Understanding the relationship between depositional facies, diagenetic evolution and reservoir character in The Cretaceous Shuaiba and Natih Formations of North Oman

Jiraporn Pidnoi

Petroleum Geoscience Program, Department of Geology, Faculty of Science,
Chulalongkorn University, Bangkok
10330, Thailand

*Corresponding author email: kloy.pidnoi@gmail.com

Abstract

The Shuaiba and Natih Carbonate Formations are the most important petroleum reservoirs in North Oman. The reservoir character is significantly heterogeneous and the entrained hydrocarbons accumulated in a complex suite of pore types, so as a result it is a reservoir association that is difficult to produce. This is a major challenge to the economics of exploration and enhanced reservoir recovery programs, focused on these complex reservoirs. To help resolve some of the complexity a study of core from well that intersects both the Natih and the Shuaiba was done. It uses an integrated combination of stable-isotope data, petrographic study and core observations to construct the diagenetic and poro-perm history and so evaluate the related influences of depositional facies and diagenetic evolution on porosity and permeability distribution in well A.

Reservoir properties of both formations are controlled by different pore response/ mechanical-strength responses, which can be recognized from the different poro-perm relationships in the two formations. The Natih is shallower than the Shuaiba, but has a less consistent poro-perm trend, which is likely caused by a wider range of grain and crystal sizes. Natih is comprised of lagoonal bioclastic shales and open marine skeletal wackestones/packstones, which are finer grained, with higher mud contents and lesser corroded and friable fragments than the Shuaiba. Cm to dm-scale grain-rich layers in the Natih carbonates are generally encased by mudstones. Therefore, the contrast in mechanical stress response between shale and grain-rich intervals is obvious in Natih core. Groups of microfractures are obvious in the formation, especially in association with mud-rich zones. In contrast the Shuaiba is mainly comprised of upwards-coarsening rudist rudstone/floatstone units that were deposited in current-reworked rudist banks or shoals. The poro-perm trend of Shuaiba core-plug samples is similar to that seen in many siliciclastic reservoirs; high porosity results in high permeability, although the trajectory of this poroperm trend is somewhat steeper than a typical sandstone do to the overprint of a late-stage corrosive leaching event. Even so, reservoir quality of the Shuaiba is likely defined by a somewhat more predictable relationship between depositional facies and the diagenetic history, compared to the Natih. Some stylolites and isolated microfractures were observed in Shuaiba, but microfractures are more obvious in the Natih.

Integration of core observations, petrography and texture-aware isotope study reveals a diagenetic history that in the earlier to moderate stages of burial is thermally similar for both the Natih and the Shuaiba formations. Throughout the carbon values in the Natih are more influenced by the higher levels of organics, inherent to its lagoonal depositional setting. Only the Shuaiba shows evidence of a late stage leaching event leading to creation of high porosity vuggy intervals These late stage vugs have spar-cement linings with δ^{18}Opdb values that are consistently more negative (warmer) than -6‰. Equivalent vugs and cements are not present in the Natih Formation interval in Well A.

When the isotope plotfields of the Shuaiba Formation in well A are compared with isotope values in time equivalent Shuaiba reservoirs in the highly productive oilfields of the nearby UAE, it is apparent that the Shuaiba formation in this part of Oman did not experience a flush of syndepositional and early diagenetic meteoric waters. This early flush of undersaturated waters created high levels of karstic porosity in the UAE rudist build-ups, which now hosts the hydrocarbons in the various Shuaba-reservoired giant oilfields. The lack of this isotopic signature in the Shuaiba Formation in well A implies a new exploration paradigm, perhaps tied to structural evolution and the timing of fault related fluid conduits, should be developed for this part of northern Oman

Keywords: Shuaiba; Natih; Cretaceous carbonate; Oman

INTRODUCTION

Natih and Shuaiba carbonates are significant hydrocarbon reservoirs in the Sultanate of Oman (Droste, 2010). Hydrocarbons in these carbonate reservoirs mostly accumulated in a complex overlay of intergranular, fracture and locally vuggy porosity and variable dolomitisation. This makes the development of carbonate reservoirs difficult. To help explore and produce this type of reservoir to the maximum, this comprehensive study was done. An integrated approach based on conventional core study, thin section petrography, XRD analyses and O-C isotope analyses were applied to construct the diagenetic history, fluid systems evolution and so help to understand the relationship between facies and diagenesis in these carbonate reservoirs. This comparison of both formations is a case study of how complex processes in carbonate reservoirs can cause different reservoir property responses in the same well, in this case in Natih versus Shuaiba. The results represent a potential analogue for other similar subsurface reservoirs.

METHODOLOGY

Well A was drilled on an upthrown closure against an east-dipping fault through Natih and Shuaiba reservoirs, Six conventional cores were collected in Well A, consisting of four cores from the top of Natih reservoir and two cores from the top of the Shuaiba reservoir. The cores were provided to laboratories to obtain data needed explore the potential links between sedimentary facies, diagenesis and fractures of carbonate rocks of Natih and Shuaiba. This data is utilized in this report. Core logging and description done in this study focused on depositional facies and also recognized diagenetic features. Petrographic study was used to construct detailed textural descriptions at the microscopic scale. Moreover, XRD samples were done in order to confirm the presence of minerals seen in thin-section and so understand mineralogical changes from top to bottom of the cores. In addition, carbon and oxygen stable isotope analyses were performed. This technique is given the general name "texture-aware isotope sampling." Sample results were analyzed in order to better understand the timing and mechanisms controlling rock-fluid interactions in both formations, and so obtain valuable information regarding the burial/thermal history evolution and the associated poro-perm trajectory. Finally, all results were integrated in order to better understand porosity distribution, diagenetic history and reservoir-quality evolution of Shauiba and Natih Formations.

GEOLOGICAL SETTING AND STRATIGRAPHIC

The Cretaceous stratigraphy is shown in Figure 1. The Natih and Shuaiba were deposited on a stable platform along the passive margin of the Neo-Tethyan Ocean (Permian to Late Cretaceous). In the Late Jurassic to Early Cretaceous, the Gondwanaland supercontinent rifted apart as India and Madagascar successfully broke away from the Afro-Arabian plate (Loosveld et al., 1996). Extensional forces caused by the northward drift of India created the Rayda basin in the eastern Oman into which the large scale foresets of the Habshan carbonate shelf prograded towards the plate margin. After the filling of the Rayda Basin, the region experienced further deepening, leaving another series of intrashelf basins as the dominant depositional style in the Northern Oman. The Early Cretaceous ended with the deposition of the Shuaiba, a system characterized by attached platforms and massive rudist banks and carbonate shoals along the edges of the large intrashelf basin centered to the northwest in Abu Dhabi. In the Late Cretaceous, the NahrUmr and Natih formations were the last sequences deposited in northern Oman. The NahrUmr is composed of marine shales and is an important regional seal for the underlying Shuaiba. It grades conformably upwards into the Natih Carbonates. The study area was subject to two main orogenic events and associated fluid systems, separated by a period of tectonic relaxation (Fontana et al., 2012). These events include Late Cretaceous tectonics, associated with ophiolite obduction in the re-

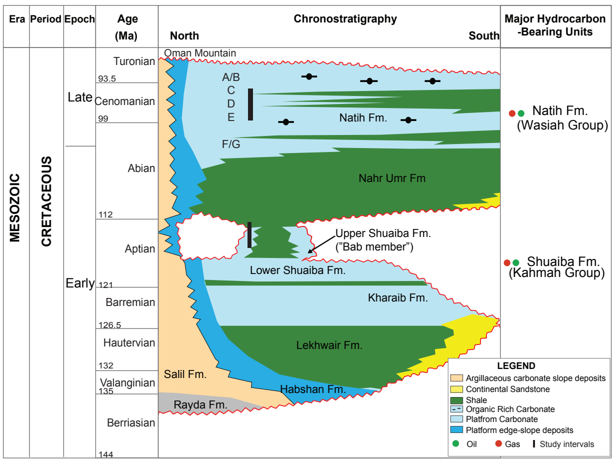

Figure 1 Simplified Cretaceous stratigraphy of Oman and the study intervals (Modified from Droste, 2004) gion of the Oman Mountains. The compression created a foreland basin (via "The first Alpine event"), and was followed by Cenozoic deformation that drove folding and thrusting in the Northern Oman Mountains ("The second Alpine Event"). During the second Alpine Event, the Oman Mountains were uplifted to their culmination collapse, forming large extensional structures (Loosveld et al. ,1996).

RESULTS

Meso-Scale Core Observation and Interpretation

Core observation and description were completed on 85.79 meters of core collected from two intervals from well A. The upper interval was collected from the Natih Formation (Members C-E) and the lower interval was collected from the upper part of the Shuaiba Formation.

The Natih Formation: Natih is mud-dominated lagoonal carbonate, composed of skeletal wackestones grading to packstones and the lower part was interbedded with mudstone. The overall depositional setting was interpreted as a shallow platform interior characterized by alternations of influxes of clay into isolated lagoons and subsequent return to normal marine lagoonal conditions. Natih has a high stylolite density, with both parallel-to bedding and inclined-to-bedding stylolites. Only microfractures were observed and most of fractures were subsequently cemented. Natih shows higher fracture densities compared to the Shuaiba, with dominantly horizontal and lesser inclined fractures (Figure 2).

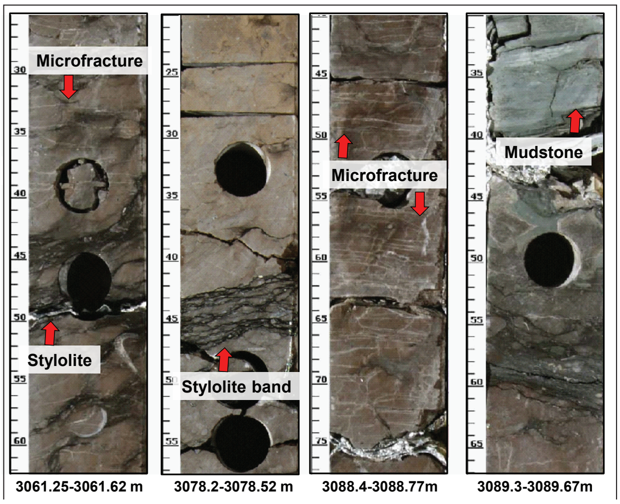

Figure 2 Core photos of Natih Fm., comprised of mud-dominated lagoonal carbonate with pervasive microfractures and stylolites.

The Shuaiba Formation: Shuaiba is a grain-dominated platform edge carbonate succession. Core lithologies are comprised of rudist and coral floatstones to rudstone and some intervals of peloidal packstones. The peloidal packstone facies indicates relatively low energy and shallow lagoonal environments, while the rudist and coral floatstones indicate reworked coral rudist bank and shoal deposits, developed at the platform edge. Visible porosity is dominantly isolated-vuggy, developed within rudist floatstone facies, comprising large voids within corals and rudist shells. The Shuaiba core has a lower microfracture and stylolite density compared to the Natih. The Shuaiba has only a few isolated microfracture zones; almost the entire Shuaiba core shows no evidence of fracturing (Figure 3).

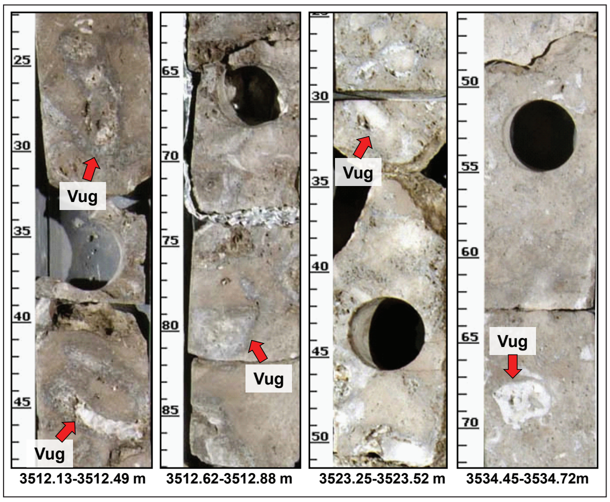

Figure 3 Core photos of Shuaiba Fm, comprised of grain-dominated platform-edge carbonate with variable development of isolated partially-cemented vugs.

In summary, the Natih and Shuaiba formations are made up of different lithofacies, which were deposited in different depositional environment settings. As a result of different primary rock properties, both formations likely show significant differences in their diagenetic responses. Moreover, observed vertical porosity and permeability variations correspond to changes in vertical facies associations and subsequent diagenetic history. Therefore, the micro-scale observations and isotope determinations were required, in order to understand the fluid evolution in both formations, and so construct an understanding of controls on porosity and permeability distributions.

Micro-Scale on Petrographic Study

Porosity modification

In both the Natih and Shuaiba formations, remnant primary porosities are rarely seen in thin section. Instead, intergranular and intragranular primary porosities are pervasively cemented. However some porous intervals remain, mainly secondary porosity, dominated by a combination of moldic, vuggy and microfractured textures. In addition, solution-enhanced porosity related to late stage burial leaching (hydrothermal?) was found patchily developed in the Shuaiba cores.

Moldic porosity: Moldic porosity indicates texture-selective removal, typically by dissolution of metastable components, which in early burial is mostly aragonitic shells. Almost all of this style of Natih moldic porosity is now filled by cement, as illustrated in Figure 4A, and there was some isolated moldic porosity developed in the Shuaiba, as illustrated in Figure 4B

Microfracture porosity: Microfracture porosity is more abundant in Natih. However, thin section study shows many microfractures in the Natih are real and not induced artifacts as they are filled or partially-filled with cement (Figure 4C). Clearly, there are some open microfractures, as illustrated in Figure 4D.

Late stage (hydrothermal?) porosity development: The dominant style of open porosity still present in the Shuaiba is likely related to a late stage diagenetic event. The earlier calcite vein fills have been dissolved and recrystallized as a second generation of porosity developed locally in the Shuaiba via a combination of isolated solution-enhanced vug porosity and isolated enlarged-microfracture porosity. Figure 4E shows a large vug that is the result of late stage leaching in peloidal packstones and now partially-filled by later calcite cements. Figure 4F shows large-vug features, occluded by later stage calcite spar cements. Some samples show dissolution-etched edges, which is evidence of late stage corrosion that overprints both vug cement and matrix, as illustrated by blue arrows in Figure 4. It is likely that this later stage dissolution and calcite precipitation occurred in the mesogenetic realm, driven by crossflowing hydrothermal mineralizing solutions that moved through focused zones of access in these rocks. Such porosity may have formed via fluid crossflows associated with the compressional tectonism that formed the Oman Mountain suture belt (see later isotope discussion related to these cements).

In summary, petrographic analysis shows porosity levels in the Natih are poor and largely reflections of the original low-energy depositional environment, where there was a distinct lack of grain-supported deposits. Where the Natih shows

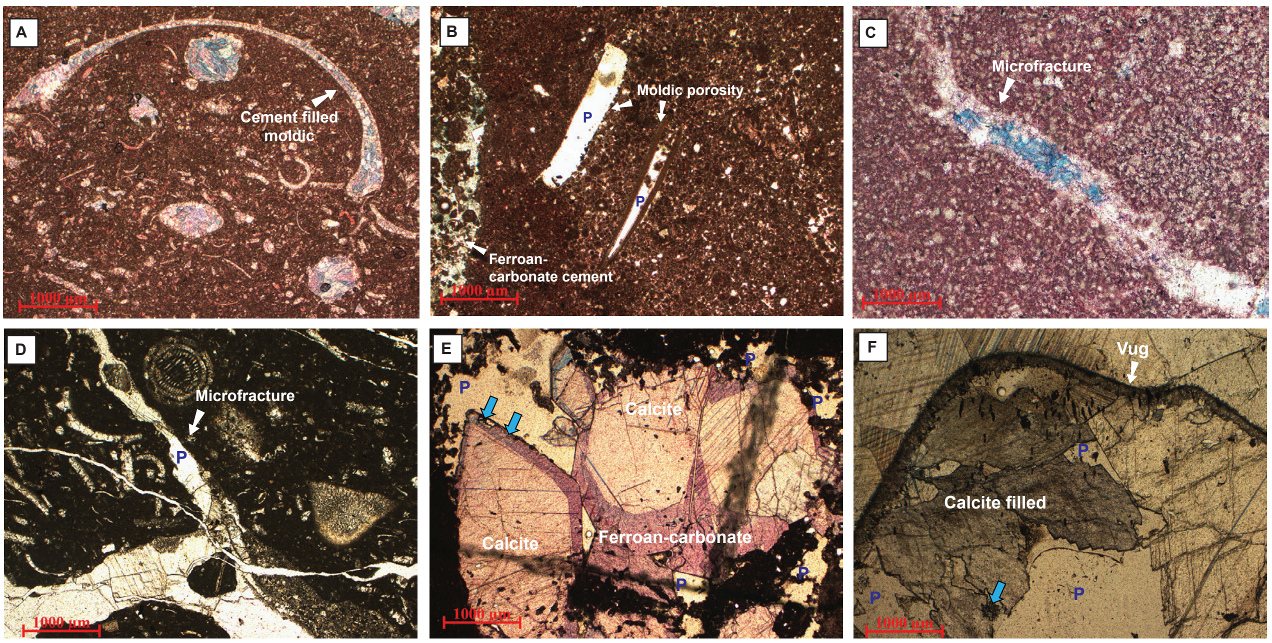

Figure 4 Representative micro-scale features related to porosity modification

high permeabilities within this low porosity frame, it tends to be associated with the preservation of partially-mineralized open microfractures. Likewise, petrographic study shows Shuaiba porosity was largely controlled by its depositional facies association. However there is evidence late-stage porosity creation in some parts of the Shuaiba, via corrosive crossflows during late stage burial diagenesis. The creation of such corrosive intervals via non-fabric-selective leaching probably helps explain the steep poroperm trajectory, so obvious in Figure 6 (indicated by deep blue arrow). The details of various diagenetic processes, as seen in thin section, culminate in one central issue, which is: What controls the current porosity and permeability levels in well A? In particular, the ability to recognize secondary porosity outside of the cored intervals is critical to the formation evaluation process in such wells. In the next section, we will see how stable isotope analysis can help address this problem.

Oxygen and Carbon Isotope Study

The $\delta^{13}C$ and $\delta^{18}O$ compositions of Natih and Shuaiba samples are plotted in Figure 5A. The most obvious separation in the plot is between the Natih (blue) and the Shuaiba (red). Throughout the carbon values in the Natih are more influenced by the higher levels of organics, inherent to its lagoonal depositional setting. The Shuaiba's isotope plotfield shows a wider range of $\delta^{18}O$ values and less depleted of $\delta^{13}C$ values, compared to the Natih. It is likely that the Shuaiba cements indicate precipitation from a wider range of fluid temperatures compared to the Natih. Within the trend of temperatures increasing with burial, an oxygen value ($\delta^{18}O_{PDB}$) of -6‰ was chosen to separate earlier from later stage burial diagenesis.

In summary, based on the oxygen isotope values, there are two groups in samples from the Shuaiba and Natih in Well A (pink and green shaded zones in Figure 5). Group-I was interpreted as shallower and earlier stages of burial, prior to the complete loss of matrix permeability and cessation of significant rock fluid interaction ($\delta^{18}O$ = -1.5 to -6%) Group-II is interpreted to reflect fluids derived in deeper and high-temperature conditions. Only the Shuaiba shows evidence of a late stage leaching event, leading to creation of high porosity vuggy

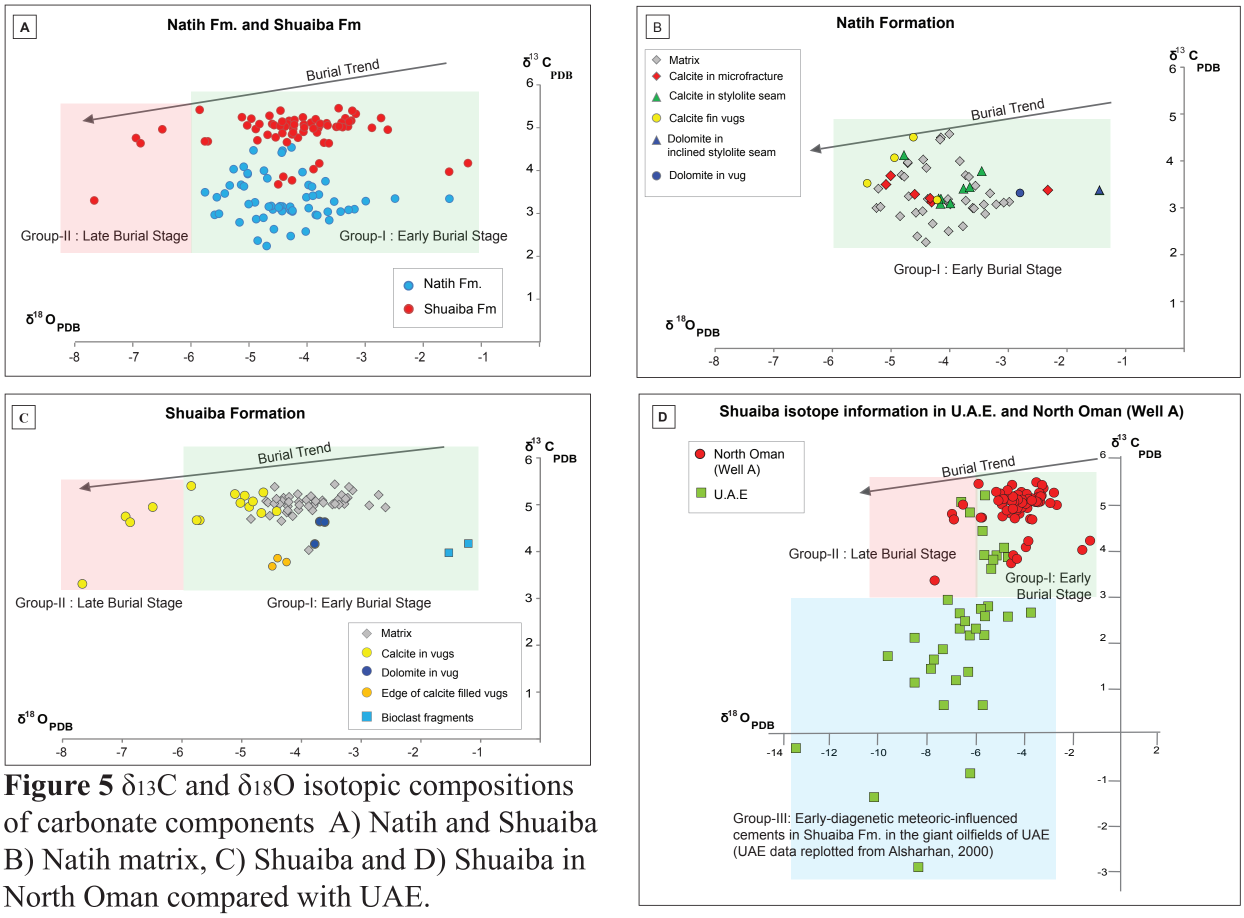

Figure 5 δ13C and δ18O isotopic compositions of carbonate components A) Natih and Shuaiba B) Natih matrix, C) Shuaiba and D) Shuaiba in North Oman compared with UAE.

intervals These late stage vugs have spar-cement linings with $\delta^{18}O_{pdb}$ values that are consistently more negative than -6‰. Equivalent vugs and cements are not present in the Natih Formation interval in Well A.

When the isotope plotfields of the Shuaiba Formation in well A are compared with isotope values in time-equivalent Shuaiba reservoirs in the highly productive oilfields of the nearby UAE (Figure 5D), it is apparent that the Shuaiba formation in this part of Oman did not experience a flush of syndepositional and early diagenetic meteoric waters. This early flush of undersaturated waters created high levels of karstic porosity in the UAE rudist build-ups, which now hosts the hydrocarbons in the various Shuaiba-reservoired giant oilfields. The lack of this isotopic signature in the Shuaiba Formation in well A implies a new exploration paradigm, perhaps tied to structural evolution and the timing of fault related fluid conduits, should be developed for this part of northern Oman.

Diagenetic History

Integration of core observations, petrography and texture-aware isotope study reveals a diagenetic history that in the earlier to moderate stages of burial is thermally similar for both the Natih and the Shuaiba formations. A subsequent hot-corrosive set of solutions moved through the Shuaiba Formation in well A, but did not penetrate the Natih as summarized in Table 1.

However, the difference in thermal history between two formations can hardly be construed reliable or appropriate, using only one well without considering the areas outside the vicinity of the well and any possible tie back the region's structural evolution. The corrosive hot fluids that affected the Shuaiba might be related to intense tectonic activity, such as Late Cretaceous Ophiolite obduction and following by folding/uplift of Oman Mountain during Late Tertiary. The driving force for the late-stage porosity-creating event is a subject for further investigation.

Reservoir properties

Reservoir properties of both formations are controlled by different pore response/ mechanical-strength responses, which can be recognized from the different poro-perm relationships in the two formations, as illustrated in Figure 6. The Natih is shallower than the Shuaiba, but has a less consistent poro-perm trend, which is likely caused by a wider range of grain and crystal sizes. Natih is comprised of lagoonal bioclastic shales and open marine skeletal wackestones/packstones, which are finer grained, with higher mud contents and lesser corroded and friable fragments than the Shuaiba. Cm to dm-scale grain-rich layers in the Natih carbonates are generally encased by mudstones. Therefore, the contrast in mechanical stress response between shale and grain-rich intervals is obvious in Natih core. Groups of microfractures are obvious in the formation, especially in association with mud-rich zones. Natih was originally mud-dominated sediment (mostly Class-3 in a Lucia (1992) crossplot). In the cores, Class-1 type sediment was not seen in the Natih depositional style, but some poro-perm values do locate in the lower permeability end of Lucia's Class-1. This shift in values is likely caused by locally open microfractures. Thin sections show some microfractures in Natih create small-scale touching-vugs. Microfrac-

Formations	Stage	Early Shallow burial → Late Deep burial	Comment
Shuaiba Fm., Natih Fm.	**Eogenesis**		
Shuaiba Fm., Natih Fm.	Deposition with early marine cement		Rare fringing calcite scalenohedra – partly removed by dissolution
Shuaiba Fm., Natih Fm.	**Mesogenesis**		
Shuaiba Fm., Natih Fm.	Dissolution and burial calcite precipitated in cavity of bioclast		Preservation of structures can be enhanced by the precipitation of fine-crystalline drusy calcite mosaics. The interior is completely dissolved, producing open molds. The molds are stabilized by cement. Dissolution may occur in a early burial environment.
Shuaiba Fm., Natih Fm.	Development of microfracture and stylolites		
Shuaiba Fm.	Late leaching-dissolution by hydrothermal alteration and formation of vuggy porosity		
Shuaiba Fm.	Non ferroan and later ferroan carbonate cement occluding dissolution and interparticle pores.		Coarse blocky calcite and later ferroan carbonate filling moldic pores (minor dolomite?)

Porosity enhancement
Porosity destruction

Table 1 Diagenetic events of the Natihand Shuaiba formation

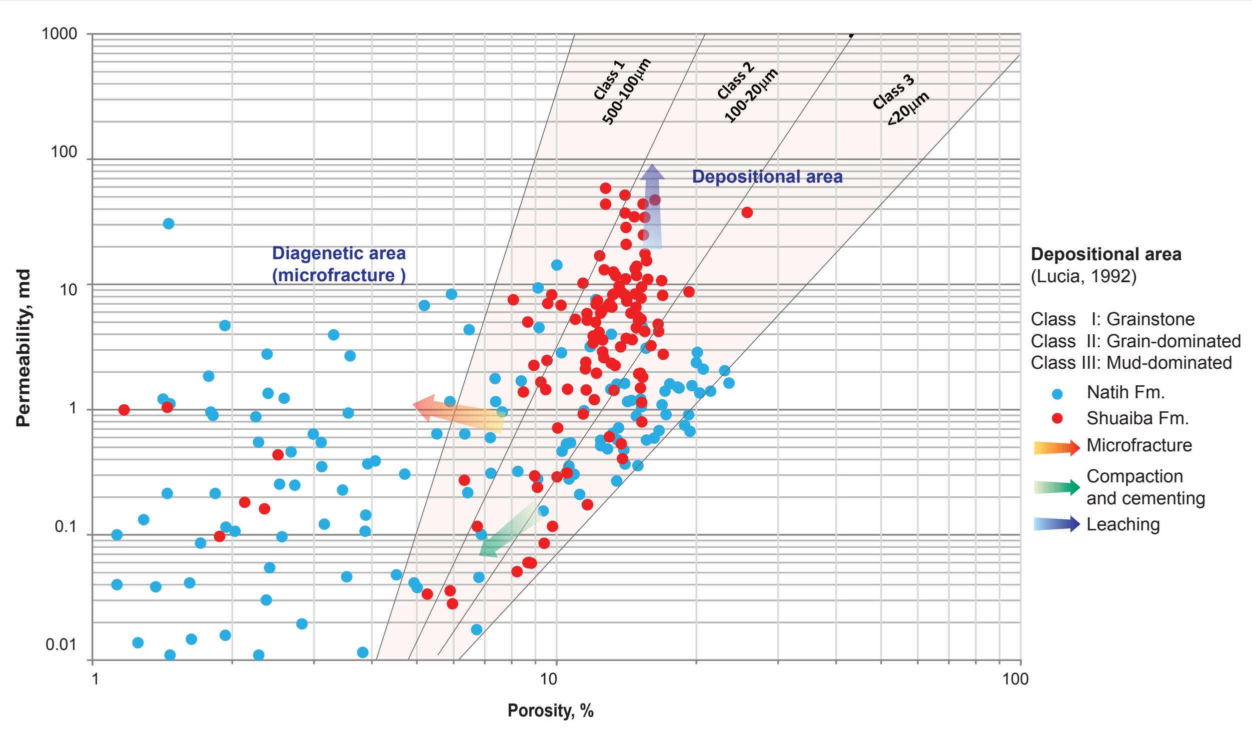

Figure 6 Cross plot of porosity-permeability (air-Klinkenberg corrected) relationships for various particle-size groups of Natih and Shuaiba overlaying with Lucia crossplot.

tures are assumed to slightly enhance permeabilities because matrix storage tends to be somewhat more connected in such a setting. In contrast the Shuaiba is mainly comprised of upwards-coarsening rudist rudstone/floatstone units that were deposited in current-reworked rudist banks or shoals. The Shuaiba mainly comprises rudist rudstone and floatstone units (Class-2 in a Lucia (1992) crossplot) originally deposited as reworked rudist banks or shoals. This plot field is consistent with expectations of a class-2 plot field based on depositional texture alone, as defined by Lucia (1992). The poro-perm trend of Shuaiba core-plug samples is similar to that seen in many siliciclastic reservoirs; high porosity results in high permeability, although the trajectory of this poroperm trend is somewhat steeper than a typical sandstone, due to the overprint of a late-stage corrosive leaching event. Even so, reservoir quality of the Shuaiba is likely defined by a somewhat more predictable relationship between depositional facies and the diagenetic history, compared to the Natih. Some stylolites and isolated microfractures were observed in Shuaiba, but microfractures are more obvious in the Natih.

RECOMMENDATIONS

According to the results of isotope studies in well A, future wells in the region should be analysed across zones of interest (cuttings or core and texture-aware sampling) in order to identify isotopic signatures, possibly related to corrosive fluid events, and then correlated with seismic data to identify possible controls on early versus late stage fluid conduits, and so optimize future well locations and development levels. This may provide a new exploration paradigm in a region that contains no isotopic or petrographic evidence of the porosity-creating events that formed the giant Cretaceous platform fields of the UAE.

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