

DIAGENETIC CONTROLS ON RESERVOIR QUALITY IN THE SHUAIBA FORMATION OF NORTH OMAN

Muchimaporn Khumputorn

Petroleum Geoscience Program, Department of Geology, Faculty of Science,
Chulalongkorn University, Bangkok, 10330, Thailand
Corresponding author email: numuchi@hotmail.com

Abstract

The Shuaiba Formation and its equivalents are a prolific hydrocarbon reservoir across the Middle East and the unit is one of the main producers in the U.A.E. and Saudi Arabia, with lesser levels of production in Oman. In the northern part of the Sultanate of Oman, the Shuaiba Fm. can act as a reservoir, but so far, it is not of the same quality as where it constitutes reservoirs in the UAE. There, the Shuaiba Formation is the main producing interval in a number of giant fields. This study looks at why there is such a contrast in reservoir quality using an integrated combination of sedimentological core logs, thin section petrography, XRD analyses, and texture specific C-O isotope analyses.

A core-based study of 5 wells in Northern Oman shows the depositional setting is a combination of muddy poorer-quality sediments that are combinations of mid-ramp and lagoonal sediments and grainier better-quality wave-dominated sediments. Isotopic sampling across this depositional spectrum defines two covariant carbon-oxygen trends: 1) a burial trend defined by increasing fluid temperatures in later cements. This trend dominates the grainier units and is consistent with the burial trend first established in Cretaceous carbonates of Northern Oman by Pidnoi (2014) and; 2) an organic-mixing trend mainly found in wells with sediments deposited in the lagoon and mid ramp. The muddier sediments show isotope evidence of losing their permeability earlier in their burial to greater depths (exposed to warmer diagenetic fluids). Of the five wells considered, only two produce from the Shuaiba Fm and both these wells show evidence of late stage leaching with cements in partially-filled late stage vugs, with $\delta^{18}\text{O}_{\text{PBD}}$ values that are $<-6\text{‰}$ (warmer fluids). That is, the development of economic porosity and permeability in the Shuaiba of Northern Oman is a response to crossflows of a late-stage diagenetic burial fluids.

Both isotopic trends seen in the various diagenetic textures in the Shuaiba of northern Oman have C-O plotfields that are different from plotfields of cements associated with reservoir porosity creation in the giant fields hosted in the Shuaiba Formation of the UAE. It seems the Shuaiba in northern Oman lacks isotopic evidence of the meteoric processes that was the key in the creation of new pore spaces and pathways that formed the excellent reservoirs in the U.A.E.

Keywords: Shuaiba Formation; Diagenetic controls; Early carbonate; North Oman

1. Introduction

Shuaiba formation is a prolific hydrocarbon reservoir across the Middle East and one of the main producers in the U.A.E, Oman and Saudi Arabia (Alsharhan and Kendall, 1995). Hydrocarbons in these carbonate reservoir mostly heterogeneous and complex pore. To develop are difficult, so for more exploration and production have to understand in reservoir characterization.

The main objectives of this study are to better understand the depositional processes and diagenetic evolution (with associated porosity and permeability distribution) in the Cretaceous Shuaiba Formation in north Oman and to compare the results to the known history of the Shuaiba reservoir quality in the UAE.

2. Geological setting and Stratigraphy

Oman is located on the southeastern margin of

the Arabian plate (Figure 1). Consequently, plate movements have resulted in complex structural, sedimentation, and burial histories. Oman is tectonically bound on the south by the Gulf of Aden spreading zone, to the east by the Masirah Transform Fault and the Owen Fracture Zone Trough, and to the north by the complex Zagros-Makran convergent plate margin, compression along which produced the Oman Mountains (Loosveld and others, 1996). There are two main tectonic events which is associated to imposed two hydrothermal fluid systems; Late Cretaceous – Ophiolite obduction

3. Methodology

Four cored wells were collected from The Cretaceous Shuaiba Fm. in the study block. The core interval totals 124.23 meter, providing the core result by laboratories to obtain data needed explore the potential links between sedimentary facies, diagenesis and reservoir quality in the Shuaiba formation by study in core logging and thin section to study depositional facies and diagenetic feature and intergrated with the stable isotope and XRD result which is analyze diagenetic evolution, mineral content. All the result to solved the problem and better

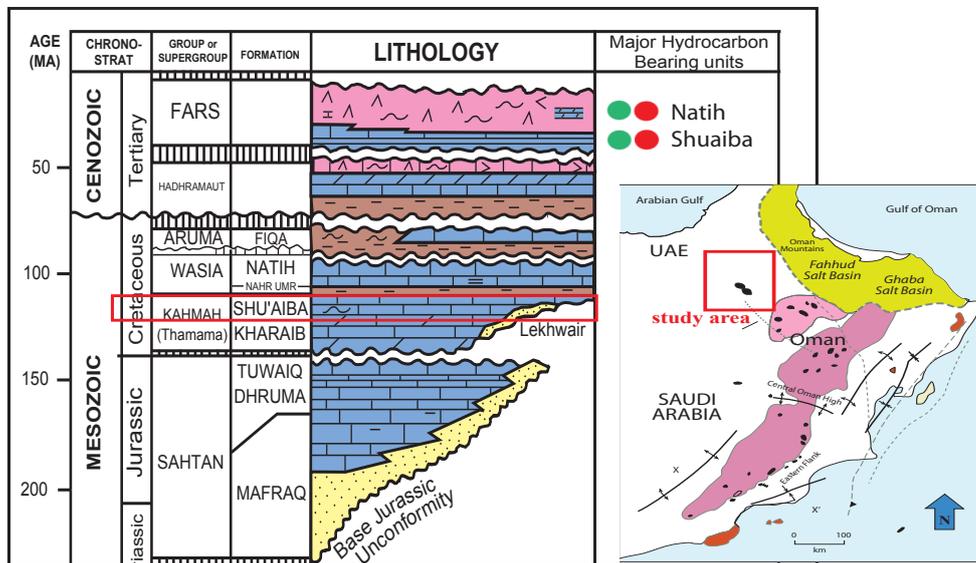


Figure 1 Locations of study area and Stratigraphy in the study area.

in region of the Oman mountains. and Tertiary – compressional tectonics formed the Oman mountain. This study focuses on the Shuaiba Formation, it was deposited on a stable platform along a Lower Cretaceous passive margin. The formation, where it is made up of shallow water, shelf-margin carbonate buildups (mainly rudist reefs) and associated grainstones (debris shoals) formed on and around low-relief structural highs (mostly formed by salt pillows and tilted, upthrown fault blocks) comprises the better reservoir (Frost et al, 1983). Uplift from both tectonic and halokinetic movements produced secondary (mostly moldic and vuggy) porosity from subaerial erosion and meteoric diagenesis.

understand depositional facies, diagenetic history and reservoir quality evolution of the Shuaiba formation.

4. Result Lithofacies

Study of core from four wells identified carbonate lithofacies in the Shuaiba Formation tied to 12 carbonate lithofacies deposited across two main depositional environments; lagoonal and inner ramp. Well A and well B are located in the northern part of the study block, well C is central and Well D lies in the southern part of the block, as shown in Fig 2. A brief description of lithofacies is given below, arranged from lagoonal to

inner ramp facies.

Rudist lime floatstone/grainstone

This facies typifies the middle section of well D, dominated by carbonate grains that are larger than sand size. These grains float or are embedded in a finer sandy matrix of fine to medium-grained peloid grainstone. The larger granules are generally derived from the fragmentation of reef builder skeletons, such as rudists, echinoid debris, corals and benthic forams. Visible porosity is moderate and predominantly made up of moldic porosity with some microporosity within grains.

Rudist floatstone/packstone

It typifies the upper and lower sections of well B and middle section of Well D. It consists of a packstone matrix of fine to medium sand grade peloids with lime mud and argillaceous material between matrix grains. Granule to pebble grades are composed of abundant bioclasts of rudists, gastropods and echinoderm debris, along with coral and highly leached benthic foraminifera. Porosity is poor to moderate and comes from leached zones, intraclasts and matrix, with local zones classed as having good moldic porosity.

Rudist floatstone/wackstone (Algal)

This lithofacies typifies the top of core in the upper section of Well B. These sediments are matrix-supported and include poorly sorted pebble-grade bioclasts floating in a wackstone matrix. Dominant bioclasts include algae *Lithocodium/Baciella* and molluscan fragment from rudist bivalves and gastropods and rare coral fragments. The wackstone matrix is dominated by abundant lime mud with fine skeletal debris. Porosity is poor and made up of matrix porosity and rare growth framework porosity.

Skeletal foram wackstone graded to packstone

These wackstone units (cycles) grade upward to packstones and typify the upper and middle sections of well C. They are composed of fine silt to fine-grain peloidal skeletal material (micritised), grains are typically rounded and well to moderately sorted.

These sediments contain abundant skeletal debris, dominated by peloids, with recognizable echinoid fragments, as well as benthic foraminifera, trace bivalves and ostracods. Poor moldic and microporosity are common within skeletal grains and result from complete or partial dissolution.

Coral lime packstone

Observation in thin sections from the lower section of well B, but were not clearly resolvable in core as at the hand specimen scale the proportions of neomorphosed grain types were not clearly identifiable. The sediment are poorly sorted, with occasional large pebble-sized bioclasts, including coral fragments. Larger fragments are bivalves, coral floating in fine to coarse grain skeletal packstone matrix. It is a massive unit and is show bioturbated. Porosity is poor from intrafossil moldic and vuggy, micro porosity within grains.

Skeletal peloidal packstone/Lithocodium wackstone

Encounter in the middle and lower section of well A. There it consists of poor-moderately sorted, very fine to coarse, faintly laminated packstone to wackstone with *Lithocodium* with interbedded with slightly argillaceous wackstone horizons with small intraclasts. It contains Skeletal debris, echinoids, peloids, rudist debris, benthonic and miliolid foraminifera. The core shows slight bioturbation, with heavily stylolitic intervals and common nodules of pyrite. The porosity is poor, including rare intraparticle porosity and minor microporosity and rare mouldic macroporosity.

Bioturbated skeletal wackstone

These facies were mainly penetrated in the middle and lower sections of well B, the middle section of well C and the upper section of well D. They are poorly sorted, matrix-supported, silt to lower fine undifferentiated grain (mainly bioclasts) with minor peloidal, wackstone matrix that is highly bioturbated, with argillaceous wispy microstylolitic seams. Poor moldic porosity and leached microfossils are present.

Lime mudstone

These are encountered in the lower section of well C and the upper section of well D. This lithofacies is the most mud-rich and is noticeably barren with isolated ostracods, echinoderm debris, bivalves and miliolid foraminifera. Porosity is my considered to be very poor.

Rudist Rudstone (Molluscan)

This is the most common lithofacies in the middle and lower section of well D, and constitutes over 30 % of the middle section of well B. Sediments are comprised of moderately to poorly sorted granule to pebble grade, neomorphosed molluscan-dominant bioclasts (bivalves, rudists, echinoids, gastropods and corals) that are broken up and rounded. Porosity is good, and interparticle pores are present, but are extensively cemented by calcite. Thin sections show dissolution has created a combination of intrafossil, moldic and solution enlarged vugs. Pyrite is present.

Rudist floatstone

In the middle section of well B, These sediments are made up of poorly sorted, granule to pebble grade, bioclastic components that float in a fine to coarse-grained calcite matrix with lime mud. The bioclasts are dominated by broken and rarely whole rudist fragment as well as gastropods; in addition clasts of algae *Lithocodium/Baciella*, echinoids and coral were present. Porosity is moderate to good, mostly developed as intrafossil, moldic and solution enlarged vugs that are the result of dissolution.

Muddy Molluscan rudstone

This unit occurs in the middle and lower section of well D. It is very similar to the Rudist rudstone lithofacies but with higher levels of mud. It forms interbeds within the Rudist rudstone unit.

Skeletal packstone/grainstone (rudist)

This unit was mainly penetrated in the upper section of well A. It is composed of combinations of mainly skeletal packstone to grainstone, (and rare wackestone) with grain components that are composed of fine-coarse sand sized, angular to

moderately rounded, moderately sorted, skeletal debris composed of rudists with lesser bivalves, corals, echinods and *Lithocodium* debris. Fine to coarse calcite cements fill most pores and any remaining porosity is a combination of moldic, intergranular and microporosity.

Petrography study

Thin sections collected for this report define two main groups that are separated by reservoir quality based on depositional environment into two main group (Fig3) in the detail below;

Main reservoir quality resides in the Inner ramp depositional association

Rudist skeletal floatstone or rudstone

Thin section studies show moderately to poorly sorted granule to pebble grade neomorphosed well rounded molluscan bioclasts (Fig 3), rudists and gastropods, corals, stromatoporoids, echinoderm debris and benthic foraminifera are also present. Interparticle pores are present but can be extensively cemented and replaced by coarse calcite. Porosity therefore, largely occurs within isolated moldic pores where grains have been leached. Porosity also occurs where fine-scale partial leaching of grains has created highly microporous relic grains.

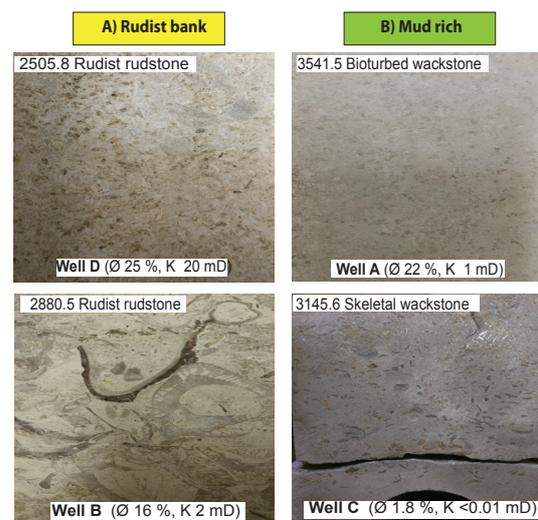


Figure 2. A) Rudist bank system which is deposited in Shoal setting, observation in well B and well D. B) Mudrich system in lagoon and mid ramp as almost seen in well A and C.

Peloidal Bioclastic Lime Floatstone/ Grainstone

Thin section studies show granule to pebble grade bioclasts (broken and rounded molluscan material of whole rudists and gastropods) floating within a grainstone matrix of fine to medium sand grade peloids. Echinoderm debris, corals and highly leached benthic foraminifera are also present. Porosity is good, present as moldic porosity and microporosity within grains.

Rudist floatstone packstone to wackstone

Thin section study shows poorly sorted sediments made up of pebble grade rudists, algal fragments, echinoderm and neomorphosed bioclasts floating in a packstone to wackstone matrix. The matrix comprises fine to coarse skeletal grains mixed with micrite mud. Visible porosity is moderate and made up of mainly moldic and vuggy porosity with some intrafossil. Fractures are observed, but mostly filled by calcite cement.

Poor reservoir quality in the Lagoonal/Back shore and Middle ramp associations (Fig 4)

Bioclastic skeletal packstone

Thin section studies show these skeletal peloidal packstones are made up of silt to pebble grade, dominantly lower medium grained-size, poorly sorted sediments containing echinoderm fragments and peloidal grains, along with occasional large rudist fragments packed in a micrite matrix. Visible porosity is fair, mostly isolated moldic porosity reduced by later calcite cements with lesser interparticle porosity.

Skeleton wackstone

It is dominated by silt with lesser very fine skeletal sand. Skeletal material dominantly made up of abraded fragments of undifferentiated bioclastic debris with minor amounts of small benthonic forams, minor mollusc and echinoderm fragments floating in a micrite matrix (Figure 5A). Visible porosity is poor, mostly poorly interconnected moldic and intraparticle porosity. Trace late ferroan saddle dolomite fills a few molds and intraparticle areas.

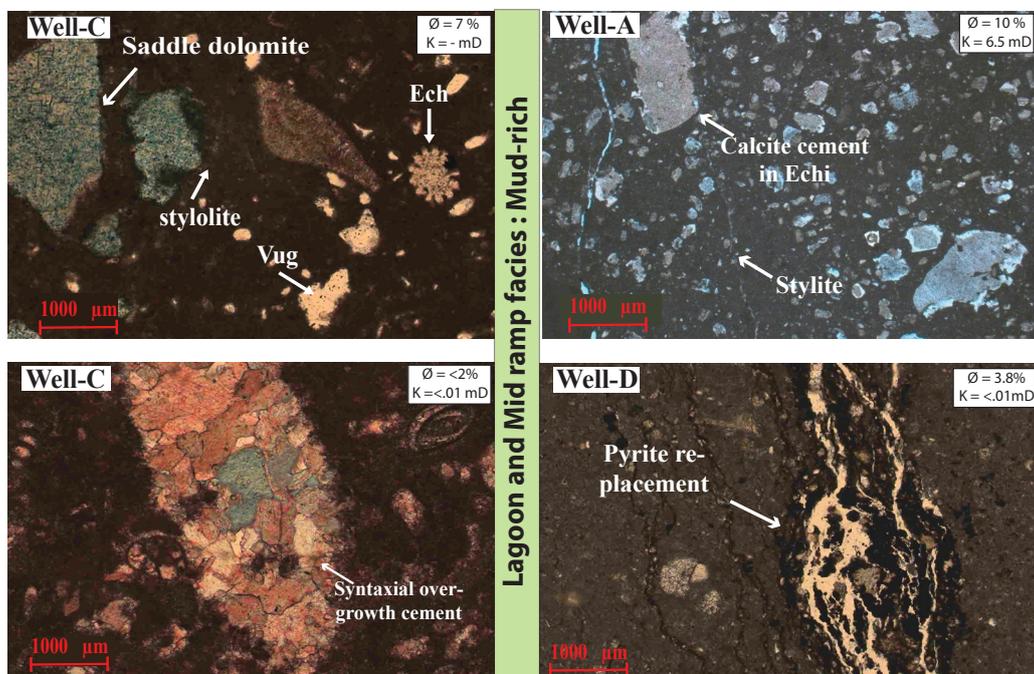


Figure 4. Mud rich setting show poor reservoir quality ; Almost microporosity filled by calcite cement and many stylolite are present, some replacement by saddle dolomite, late-stage calcite cements

Lime Mudstone

These sediments are dominated by silt grade skeletal debris along with minor amounts of echinoderm fragments, trace small benthonic forams and ferroan dolomite-cemented green algal molds, common peloids and partly pyritised organic matter floating in a micrite matrix. Slightly stylolitized organic matter wisps are seen and minor ferroan dolomite can fill early dissolution pores.

Reservoir properties

Understanding the relationship between the rock fabric and the pore size distribution is fundamental to reservoir characterization. Characteristic pore types and diagenetic features that have influenced reservoir properties are described below.

Moldic pores (mainly observed)

Moldic pores are very common and occur in variety of bioclastic lithofacies, but are much less common in mud-supported textures. Moldic pores provide most of the bulk storage of the reservoir and occur where micritic grains have been leached. However, due to pervasive interparticle cementation, the moldic pores are mostly isolated and this results in relatively low permeability throughout the reservoir, even in zones where wireline-measured porosities are elevated.

Microporosity

This type of porosity is also very common, but is rarely visible within muds. It occurs where non-skeletal grains have been partially leached, leaving behind a highly microporous, partially dissolved, relic pervasive interparticle calcite cementation and so the permeabilities remain low. These porosity types typify well A and well C in the wackestone and packstone facies.

Interparticle porosity

Interparticle porosity is primary porosity, and varies according to size and sorting of grains and crystals. Primary interparticle pores are rare in the study area, once again because of pervasive calcite cementation, which has greatly reduced primary porosity within most bioclastic rock types.

Porosity vs. permeability

The Shuaiba formation comprises three main facies associations, they are 1) Lagoonal/back shoal, 2) Inner ramp (wave-dominated), and 3) mid ramp. The porosity varies from 2 to 23 % and in a global plot porosity at first appears independent of permeability, but is likely responding to different pore and mechanical/chemical compaction controls. Broken out on a well-by-well basis the different poro-perm relationships are illustrated in Fig 5.

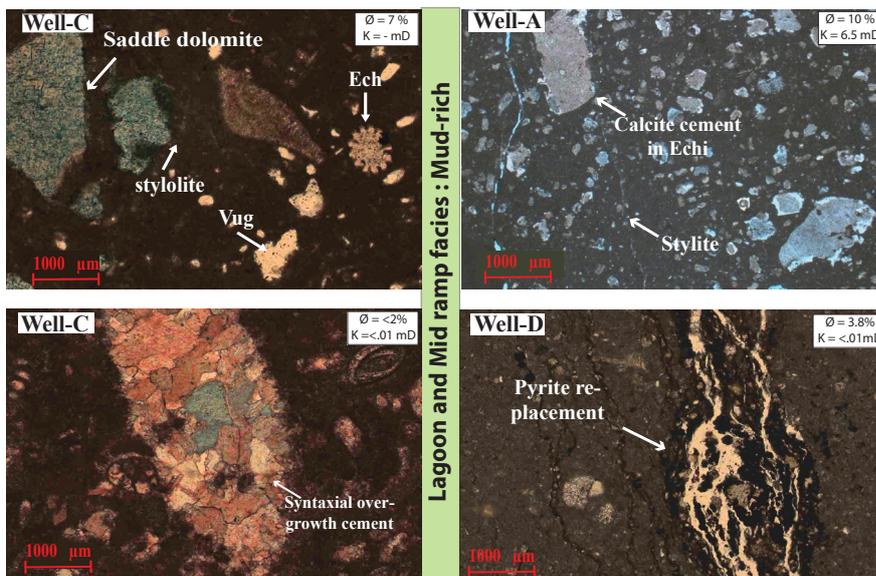


Figure 4. Mud rich setting show poor reservoir quality ; Almost microporosity filled by calcite cement and many stylolite are present, some replacement by saddle dolomite, late-stage calcite cements.

The distribution of sediments deposited in the north eastern part of the study area (well A and well C) are more influenced by lagoonal processes and are dominated by bioclastic wackstone and packstones as well as inner ramp wackstone, mudstone. In the south western part of the study block (well B and well D) the deposition was somewhat higher energy and is typically a more inner ramp (wave-dominated) setting made up of rudist rudstone and rudist floatstone/grainstone.

When the poroperm values are plotted on a Lucia (1992) template, the data can be better clustered and interpreted, as below;

Class 1 type sediment are not typical of the Shuaiba Formation in the study area. A few values with relatively low porosities and permeabilities from well B and well D are scattered across the lower part of Lucia's class 1 plotfield. The various floatstones/wackstones have low permeability because, as seen in thin section, they are dominated by isolated porosity, while microfractures are rarely seen in core from the study area.

Class 2 type sediment includes the most of the rudist rudstone, rudist floatstone/grainstone and rudist floatstone/packstone units, which were originally deposited as reworked rudist back shoal or shoals. In contrast, higher mud content zones show poor to fair porosity. Reservoir quality is controlled mainly by matrix porosity, which in thin section can be seen to be composed of a various levels of intercrystalline porosity, within a diagenetic microcrystalline calcite matrix, that can join up secondary moldic and vuggy porosities to give better permeability. This class type is responsible for very good to excellent reservoir quality zone in Shuaiba Formation.

Class 3 type is mostly populated by core plug values from by Well A, ranging from 4.1 - 24 % porosity. These results when tied to thin section observations indicate the presence of porosity but it tends to be highly ineffective microporosity within a micrite matrix. It mostly resides in isolated, partly-leached, micritised grains separated

by much tighter muds. Hence, permeabilities are low, as pore interconnectivity is reduced by patchy micrite matrix and minor pervasive late ferroan cement.

Stable Isotope Analysis

Stable isotope samples were drilled from various pore type fill matrices in order to better understand porosity evolution, diagenetic processes, the timing and mechanisms of diagenetic alteration in the Shuaiba Formation, as well as obtaining valuable information regarding fluid-rock interactions and the burial/thermal history. $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of 112 samples from different textures and facies of the Shuaiba Limestone are given in table 3 in Appendix and shown plotted in figure 13. Data breakdowns are discussed in the following section and summarized in Figure 6.

Discussion and Implications

The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values from all 4 wells are compiled in Fig 7. It shows two C-O covariant trends, 1) a burial trend consistent with a trend first established in Cretaceous carbonates of Northern Oman by Pidnoi (2014). Trend is shown as a grey arrow fig 6. The trend encompasses most C-O values from wells B and D, with a range of somewhat negative $\delta^{18}\text{O}$ values from -3 to -6.6‰, along with positive $\delta^{13}\text{C}$ values ranging from +3 to +5‰. Sediments in the wells (B and D) were mostly deposited in inner ramp or rudist bank settings (wave dominated), with lesser volumes deposited in lagoon/back shoal settings. The second trend (interpreted as an organic-mixing or catagenesis trend) shows a wider range in carbon with somewhat more negative $\delta^{13}\text{C}$ values from +1 to +5‰ and a less depleted and slightly narrower range of $\delta^{18}\text{O}$ values from -3 to -5‰. This trend encompasses most of the samples from wells A and C. Sediments in these wells are predominantly mud-rich and were deposited in lagoon and mid ramp settings (indicated by the green and yellow shading and the narrower grey arrow in . Oxygen value ranges in the two trends imply that the organic mixing/catagenic carbonates were precipitated/re-equilibrated at lower temperatures (less negative oxygen values) while the burial trend carbonates

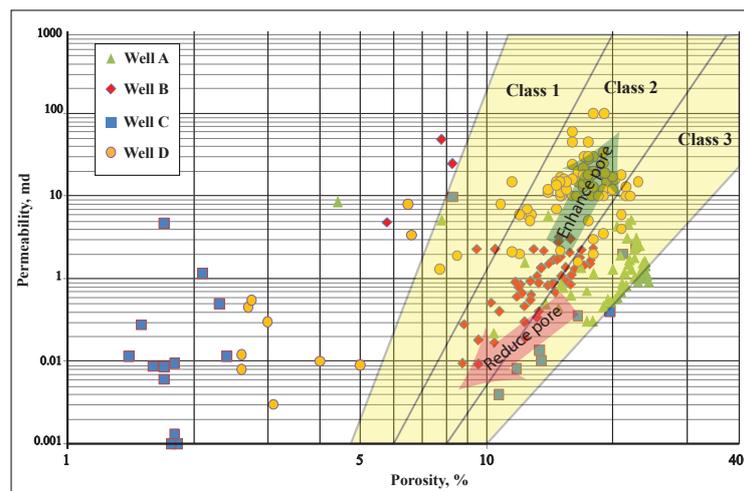


Figure 5. Porosity- permeability cross plot for 4 wells. The better reservoir come from well D in class 2. as green color and inner ramp with rudist setting in yellow area. B) 2 Group of Burial stage of Early burial stage and Late burial stage.

preserve isotope values indicative of somewhat warmer or more thermally evolved fluids. This difference in thermal character is interpreted as likely indicating earlier (cooler) versus later (warmer) burial fluids, tied to earlier versus later burial histories.

Burial evolution

In Figure 6 the C-O values are broken down according to rock textures that were used in choosing the isotope samples. The separation between earlier versus later carbonate cements within the burial trend is most obvious in Well D. Calcite in the covariant trend in this well is dominated by matrix values at the upper or cooler (less negative) end of the plot field, while calcite in vugs shows a more thermally evolved (more negative) set of oxygen values. The separation of the two responses in well B occurs at an oxygen value of -6%. This value of -6% is used to separate earlier from later burial effects in the global plot of all isotope values. It seems the only well of the four studied wells with this more thermally evolved signature is Well D.

When depositional settings are plotted as overlays on a C-O crossplot (called the Organic mixing trend) is most well developed in well A and also seen in the plotfield of values collected in Well C. Both of these wells, especially well A,

are dominated by muddy facies of the lagoon and the mid ramp. Levels of organics would have been higher in these sediments at the time of deposition, compared to the higher energy, more oxygenated settings that typified the grainier depositional settings of most of the sediments in wells B and D. Hence, as the muddier sediments of wells A and C were buried, this organic matter would have escaped and passed through a variety of chemical diagenetic systems [methanogenesis, bacterial sulfate reduction, organic maturation (CO₂ in catagenesis) and thermochemical sulfate reduction. These systems would have contributed carbon to the bicarbonate that then formed diagenetic carbonate cements in the muddy sediment matrices of wells A and C.

When one compares the spread of oxygen values across the two trends (burial versus organic mixing), the organic mixing trend (wells A and C) has the oxygen values that are never more negative than -5%, and mostly centred around values of -4%. In contrast, almost all the oxygen values that define the burial trend in wells B and D, have oxygen values that are more negative than -4.5%. If one assumes that the more negative oxygen values indicate higher temperatures, then the argument can be made (as was done by Warren et al., 2014 for buried Permian carbonates of central Thailand) that the matrix in the muddy

sediments became tight and shut down the rock-fluid exchange processes earlier in the burial curve than happened in the grainier sediments that dominate the Shuaiba in wells B and D. These grainier sediments likely had higher depositional porosities and permeabilities than the muddier sediments of wells A and C and so likely retained effective permeabilities to greater depths, where they were flushed by warmer fluids.

When the isotope values collect from the four wells in this study are compared with those of Well E, which also comes from the Shuaiba Fm. in the same field (studied by Pidnoi, 2014) and with isotope determinations made from reservoir carbonates in giant fields producing from the Shuaiba Fm. in the UAE, two interesting overlaps can be seen (Figure 7).

- 1) Only wells E and D in North Oman have oxygen values which are more negative than -6 ‰
- 2) Isotope plotfields for both the burial trend and the organic mixing trend do not overlap with the plot field defined by reservoir carbonates of the UAE.

Interestingly, wells D and E are the only two wells of the studied wells that are producing hydrocarbons from the Shuaiba Formation in the study area.

5. Conclusions

- 1) The Shuaiba Formation in wells D and E have experienced fluid crossflows that are more thermally evolved (hotter) than the other three wells in the same area. Based on their more negative oxygen values (<-6‰), it seems these fluids

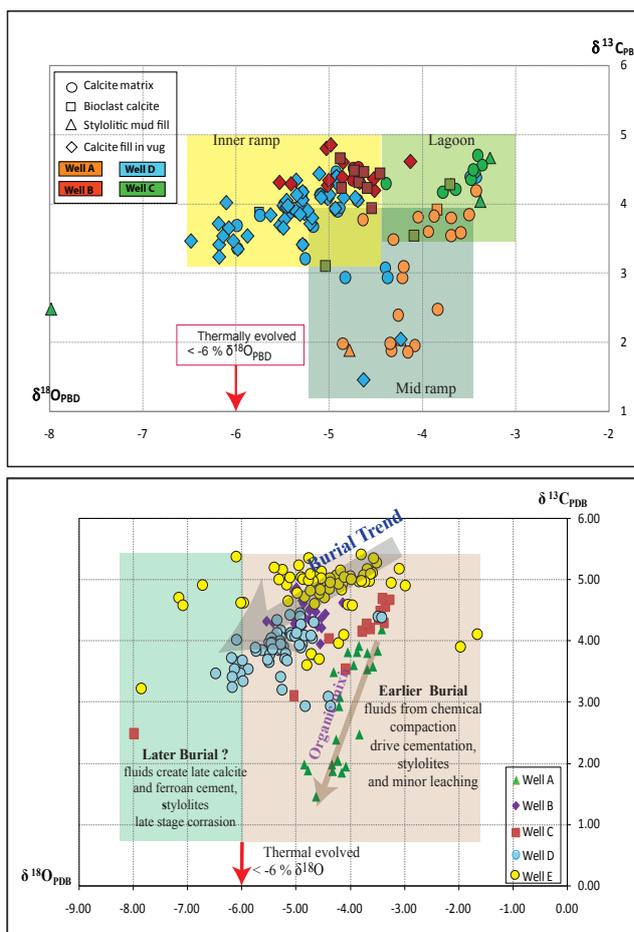


Figure 6. $\delta^{13}C$ versus $\delta^{18}O$ plot of the samples. A) Isotope sample from different calcite source and 3 facies group Lagoon, Mid ramp as green color and inner ramp with rudist setting in yellow area. B) 2 Group of Burial stage of Early burial stage and Late burial stage.

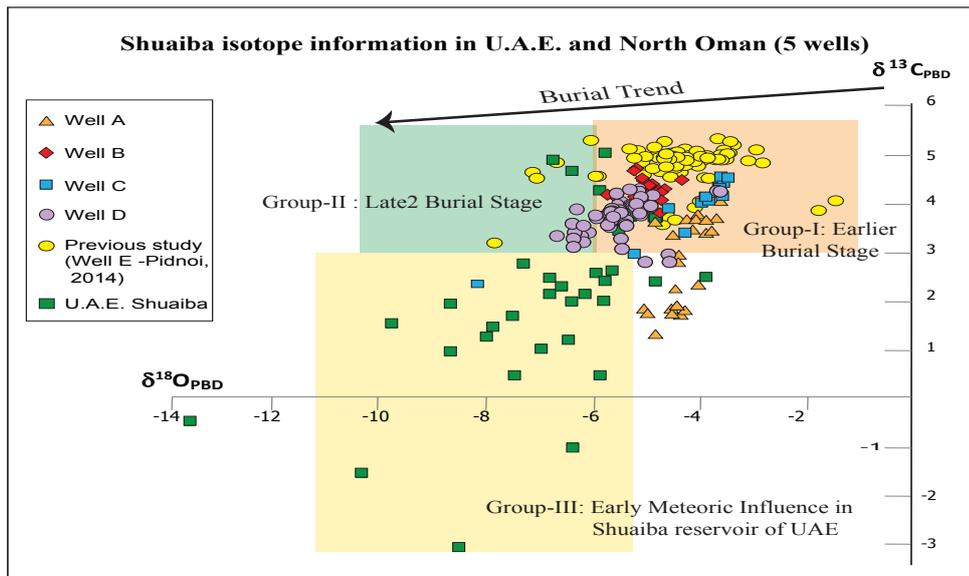


Figure 7. $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ plot is comparison between 5 wells from North Oman block by add more 1 well from previous study (Pidnoi, 2014) and UAE.

are associated with the creation of late stage vuggy calcite in pores created by late stage leaching.

2) These same fluids define a different isotopic plotfield from cements associated with reservoir porosity creation in the giant fields of the UAE.

3) An exploration and development paradigm needs to be constructed for the Shuaiba Fm. in North Oman that does not draw heavily on a-model based on the giant fields in the Shuaiba of the UAE.

6. Recommendations

Need to revise existing seismic interpretation, which emphasised sequence stratigraphic correlations in order to better understand likely structural and tectonic signatures associated with late stage fluid flow and poroperm evolution in the Cretaceous carbonates of northern Oman.

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