoonal clay cap, however, suggest a somewhat different development through time. It is beyond the scope of this paper to discuss these variations in detail.

Some wireline log evidence exists in wells K18-

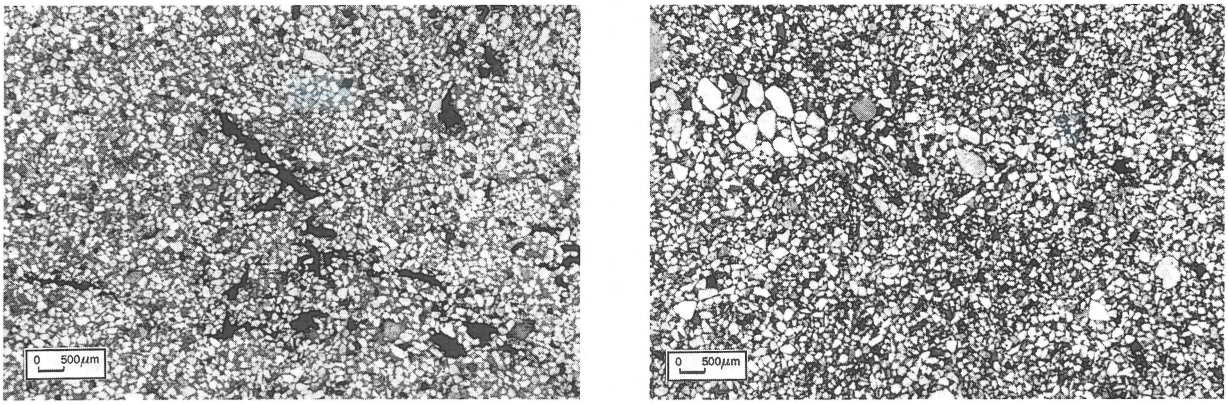

Fig. 10. Thin section photos from Geological Layer 9 in well K18-Kotter-9. A. Very fine- to fine-grained sandstone (quartz arenite) of the lower shoreface facies. Detrital clay occurs both as thin laminae (disrupted by bioturbation) and as dispersed faecal pellets. The discontinuous clay laminae will act as baffles to fluid flow. However, high porosity and good pore interconnection (medium- to dark-grey tones) are evident. B. Very fine- to fine-grained, strongly bioturbated lower shoreface sandstone (quartz arenite). Pockets of coarser material represent burrow infills. Note the heterogeneity of grain packing throughout the sample, which will cause permeability to be anisotropic on a microscale.

Kotter-5, -6 and -12a for the presence of a thin layer of lower shoreface sediments within Cycle Z, i.e. Layer 12. This suggests that Cycle Z may consist of two regressive-transgressive trends or cycles. In the absence of conclusive evidence for two distinct cycles, however, Cycle Z has been subdivided into two layer groups only. The paleogeography of Layer Group Z1 is thought to have been quite similar to that of Cycle X. Relatively uniform shallow water and high energy conditions existed throughout most of the area during the lifetime of Layer Group Z2.

With the exception of Layers 1, 11 and 13, the layers do not extend laterally across the whole field but show lateral transitions. This is best demonstrated by Cycle Y, where Layer 5 passes both laterally and vertically into layer 6. This is thought to reflect both lateral facies variations and the progradational nature of the deposits within this cycle. Within each cycle the vertical transition between layers reflects the upward coarsening and cleaning nature of the sequence, resulting in a distinctive vertical trend in which the lowermost layers represent the finer grained, more argillaceous, tighter sediments and the uppermost layers comprise the cleaner more permeable sandstones. This not only results in the development of an overall permeability profile of increasing values upward within each cycle but also in a juxtaposition of relatively tight and relatively permeable sediments across each cycle boundary. This will result in reduced vertical communication between cycles. Similarly, the presence of a thin, possibly laterally extensive, lagoonal shale at the top of Layer 6 is expected to severely reduce fluid communication with the overlying cycle.

The regular layering of the sediments and the uniformity of depositional processes suggest a uniform, large-scale sedimentary 'grain' with units of similar permeability likely to occur parallel to the shoreline. However, within the spatially restricted tidal delta/channel facies (Layers 8 and 10) such a sedimentary 'grain' is expected to be perpendicular to the shoreline. These sedimentary 'grains' may result in preferred directions of fluid movement during production.

Mineralogy, diagenesis and reservoir quality

The sandstones of the Kotter Field Vlieland Sandstone comprise fine-to coarse-grained, moderately to well sorted, mineralogically mature, quartz arenites (Figs 10A, 10B, 11A, 11B). Packing and compaction are moderate throughout the sandstones. Feldspar and ductile clay intraclasts/faecal pellets occur in subordinate amounts. Carbonaceous debris is generally a minor component, but in some

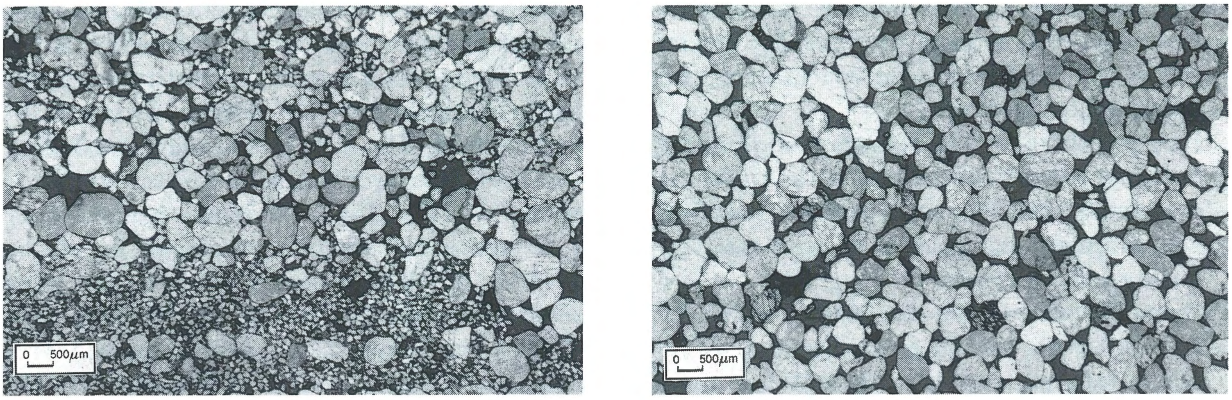

Fig. 11. Thin section photos from Geological Layer 10 (A) and Geological Layer 13 (B) in well K18-2a. A. Bimodally sorted (very fine- to fine-grained and medium- to coarse-grained) sandstone (quartz arenite) of the tidal delta or tidal channel facies. Common oversized grain dissolution pores (medium- to dark-grey tones) are present in the coarser grained laminae. Permeability is expected to be strongly anisotropic. B. Well-sorted, medium- to coarse-grained sandstone (quartz arenite) of the upper shoreface/foreshore facies showing high porosity and well-interconnected pores (medium- to dark-grey tones). Note the lack of cementation and the common oversized grain dissolution pores.

layers may comprise 25% of the sediment. Detrital clay is generally of minor importance (<4%) forming either thin laminae or widely disseminated matrix.

Authigenic cements are volumetrically of minor significance. Quartz is the most important cement, typically forming poorly developed, euhedral, syntaxial overgrowths. However, quartz cement is volumetrically still unimportant comprising a maximum of 4% of the sediment. Carbonate cements comprise rare ferroan calcite and occasional dolomite and/or siderite nodules formed within claystones, but are overall insignificant volumetrically. Pyrite is a typically minor replacive phase associated with argillaceous and carbonaceous material. Minor kaolinite occurs as isolated pore-filling aggregates of booklets. Illite-smectite is generally a platy pore-lining phase which is often associated with degraded clay lithoclasts.

Reservoir quality is typically good to excellent throughout the Vlieland sandstones of the Kotter Field. Pores are dominantly secondarily enlarged, intergranular types with variably enlarged pore throats resulting in good to excellent permeabilities. Secondary porosity enhancement resulted from a late phase of intense dissolution of alumina-silicate framework grains, which caused strong leaching of feldspar and clay clasts. Corrosion of silica grains and cements is minor. Textural evidence for dissolution includes the presence of abundant enlarged and oversized pores, elongate and/or channelised pore systems, re-opened grain contacts, dissolution remnants of grains and occasional tight zones containing small primary pores.

In addition to the possible influence of the large-scale sedimentary 'grain' on fluid movement within the reservoir, a number of macroscale controls on fluid flow has been identified from integrated petrographic work. These are:

- Thin claystone horizons (offshore facies; lagoonal facies), which may be of significant lateral extent, are expected to act as vertical permeability barriers.
- Tight carbonaceous-rich horizons, as observed in the foreshore facies, are thought to be laterally extensive across parts of the field and are expected to act as vertical permeability barriers.
- The overall upward coarsening and cleaning nature of each depositional cycle results in an upward improvement of permeability within each cycle (Fig. 5).

A number of microscale controls upon reservoir quality has also been determined, which result in reduced reservoir quality or significant reservoir anisotropy:

- Clay occurring as matrix and as discrete laminae, especially in the lower energy, lower shoreface sediments, reduces permeability, creates baffles to fluid flow and introduces significant permeability anisotropy.

- Biogenic churning and homogenisation of the sediment has introduced matrix clays into the sandstones which may act as baffles to fluid flow and which created pockets of poor reservoir quality and low recovery.
- Bimodally sorted grain size laminae within the cross-stratified, coarser grained sandstones result in reduced ratios of vertical to horizontal permeability.
- Discontinuous tight streaks associated with carbonaceous debris may act as baffles to fluid flow.
- Variations in quartz cement distribution may cause reservoir anisotropy.

Because limited core permeability data was available, the permeability variation throughout the field had to be modelled. Data of both macroscale and microscale controls on fluid flow proved to be useful in this exercise, a discussion of which is beyond the scope of the present paper.

Layer mapping

As part of constructing a Field Geological Layer Model, contour maps have been made portraying the distribution of geological parameters such as thickness and porosity. The maps render insight into the distribution of the parameters over the entire field. Through corresponding computer grids, they also constitute the geological input to the reservoir simulation study. A detailed discussion of the subject is beyond the scope of the present paper.

Field Engineering Layer Model

The Field Geological Layer Model has been translated into the Field Engineering Layer Model to optimize its use in reservoir simulation modelling and history matching. The resulting layer scheme is displayed in Fig. 7. Geological Layers 7, 8 and 9 have been amalgamated in the simulator. The reduced data input to the simulator leads to an increased cost-effectiveness and at the same time the number of layers with limited distribution is reduced. The result is improved simulator performance. Geological Layer 13, however, was considered too thick (Fig. 8) to give adequate modelling resolution. The layer has therefore been subdivided into two units. The subdivision is based on subtle changes in the wireline log character, for which, however, no clear geological evidence has been found in the cores. At the same time, the lower unit of Geological Layer 13 has been combined with Geological Layer 12, which is thin and has only limited distribution over the field. Engineering Layer 1 comprises the entire Vlieland Sandstone section below Layer 2, thus enabling proper modelling of the water drive.

Discussion and conclusions

Of the three models presented above, the Field Geological Layer Model is the most elaborate and forms the synthesis of the available geological knowledge. The Idealised Vertical Facies Association and the Field Engineering Layer Model are intimately related to the Field Geological Layer Model and serve to meet the specific objectives of making a sedimentological model of the Kotter Field Vlieland Sandstone and of providing 'tailored' geological input to reservoir performance modelling.

The Idealised Vertical Facies Association is the formal field sedimentological model. It describes an overall regressive trend produced by the progradation of a barred shoreface sequence. The top and bottom surfaces of the sequence represent transgressive events, commonly associated with truncation. The trend described by the Idealised Vertical Facies Association is cyclically repeated within the reservoir interval. The identification of the main depositional environment of the sands offered no major problems and the grouping of individual facies into an Idealised Vertical Facies Association was relatively simple. The tidal delta and/or tidal channel facies is part of the Idealised Vertical Facies Association. Conclusive evidence for the presence of such deposits, however, has not been found. It is anticipated that data from new wells or additional data for existing wells will not lead to major revisions of the Idealised Vertical Facies Association. The association is, first and foremost, the foundation of the Field Geological Layer Model, but it also contributes to the ongoing exploration activities in the area by offering a model for predicting reservoir distribution and quality.

The Field Geological Layer Model provides a detailed three-dimensional description of the reservoir, integrates the available geological data at field- and micro-scale, and is designed to meet the requirements of the reservoir performance simulation. A minimum of four regressive-transgressive cycles with a total of thirteen layers has been identified, characterized and mapped. Because of the limited core coverage and the somewhat non-unique wireline log character of the facies, the model is not a unique 'solution', but rather a 'best-fit'. New or additional data may necessitate revisions to the model. However, it is thought that such revisions will be relatively minor in nature.

The Field Engineering Layer Model is derived from the Field Geological Layer Model and forms the actual, 'tailored' input into the reservoir simulation simulation. The results of the simulation study themselves form a check on the validity of the geological modelling and may necessitate modifications to be made not only in the Engineering Layer Model but also in the Geological Layer Model. As part of the simulation study, a calculation of the volume of oil originally in place in the reservoir was made. It is beyond the scope of this paper to present the results of the ongoing reservoir simulation study. Suffice to say that the reservoir performance results up to the end of the study (December 1990) were satisfactory and did not necessitate changes in the model.

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