Combining high-resolution sequence stratigraphy and mechanical stratigraphy for improved reservoir characterisation in the Fahud field of Oman

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ABSTRACT

In the Fahud field of Oman, the integration between hierarchies of sequence stratigraphic units and fracture systems has proven to be crucial to explain the distribution of flow and mechanical units. The study focused on the Upper Cretaceous, Albian to Lower Cenomanian Natih e unit (Natih Formation, Wasia Group), a 170-m-thick carbonate sequence/reservoir, which exhibits heterogeneities in both facies and reservoir quality. Based on a core-derived high-resolution sequence stratigraphic analysis, the Natih e reservoir can be subdivided into four orders of depositional cycles (from 6th-order to 3rd-order). Each cycle consists of a transgressive and regressive hemicycle with characteristic facies and rock properties. The facies and diagenetic overprint of the higher-order cycles vary according to their position within the 3rd-order sequences. Analysis of core, borehole images, seismic, tracer and production data indicate a hierarchy of fractures and faults that seems to follow the stratigraphic subdivisions. A relationship between depositional and diagenetic architecture of the cycles, and the aforementioned data, led to the identification of mechanical layering and stratigraphy within the reservoir. This finding was validated and supported by the successful history match of the three-phase production data within the dynamic model of the reservoir. The combination of sequence and mechanical stratigraphy provides a framework for the correlation of facies and mechanical units across the field. Furthermore, the facies and mechanical units are related to reservoir quality and fracture distribution for consistent upscaling into large-scale reservoir models. Through close co-operation between geologists and reservoir engineers utilising dynamic data, it was possible to determine the most appropriate scale for flow and ensure that such a scale was then used as input for dynamic modelling and for planning of the future exploitation of the Fahud field. As a result of this study, Petroleum Development Oman (PDO) has evaluated a 20% increase in risked reserves, and a 25% reduction of well costs.

INTRODUCTION

The Late Cretaceous Natih Formation (Wasia Group) and Early Cretaceous Shu’aiba Formation (Kahmah Group) represent the most important petroleum reservoirs in Oman (Figure 1). The Natih Formation is the main hydrocarbon contributor in the Fahud field (Figure 2), which is the largest field in Oman with 6.5 billion barrels of oil-in-place (a lesser contribution also comes from the Shu’aiba Formation). In the Fahud area, the Wasia Group carbonates were primarily deposited in an interior platform area. Occasionally open-marine carbonate deposition was drawn on to the platform by regional transgressions (Lapré, 1968; van Buchem et al., 2002; Figure 3). The interior part of the platform, like others that covered the eastern part of the Arabian Plate during Mesozoic times, shows a complex internal architecture with prograding carbonate bodies and lateral variations of biogenic shoals as opposed to a “layer-cake” configuration (Droste and van Steenwinkel, 2000, 2002, 2004). This complex internal architecture implies a high degree of vertical and lateral heterogeneity in the reservoirs. The understanding of these variations has proven to be critical for secondary recovery schemes, like the water-flood development and Gas Oil Gravity Drainage (GOGD) in the Natih Formation of the Fahud field (Figure 4).
In the past, production problems linked to fractures have affected the Fahud field. These problems resulted in a change of the production strategy from waterflood to GOGD, and later to a combination of waterflood and GOGD (Figure 5). In order to account for both matrix and fracture heterogeneities, a multi-disciplinary study was undertaken to construct an extensive 3-D, 3-phase reservoir model, which establishes the methodology for understanding large and complex carbonate fields.

To assess the vertical and lateral reservoir heterogeneities, sedimentary cyclicity, and their hierarchical stacking into reservoir units, we applied High Resolution Sequence Stratigraphy (HRSS) to the outer ramp, shoal and intrashoal sediments of the Natih e unit of Fahud field. HRSS is the application of sequence stratigraphy using data with a resolution scale of core, outcrop, and electrical log, i.e. at the subseismic scale (Homewood and Eberli, 2000). The cores are divided into the smallest-scale sedimentary cycles (genetically related units) that are formed during one cycle of relative sea-level rise and fall and created accommodation space. Each genetic unit does not have a predefined time span. The units are then grouped into the hierarchy of larger-scale cycles and sequences. The genetically related units contain the facies and diagenetic signature that determine, in turn, the physical properties of the strata (Figure 6).

By dividing the reservoir into a hierarchy of genetic units, the reservoir’s heterogeneities can be captured at their highest cyclicity (6th-order). These can then be grouped into lower-order cycles (5th, 4th and 3rd) to provide the stratigraphic framework for the Natih e static model. Assignment of flow properties can potentially be improved by the identification of primary natural flow units. These natural flow units can then be grouped into subdivisions, which can be hierarchically up-scaled with a consistent methodology. This methodology provides the transfer of geological understanding to the dynamic model in a robust manner (Massaferro et al., 2001).

At the start of the HRSS study, in January 2000, 316 wells had been drilled on the field. The study was initiated with the correlation of rock units using sequence stratigraphy and mechanical stratigraphy (Eberli et al., 2001, 2003). The two methodologies together deemed to be a potentially powerful combination of tools in the understanding of the production history of the Fahud field (highest

![Figure 1: Simplified Oman Stratigraphy. The Natih Formation is divided into seven units, Natih a to Natih g. Produced oil from several reservoirs is indicated in green.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/10/3/17/5442053/morettini.pdf)
Figure 2: Location of the Fahud field in Oman, and simplified structural map of the northernmost portion of the Fahud field in metres below sea level.
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STOOIP reservoir). The expectation was that HRSS analysis would identify through mechanical stratigraphy the fractured and unfractured portions of the reservoir, and determine the cause of the significantly varying production rates in different wells. As such, the study on the Natih e reservoir of the Fahud field was intended to improve methods to develop the field through identification of fractures-free versus fractured areas, so that well paths could be optimised for a successful matrix waterflood development scheme.

The specific objectives of the study were to:

- Build a HRSS model for the upper Cenomanian Natih e reservoir unit of the Fahud field.
- Evaluate the added value of a high-resolution sequence stratigraphic approach compared to a lithostratigraphic one.
- Assess the correlation-relationship between transgressive-regressive cycles and mechanical layering.
- Understand the 3-phase production history of the last 35 years in the field.
- Suggest a waterflood strategy to recover remaining oil.

Figure 3: Palaeogeography of the Natih Platform during the Early Cretaceous as interpreted by (a) Lapré (1968), and (b) van Buchem et al. (2000). The interpretation by Lapré was based on limited data and is considered outdated (Droste, 2005, written communication).
This study is focused on the Natih e reservoir, named after the informal subsurface subdivision of the Natih Formation into seven units (a to g; see Figure 1). The Natih e Unit is further subdivided into subunits from e1 to e5. These subunits used to be grouped into a fractured upper zone (red and green e1 and e2 subunits) and an unfractured lower zone (pink e3, e4 and e5 subunits). The aim of this study is to understand why some of the Fahud wells were not responding to this vertical zonation scheme (fractured versus unfractured wells). Modified after Nicholls and Kolkman (2000).

Figure 4b: Seismic line over the Fahud field shows the major fault zone that defines the southwest limit of the structural trap.
Figure 5: Production profile for the Fahud field of oil, gas and water between 1967 and 2000. During the initial 'Fracture Spurt Production' (1967-1972) the depletion was characterised by high oil rates of about 7,500 cubic metres of oil per day. From 1972-1976, the production rate dropped from about 5,000 to 2,500 cubic metres of oil per day and the gas/oil ratio (GOR) increased due to lower reservoir pressure. Between 1976 and 1986, a peripheral water injection (WI) program was introduced and the water cut increased reaching 50% in 1981 (blue line touches green line). Between 1986 and 1996, gas oil gravity drainage (GOGD) was introduced and the production rate of oil was stabilised from about an initial rate of 3,000 to a later 2,000 cubic metres of oil per day. During this same period the GOR became much greater. In 1996, GOGD and a new water injection scheme were introduced resulting in increased oil production with high GOR.

Figure 6: Classic example of an idealized genetic unit (modified after Enos and Perkins, 1967). In the Natih e unit of Fahud field, many of the sedimentary cycles are defined by argillaceous bioturbated wackestones in the transgressive part and by clean coarse-grained bioclastic grainstones and rudstones in the regressive part (see detailed description of the different genetic units).
GEOLOGICAL SETTING AND PREVIOUS WORK

The Natih Formation is latest Albian, Cenomanian and early Turonian in age. It forms part of the Wasia Group, and the lateral age-equivalent formations in the Gulf Region are the Mishrif Formation, Mauddud Formation, and Shilaif/Khatiyah Formation (van Buchem et al., 2002; Droste and van Steenwinkel, 2004). During the Albian-Turonian, a shallow-marine carbonate platform existed to the northeast of the studied area; however, during the Cenomanian embayments and intrashelf basins developed to the west and north (Figure 3).

The Natih Formation of Oman has been the focus of extensive work by the oil industry and academia through field and core studies for over 30 years. Lapré (1968) studied the sedimentology and petrophysics of the Cretaceous Wasia limestones in order to obtain “guide-lines for the primary development drilling and to establish optimum production policies”. Lapré’s detailed sedimentologic study clarified the distribution of porosity, permeability and their lateral and vertical distribution. He described the Wasia Formation as “regressive carbonate depositional cycles that carry shoal bodies”. These shoal bodies are thicker than the intershoal portions of the cycles. During periods of subaerial exposure, the crestal areas of the shoals were altered by fresh water that created secondary porosity. Lapré recognised that the palaeogeographic position of Fahud field was at the margin of an intrashelf basin with more basinal facies developing to the east of these shoal crests or palaeohighs. His main findings can be summarised as:

- Regressive sedimentary cycles built the Natih e reservoir unit.
- Lateral and vertical variation of depositional and diagenetic facies in these cycles produced porosity and permeability variations.
- Intrashelf basinal facies are to the east of the palaeohigh-crestal areas, i.e. down-dip of the actual Fahud structure.

Van Buchem et al. (1996) developed a high-resolution sequence stratigraphic model of the Natih Formation in Northern Oman, based on the outcrop successions of the Oman Mountains (Al Jabal Akhdar and Adam Foothills). They recognised the stratigraphic architecture of the Natih carbonate system as an organisation of depositional sequences at different scales of hierarchy. The main results of van Buchem et al. (1996, 2002) are:

- Eustasy was the main controlling mechanism for the 3rd-order sequences.
- Both 3rd- and 4th-order sequences are bounded by regionally correlatable surfaces marking lateral shifts of the facies belts.

Using petrographic and δ¹³C isotopic evidence, Immenhauser et al. (2000) interpreted the discontinuity surfaces in the middle Cretaceous succession of Oman (Shu’aiba, Nahr Umr and Natih formations) and noted that they often record superimposed marine hardground and subaerial exposure. Furthermore they showed that:

- Marine hardgrounds are more common than subaerial exposures. The interpretation of the latter is often uncertain.
- The record of a shoaling phase prior to exposure is commonly subtle and incomplete, with supratidal deposits conspicuously absent.
- Porosity and permeability distribution underlying the discontinuities are affected and rearranged by subaerial exposure and subsequent burial, through leaching and enhanced compaction.

Droste and van Steenwinkel (2004) presented improved seismic data that revealed internal geometries within the Cretaceous carbonate platforms of Oman. In particular, mapping of clinof orm belts shows that the Natih e unit consists of a number of separate platforms that merged by lateral accretion. It is beyond the scope of this paper to review in detail the regional geology of the Natih Formation.
However, the reader is advised to also consult the following authors for a more comprehensive treatment of the general geology and stratigraphy of the Natih Formation: Murris (1980), and Frost (1984), Clarke (1988), Pratt and Smewing (1993), Philip et al. (1995), Sharland et al. (2001), and van Buchem et al. (2002).

THE FAHUD FIELD

The Fahud field is located in northwest Oman, at a shallow depth (crest of the field at about 70 m subsea). The field is a monoclinal structure (Figure 4), 16 km in length and 2 km across, elongated along a NW-trending axis. The top of the structure and internal reservoir layers dip at 15° to the NE, and a major normal fault forms the southwest margin to the field. The Natih Formation contains the main reservoir, and the Shu’aiba Formation is the secondary reservoir (separated from the Natih reservoir by the Nahr Umr shales). The Natih Formation consists of seven units, named Natih a to g, and is overlain uncomfortably by the Fīqa Formation. The faulted scarp, on the southwest side, was heavily eroded during the Late Cretaceous and allows pressure communication among the reservoir layers.

The Natih e unit in Fahud field has porosity values between 5 and 25%, permeability values between 10 and 100 mD and a crude API gravity of 34°. The production history of the field is shown in Figure 5, where the different production mechanisms deployed in Fahud are outlined. The Fahud field has undergone a number of phases of reservoir development (O’Neil, 1988).

Natural Depletion (1967-1975)

Initially, the whole of the Fahud field including the Natih e reservoir was produced by natural depletion, which was at that time supported by gas injection (for disposal) from 1968 into the Natih a reservoir. The first production from the Natih e reservoir was in 1967 and came from the updip wells 10, 13, and 15. The first two of these wells achieved the highest production rates seen in the Natih e reservoir of up to 3,000 m³/day. From 1969 onwards, a number of wells were drilled down-dip in the vicinity of the aquifer, and achieved production rates of up to ca. 2,000 m³/day. The high off-take rates rapidly lowered the gas/oil contact (GOC) within the fracture network resulting in the gassing-out of wells completed in up-dip locations, and increasing the gas/oil ratio (GOR) in wells which were down-dip. To reverse the increasing GOR trend, it was decided in 1976 to implement a waterflooding program.

Waterflood Production Period (1976-1983)

Water-injection schemes were implemented in four of the six Fahud reservoirs including the Natih e reservoir in 1976. However, water broke through to producing wells—often within weeks—with little additional oil production. The poor performance of the waterflood led to a thorough review during which a number of Thermal Decay Time (TDT) logs were run, and tracer tests were conducted. It was concluded that due to the reservoir rock being fractured and intermediate to oil-wet, recovery factors from waterflooding would remain low.

Gas Oil Gravity Drainage (GOGD) Development (1984-1996)

Water injection was subsequently phased out in all the reservoirs (including the Natih e in 1985), down-dip grids of producers were completed and full replacement of voidage by gas injection was planned with recovery to be achieved by the GOGD process. All gas injection was through four wells completed in the Natih a, two each in the northwest and southeast parts of the field. Throughout this period the decline in oil production was greatly reduced, GOR however increased steadily.

GOGD and Waterflood (1996 to present)

Current development is based on a combination of continued GOGD with localised waterflood development in regions of the field considered to be unfractured or sparsely fractured. Current waterflood activity is achieved using horizontal wells grouped in injector producer pairs concentrated...
in the lower Natih e to the NW of the northwest reservoir. Application of waterflood outside the Natih e, NW of the northwest reservoir, had mixed success due to some wells encountering unpredicted fractures. Locating the unfractured areas is considered a key element to the successful placement of water injection/producer wells, and is the main objective of this study.

**CORE EVALUATION AND CORE-TO-LOG CALIBRATION**

The methodology followed in HRSS comprises six main steps in core evaluation and 3 main steps in core-to-log calibration. The following steps were taken to determine cycles’ hierarchy within the Natih e reservoir:

1. Identification of facies trends on core;
2. Recognition of cycle bounding surfaces;
3. Separation into packages of transgressive/regressive hemicycles;
4. Stacking of the genetic units into hierarchical lower-order cycles and sequences;
5. Interpretation of flow units within cycle hierarchy;
6. Interpretation of mechanical units within cycle hierarchy.

PDO lithostratigraphic subdivisions of the Natih e unit comprise e$_1$, e$_2$, e$_3$, e$_4$a, e$_4$b and e$_5$. A substantial limitation to a full core-based assessment of the reservoir architecture is the scarce core-coverage of the reservoir units. For example, the Natih e$_4$b-e$_5$ interval was rarely cored. In the Fahud study, the HRSS core analysis was limited to seven existing cores, incompletely covering the Natih e interval. The cored intervals for each well are given in Table 1 and Figure 7.

| Well | Cored Interval | Core Status |
|------|----------------|-------------|
| FN7  | e$_1$-e$_2$    | very fragmented (no wire-line logs for calibration) |
| FN13 | e$_1$          | fairly good |
| FN16 | e$_2$-e$_3$    | fairly good (missing intervals) |
| FN29 | e$_2$-e$_3$-e$_4$a | fairly good (missing intervals) |
| FN176| e$_2$-e$_1$    | fairly good (highly fractured) |
| FN180| e$_4$a-e$_3$-e$_2$ | good state |
| FN290| e$_4$a-e$_3$-e$_2$ | very fragmented; missing intervals |

The following steps were taken to calibrate cores to logs and to correlate cored to uncored wells.

1. Calibrate core to the best suite of logs and, based on a matching of signatures, determine correlation between HRSS and logs.
2. Identify appropriate order of cyclicity for reservoir modelling.
3. Correlation of calibrated logs to uncored wells at the scale of the chosen cycle.

An important task in the core-to-log correlation for modelling input is the assessment of the appropriate hierarchy for modelling. The highest-order cycles (6$^{th}$-order in case of Fahud) are often below the resolution of logging tools and the grid cells used in the modelling. In this study, the 4$^{th}$-order sequences, and their transgressive and regressive packages, were used for field-wide correlation and for input into the dynamic reservoir simulation. This scale is the most suitable reservoir subdivision.
Figure 7a: Natih e cored wells in the Fahud field (FN29, FN180, FN13, FN290, FN176, FN16) shown in Figure 7b on facing page. In well FN7 no wire-line logs are available for cored interval e1 and e2. In Figure 8, the GR and cored interval are shown with sequence stratigraphic interpretation.
Figure 8: Example from well FN16 of GR log-core calibration. Red arrows indicate regressive 5th-order hemicycles, blue arrows indicate transgressive 5th-order hemicycles. Note the correspondence between regressive, cleaning-upward trends and GR API values decrease and transgressive trends and GR API values increase. The increase in GR values during transgressive intervals is possibly due to the presence of argillaceous material in limestones.

Figure 7b: Natih e isotime map and location of studied wells.
for history matching of the complex production history of the Fahud field. In other fields, however, a 5th-order cycle might be the appropriate scale to model, depending on boundaries and sedimentation rates. In general, it is preferable to model at a scale one level more detailed than what is estimated can be modelled dynamically. This refinement enables features to be modelled accurately that occur on a higher-order of cyclicity but are still important to flow, e.g. high permeability streaks.

The Gamma Ray, Density, Sonic, Neutron and Resistivity logs were used for core-to-log correlation. The most suitable wire-line log to record the 6th- and 5th-order cyclicity is the Gamma Ray log (scale 0–60 API units, Figure 8). The character of genetic units and their log signature changes through the section, depending on the facies and diagenetic component, which also change in relation to the position within the hierarchical stacking. For example a transgressive hemicycle in a long-term transgression is more likely in deeper-water facies, whereas a transgressive hemicycle in an overall regression might only be represented by shallower subtidal facies. Consequently, there is no unique petrophysical signature for either transgressive or regressive hemicycles.

**MECHANICAL STRATIGRAPHY**

With the term “mechanical stratigraphy” we indicate the assessment of a correlation between depositional and/or diagenetic facies and fracturing within the same sedimentary interval. The main indication of fracture influence on well production is derived from the production data itself, which shows a heterogeneous distribution. Production data also indicate that the fracturing is related to certain stratigraphic intervals in the Natih Formation. In order to evaluate the relationship between the mechanical and stratigraphic units, the mechanical behaviour of HRSS units was assessed. This

**Lithology, Sequence Stratigraphy, Mechanical Units and Flow Behaviour**

![Figure 9: Lithology, sequence stratigraphy (4th- and 3rd-order) flow behaviour and diagenesis for the Natih e unit. The partitioning of facies, diagenesis in transgressive and regressive units leads to a fracture partitioning and a correlation between the sequence stratigraphic and mechanical units.](http://pubs.geoscienceworld.org/geoarabia/article-pdf/10/3/17/5442053/morettini.pdf)
step led to a successful integration of sequence and mechanical stratigraphy in the Fahud study. Mechanical units were assessed from core observation by dividing the strata into fractured versus unfractured intervals. In addition, tracer tests and water-breakthroughs from well data were used to evaluate the horizons and zones of preferred fracturing (see below). Both of these observations were combined into a conceptual model of hierarchy of fractured horizons following HRSS layering (Figures 9 and 10; Rawnsley et al., 2002).

| Lithology Facies, Bedding and Proposed Mechanical Behaviour |
|---------------------------------------------------------------|
| 4th-order Cycles                                              |
| et1 Non-calcareous unit with smectitic shale containing nodules. Evidence of erosive channels. Mechanical behaviour: "Ductile" unit. |
| et2 Grainstone-rudstone unit medium-thin bedded. Frequent subaerial exposure surfaces, hardgrounds and dolomite intervals. Heterogeneous facies. Mechanical behaviour: Heterogeneous unit with "brittle" beds. |
| et3 Clay-rich wacke-packstone unit. Mechanical behaviour: "Ductile" unit. |
| et4 Grainstone-rudstone unit medium-thin bedded. Frequent subaerial exposure surfaces and dolomite intervals. Mechanical behaviour: "Ductile" unit with brittle beds. |
| et5 Bioturbated argillaceous wackestone unit, with skeletal debris, thin bedded. Mechanical behaviour: "Ductile" unit. |
| et6 Bioturbated argillaceous wackestone unit, with skeletal debris, thin bedded. Mechanical behaviour: "Ductile" unit with brittle beds. |

Figure 10: The mechanical unit model proposed for Natih e.
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Production Data Analysis

Variation in facies and fracture density is the primary cause of the difference in well productivity; for this reason a comparison was made of the different types of wells (matrix-producing wells versus GOGD wells), and the reservoir units from which the wells produced.

With 35 years of production and 350 wells, the Fahud field has a significant amount of production related data, which was a significant undertaking in itself to understand. The available data included:

- Three-phase production histories of every well in the field;
- Tracer and water-breakthrough directions and times;
- Production Logging Tool (early 1970s vintage);
- Well tests (1960s vintage);
- Static downhole pressures;
- Well files (for knowledge of workovers and remedial treatments).

Well tests, which are commonly used to characterise reservoirs, were not suitable since a mechanical gauge had been used, which rendered the analysis of the derivative impossible. Hence only an overall permeability could be determined but not an understanding of the fracture locations. The production logs were used to detect gas, which was found to come in from the very top perforations. Due to the lower specific gravity (SG) of gas, it was impossible to determine if underlying perforations connected to fractured units. Variations in the response of the Production Logging Tools (PLT), below the gas influx, could not be interpreted due to lack of precision in the tool.

All production data from the wells located in the Natih e reservoir were investigated, including those wells that produce only after the simulation time period. Investigating the well productivity enabled us to group them by location and production behaviour.

**Group A** (FN10 and FN13, Figure 2b) includes the wells located near the erosional edge of the field and shows the highest initial production rates in the Natih e reservoir. The location of these wells in an up-dip location of the field in the vicinity of the erosional edge led to the wells gassing-out in less than two years.

**Group B** (FN23, FN29, FN33, FN34, FN35 and FN48, Figure 2b) includes all the wells that came on-stream before 1970, and which by vicinity to the aquifer were regarded as being Gas Oil Gravity Drainage (GOGD) wells. Based on their production history, these wells produce mostly through fractures. In contrast to Group B wells, other wells are assumed to produce mostly from the matrix and much less so from fractures. This split of wells into two groups is only a guide as there are wells that exhibit both GOGD and matrix productivity characteristics. Comparing the completion and production history of these wells resulted in the identification of a link between the lithostratigraphic reservoir units and production performance. Production in most of these wells was limited to the uppermost perforations that were located in the Natih e1 and e2 reservoir units. The evidence for this was, according to the wells files (noted in italics):

- **Well FN23** “10/12/67: Ran PLT, all flow from top set of perforations”.

- **Well FN29** “January 1968: Well failed to produce to flowstation and was swabbed by Rig-3, production rate 380 m³/day gross”. The production rate of 380 m³/day is far lower than well FN29 reached after the re-completion up into the Natih e2 reservoir unit, “February 1968: Shot additional perforations from 602.3 to 614.5 m, 632.2 to 635.2 m, 645.6 to 648.0 m and 658.4 to 663.5 m, production rate increased to 1,510 m³/day gross. PLT run indicates production from top three intervals at 37, 41 and 22% respectively, no contribution from deeper layers.”
Well FN34  “04/04/68 Perforated well from 688.8 to 694.9 m and stimulated using 14 m³ 15% HCL. Swabbed well several times to get it to flow.” The well was not productive when it was completed only in the e3 reservoir unit as can be determined from the number of times the well had to be swabbed to get it to flow. The well was then re-completed upwards, but still in the Natih e3 reservoir unit. “17/04/68: Shot additional perforations on wireline from 649.9 to 696.6 m and from 707.4 to 713.5 m.” Even with a number of extra perforations in the e3 reservoir unit, Well FN34 in “03/05/68: Produced only 60 m³/day”. Until “02/07/68: Perforated well from 635.5 to 643.1 m and from 647.7 to 652.3 m”. After completing these extra perforations, Well FN34 achieved a top productivity of 1,500 m³/day.

Wells FN23, FN29 and FN34 were regarded as e2 producers and it was assumed that in the vicinity of these wells the Natih e3 reservoir unit was not productive; at least not of the same magnitude as the e2 reservoir unit and consequently not fractured. However, wells FN33, FN35 and FN48 were all completed exclusively within the e3 reservoir unit and all three wells achieved a productivity greater than 1,000 m³/day, i.e. fracture assisted productivity. The variation in productivity between the wells completed in the e3 unit suggests that there is areal variation with both fractured and non-fractured zones existing in this unit.

The identification of the difference in productivity between the e2 and e3 reservoir units influenced the development of the initial fracture models. Since all wells producing from the e2 reservoir unit were assumed to be located in fractured zones, the unit itself was assumed to be fractured. The areal variation in fracturing in the e3 reservoir unit suggested that the unit itself was not fractured and that the cause of fracture production was linked to interbed features, which affect all units in the Natih e reservoir and possibly the whole of the Natih reservoir in Fahud.

HIGH-RESOLUTION SEQUENCE STRATIGRAPHY ANALYSIS

A genetic unit (Figure 6) is the smallest element of stratigraphic architecture identified in core, outcrop or well log consisting of genetically linked facies. The genetic unit is independent of scale, only depending on sedimentological resolution (Homewood et al., 2000). Genetic units evolve through time, resulting in different expressions of sedimentary cycles from the bottom to the top of the reservoir. The reason for changing thickness and facies content of genetic units is the interference of different orders of relative sea-level changes (Strasser et al., 1999).

Each cycle consists of a transgressive and a regressive hemicycle. In the transgressive hemicycle the accommodation space/sediment supply ratio (A/S) increases, while it decreases in the regressive cycle. The turnaround point separates the two hemicycles (Homewood and Eberli, 2000; Eberli et al., 2002).

The following section outlines the different genetic units encountered in cores from e4b to e1, and summarises their main character. A short description of the various 6th-order genetic units encountered in different parts of the sections is given, the indication for placing the turnaround point is outlined, and an interpretation of the depositional environment is given.

Genetic Units of the Natih e (6th-order)

Genetic Unit 1 (Natih e4a-e3 lithostratigraphic interval, Figure 11) consists of organic and silica-rich pelletal wackestone. The transgressive hemicycle is characterised by bioturbated wackestone and abundant chert nodules. The turnaround from the transgressive to the regressive hemicycle is recorded by a decrease in chert nodules and by dense bioturbated horizons possibly indicating a starvation in sediment supply. The regressive hemicycle is also bioturbated but wackestone textures show more abundant skeletal content (foraminifera) and less chert nodules. The depositional environment is interpreted as a deeper ramp with water depth of approximately 20 m.

Genetic Unit 2 (Natih e3 Lower-Middle lithostratigraphic interval, Figure 11) consists of a couplet of facies. The transgressive hemicycle is characterised by a bioturbated wackestone with rare chert nodules. The regressive portion consists of a rudist rudstone overlain or preceded by orbitolinid grainstones, which are coexistent biofacies.

The depositional environment is interpreted as a foreshoal-middle ramp with water depth between 5 and 15 m.
Genetic Unit 3 (Natih e3 Middle-Upper lithostratigraphic interval, Figure 11) has a clear separation of facies in the transgressive and regressive hemicycles. Bioturbated wackestone intervals with horse-tail structures comprise the transgressive hemicycle. Rudist rudstones form the regressive hemicycle. A horizon with intensive burrowing or occasionally a bored surface (hardground) marks the base of the regressive hemicycle, indicating the turnaround point (core FN29). The same genetic unit in Core FN16 shows frequent dolomitised layers of rudist rudstones, intercalated with bioturbated wackestone-packestones. Soil horizons with rootlets indicate emersion surfaces at the top of regressive hemicycles. The depositional environment is interpreted as a foreshoal-inner ramp with water depth between 0 and 5 m.

Genetic Unit 4 (Natih e3-e2 lithostratigraphic interval, Figure 11) is an extensively dolomitised unit where the top of the regressive cycle is often marked by an exposure surface. The facies within the regressive cycle consist of high-energy packestone to grainstone that contain ripple lamination. The
transgressive hemicycle is mostly thin consisting of shallow shelfal mud and mottled bioturbated wackestones. The turnaround point is marked by a firmground (core FN29). The cycle is deposited on a tidally influenced ramp with water depth between 0 and 10 m.

**Genetic Unit 5** (Natih e2 lithostratigraphic interval, Figure 11) comprises microcrystalline hard limestone alternating with burrowed intervals with grainy matrix, to burrowed intervals with clay matrix. The top of the regressive hemicycles is often marked by a hardground (core FN176, lower part). Transgressive hemicycles are thin and consist of bioturbated wackestones. The depositional environment is a deeper ramp with water depth between 15 and 20 m (Figure 11).

**Genetic Unit 6** (Natih e1 lithostratigraphic interval, Figure 11) is characterised by a mixture and succession of carbonates and clays. The transgressive hemicycle is a metre-thick interval of laminated, non-calcareous shales (core FN7, upper part). The regressive hemicycle consists of mottled, intensively bioturbated bioclastic marly limestones with wackestone texture. The depositional environment is a deeper ramp with a water depth between 15 and 20 m.

### Stacking of Genetic Units of the Natih e

Genetic units stack into lower-order cycles that are often referred to as cycle sets (5th-order), parasequence sets (4th-order), depositional sequence (3rd-order) and supersequence (2nd-order). In each of these lower-order cycles a transgressive part can be distinguished from a regressive part. Similarly as in each genetic unit, these transgressive and regressive parts are different in facies and diagenesis. Consequently, variations exist in primary and secondary porosity between the transgressive and regressive hemicycles and intervals of sequences.
Figure 13a: Correlation panel of the 4th-order HRSS cycles in the static reservoir model.
Figure 13b: The Natih e HRSS cycles (5th to 3rd) compared to the Natih e lithostratigraphic units. The 4th order HRSS cycles have been used as input for both static and dynamic modelling. The Natih and Natih e cycles from Droste and van Steenwinkel (2004), show example of intra-platform carbonate cycles and type log for the Natih Formation from well Fahud North-3. Correlation with well Fahud North 29 from this study are shown and their correlations with this study. See text for more discussion.
In the Natih e Formation, the stacking of genetic units resulted into the subdivision of the reservoir into a hierarchy that goes from the 6th-order of the genetic units, up to the 3rd-order level (Figures 12 and 13). Breaking-up lithology into facies results in the distinction between transgressive and regressive deposits, i.e. those facies that characterise the system during periods of transgressions and those that characterise the system during regression. The breaking-up of facies according to accommodation space and sediment supply has led to the construction of a HRSS model shown in Figures 9, 10 and 13. In this study, the Natih e unit is subdivided into two complete 3rd-order sedimentary cycles. At the 4th-order scale, the reservoir consists of 6 transgressive and 5 regressive units named with a letter e (for Natih e), a small letter to indicate the transgressive or regressive hemicycle (t or r) and a number going from 6 (bottom of the reservoir) to 1 (top of the reservoir) to characterise each cycle (Figures 10 and 13a).

This stratigraphic subdivision of the Natih e into two 3rd-order sequences and six 4th-order cycles contrast with findings of van Buchem et al. (1996, 2002) and Droste and van Steenwinkel (in press), who distinguish one large-scale cycle and four medium-scale cycles in the Natih e unit. Our subdivision into two sequences is based on the occurrence of a marly interval in a transgressive unit et3 that separates Natih e into two major successions. This interval correlates to the transgressive portion of the I-3 medium cycle of van Buchem et al. (2002). Nevertheless, we also recognise the long-term shoaling trend (our second-order sequence) that was previously observed in the field and at a regional scale (Burchette 1993; Philip et al., 1995; van Buchem et al., 2002). Table 2 shows the average thickness of the cycles, from 6th- to 3rd-order.

**THE NATIH E HIGH-RESOLUTION SEQUENCE STRATIGRAPHY AND MECHANICAL STRATIGRAPHY MODEL**

The HRSS model is based on a hierarchy of genetic units ranging from 6th- to 3rd-order of cyclicity, with the 4th-order cycle and their transgressive and regressive packages being chosen for input to the static and dynamic models. The facies and diagenetic variations that lead to porosity partitioning in the transgressive and regressive units also influence the fracture pattern and fracture porosity of cycles and sequences. In the following section, the relationship between the depositional and diagenetic architecture of the reservoir and the fracturing is described.

The Natih e reservoir in the Fahud field begins with the sedimentation of a 1-m-thick clay-rich layer, representing the first sediments of a transgression. The subsequent genetic units within the transgressive 4th-order cycle are also characterised by organic-rich intervals at the base, and by bioturbated wackestones-packestones with chert nodules and minor clay going upsection. Cementation is submarine throughout the transgressive interval.

This facies and diagenesis produces a homogeneous low-porosity flow unit, with a ductile mechanical behaviour (corresponding to the e4a and e4b lithostratigraphic units). In particular the maximum flooding zone at the turnaround point to the regressive part of the first 3rd-order cycle, which is an argillaceous wackestone, is a low-flow mechanical boundary; i.e. an interval across which (a) vertical flow can be hindered, and (b) mechanical characteristics of the sediments vary.

The following regressive unit is characterised by wackestones to packestones with interbedded orbitolinids grainstones and rudist rudstones. Dolomite layers are frequent within the thick-bedded units. In addition, a strong meteoric overprint from the exposure at the top of the unit occurs that produced meteoric diagenesis and localised leached horizons. Consequently, the flow behaviour of this e3 lithostratigraphic unit is porous and homogeneous in the lower part and more heterogeneous further up. This interval is mechanically characterised as being overall ductile with brittle layers getting more and more frequent towards the top of the unit.
Approximately 10 m of compacted clay-rich wackestones in the next transgressive unit at the transition at the base of e2 is an important boundary in the Natih e unit in the Fahud field. The whole flooding zone marks a major break in flow and mechanical transmission, separating two 3rd-order regressive intervals that are excellent reservoirs.

The overlying regressive cycle (crossing e2 and e1 lithostratigraphic units) consists of medium-thin bedded rudstone-grainstones, with interbedded bioturbated wackestones. Subaerial exposure surfaces recorded by rootlets and silica-replaced laminae and hardgrounds are frequently observed together with dolomite intervals. Cementation is mixed, marine and meteoric. Generally the facies are heterogeneous, producing a porous, heterogeneous flow unit. The frequent brittle beds probably cause a brittle mechanical behaviour.

A clay-rich, low-flow transgressive unit overlies this second regressive 3rd-order unit. This clay-rich interval forms with the other 3rd-order transgressive intervals a pattern, with ductile units at the base, middle and top that constrain the brittle high-flow units in the middle.

The thinner, harder, less muddy, more cemented horizons, in the upper 3rd-order regressive portions (e2) are more prone to fracturing than the lower muddy, finer-grained, transgressive and lower regressive portions (e3–e4). In general, the regressive hemicycles at any scale (6th- to 3rd-order) in the Fahud field are more prone to fracturing than their transgressive counterparts. This finding is corroborated with the acquired knowledge that the e2 interval is more fractured than the e3 (Nicholls and Kolkman, 2000).

Our main conclusions from the stratigraphic and mechanical correlation can be summarised as follows:

- The 3rd-order maximum flooding surface near the base of e3 separates good from poor reservoir intervals (e3 versus e4-e5).
- Dolomitised and cemented regressive facies are prone to fracture (middle-upper e2; e3 top beds, see also Figure 14).

Figure 14: Wadi Nakhr outcrop showing Natih b transgressive and regressive 6th-order fractures. Note how transgressive hemicycles show less cement-filled, bed-bounded fractures. Modified after van Buchem et al. (2000) and Rawnsley et al. (in press).
The clay-rich 3rd-order flooding intervals at base of e2 act as a flow barrier and mechanical barrier for fracture propagation.

**DOES HIGH-RESOLUTION SEQUENCE STRATIGRAPHY EXPLAIN THE VARIATION IN WELL PRODUCTIVITY?**

There is evidence that the Natih e2 unit is pervasively fractured (Nicholls and Kolkman, 2000) and that the Natih e3 unit’s lithofacies are laterally variable. However, not all well behaviour can be explained through the use of lithostratigraphy to constrain the location of fractures. Wells FN33, FN35, and FN48, which achieved peak production rates, are completed exclusively in the Natih e3; but FN60, FN102 and FN114, which are also completed in the Natih e3 only, are incapable of reaching their peak historical production rates. If all of these wells were assumed to reside in fracture zones, which are constrained within the Natih e3 unit, virtually all of the Natih e3 would need to be fractured. This interpretation is clearly not the case as wells such as FN23, FN29 and FN34 would also have had fracture-enhanced productivity. An additional contradiction for the Natih e3 being the constraining feature for fractures comes from FN33. It was initially thought to be located in a fractured zone, yet horizontal wells that also produced from the Natih e3 acted as if their production was matrix dominated. Hence the lithostratigraphic reservoir units do not provide sufficient stratigraphic detail or accuracy to understand all well behaviour across the reservoir.

**Figure 15: The Fractured Layers Applied in the dynamic simulation of the HRSS Natih e model.**

**Figure 16: Tracers and production tests for the Natih e unit in Fahud field. Very quick water breakthrough occurred for wells FN48 and FN35 (light blue arrows), indicating a NE-preferential fluid path.**
Since the lithostratigraphic reservoir model appeared insufficiently detailed to explain all the variation in well productivity, the application of 4\textsuperscript{th}-order cyclicity for locating the fractured units was investigated. The application of HRSS required numerous iterations to determine the order, or combination of orders, required to model the production behaviour.

In order to develop the reservoir model, geologists and reservoir engineers worked together to determine the appropriate order of sedimentary cyclicity and the fractured units. This meant that only realistic scenarios were evaluated; i.e. scenarios that could be explained by the observed sedimentary features and fracture patterns in cores and outcrops. This approach significantly reduced the time needed to determine that a combined 3\textsuperscript{rd}- and 4\textsuperscript{th}-order cyclicity explains the production behaviour of the wells in the field. The units that were assumed to be fractured are shown in Figure 15.

The 3\textsuperscript{rd}- and 4\textsuperscript{th}-order HRSS model also helped explain the results obtained from borehole image (FMI) data. FMI logs through the Natih e reservoir encountered fractures infrequently, even in the Natih e: unit, which was previously assumed to be heavily fractured. These data are in concert with the analysis of this study that found that only certain regressive units are fractured within this interval. The link between the HRSS model with 4\textsuperscript{th}-order regressive hemicycles that are more prone to fracturing, and zones of the reservoir characterised by fracture flow was therefore achieved.

**Fracture Corridors**

Although the combined HRSS and mechanical stratigraphy model was able to explain much of the productivity distribution, two wells (FN35 and FN48) showed very early gas breakthrough even though they are completed stratigraphically low. The HRSS model and related mechanical

![Figure 17: Two different reservoir models were tested using sequence stratigraphic units to constrain the distribution of fractures. (a) In the first case the reservoir was assumed to be fully fractured, while Fracture Zones 35 and 48 were not modelled. The reservoir was assumed to be preferentially fractured in the transgressive layers. (b) In the second case, Fracture Zones 35 and 48 are included in the model. They represent high permeability vertical corridors and used to explain gas breakthrough in wells that are completed in low stratigraphic positions. Transmitting fractures are assumed to be connected across the whole reservoir through 3\textsuperscript{rd}-order fracturing and 4\textsuperscript{th}-order matrix layers.](image)

![Figure 18: The waterflood potential areas. Through this study, a map of hazardous versus potential water-flooding areas was delivered to Petroleum Development Oman. Horizontal drilling until 2003 has confirmed the proposed model for fractured and unfractured areas.](image)
stratigraphy, could not explain such behaviour. Rawnsley et al. (in press) hypothesised, from seismic data and the position of a brecciated core, the existence of high-permeability/high-fracture corridors that could cross the whole of the reservoir following a NE trend. This NE trend was also noticed as the preferential direction of tectonic lineaments both in outcrops, and in the Natih field. The NE fracture corridors near to wells 35 and 48 (Figure 16) were therefore identified by seismic data, tracers tests, production tests and brecciated core.

Both mechanical layering and fracture corridors are fundamental elements of the history match achieved for the Natih e unit of the Fahud field. Different geological models were tested to reach this conclusion, ranging from a fully-fractured reservoir (Figure 17a), to the absence of fracture corridors near wells 35 and 48, to preferentially fractured transgressive 4th-order cycles (Figure 17b). Fracture connectivity across the whole reservoir was also tested. The base case model of Figure 17 showed the best history match among all the models tested (Figure 18).

CONCLUSIONS AND IMPLICATIONS

High-resolution sequence stratigraphy (HRSS) was used for carbonate reservoir characterisation in the Natih e unit of the Fahud field. This analysis of the Natih e reservoir resulted in a new correlation from which a new static-matrix model was constructed. HRSS provided the framework for mechanical stratigraphy that explained a significant portion of the variation in well productivity; this model was then completed with the presence of fracture corridors. The integration of sequence and mechanical stratigraphy yielded the following conclusions.

1. The hierarchy of genetic units allows for systematic “upscaling” from 6th- to 3rd-order cyclicity, which constrains the flow units.
2. In the case of the Natih e unit, transgressive hemicycles are generally characterised by fine-grained wackestones (to packestones), whereas the overlying regressive cycles are dominated by packe- to grainstones, and occasional rud- and floatstones. This difference in depositional texture has a profound impact on the distribution of porosity (and permeability).
3. Early diagenesis follows the stratigraphic architecture. The transgressive portions of the larger sequences display stronger diagenetic overprint that impairs porosity and permeability. In the reservoir, high permeability zones occur in leached zones of the regressive parts and in the dolomitised parts of the transgressive cycles.
4. The HRSS analysis has refined the existing reservoir subdivisions.
5. The 4th-order cycles were used as the basis for the static model. They comprise 6 transgressive and 5 regressive units, a total of 11 subdivisions for the sequence stratigraphic model versus 6 subdivisions in the lithostratigraphic model.
6. Similar to the stratigraphic hierarchy, a hierarchy of mechanical units is inferred from analysis of core, seismic, tracers and production data.
7. The increased amount of emersion horizons and dolomitisation in the regressive cycles of the 3rd-order sequences produces more fracturing in these brittle horizons, while the more homogeneous transgressive hemicycle is less prone to fracturing.
8. The turnaround between transgressive and regressive trends (maximum flooding zone) at the 3rd-order scale separates large mechanical units.
9. The application of mechanical stratigraphy and the identification of fracture corridors advanced the understanding of the production history of the field, indicating the importance of a multidisciplinary approach to field-production assessment and planning. Previous to this study, any explanation of production behaviour always included a significant number of wells that acted anomalously.
10. The results of this study enabled the identification of regions of the Natih e reservoir, which are most likely to be successful if exploited by waterflood. This is especially important as the vast majority of the 6.5 billion barrels (STOIIP) remains within the field. In addition, the reason why the gas oil gravity drainage (GOGD) process did not generally work as well as expected was explained by the disconnected nature of the fracture network due to the unfractured trangressive units. Based on this study, wells can now be targeted correctly into the larger fractured regions (Figure 18).
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REFERENCES

Burchette, T.P. 1993. Mishrif Formation (Cenomanian-Turonian), southern Arabian Gulf: carbonate platform growth along a cratonic basin margin. In, J.A.T. Simo, R.W. Scott and J.P. Masse (Eds.), Cretaceous Carbonate Platforms. American Association of Petroleum Geologists, Memoir 56, p. 185-199.

Droste, H.J. and M. van Steenwinkel 2000. Strata geometries and patterns within Cretaceous platform carbonates, the Natih Formation of Oman. GeoArabia, Abstract, v. 5, p. 83-84.

Droste, H.J. and M. van Steenwinkel 2002. Stratigraphic architecture of Cretaceous Platform interior carbonates: impact on flow unit geometry and continuity. American Association of Petroleum Geologists Bulletin, Abstract, v. 86.

Droste, H. and M. van Steenwinkel 2004. Stratigraphic organization of platform carbonates: the Cretaceous of Oman. In, G. Eberli, J.L. Massaferro and J.F.R. Sarg (Eds.), Seismic Imaging of Carbonate Reservoirs and Systems. American Association of Petroleum Geologists, Memoir 81, p. 185-206.

Eberli, G.P., E. Morettini, K.D. Rawnsley and W. Kolkman 2001. Combining high-resolution sequence stratigraphy and mechanical stratigraphy for improved reservoir characterisation, Fahud field, Oman. American Association of Petroleum Geologists Annual Convention, Program with Abstracts, Abstract, v. 10, p. A55.

Eberli, G.P., L.B. Smith, E. Morettini and L. Al-Kharusi 2002. Porosity partitioning in sedimentary cycles: implications for reservoir modeling. American Association of Petroleum Geologists Annual Convention, Program with Abstracts, p. 270.

Enos, P. and R.D. Perkins 1978. Evolution of Florida Bay from island stratigraphy. American Geological Society Bulletin, v. 90, p. 59-83.

Harris, P.M. and S.H. Frost 1984. Middle Cretaceous carbonate reservoirs, Fahud Field and Northwestern Oman. American Association of Petroleum Geologists Bulletin, v. 68, no. 5, p. 649-658.

Homewood, P.W. and G.P. Eberli (Eds.) 2000. Genetic Stratigraphy on the Exploration and Production Scales - Case Studies from the Paradox Basin and the Upper Devonian of Alberta. Bulletin Centre Recherches Elf EP Editions, Mémoire 24, 290 p.

Homewood, P.W., P. Mauriaud and F. Lafont 2000. Best Practice in Sequence Stratigraphy. Elf EP Editions, Mémoire 25, 81 p.

Hughes C.M.W. 1988. Stratigraphic and rock unit nomenclature in the oil-producing area of interior Oman. Journal of Petroleum Geology, Beaconsfield, vol. 11, no 1, p. 5-60.

Immenhauser, A., A. Creusen, M. Esteban and H.B. Vonhof 2000. Recognition and interpretation of polygenic discontinuity surfaces in the middle Cretaceous Shu’aiba, Nahr Umr, and Natih formations of northern Oman. GeoArabia, v. 5, no. 2, p. 299-322.

Lapré, J.F. 1968. Production Sedimentology of the Fahud oilfield, Oman. Report EP-39728 (PDO/PED No. 509).

Massaferro, J.L., E. Morettini and G.P. Eberli 2001. Stratigraphic control on reservoir heterogeneity in cyclic carbonates – examples from the Upper Thamama Group and Natih Formation, Abu Dhabi and Oman. Society of Petroleum Engineers paper 68196.

Murris, R.J. 1980. Middle East: stratigraphic evolution and oil habitat. American Association of Petroleum Geologists Bulletin, v. 64, p. 597-618.

Nicholls, C.A. 1998. Fahud field Northwest Natih E: reservoir geological model for a matrix waterflood OFP/98/030R Petroleum Development Oman.

O’Neil, N. 1988. Fahud field review, a switch from water to gas injection. Society of Petroleum Engineers paper 15691.

Rawnsley, K., A. Thompson, E. Morettini, T. Cortis, W. Asyee, J.H. van Konijnenburg, P. Christman, K. Foster, V. Hitchings, W. Kolkman and G.P. Eberli (in press). Bringing together fracture characterisation, seismic and sequence stratigraphy into a fully integrated reservoir model of the Fahud field, Oman. American Association of Petroleum Geologists.

Philip, J., J. Borgomano and S. Al-Maskiry 1995. Cenomanian-early Turonian carbonate platform of Northern Oman: stratigraphy and palaeoenvironments. Palaeogeography, Palaeoclimatology and Palaeocology, v. 119, p. 77-92.
Pratt, B.R. and J.D. Smewing 1993. Early Cretaceous platform margin configuration and evolution in the central Oman Mountains, Arabian Peninsula. American Association of Petroleum Geologists Bulletin, v. 76, pp. 225-244.

van Buchem, F.S.P., P. Razin, P.W. Homewood, J.M. Philip, G.P. Eberli, J.-P. Platel, J. Roger, R. Eschaed, G.M.J. Desaublaux, T. Boisseau, J.-P. Leduc, R. Labourdette and S. Cantaloube 1996. High resolution sequence stratigraphy of the Natih Formation (Cenomanian/Turonian) in northern Oman: distribution of source rocks and reservoir facies. GeoArabia, v. 1, no. 1, p. 65-91.

van Buchem, F.S.P., P. Razin, P.W. Homewood, H. Oterdoom and J. Philip 2002. Stratigraphic organization of carbonate ramps and organic-rich intrashelf basins: Natih Formation (middle Cretaceous) of Northern Oman. American Association of Petroleum Geologists Bulletin, v. 86, no. 1, p. 21-54.

Rawnsley, K.D., E. Morettini, A.R. Thompson, J-H van Konijnenburg, W.H. Asyee, T. Cortis, G.P. Eborli, V.H. Hitchings, K. Foster and W.H. Kolkman 2002. Bringing together fracture characterization, seismic and sequence stratigraphy into a fully integrated reservoir model of the Fahud field, Oman. 5th Middle East Geosciences Conference, GEO 2002. GeoArabia, Abstract, v. 7, no. 2, p. 289.

Rawnsley, K., A. Thompson, E. Morettini, T. Cortis, A. Wenche, J.-H van Konijnenburg, P. Christman, K. Foster, V.H. Hitchings, W. Kolkman and G.P. Eberli. Bringing together fracture characterization, seismic and sequence stratigraphy into a fully integrated reservoir model of the Fahud field, Oman. Submitted to AAPG Bulletin.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons 2001. Arabian Plate Sequence Stratigraphy. GeoArabia Special Publication 2, Gulf PetroLink, Bahrain, 371 p., with 3 charts.

Strasser, A., B. Pittet, H. Hillgärtner and J.-B. Pasquier 1999. Depositional sequences in shallow-dominated sedimentary systems: concepts for a high-resolution analysis. Sedimentary Geology, v. 128, p. 201-221.

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