Controls on Reservoir Quality and Reservoir Architecture of Early Cretaceous carbonates in an Abu Dhabi Onshore Field Lekhwair, Kharaib and Lower Shuaiba Formations

Jaehoon Jeong, Abdulla Ali Al-Ali, Hyunyoung Jung, Alyazia Abdelrahman, Al Dhafra, and Hesham T. Shebl, ADNOC; Jeonggil Kang, KADOC; Aurélie Bonin, Matthieu Deville de Perriere, and Alexander Foote, Badley Ashton and Associates Ltd.

Abstract

Reservoir quality of carbonate rocks is usually controlled by the interplay of both the primary depositional and secondary diagenetic parameters. The assessment of the respective impact of these controls together with the understanding of the field-scale sedimentological organisation and diagenetic trends assist in the reconstruction of reservoir architecture and help production and appraisal programs. This work focuses on three formations recorded in the onshore Abu Dhabi area with the final aim of understanding their field-scale architecture through the study of six wells. Sediments reflect deposition in clay-prone and cleaner inner ramp to distal mid-ramp, where biotic assemblage is either dominated by *Lithocodium/Bacinella* (i.e. within lower Shuaiba and lowermost Lekhwair), rudists or peloids (i.e. within Kharaib).

The sedimentological framework has been established through a detailed sedimentological description of c.2545ft of core and sequence stratigraphy interpretation. The occurrence of diagenetic processes (i.e. dissolution, cementation and fracturing/compaction) and their respective impact on pore system have been assessed through the observations of 804 thin-sections and the structural logging of c. 1936ft of core. The integration of the field-scale sedimentological organisation together with the distribution of the assessed reservoir quality controls and porosity/permeability data results in the establishment of the reservoir architectures of the three formations.

In this area, the depositional fabric is characterised to be the primary parameter on the reservoir properties of the cored Thamama deposits with the exception of the lowermost cored Lekhwair and fractured reservoir: the best reservoir quality is found within inner ramp (locally dominated by *Lithocodium/Bacinella*) to backshoal grainstones and rudist-rich floatstones associated with a grainstone matrix. The reservoir quality decreases with the progressive increase in micrite matrix and clay content. The lowest porosity/permeability values are linked to the clay-rich inner ramp deposits recorded within the Dense Units, forming thick seals between the cleaner carbonate reservoir units. The localised occurrence of late dissolution phases has locally enhanced pore connectivity and preferentially affects the deposits which are initially characterised by good pore connectivity and volume (as observed in the lowermost Lekhwair and upper Kharaib Formations). Finally, cementation only locally decreases the reservoir properties and is broadly preferentially developed.
within and nearby clay-enriched deposits and at sharp lithological contacts often overprinted by stylolites. The focus of cementation on these surfaces results in one extensive ft-thick baffle within the Kharaib reservoir while a similar baffle is locally breached by rare 20cm-long fractures in Lower Shuaiba reservoir developed at the hinge of the anticline. Finally, the abundant and connected fracture network occurring within the lower Lowermost Lekhwair is likely to play a role on fluid flow in subsurface.

The reservoir architecture will be integrated in the rock typing workflow to assist in the prediction of rock type vertical distribution and their lateral extent.

Introduction

The carbonate Lekhwair, Kharaib and Shuaiba deposits form important hydrocarbon reservoirs in the Abu Dhabi area. A reconstruction of their reservoir architecture is carried out in this work, with the aim to help the field development and optimise the production. Reservoir architecture interpretations require the establishment of the sedimentological framework, understanding of the diagenetic overprint together with the spatial distribution of the diagenetic phases and the assessment of depositional/diagenetic controls on reservoir quality. When structural features are expected to be involved into reservoir property variations, a structural study is conducted in order to assess the distribution of the various structural features (e.g. stylolites and fractures) and predict their lateral occurrence. Although the impact of fractures is difficult to assess accurately on permeability in subsurface conditions, their development and connectivity has to be taken into consideration to be integrated into the static model at a later stage of the field development.

This paper primarily discusses the controls on reservoir quality and reservoir architecture of the three Lekhwair, Kharaib and Shuaiba carbonate groups, studied in an Abu Dhabi onshore area. The work relies on observations carried from core and thin-sections from six wells, which have been studied to characterise the sedimentological make-ups and vertical/lateral facies organisation, sequence stratigraphic framework, diagenetic and structural overprint and pore system composition. Most importantly, this contribution suggests a classification of geological rock type helping in the characterisation of the depositional and diagenetic controls on reservoir properties. Whilst the focus of this paper is the reservoir quality control assessment and reconstruction of the reservoir architectures, a summary of the sedimentological and diagenetic aspects is only provided for context.

Geological background

The cored Lekhwair deposits belong to the lowermost Lekhwair, which is likely to date from the late Valanginian (Granier, 2000) to possibly early Hauterivian (e.g. Simmons, 1994; Aziz and Abd El-Sattar, 1997). The deposits have been formed on a wide ramp system (Ziegler 2001), oriented SW-NE, with the basin facies facing NE (Figure 1). In more detail, the refined depositional settings are discussed by Jeong et al. (2016) and summarised in this paper. As defined by the same authors, the Lekhwair depositional organisation is characterised by an alternation of cemented clay/organic-rich and cleaner carbonate layers, which are labelled respectively Lekhwair 1, 2 and 3 Dense and Lekhwair 1, 2 and 3 (Figure 2). The upper part of the Kharaib group is studied in this contribution and is subdivided into Kharaib 1 Dense and Kharaib 1. The deposits are dated from Barremian with an early Aptian age interpreted for the Kharaib 1 Dense and uppermost Kharaib 1 layers (e.g. Strohmenger et al. 2010). During this period, the Abu Dhabi area is marked the opening of the intrashelf Bab Basin, which expanded toward the north during the Aptian (Ziegler 2001; Figure 1). The Kharaib Group is overlain by the Shuaiba Group, which is Aptian in age. Shuaiba is subdivided into three Formations, named from the top to the base Shuaiba 1, 2 and 3, based on their lithological characteristics and wireline log signature. It has to be noted that the core coverage of Shuaiba 1 is very poor.
Figure 1—Palaeogeographic reconstruction of the Early Cretaceous (A; Blackey, 2006) and palaeoenvironmental maps representative of the Berriasian/Valanginian (B1), Barremian (B2) and Aptian (B3) periods (Ziegler 2001).

Figure 2—Stratigraphy of the Early Cretaceous carbonate deposits in the study area and available dataset.
The six study wells (named wells A, B, C, D, E and F for confidentiality in this paper) have been drilled along a c. 5km long transect broadly oriented North-west/South-East. This transect is thus slightly oblique to the palaeo-depositional strike illustrated on the palaeoenvironmental reconstructions (Figure 1). It has to be noted Well A is located at the hinge of the field anticline structure while Well F represents a flank well. With the exception of Shuaiba 1 and the middle part of Shuaiba 3, the coverage of the reservoirs is relatively good within the six cored wells and represents a total of c.2545ft of core, enabling the characterisation of the sedimentological make-up and structural features within the base of the lowermost Lekhwair, upper Kharaib and Shuaiba deposits (Figure 2). This study also benefits from complete conventional log suites, which have notably been used to pick key sequence stratigraphic surfaces. 804 thin-sections have been observed and helped with refinement of depositional environments, identification of the diagenetic overprint and characterisation of geological rock types.

Sedimentological characterisation and lateral facies variability across the reservoirs

The variability in the broad sedimentological make-up and particularly biotic assemblage observed between the three Lekhwair, Kharaib and Shuaiba groups reflects deposition under different oceanic and climatic conditions. As a result, the extent of the geobodies is likely to differ between them, which could have a potential impact on reservoir architecture considerations. For these reasons, the sedimentological characteristics are considered separately for the three groups in the following.

Depositional setting and variability in Lekhwair

The sedimentological study of this interval in the same field has been detailed in Jeong et al. 2016, who describe the depositional environment to range from intertidal (IT) to inner ramp/proximal mid-ramp (IRME/MPR) settings (Figure 3). The inner ramp settings are episodically subject to the land-derived clay influxes (IRLE.a/IRME.a), which are recorded within the Dense Zones. The cleaner skeletal packstones and floatstones deposited in inner ramp (IRME) and inner ramp/proximal mid-ramp (IRME/MPR) are encompassed within the reservoir Units, with the most opened setting marked by the development of patchy/cloudy Lithocodium/Bacinella (sensu Rameil et al., 2010). These allochems are inferred to develop in metre-scale patches as observed on outcrops by Huck et al. (2010). Their patchy development is likely to impair lateral connectivity; however, their significant development in the middle part of Lekhwair 2 is inferred to facilitate the vertical stack and connectivity of the patches (Jeong et al. 2016).

Vertically, the whole system transgresses upward from dominant intertidal/detrital clay-influenced inner ramp setting (IT and IRME.a) at the base of lowermost Lekhwair toward Lithocodium/Bacinella-rich inner ramp/proximal mid-ramp setting (IRME/MPR) in the middle of Lekhwair 2. The uppermost Lekhwair 2 records a shallowing upward phase with a transition toward more internal and inner ramp settings. The regression is capped by a regional karstified surface picked as a large-scale sequence boundary (Jeong et al. 2016).

The same authors describe the Lekhwair depositional organisation to be broadly layer cake with alternating layers of clay/organic-rich and cleaner inner ramp deposits. In terms of sequence stratigraphy, the clay-rich depositional layers represent the transgressive phase of intermediate-scale cycles while the cleaner carbonate intervals represent the maximum flooding conditions of these cycles and record their regressive phase. Most importantly, the middle Lekhwair 2 is made up of an extensive 20-30ft thick layer made up of Lithocodium/Bacinella-rich deposits developed at the maximum flooding conditions. The reservoir potential of these deposits is the best of the whole cored Lekhwair succession.
Depositional setting and variability in Kharaib 1

The Kharaib 1 unit is composed of clean carbonates characterised by a wide variety in textures from wackestones to floatstones/rudstones and also various skeletal allochems (with notable rudists) changing along the stratigraphic column.

**Depositional model.** The deposits observed in Kharaib 1 reflect a wide range in depositional environments from distal mid-ramp (MRD) to inner ramp (IRME/IRLE) settings (Figure 4). The inner ramp setting is characterised by the development of rudist complexes (requienids), leading to deposition of rudist-rich shoal (IRS.r) and rudist-rich foreshoal and backshoal (IRFS.r and IRBS.r, respectively) sediments, represented by rudstones and floatstones. The growth of these rudists results in a great facies heterogeneity within the broad inner ramp area, where the rudist-bearing deposits will pass laterally to peloidal packstone to grainstone intershoal sediments. The lateral extent of these complexes is difficult to accurately assess as the observations are restricted to cored wells with the km-scale well spacing to be significantly larger than the expected extent of individual rudist build-ups. Based on European outcrop studies, the requienids grow in clusters to small build-ups extending laterally for <5 metres during the Early to Mid-Cretaceous (Masse and Philip 1981). The *in situ* organisms are reworked by fair-weather waves and episodic storm currents into fore and backshoal areas. Considering the level and intensity of reworking, the lateral extent of the rudist-rich complexes (in situ and reworked bodies together) is uncertain and may vary.

Figure 3—Conceptual depositional model for the lowermost Lekhwair deposits in the eastern Onshore Abu Dhabi area (Jeong et al., 2016).
Locally between shoals, subtidal channels are likely to occur as suggested by the 3-4ft thick very well sorted and locally planar laminated peloid-rich packstones to grainstone package, which are bound at their base by an erosive surface; such deposits, providing good reservoir potential, are localised and are present at different stratigraphic levels in the wells.

**Vertical and lateral facies change.** A large-scale upward shallowing from distal mid-ramp (MRD) to inner ramp deposits (IRME, IRLE) is recorded across Kharaib 1. This regression is capped by a karstified surface which is present in all wells and has been recognised regionally (e.g. van Buchem et al., 2002). This surface indicates the subaerial exposure of the ramp system due to a significant sea level drop (Hardenbol et al., 1998). It is associated with a subsequent percolation of meteoric waters leading to extensive dissolution of the reservoir top as indicated by the occurrence of 3-5cm wide dissolved cavities within the uppermost c.15ft of the reservoir.

At least four smaller scale cycles superimpose the large-scale regression and are capped by firmground and sharp surfaces, locally overprinted by stylolitic surfaces. While the flooding surfaces of these cycles are difficult to accurately assess in these shallow water carbonates, the cycle boundaries are used in the reservoir architecture reconstruction as correlative guides across the field. The three uppermost cycles encompass the rudist-rich deposits (IRS.r, IRBS.r and IRFS.r), which are c.5 to 10ft thick and particularly well developed in the upper part of the cycle (possibly corresponding to the smaller scale regressive phases).

The depositional organisation of Kharaib 1 is grossly layer cake organisation, with no lateral change in its lower part, showing relatively homogeneous distal mid ramp and proximal mid-ramp deposits. The development of inner ramp deposits, together with rudist growth, involves the occurrence of potential 10s to 100s metre scale rudist-rich floatstone and rudstone complexes passing laterally to peloidal packstone to grainstones in the upper half of Kharaib 1. Whilst the extent and connectivity of the rudist geobodies is difficult to assess accurately, they are recorded in all wells except in Well B. Their absence in Well B is likely to indicate variation in environmental conditions (possibly topography) and emphasize the patchy occurrence of the rudist geobodies.
Depositional setting and variability in Shuaiba

This section outlines the depositional interpretations for the Shuaiba and Kharaib 1 Dense deposits, which overlay the karstified surface and major large-scale sequence boundary capping Kharaib 1. This sequence boundary is associated with an abrupt change from clean to argillaceous deposits from Kharaib 1 to Kharaib 1 Dense Formations, respectively, which is interpreted to be controlled by a change from dry to humid conditions during the earliest Aptian.

Shuaiba 2 and 3 are almost entirely composed of mud-dominated textures except for the base of Shuaiba 3 and Kharaib Dense 1, where *Lithocodium/Bacinella* floatstones and orbitolinid-rich packstones are developed, respectively. The Aptian is marked by a notable crisis in carbonate production (e.g. Follmi, 2012), the first signs of which is reflected by higher clay/organic matter content within Shuaiba 2. For this reason, the depositional model of Shuaiba 2 has been separated from the illustration of the depositional organisation of the Kharaib Dense 1 and Shuaiba 3 deposits (Figure 5).

Figure 5—Conceptual depositional model for the Kharaib Dense 1, Shuaiba 3 and Shuaiba 2 units (including also Kharaib Dense 1) in the study area.
**Depositional model.** The Kharaib Dense 1 to Shuaiba 2 succession developed into four depositional environments ranging from an inner ramp (IRME.a and IRME) to outer ramp settings (OR; Figure 5). Depositionally, the Kharaib Dense 1 deposits reflect the most proximal position while Shuaiba 2 represents the most distal deposits of the whole succession.

As for the Lekhwair interval, the most proximal inner ramp setting is subject to land-derived detrital influx driven by humid conditions, which results in deposition of the clay/organic matter-rich and dense Kharaib Dense 1. In the overlying Shuaiba 3 Unit, the proximal mid-ramp (MRP) and distal mid ramp (MRD) environments are clean, which suggests isolation from the continental input in response to their more seaward position on the ramp. This Unit is markedly characterised by the development of patchy-cloudy to locally laminar *Lithocodium/Bacinella*, which according to outcrop observations typically form 5-10 metre-scale patches (Huck *et al.*, 2012). The petrographical observations have revealed the rare occurrence of green algae and a benthic foraminifer assemblage dominated by textulariids with rare miliolids, which indicates that the *Lithocodium/Bacinella* are likely to be developed in a proximal mid-ramp to distal inner ramp setting (MRP/IRME). Their development is considered to be impaired by the high clay content suspended in the water column (Banner *et al.*, 1990) and restrictions in light (Leinfelder *et al.*, 1993). For these two reasons, the occurrence of *Lithocodium/Bacinella* decreases in a landward direction towards the proximal and clay-prone inner ramp (IRME.a) but also in a seaward direction towards the distal mid-ramp (MRD), where light cannot sufficiently penetrate into deeper waters. In the transitional proximal to distal mid-ramp (MRP/MRD), the growth of *Lithocodium/Bacinella* is restricted to the encrustation of allochems and the subsequent formation of minor coarse-grained (c.5mm) coated grains.

The Shuaiba 3 depositional model (Figure 5) comprises distal mid-ramp and outer ramp depositional environment. Whilst the latter is characterised by homogeneous mudstones/wackestones due to very low-energy conditions, the former is heterogeneous as it includes wacke-packstones to floatstones beds interbedded with mudstone/wackestone textures. These are related to variable depositional energy levels with the occurrence of episodic storm currents and the reworking of allochems from proximal areas related to intermediate and high frequency shallowing successions.

**Vertical and lateral facies change.** The entire Kharaib 1 Dense to Shuaiba 2 succession is organised in two large-scale transgressive/regressive cycles, the top of the uppermost cycle extending beyond the core. The lowermost cycle encompasses the Kharaib Dense 1 and Shuaiba 3 Units and the uppermost cycle comprises the Shuaiba 2 Unit. They are separated by a sharp surface overprinted by a stylolite which tops Shuaiba 3, coincides with a GR peak and a change from clean to slightly argillaceous/organic facies.

The lowermost large-scale cycle is characterised by the upward evolution of clay-rich inner ramp (IRME.a) to cleaner proximal mid-ramp *Lithocodium/Bacinella-* rich deposits (MRP/IRME) in the lower Shuaiba 3 and pass into homogeneous distal mid-ramp mud-dominated facies (MRD) in the upper part of the formation. This interval represents the maximum flooding conditions of the system prior a return towards slightly more proximal settings in association with an increase in bivalve shell reworking. Two intermediate-scale cycles are tentatively identified within this Shuaiba 3/Kharaib 1 Dense interval and are separated by a sharp surface marking the transition between a *Lithocodium/Bacinella-* dominated towards *Lithocodium/Bacinella-* free system. Only algal coated grains are identified at the base of the upper intermediate-scale cycle.

The transgressive phase of the uppermost large-scale cycle identified within the argillaceous Shuaiba 2 Formation is c.10-15ft thick and is reflected by distal mid-ramp wackestones (MRD) passing into outer ramp c. 5ft thick homogeneous mudstones (OR) occurring in the basal part of the formation. The remainder of the formation (representing c.100ft of core) records the regressive trend of the large-scale cycle, which is associated with a return toward distal mid-ramp settings (MRD) and an upward-increase in bivalve shell reworking as a result of the whole system progradation. Higher occurrences of mudrock horizons increasing in thickness upward are observed in the c.20ft uppermost Shuaiba 2 Formation; this is interpreted to reflect
the carbonate production decline marking the Aptian period worldwide (Bonin et al., 2015). At smaller-scale, the cycle identification within Shuaiba 2 is impaired in core due to the homogeneity of the deposits.

**Diagenetic overprint and diagenetic/structural trends**

The impact of cementation and dissolution is overall weak across Thamama deposits except in the clay/organic matter-rich units (i.e. Dense intervals) and certain horizons of the cleaner reservoir units within which both pore-decreasing and pore-enhancing phase lead to the decrease and improvement of reservoir quality, respectively. Fractures, especially developed in Lekhwair 3, can provide a connected network in this reservoir only. The key diagenetic phases are outlined in the following.

**Major pore-decreasing phases**

Regardless of their stratigraphic occurrence, timing and chemical composition, 3 major cementation calcite and dolomite phases have been identified to partially, or locally completely occlude macroporosity. Two calcite phases, one non-ferroan to locally ferroan, medium-crystalline, rhombic to equant and the other being a non-ferroan, coarse-crystalline, blocky phase are observed across all cored Thamama Units. While the medium-crystalline calcite is present relatively everywhere across the cored succession partially occluding macropores, the development of the coarse-crystalline blocky calcite is restricted to the top of Kharaib 1, Lekhwair 2 and Lekhwair 3, and to the Dense Units. Laterally in Shuaiba 3 and Kharaib 1, calcite cements increase in Well E and also probably in Well F (while less petrographical samples are available) and partially occlude macroporosity. A saddle dolomite phase is also observed to precipitate with a coarse-crystalline habit. It rarely completely occludes macroporosity except within the base of Lekhwair 2 and across Lekhwair 3.

**Major pore-enhancing phases (i.e. dissolution events)**

The early dissolution phase is the most significant of the pore-enhancing phases and results in the creation of the majority of the secondary macroporosity. It has also possibly enhanced microporosity hosted within the micrite matrix and allochems. Late dissolution events have also been identified as dissolving earlier developed cementation phases and led to the creation of rare but large vugs (>500µm). These phases are observed to dominantly impact on restricted horizons within Lekhwair 1 and Kharaib 1 that have had an originally well-developed primary pore system. Such late dissolution events are not significant in the Shuaiba units.

**Structural features**

Three dominant types of structural feature are observed and are outlined in this section. Stylolites and associated fractures developed as a result of compaction and are the most prolific form of deformation. A result of pressure dissolution on stressed focal points, stylolites have varying morphologies throughout the cored intervals studied, including anastomosing, columnar and plateau/stepped morphologies. Depending on overall morphology and the stylolites propensity to facilitate brittle deformation that compromises the seam, fluid flow modification within the reservoir is variable. The development of stylolites is usually associated with the formation of a cemented horizon, as a result of the pressure-dissolution and thus can form both localised and extensive baffles. The occurrence of stylolites increases with proximity to significant surfaces picked as large-scale sequence boundaries (e.g. top of Lekhwair 2). Significant facies heterogeneity is linked to the formation of high amplitude stylolites capping rudist-rich and Lithocodium/Bacinella-rich beds in upper Kharaib 1 and base of Shuaiba 3, respectively. This has resulted in the cementation of 10-20cm thick sediments which are potential baffles within the reservoirs. Furthermore, the frequency of stylolites is observed to vary laterally and be more abundant in the flank Well F.

Fractures in the field, being open to fully cemented, are generally small in scale, below 0.5mm in apparent aperture and very rarely exceeding 20cm in length. The majority of fractures in the studied intervals of
the Haliba Field are the result of compaction related horizontal dilation perpendicular to the direction of maximum compression, in association with stylolite formation. Overall, the fractures are observed to increase in Well A located in the North-west of the study area, which is at the hinge of the anticline.

Carbonate hosted deformation bands are the result of the early-stage pore collapse and reorganisation with subsequent preferential cementation along these bands due to enhanced dissolution (Fossen, 2009; Wennberg et al., 2013; Moreau et al., 2016). By definition, these deformation bands are not open fractures and, therefore, have a detrimental impact on fluid flow, particularly where complex anastomosing clusters are present. These are typically core spanning, 1-3mm in width with heavily cemented planes that commonly have anastomosing splays. They have been observed in the Kharaib in Wells A, B and E with increasing occurrence and decreasing spacing in Well E. With that being said, deformation bands have only been observed outside of the Kharaib interval in Well E due to a greater impact of field-scale structural controls affecting this well.

A Pore System/Geological Rock type Classification

The observation of the 804 thin-sections has enabled the establishment of a geological rock type classification, based on the pore system characteristics, with the view to help in the reservoir quality control assessment (next section). Three categories of rock type, labelled 1 to 3, have been identified based on the dominance of macropores and micropores within the pore system, which directly relates to sedimentological make-up and thus depositional conditions. Within each of these categories, the rock types are defined based on the variation in abundance, size and connectivity of pores, which mainly varies along the impact of post-depositional dissolution and cementation events. Each rock type is detailed in Figure 6, a summary of the main classes is provided below together with the rationale behind the classification.

<table>
<thead>
<tr>
<th>Geological rock type</th>
<th>Description of the rock (based on pore system composition characterised in thin-section)</th>
<th>Trends</th>
<th>Depositional characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type 1 (Macropore-dominated system)</td>
<td>Abundant and large interparticle macropores, reaching c.100-200μm. Minor to common microporosity is hosted within allochems.</td>
<td>Increase in grain size</td>
<td>Inner ramp grainstones to packstones with a graptolite matrix</td>
</tr>
<tr>
<td>1a</td>
<td>Abundant interparticle and touching macropores. Minor to common microporosity is hosted within the allochems.</td>
<td>Increase in cementation</td>
<td></td>
</tr>
<tr>
<td>1b</td>
<td>Abundant and touching interparticle macropores, which are rimmed by pore-lining calcite cements visually resulting in the reduction of pore throats. Minor to common micropores are well-developed within the allochems.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1c</td>
<td>Minor interparticle macropores which are isolated due to the development of cements partially occluding pores.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock type 2 (mixed pore system composed of macropores and micropores)</td>
<td>Abundant macroporosity which includes interparticle macropores, vugs and moulds. Rare to minor vugs notably present large sizes (&lt;500μm) and have been created by late dissolution events. Macropores are locally touching. Micropores are abundant and dominantly hosted within the allochems. Microporosity is homogeneously distributed.</td>
<td>Increase in impact of late dissolution phase</td>
<td>Wackestone to packstones deposited within inner ramp, proximal mid-ramp, rudist-rich complexes</td>
</tr>
<tr>
<td>2a</td>
<td>Abundant macroporosity that comprises rarely touching interparticle macropores, vugs and moulds. Abundant micropores are developed within the matrix and more variably within the allochems, and display a homogeneous distribution.</td>
<td>Increase in cementation/occlusion of macropores</td>
<td></td>
</tr>
<tr>
<td>2b</td>
<td>Minor to common macropores (being represented by interparticle macropores, vugs and moulds) which are partially cemented and scattered throughout the sample. Micropores are present within the matrix and are rather patchily distributed due to a variable microporosity matrix</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2c</td>
<td>Rare macropores (including interparticle macropores, vugs and moulds) and microporosity is observed in rare to minor abundances within the matrix. The distribution of both the macropores and micropores is heterogeneous.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2d</td>
<td>Dominated by minor allochem-hosted micropores isolated within a visibly non-microporous micrite matrix, which has been subject to a high degree of neomorphism.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock type 3 (micropore-dominated system)</td>
<td>Abundant and homogeneously distributed micropores, which are present within the micrite matrix. Macropores (vugs and interparticle macropores) are rare and scattered.</td>
<td>Decrease in microporosity possibly due to increasing cementation compaction</td>
<td>Outer ramp and distal mid-ramp mudstones and wackestones</td>
</tr>
<tr>
<td>3a</td>
<td>Minor to common micropores are observed to be hosted within the micrite matrix and display a patchy distribution.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3b</td>
<td>Rare to minor micropores patchily distributed throughout the micrite matrix.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Rock Type Category 1
The rock types under category 1 (RT1) are macropore-dominated, notably characterised by abundant interparticle macropores. The internal subdivision into RT1a, 1b and 1c relies on the impact calcite cementation degree lining and filling the pores in RT1b and 1c, respectively. The sub-group RT1aL represent large interparticle pores which results from the increase in grain size.

Rock Type Category 2
This category classifies samples hosting a mixed macropore/micropore system, where macroporosity is dominated by intraparticle, vuggy and mouldic macropores. Such a pore system is present within grain-supported textures of broad inner ramp (IRME and also includes IRS.r, IRFS.r and IRBS.r) and proximal mid-ramp (MRP) settings. The pore system volume and connectivity can be impaired by calcite or dolomite cementation partially and/or completely occluding macroporosity in RT2b and RT2c. Connectivity and development of microporosity is also observed to vary, which depends on the primary composition of the carbonate mud and diagenetic overprint (dissolution, cementation and compaction). A patchy distributed microporosity is observed in rock types RT2b while visibly non-microporous micrite matrix is present in RT2c. RT2d has the particularity to show a microporosity isolated within allochems, while the surrounding micrite matrix is tight as a result of its neomorphism. The pore system can also be enhanced by the impact of the late dissolution creating large vugs and favouring microporosity development which is captured within RT2aL.

Rock Type Category 3
This is a micropore-dominated system developed in mud-dominated textures reflecting distal mid-ramp (MRD) and outer ramp (OR) settings. While the RT3a represents well developed and connected micropores, decrease in developement and connectivity is captured within the RT 3b and 3c.

Control on reservoir quality
The controls on reservoir quality have been assessed by coding the porosity/permeability data by core-derived information (i.e. texture, allochem content, depositional environment; Figure 7) and geological rock types (based on thin-section based information; Figure 8). Trends illustrated on Figure 8 point out the different controls on the pore system and thus on an increase/decrease in porosity and permeability values across all the Thamama reservoirs.
Figure 7—CCA data coded by the core-derived descriptors (i.e. textures, main allochem content and depositional environment) for each of the Lekhwair, Kharaiib and Shuaiba deposits.
Primary depositional fabric control on the pore system and reservoir quality

- **Abundance of clay/organic matter**: An increase in clay/organic matter content is associated with a decrease in porosity and permeability values (Figure 7; C1 and C3). Clay/organic matter material is believed to be land-derived and is likely to be present within proximal clay-influenced inner ramp deposits (IRMEm.a), typical of the Dense Intervals (Figure 2). The occurrence of diffuse land-derived clay content within deeper genetic elements distal mid-ramp (MRD) and outer ramp (OR)
within the Shuaiba 3 is related to a concentration of clay/organic matter into the deposits following a decrease in carbonate production (Figure 7; C3).

The higher proportion in clay/organic is thought to have resulted in an increase in cementation and potentially higher compaction, leading to a decrease in both the macroporosity and microporosity. The cemented and non-microporous RT2c and RT3c are typically characterised within the clay/organic-rich deposits (Figure 8).

- **Abundance in micrite matrix:** An increase in both porosity and permeability values is observed along with a decrease in mud content within the Lekhwair deposits (Figure 7, A1) while solely increasing permeability is recording along a trend of micritic matrix depletion within the Kharaib and Shuaiba intervals (Figure 7, A2 and A3). The change from mud-dominated textures (i.e. mud/wackestones) to grain-supported textures (packstones to float/rudstones) directly impact on pore system (Figure 8), as it results in:
  - an increase in the abundance of macropores, as reflected by the change from micropore-dominated system (Rock types 3) to mixed (Rock types 2) or macropore-dominated (Rock types 1; Figure 8);
  - an increase in macropore connectivity, notably within Rock types 1.

As a result, the highest permeabilities are observed within grainstones (or float/rudstones with grainstone infill), within which interparticle macropores are touching and connected through large pore throats (Rock types 1). Lower permeabilities are driven by clean mud/wackestones hosting smaller pores and thus pore throats (i.e. micropore-dominated classified under the rock type category 3).

The abundance in mud is directly related to the energy level, and therefore, depositional setting; the occurrence of grainstones is preferentially found in shallow water and high-energy deposits, occurring within clean moderate-energy inner ramp (IRMME), rudist-rich backshoal (IRBS.r) and inner ramp/proximal mid-ramp (IRME/MRP) environment (Figure 7, C1 to C3). By contrast, deposition of mud-dominated textures occurs within low-energy distal mid-ramp and outer genetic elements (MRD and OR, respectively).

- **Occurrence of **Lithocodium/Bacinella**: The positive impact of **Lithocodium/Bacinella** on the reservoir quality has been clearly highlighted within the Lekhwair interval (Figure 7, B1), in which massive **Lithocodium/Bacinella**-rich deposits are stacked within Lekhwair 2. By contrast, **Lithocodium/Bacinella**-rich deposits from Shuaiba 3 record a wide range of porosity/permeability (Figure 7, B3), with notably low values, that result from a localised pervasive cementation of the deposits. Cementation is the result of the creation of stylolites at bed interfaces between **Lithocodium/Bacinella**-bearing floatstones and finer-grained deposits (i.e. packstones).

  Excluding the impact of cementation, the reservoir potential of **Lithocodium/Bacinella**-rich deposits is good as it favours the occurrence of abundant large intraparticle macropores which compose the Rock type 2 (Figure 8). The occurrence of these macropores promotes both the pore volume and connectivity. In addition, it has been noted in Lekhwair 2, pore volume and connectivity provided by the **Lithocodium/Bacinella** allochems is assumed to help in the circulation of late dissolving diagenetic fluids, which in turn results in the increase of microporosity and macroporosity, the creation of large vugs (RT2aL) and the enhancement of the initial reservoir potential.

- For a given porosity, permeability increases from medium-grained (RT1a) to coarse-grained grainstone samples (RT1aL). The **increase in grain size** leads to the occurrence of large pore and large pore throats, which thus promote connectivity. RT1aL are only rarely observed in inner ramp deposits of the Kharaib 1 interval.
Diagenetic controls

- **Development of cementation:** The development of the probably mixed meteoric/shallow marine calcite and rare late burial calcite cements leads to the subsequent partial and complete occlusion of macroporosity that is initially present within RT2a and leads to a change into RT2b and RT2c (Figure 8). Although the impact of the cementation on the micrite matrix is difficult to assess, the deposits showing cemented macropores are characterised by a tight matrix, which suggests that microporosity has been affected by these cementation events. The cementation has been observed in both the clean and the clay-rich deposits. However, the cementation is systematically more developed in the clay-rich deposits, which suggests that the clay burial diagenesis favours the development of cements.

- **Late dissolution phase:** The late dissolution phases have locally created large vugs within the deposits (coded as RT2aL) leading to the increase of both the pore volume and connectivity (Figure 8). In such deposits, the micrite matrix also appears to be significantly microporous, which thus assumes it has undergone these late dissolution events. The late dissolution phases seem to preferentially impact the initially well porous deposits, such as Lithocodium/Bacinella-rich deposits in Lekhwair 2 or floatstones with grainstone to packstone infill in Kharaib.

- **Early dissolution phase:** The early dissolution phase has created vugs and moulds (i.e. RT2) and has also likely to have enhanced microporosity within the matrix and the allochems. Given the difference in the development of matrix-hosted micropore systems (which is dominant) between RT2a, 2b, 2c, 3a, 3b and 3c, this event needs to be considered, despite the difficulty in accurately assessing its impact on the micrite matrix. Indeed, the latter is subject to successive later circulation of cementing and dissolving fluids, which modify the micropore system.

The enhancement of microporosity by the early dissolution phase is believed to be impaired within the more impermeable clay-rich deposits (IRLE.a/IRME.a), while it is increased within clean deposits. For instance, this option would explain the poorly developed micropore system within the clay-enriched Shuaiba 2 deposits, composed of RT3b and 3c while the clean mudstones of Kharaib host a well-developed microporosity (Figure 7; A2 and A3). The initial composition of the micrite matrix in terms of aragonite is also a parameter to be considered as this mineral is not stable and easily leached during diagenesis. This parameter could explain the subtle variability in the development of microporosity within the deposits.

- **Compaction** is possibly increased within the clay-rich deposits, which results in a decrease in the micropore volume and connectivity, and the subsequent occurrence in Rock type 2b, 2c, 3b and 3c.

Reservoir architectures

The assessment of the reservoir quality controls and their distribution (detailed in section 2 and 3) enables the understanding of the variability in porosity and permeability across the succession and across the study area. It also enables its prediction, which is used as an input in the static models. The architecture of each reservoir is detailed separately in the following, which discusses the extent of the potential sweetspots/heterogeneities that may vary along with the allochem content and diagenetic phase distribution.

The lowermost Lekhwair reservoir architecture

The architecture of the Lekhwair interval is illustrated on Figure 9. Two reservoirs are developed in this interval, with the lowermost reservoir occurring in Lekhwair 3 and being a fractured reservoir. Fracture density in Lekhwair 3 is particularly elevated (8 to 10 frac/ft) in Well A and Well E and is associated with the formation of abundant stylolites with large amplitudes (10->30mm). The high level of fracturing/stylolitisation is related to lithological heterogeneity being the result of distinct bedding, skeletal allochem and cementation variations. Fracture size is limited (6 to 15mm in length and 0.2 to1mm aperture), while
cementation is variable between studied wells but largely provides a partially-open fracture network. A potentially correlatable network of fractures providing fluid flow is likely to occur along the crest of the field structure, while fracture density decreases and cementation increases away from the crest (well D), with no vertical connectivity observed. The fractured Lekhwair 3 reservoir is capped by a seal, consisting of the argillaceous/organic inner ramp deposits (IRME.a) in the Lekhwair 2 Dense Unit. Macroporosity is completely occluded and micrite matrix is tights (RT2c) across the field.

Figure 9—Reservoir architecture of the Lekhwair interval. CCA data are coded by geological rock types.

The uppermost reservoir is hosted within Lekhwair 2, the middle part of which consists of an extensive good to excellent reservoir quality layer due to the development of massive Lithocodium/Bacinella-rich deposits. The extensive character of this layer is favoured by the flooding conditions of the system. In this layer, the pore system is dominantly mixed and weakly cemented (RT2a) and locally enhanced by a late dissolution event locally promoting connectivity (RT2aL). The lowermost and uppermost Lekhwair 2 parts are likely to host sweet spots within an overall moderate reservoir quality inner ramp sediment (IRME). The sweet spots occur within thin Lithocodium/Bacinella-rich beds, which reflect a scattered development of the Lithocodium/Bacinella patches in more proximal inner ramp areas, and thus the sweet spots are unlikely to be connected laterally. In Lekhwair 2, fractures are focused around stylolites, most notable the karstified surface topping the formation. Fractures are formed on packstone/Lithocodium/Bacinella floatstone beds boundaries and can locally promote connectivity, although their extent is cm-scale only. Localised to Well E are rare carbonate hosted deformation bands where clay content is lowest. These deformation bands can locally decrease fluid flow potential across their plane and therefore compartmentalise otherwise good reservoir zones. The Lekhwair 2 reservoir is overlain by the Lekhwair 1 Dense's seal, consisting of argillaceous/organic and cemented inner ramp deposits (IRLE.a/IRME.a).

**Architecture of the Kharai 1 reservoir**

The reservoir potential of Kharai 1 is broadly moderate to locally excellent (between 1-800mD), with localised decrease in reservoir quality down to negligible permeability values in the upper part of the formation due to a pervasive development of calcite cements (Figure 10). With the exception of Wells E and F, an upward increase in porosity and permeability is observed across Kharai 1, which is associated with a change in pore system from RT3 to RT2 (to locally RT1) along with the large-scale regressive phase. In the upper half of Kharai 1, one extensive baffle is developed at a stylolitic surface (columnar stylolite) between two good reservoir layers focusing on an abrupt facies break between rudist-rich and peloidal packstone beds. Stylolitisation has resulted in the formation of a 10cm thick cemented horizon, where RT2c occur,
and thus impairs vertical fluid flow. Although cm-scale stylolite-related fractures are present, especially abundant toward the anticline hinge in Wells A and B, their extent does not enable the baffle to be breached, as a result, the uppermost Kharai 1 reservoir is likely to be compartmentalised.

Figure 10—Reservoir architecture of the cored Shuaiba and Kharai 1 reservoirs. CCA data are coded by geological rock types.

An overall decrease in permeability is noted in the south-east direction and is associated with an increase in micrite matrix neomorphism in Wells E and F, which are nearby the flank of the study field. Following micrite neomorphism, microporosity is isolated within allochems (RT2d) and thus, connectivity is limited. The increasing neomorphism is likely to be related to a higher degree in compaction occurring in the flank areas. In addition, the localised formation of deformation bands observed in Wells A, D and E are expected to impair lateral fluid flow.

Kharai 1 reservoir is sealed by the cemented uppermost Kharai 1 overlain by the argillaceous and cemented inner ramp deposits of Kharai 1 Dense. Cementation of the uppermost Kharai 1 is inferred to be related to the significant sequence boundary capping the formation.

Reservoir architecture of the Shuaiba deposits

The architecture of the Shuaiba deposits can be subdivided into two broad parts, with the Shuaiba 3 forming dominantly moderate to locally good reservoir and Shuaiba 1&2 being dominated by very poor to poor reservoir quality (Figure 10).

The base of Shuaiba 3 provides the best reservoir layer of the whole Shuaiba interval and corresponds to 5ft-thick Lithocodium/Bacinella-rich deposits hosting a mixed pore system (RT2a). These deposits are inferred to be connected laterally leading to an extensive good reservoir across the field. The occurrence of a stylolitic surface associated with the cementation of a 20cm-thick horizon above this layer leads to the presence of a baffle to vertical fluid flow. Stylolite-related fractures are developed along this surface. Their abundance and length increase toward the hinge of the anticline, in Well A, providing a localised breach to the baffle in this part of the field. Above this baffle, localised and thin sweet-spots (1-2ft-thick), developed within restricted and unconnected Lithocodium/Bacinella-rich patches, occur at different stratigraphic levels. The upper half of Shuaiba 3 provides a homogeneous reservoir within mud-dominated distal mid-ramp sediments (MRD) dominated by a well-developed micropore-dominated system (RT3a) ensuring moderate permeabilities (1-10mD).
The argillaceous/organic nature of the Shuaiba 1&2 mud-dominated deposits leads to probably higher cementation and compaction, which result in a limited development of microporosity (RT3b and 3c). As such, reservoir performance are dominantly very poor (<0.1mD). In the upper part of Shuaiba 2, three, 5ft-thick layers display poor reservoir quality (0.1-1mD) due to the increase in macropore occurrence (RT2b). The extent of these layers is likely to be limited in the south-east direction (i.e. Well E), due to the increase in calcite cementation in the part of the field.

Conclusions
The reservoir quality assessment carried out on the Thamama Groups (being Lekhwair, Kharaib and Shuaiba) has showed the primary control of the depositional make-up on the pore system and thus on permeability where reservoir was not fractured (i.e. base of lowermost Lekhwair). The preservation of the primary porosity and pore connectivity is enabled by the relatively weak diagenetic overprint, The clay content, abundance in micrite matrix, allochem content and more locally grain size (i.e. in grainstones), result in a change in pore system composition and connectivity. Cementation and late dissolution phases have an only localised impact, cementation being focused on argillaceous/organic layers and developed along key lithological surfaces. The dissolution phases have locally enhanced macroporosity within deposits, which initially hosted a good pore volume and connected pore network. Structural features are observed across both the formations and field; stylolite-related fractures only form a connected network in Lekhwair 3 in the crest of the anticline (Well A) but can locally promote connectivity or provide breaches to fluid flow baffles in other reservoir zones. Rare deformation bands are noticed to be potential but restricted baffles to fluid flow.

Following the sedimentological, diagenetic, reservoir quality analyses, the architecture of the three Lekhwair, Kharaib and Shuaiba reservoirs have been established and show the occurrence of:

- a fractured reservoir in Lekhwair 3 in the north-west part of the field, which corresponds to the hinge of the anticline structure. Decrease in fracture occurrence and increase in cementation away from the crest and toward the south-eastern part of the field result in the reduction of fracture connectivity and thus reservoir properties,
- the development of an extensive good to excellent reservoir within Lekhwair 2 related to the massive development of *Lithocodium/Bacinella*,
- a good but compartmentalised reservoir in the upper part of Kharaib 1,
- a thin-reservoir at the base of Shuaiba 3, capped by a baffle to vertical fluid flow formed along a stylolitic surface. This baffle is however locally breached in the anticline hinge area due to the development of long stylolite-related tension fractures.
- poor reservoir layers in Shuaiba 2, the extent of which is limited in the flanks of the field where cementation and/or compaction is more significant than in the crestal area.