Diagenetic controls on reservoir quality in the Miocene carbonate reservoir interval, offshore Myanmar

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Abstract

Based on long-term production from the giant Yadana gas field proving the presence of significant hydrocarbons in Miocene carbonates in the offshore of Myanmar, 10 wells were drilled Miocene carbonates in the study area in order to test the hydrocarbon potential. The study area is located some 80 to 100 kilometers from the Yadana gas field. The wells intersected a heterogeneous mix of Middle Miocene carbonates, deposited atop volcanics or volcaniclastic sediments. The wells show variable production tests in these potential reservoirs, likely responding to reservoir complexity and variable charge. A depositional model of the study area was by constructed by PTTEP in order to explain the relationship between well locations and well test performances. The result of their study suggested reservoir quality and well test performance can be related to depositionally-controlled facies belts. But this study demonstrates that not only depositional environment influences the reservoir properties, an additional, perhaps over-riding factor is diagenesis, which can be quantified across the various wells using stable isotope analysis of core and cuttings. The carbon and oxygen stable isotope determinations, which can be related to diagenetic intensity, is a new approach, not done before in the study area. And so, this study focuses on reservoir quality in the Middle Miocene carbonate, not in terms of depositional setting, but in an additional framework of diagenetic overprints and rock-fluid evolution.The isotope results suggest some sediments in the study area are in part influenced by calcite cements precipitated from circulating hydrothermal waters, moving through volcanic rocks beneath the Middle Miocene carbonate interval, and by regional burial-driven limestone recrystallization, which has significantly decreased potential reservoir quality. When results are compared to the Yadana isotope data, Yadana's reservoir is less diagenetically evolved, and experienced shallower burial with flushing by cooler burial fluids. Accordingly, there is a less pervasive diagenetic shutdown of porosity and permeability. When the study area results are plotted against isotope signatures of other south-east Asian carbonate reservoir with similar ages, it proves that diagenesis is likely to influence reservoir quality and well performance more than the porosity distribution pattern defined in the original depositional environment.

Keywords: Miocene carbonate, diagenetic control, diagenetically evolved, diagenetic overprints, reservoir quality of carbonate.

1. Introduction

The bulk of gross national hydrocarbon production in Myanmar is accounted for by the prolific Yadana and Yetagun offshore fields, which have a combined average output of over 800 MMscf/d of gas. About 80% of this yield is piped to Thailand, the balance going to domestic needs, all of which is used for electrical power generation (Mueller, 2004). The Late Oligocene – Early Miocene Yadana carbonate platform is located in the North Andaman Sea, offshore Myanmar, 80 kilometers southward of the Irrawaddy River Delta (Figure 1), lying under 40 meters of water. The Yadana Platform carbonate hosts a gas field operated by Total since 1998, which contains an Initial Gas in Place (IGIP) of around 87 trillion cubic feet. Other Oligocene – Miocene carbonate in the region have been found surrounding Yadana gas field, including those in our study area. IN one such area, 10 exploration and appraisal wells were drilled in offshore Myanmar in order to test the hydrocarbon potential in an area some 80 to 100 kilometers from the giant Yadana gas field. These wells intersected a heterogeneous mix of Middle Miocene carbonates deposited atop the volcanics or volcaniclastic sediments. The wells show variable production tests in these Middle Miocene carbonate reservoirs, likely responding

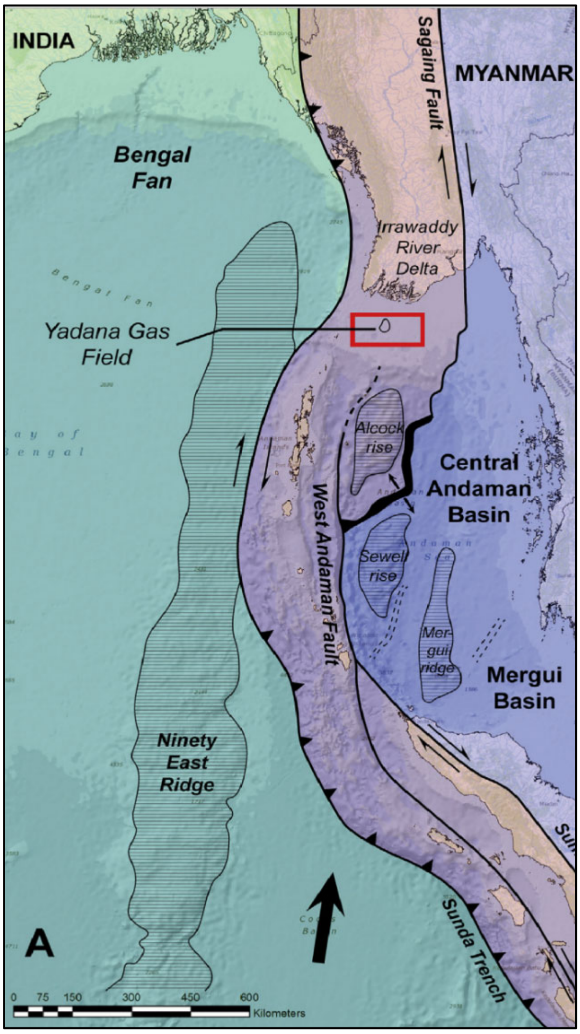


Figure 1: Simplified tectonic map of the Andaman sea region with location of Yadana gas field.

to reservoir complexity and variable charge. Diagenetic overprints in carbonates can completely change the rock's pore structure and mineralogy. In more extreme cases, diagenesis can change mineralogy from aragonite/calcite to dolomite and completely dissolve original grains to forms pores, while the original pore space becomes filled with cement to form a completely inverted porosity distribution compared to the sediment's primary porosity (Eberli et. al., 2004). Hence a study of depositional environments and processes as well as diagenetic evolution across these wells is needed to better understand the reservoir heterogeneity and so explain the relationship between diagenetic signature and the resulting porosity occlusion (Figure 2).

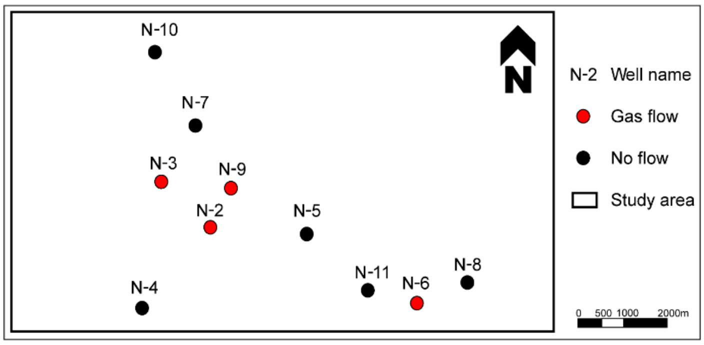


Figure 2: Well location in study area showing the results of well testing.

Accordingly, the study combines and integrates stable isotope analysis, cutting and core descriptions, thin section petrography, XRD analysis and conventional wireline log data. The results are then used to test depositional models of porosity and permeability created by geoscientists working in PTTEP. The primary aim is to understand diagenetic history as it relates to reservoir properties, sampled by the exploration and appraisal wells drilled and tested in the study area.

2. Geological setting and Stratigraphic

The complex tectonic evolution of SE Asia during the Cenozoic has strongly affected the distribution of land and sea over time, leading to the current structural configuration of the region (Lee and Lawver, 1995; Hall, 1998, 2002, 2012). During the Paleogene, the northeastward oblique subduction of the Indian plate under the Eurasian plate (Figure 3a) induced the opening of the Andaman Sea as a back arc basin (Chakraborty and Khan, 2009). Because the orientation of the subduction (northward motion of the Indian plate) is almost parallel to the plate limit, a strong strike-slip component affects the Andaman Sea. Relative to the Eurasian plate, the Burma microplate is distinguished by the creation and movement of a major dextral strike-slip fault (Sagaing Fault) from the Oligocene (Figure 3b) (Morley, 2002; Chakraborty and Khan, 2009).

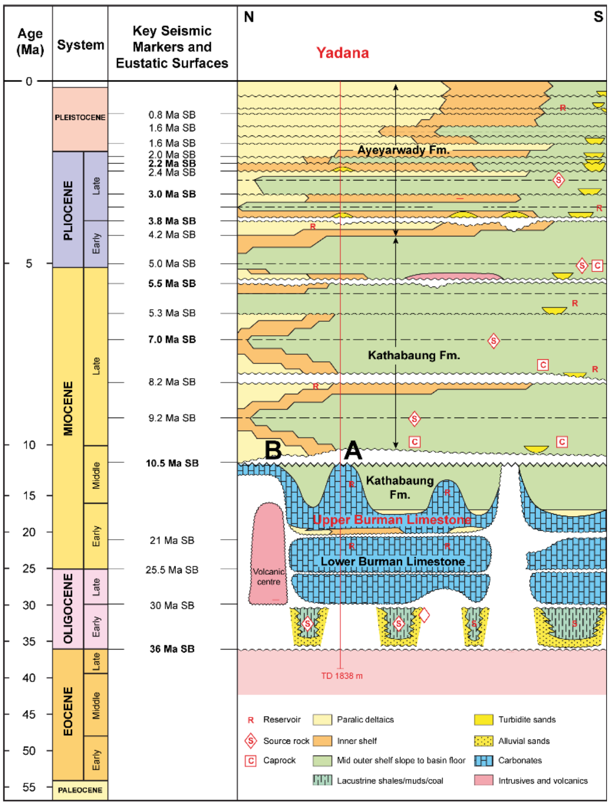


Figure 4: Generalized stratigraphy of the Moattama Basin, offshore Myanmar with location (A) indicating the Yadana gas field location and location (B) indicating the likely position of the study area.

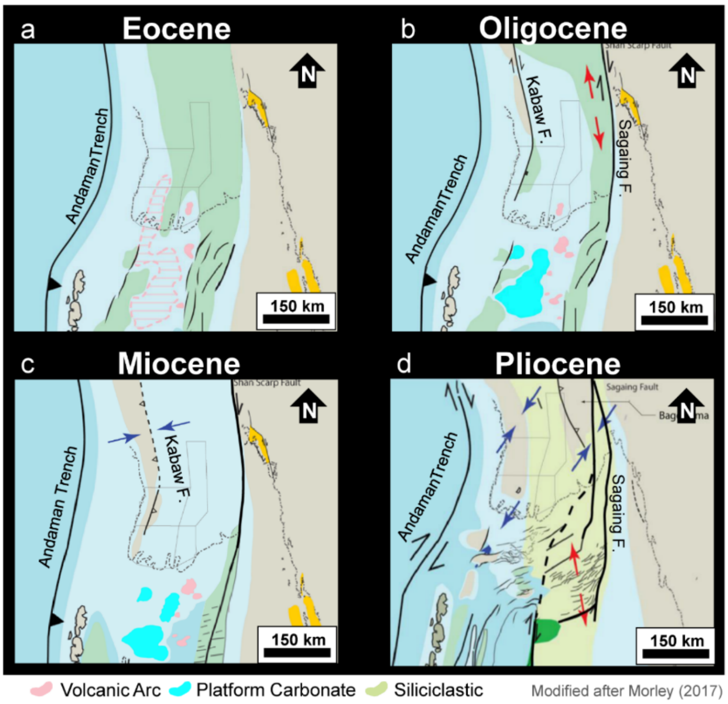


Figure 3: Simplified tectonic evolution map of Moattama Basin, offshore Myanmar. (a) Eocene, (b) Oligocene, (c) Miocene and (d) Pliocene.

In this geodynamic scenario, the Yadana platform developed above a volcanic arc, named the Yadana high or the Yadana Arch, during late Oligocene to Early Miocene (Morley, 2013; Racey and Ridd, 2015) (Figure 3b and 3c). After the Late Miocene, pro-delta shales of the Irrawaddy River Delta prograded southward to progressively onlap the carbonate platform and finally bury it to form the regional seal. During the Pliocene to Recent, the Moattama basin became a major siliciclastic depocentre (Figure 3d), with the accumulation of over 10 kilometers of terrigenous sediments, accommodated by its transtensional opening and the supply of abundant sediments from the Irrawaddy River Delta. Southward, seafloor spreading initiated in the Central Andaman Basin about 4 Ma ago, at a rate of about 38 mm per year (Khan and Chakraborty, 2005; Chakraborty and Khan, 2009).

The Late Oligocene - Miocene carbonate strata in offshore Myanmar consists of shelf edge/shoals, reefs and isolated platform. The Yadana gas field is an isolated platform composed of the Burma Limestone as seen at location A in Figure 4. It is composed of shallow marine reefal and lagoonal limestone, with large benthic foraminifera, covering areas of up to several hundred square kilometers. Similarly, the wells in the study area sample Middle Miocene slope-margin carbonate sediment, as illustrated by location B in Figure 4. In the study area the intersected succession is made up of muddier lagoonal units and sandier shelf edge/shoals consisting of stacked foraminiferal grainstones interfingering with red-algal packstone/wackestone, silty calcareous mudstones and sandy foraminiferal wackestones to packstones, over an area a few kilometers across and located atop volcaniclastics (Racey and Ridd, 2015b).

3. Data availability and Methodology

The study combines the digital dataset supplied by PTTEP and PTTEPI with my own studies of core and cutting and integrates conventional wireline logs, reservoir property data and stable isotope determination across representative interval depths. The depths chosen for isotope sampling utilized the supplied wireline logs to identify limestone-rich intervals in the wells. A total of 10 exploration and appraisal wells, wells named N-2 to N-11, are used in the study. All wells, except N-7, penetrated Middle Miocene carbonate, and all the wells were tested and sampled using a combination of conventional wireline logs, cuttings and mudlog reports. The intersected Miocene carbonate interval varies in thickness from 10 meters up to a hundred meters, and sits over volcaniclastics, as show in the correlation with bathymetry map illustrated as Figure 5.

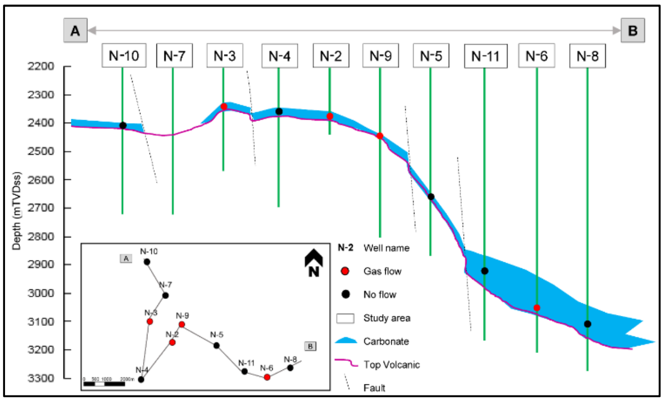


Figure 5: Miocene carbonate correlation with the bathymetry map (adapted from Khumputorn, 2019)

The N-5 well is only well that recovered core including of an upper core some 6.25 meters long sampling Middle Miocene carbonates. A total of 7 core plugs were selected in this carbonate section for thin sectioning and measurement of reservoir properties using XRD, SEM and poroperm by RCA analysis. Thin sections were half-stained for carbonate minerals with an Alizarin Red S and potassium ferricyanide solution. The upper section in the core is composed of fine to medium, moderately well sorted skeleton grainstones, deposited as a series of shallow marine inner-shelf current-washed shoals.The lower section is made up of a relatively coarse intraclastic interval, likely representing a transgressive shoreface deposit that was deposited in a relatively high energy regime. Both sections are variably stylolitized.

The sampled Middle Miocene carbonate are classified according to texture, using the scheme of Dunham (1962), and are denoted by a capital letter followed by one or more small letters used to indicate the main sedimentary features that characterize the facies. Three main facies are identified in the carbonate section of N-5 well (Figure 6). These comprise skeletal grainstone (Facies LGs), slightly argillaceous stylo-compacted skeletal packstone (Facies LPsa) and intraclastic skeletal grainstone (Facies LGi). The top of volcanic section is assigned to a Mudstone facies (Facies M).

Reservoir potential of N-5 well, based on petrographic study is negligible, as the skeletal grainstone has interparticle areas occluded by abundant calcite cement and there is abundant stylo-compaction within the argillaceous packstone. Trace of isolated porosity and dissolution porosity are noted in thin section (Figure 7a and 7b), stylolites are illustrated in Figure 7c, widespread lime mud matrix has been recrystallized to microspar and fine pseudo spar (Figure 7d) and some portions of the carbonate are occluded by authigenic kaolinite (Figure 7e and 7f). SEM images confirm the presence of significant microporosity within the clays and also indicate the very poor interconnectivity of the pore system, while plug porosity ranges from 4.92 – 8.85 % (average 6.64%) and permeability ranges from 0.001 – 0.199 mD (average 0.076 mD).

A depositional model of the study area was by constructed by PTTEP in order to explain the relationship between well locations and well test performances as summarized in Figure 8 and Table 1. The model is constructed using wireline log character, integrated with cutting and core descriptions, and sedimentological data from core and biostratigraphic analysis. The result and suggestion from their study were that the reservoir quality and well test performance are related with depositional environment facies. This model is tested using isotope analysis in the present study.

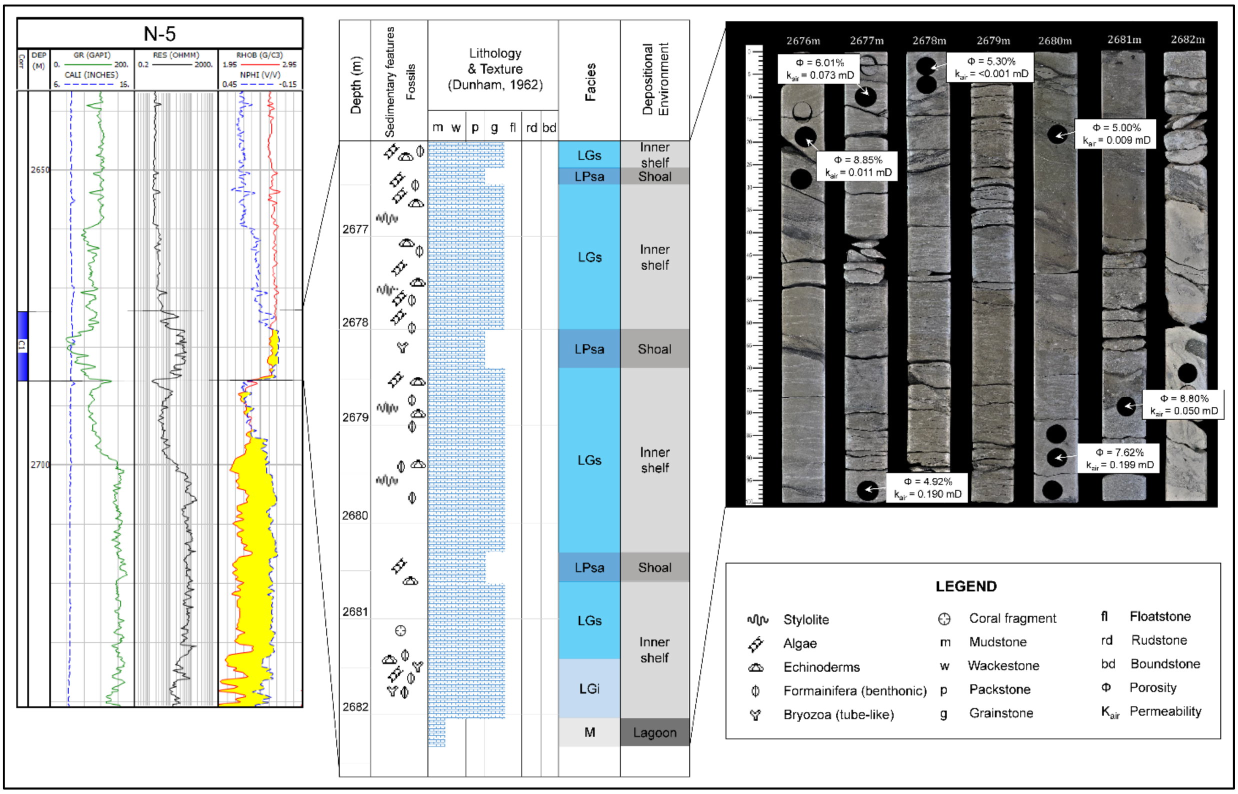
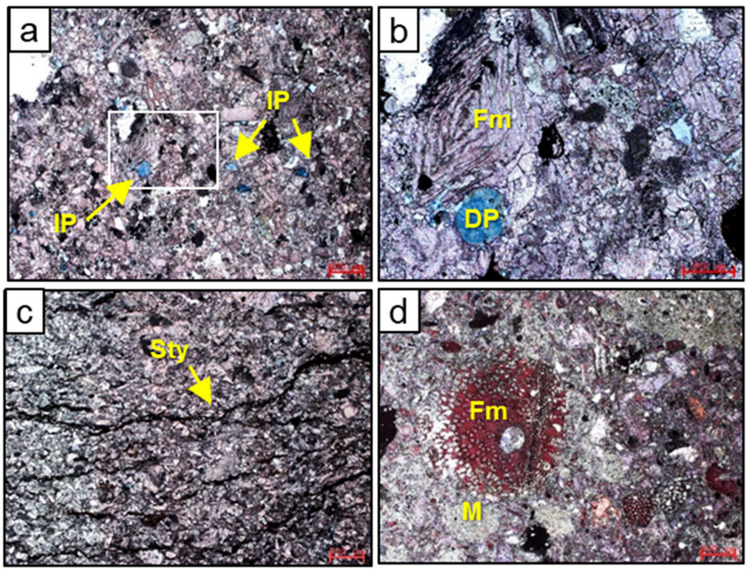


Figure 6: Sedimentological core logs of N-5 well with core photo and porosity & permeability at measured are each core plug depth (adapted from core description report, 2013).



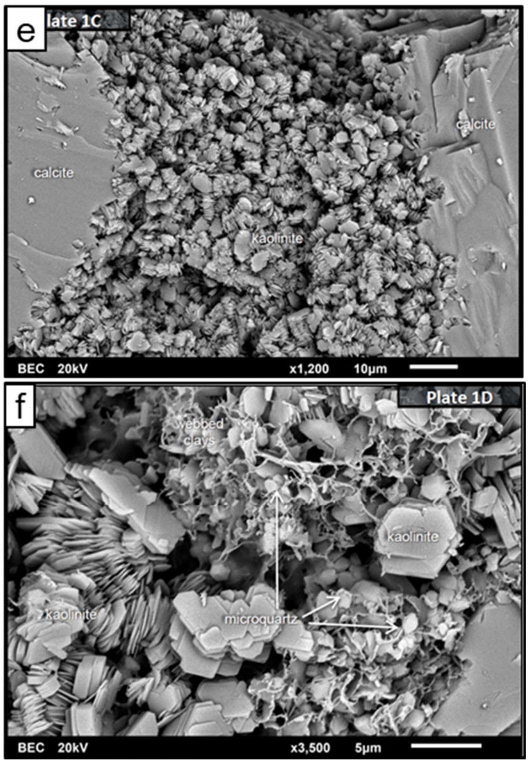


Figure 7: Photomicrographs showing lithofacies (a) isolated porosity (IP) in a skeleton grainstone (b) dissolution porosity (DP) and larger foraminifera (Fm) indicative of high energy on the inner shelf (c) stylolite within the argillaceous packstone. (d) mud matrix has partly been recrystallized to microspar (M). (e) calcite grain with occluded porosity due to authigenic kaolinite (f) typical vermicular kaolinite and probably dickite made up of book-shaped pseudo-hexagonal stacked plates and webby clays.

Depositional Environment	Distribution	Lithology	Components
Lagoon	N-4, N-9, N-10	Carbonate mudstone, wackestone/ packstone	Planktonic foraminifera, small benthonic foraminifera
Inner shelf	N-2, N-3	Skeletal packstone/ wackestone	Large benthonic foraminifera, calcareous benthonic foraminifera
Shoals	N-5	Peloids Intraclastic grainstone/ skeletal packstone	Benthonic foraminifera, bryozoal fragments
Outter shelf/ slope	N-6, N-8, N-11	Skeletal packstone/ wackestone	Planktonic foraminifera

Table 1: Depositional environments summary

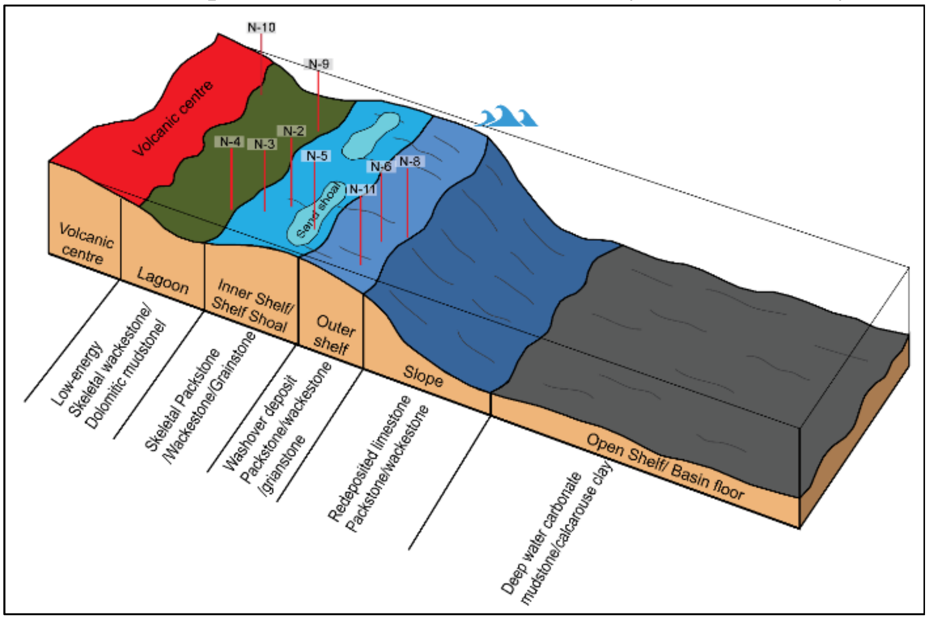


Figure 8: Depositional model for the Middle Miocene carbonate in study area with well location

Not only lithological facies tied to depositional environments influence the reservoir properties and additional important factors is diagenesis which can be quantified using stable isotope analysis. Thus, carbon and oxygen stable isotope determinations, which can be related to diagenetic intensity is a new approach, not done before in the study area. And so this study focuses on current reservoir quality in the Middle Miocene carbonate not on porosity in depositional setting by considering the additional framework of diagenetic overprints and rock-fluid evolution.

Changing stable $\delta^{13}C$ (carbon) and $\delta^{18}O$ (oxygen) isotope values reflect ongoing rock-water interaction and fluid evolution during progressive carbonate rock cementation, recrystallization and re-equilibration of $CaCO_3$ minerals in a progressively higher temperature burial regime as well as other post depositional fluid entries (Laya, 2015). Stable isotope values were determined on total a total 161 carbonate samples, made up of 53 samples selected from the Middle Miocene carbonate conventional core in the N-5 (Figure 9) and 11 samples of calcite veins in the N-7 well that recovered core some 26.34 meter long sampling volcaniclastics crosscut by occasional calcite-filled veins (Figure 10). In the core-based samples, stable isotope analyses were carried out mainly on matrix and some of the bioclasts, stylolite matrix and cemented vein material. All samples were extracted as rock powder using a hand-held dental drill. The other 97 isotope samples were collected from cutting samples across 9 wells. All cutting samples were crushed into rock powder for stable isotope analysis. Isotope analyses were run using laboratory facilities at Monash University, Australia. The carbon isotope results were reported in the % Pee Dee Belemnite (PDB) scale, while the initial

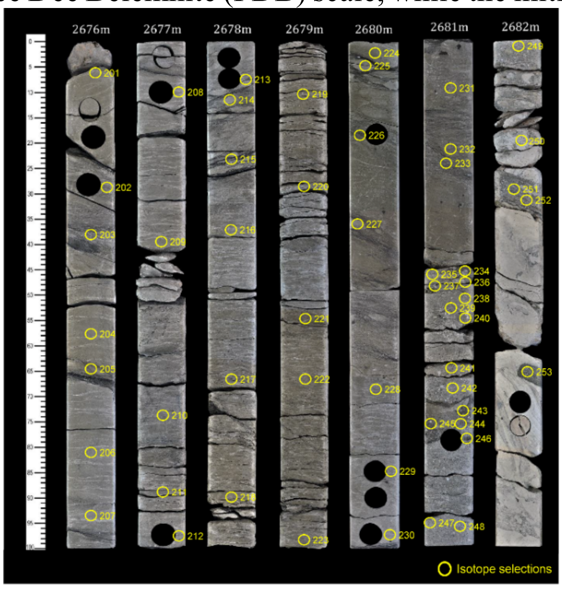


Figure 9: Core image in well N-5 recovered in Middle Miocene carbonate.

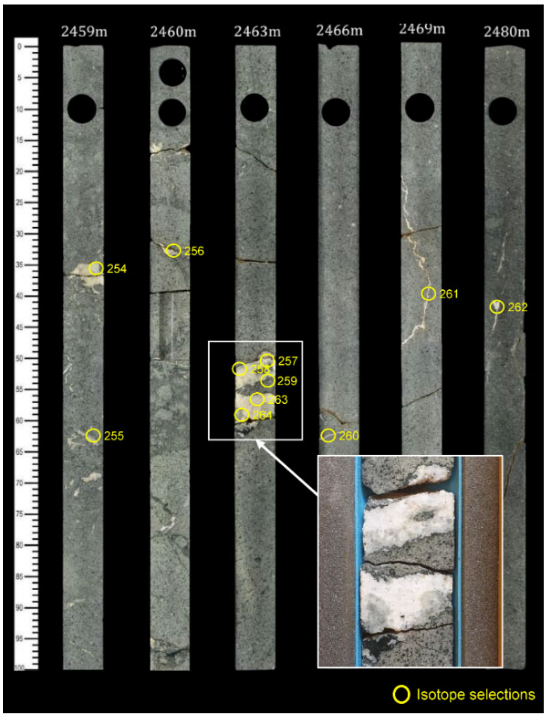


Figure 10: Core image in well N-7 recovered volcaniclastics crosscut by occasional calcite-filled veins.

oxygen isotope results were reported in the % Standard Mean Ocean Water (SMOW) scale. SMOW values were converted to the % PDB international standard scale, as the PDB scale isgenerally used for geological studies. Coplen, 1998 published a standard conversion equation which is $\delta^{18}O$ (PDB) = ($\delta^{18}O$ (SMOW) – 30.92)/1.03092. Finally, all results were plotted and integrated together to better understand porosity distribution, depositional environment, diagenetic history and reservoir quality evolution in Middle Miocene carbonates from offshore Myanmar.

4. Results and Discussions

The stable isotope values across the study area, range from -10.0‰ to 0.4‰ for $\delta^{13}C$ and -18.0‰ to -3.0‰ for $\delta^{18}O$, and define two clusters of data. The first group sits in the orange shaded region of Figure 11 and ranges from -5.0‰ to 1.0‰ for $\delta^{13}C$ and -14.0‰ to -1.0‰ for $\delta^{18}O$, while the second group (shaded blue) ranges from -10.0‰ to -4.0‰ for $\delta^{13}C$ and -18.0‰ to -11.0‰ for $\delta^{18}O$, as shown in the Figure 11 below.

The $\delta^{18}O$ signature of a carbonate precipitated from an evolving pore water depends chiefly on the $\delta^{18}O$ composition and temperature of water. Increasingly lighter (more negative) oxygen values tend to be associated with decreasing salinity and with increasingly higher temperatures (Nelson, 1996). The $\delta^{13}C$ composition of precipitated carbonates primarily reflects the sources of bicarbonate dissolved in the water, which can include sea water, marine shell dissolution, soil weathering processes (meteoric water), catagenic fluids, and bacterial oxidation or sulphate-reduction of organic matter (Nelson, 1996). The majority of the isotope data in the study area are clustered into a burial trend, characterized by increasingly negative oxygen values due to the increasingly elevated temperatures of fluids in burial. In that orange-shaded trend the carbon values show a slight decrease with increasing temperature because the limestones itself is the main reservoir of carbon in diagenetic fluids and it does not fractionate significantly with increasing temperature. Carbon values are consistent with recrystallization of early marine cementation which tend to be more influenced by the relative levels of organic material (organic matter or catagenic products). These finer-grained sediments the group of data below the normal burial trend, with somewhat more negative $\delta^{13}C$ values (Figure 11; grey shaded area).

To the left side of burial trend, with values of $\delta^{18}O$ more negative than -10.0‰, lies a group of plot points from samples that were collected in calcareous intervals closer to underlying volcanic rock and below the main Middle Miocene carbonate reservoir level. This interval reveals higher temperature effects in the calcite precipitates, that were likely caught up in circulating hydrothermal fluids, cycling up into the sediments from the underlying volcanics. These sediments today form a regional seal and are extensively recrystallized and silicified. In the cuttings, the silicified limestones that form a regional seal show a less intense reaction with HCl. The vertical dashed red-dotted line in

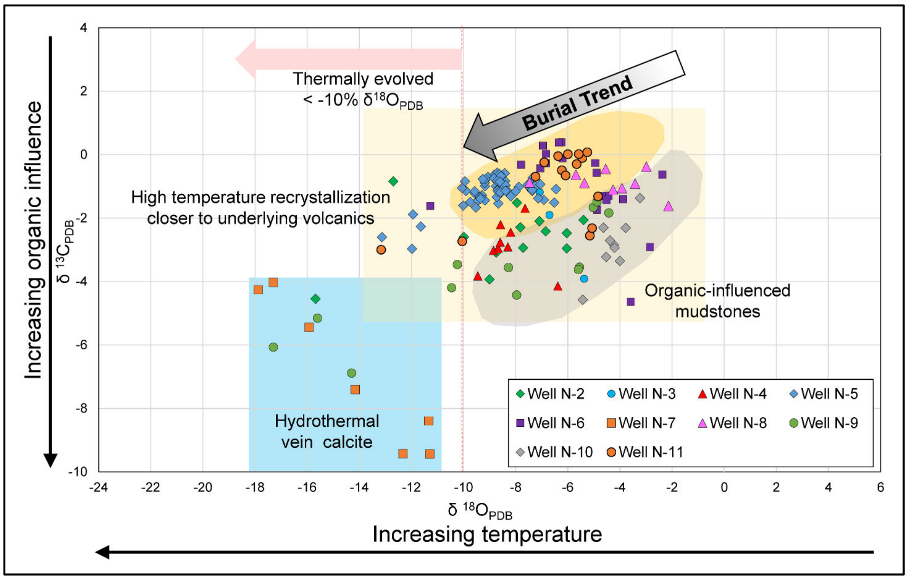


Figure 11: δ^{18}O and δ^{13}C plot from the wells in study area

Figure 11 separates samples that are more thermally evolved either in the silicified limestones or as we shall see in hydrothermal sparry-calcite vein fills within the volcaniclastic section.

The other cluster of δ^{13}C and δ^{18}O values that are separate from the burial trend comes mainly from samples in the N-7 well that were collected in the deeper core interval from a sparry calcite vein fills within in the volcanic pile (Figure 10). The more negative δ^{18}O values of these vein calcites, compared to the various limestone cements, is consistent with their formation from post-lithification higher temperature fluids, (Harris, 1986). The more δ^{13}C negative values were precipitated in fractures in the volcanic pile, under the influence of circulating hydrothermal fluids.

Stable isotope determinations on samples across the study area show no evidence of freshwater-driven (meteoric) alteration in any wells, implying there is little or no early secondary porosity preserved in the study area.

Bivariate plots involving δ^{13}C and δ^{18}O are a common and convenient way of distinguishing the depositional and/or diage-netic (paleo) environment responsible for carbonate formation, as plotted in the Figure 12.

The result of the depositional environment study, illustrated in Figure 8 and Table 1, when overlain on the measured isotope values defines three clusters (Figure 12). Limestones in the wells N-4, N-9 and N-10 were mostly deposited in the lagoon, illustrated by δ^{13}C values decreasing to -2.0‰ to -5.0‰ (green shading). This reflects the predominantly mud-rich organic-influence in fine-grained sediments deposited in a lagoon. Wells with samples interpreted as deposited in inner shelf, versus samples from an outer shelf setting, cluster into two groups that are separated by their δ^{18}O values. The more negative oxygen values of the inner shelf cluster within the burial trend and show that inner shelf carbonate samples preserve isotope values indicative of somewhat warmer or more thermally evolved fluids. That is the difference in thermal character of the two groups is interpreted as pore

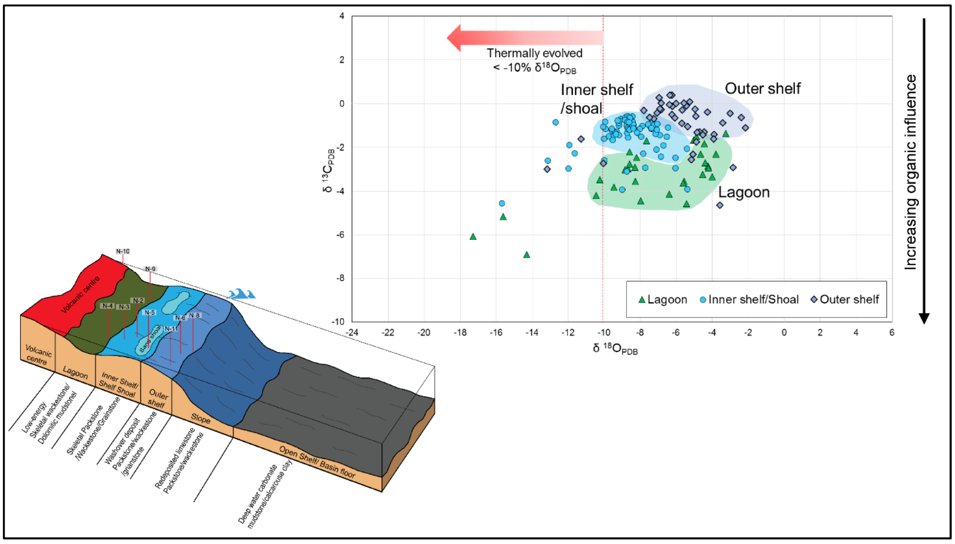


Figure 12: δ^{18}O and δ^{13}C plot from wells in study area overlain with results of in-house determinations of depositional environment.

occluding cements in the inner shelf sediments are more thermally evolved fluids than outer shelf sediments.

Next, the combined $\delta^{13}C$ and $\delta^{18}O$ plot is overlain with the depositional environment interpretation and with flow test results from the various wells, as shown in Figure 13.

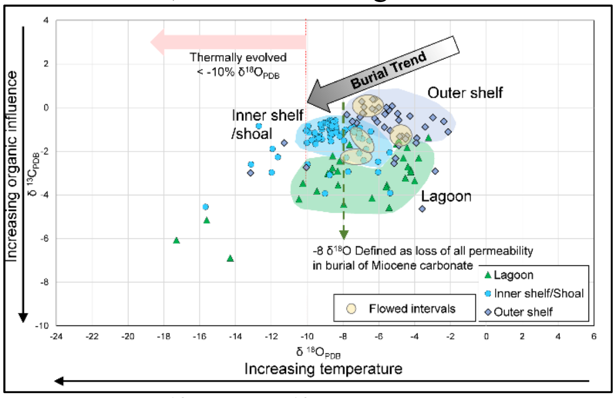


Figure 13: $\delta^{18}O$ and $\delta^{13}C$ plot over the wells in study area with results of the in-house depositional environment study and the well flow results from well testing.

Observations and interpretations based on this plot are listed below;

1) Diagenesis is more important than depositional environment in terms of reservoir properties, as the wells with less thermally-evolved isotope signatures tend to flow (indicated by the four brown-shaded groupings in Figure 13) and so have better preserved poroperm values compared to sediments further down the burial trend. The latter are the inner shelf sediments, which have experienced higher temperature fluids.

2) The green-dotted line defines a cut-off observation, whereby samples with $\delta^{18}O$ more negative than -8.0‰ have lost all effective permeability, due to ongoing burial of the Middle Miocene carbonate reservoir. This implies inner shelf sediment once continued to circulate warmer burial fluids, giving isotope values from fluids further down the burial trend until their porosity was finally occluded.

3) The finer grained sediments of the lagoonal environment show oxygen values that range across the temperature range of both the outer and inner shelf, while the inherently lower carbon values across this thermal range indicate a persistent organic influence. Ongoing organic maturation may have allowed ongoing crossflows of increasingly warmer basinal fluids.

Next, isotope values in the study area are compared to a depositionally similar carbonate platform, namely the giant Yadana gas field reservoir (Late Oligocene – Early Miocene age), located some 80 to 100 kilometers from the study area. Yadana C-O isotope compilations also show a burial trend but with $\delta^{18}O$ values ranging from -4.0‰ to 3.0‰, which This indicates the reservoir carbonates the reservoir carbonates in Yadana are less diagenetically evolved (more positive $\delta^{18}O$ values) and possibly less influenced by warmer organic-entraining fluids coming from compacted organic-influenced mudstones (indicated by more negative $\delta^{13}C$ values) (Figure 14).

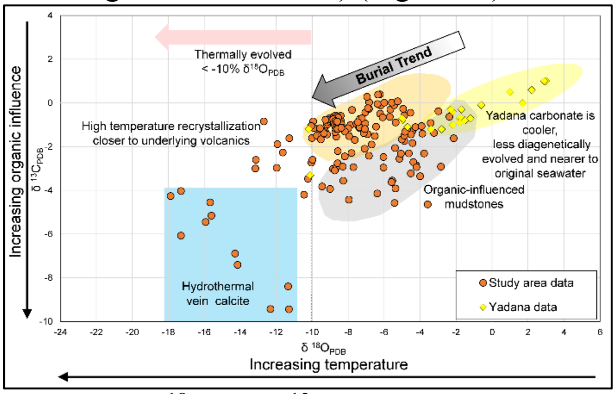


Figure 14: $\delta^{18}O$ and $\delta^{13}C$ plot over the wells in study area compare to Late Oligocene – Early Miocene Yadana carbonate, offshore Myanmar.

The outer shelf and inner shoal grainy sediments in study area are more diagenetically evolved than Yadana carbonate platform sediments. Some poro-perm is still preserved in the packstone-wackestone of the outer shelf (they flow hydrocarbons), while the high depositional porosity of the inner shelf sediments has been lost during ongoing burial driven cementation and compaction (stylolitisation). The Yadana platform reservoir preserves early leachate porosity as the depth of platform is shallower (<2,000 mTVDss) than in the study area. Also, Yadana field is perhaps characterized by the early entry of hydrocarbons, which then largely shutdown ongoing diagenesis (Figure 15).

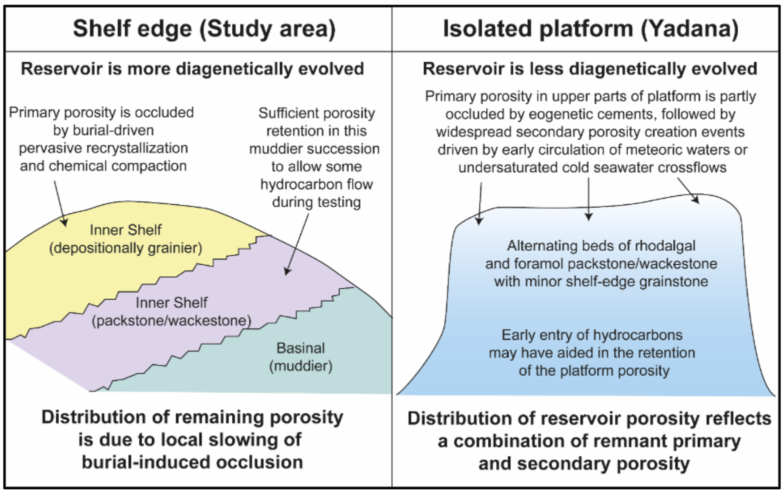


Figure 15: Scheme of carbonate reservoir styles in the study area (deposited at a shelf edge) compared to Yadana field (deposited as an isolated carbonate platform).

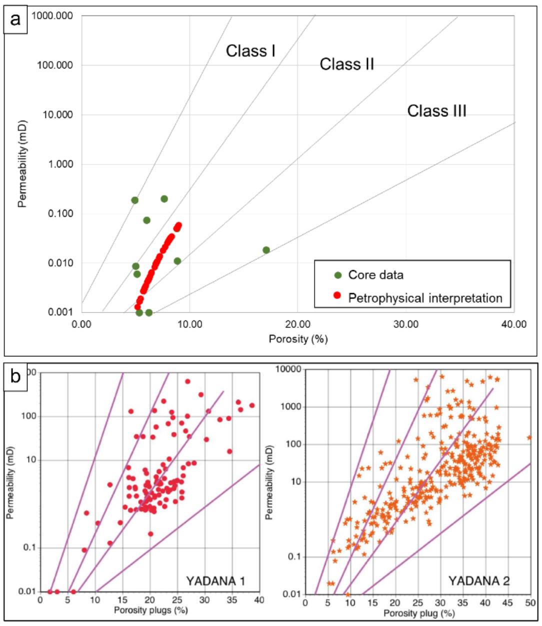


Figure 16: Comparison of poroperm fields between (a) Middle Miocene carbonate in study area and (b) example of Yadana wells.

In summary, comparison of $\delta^{18}O$ and $\delta^{13}C$ plot clusters in the study area compared to Yadana field, shows Yadana reservoir carbonates have experienced shallower mesogenetic burial that preserves regional and local poro-perm, likely aided by early hydrocarbon entry into the reservoir. When porosity plots are compared between wells in the study area and wells in Yadana (Figure 16), a much greater proportion of plug values from Yadana field plot in class III, which is the mudstone field as defined by Lucia (1995). This indicates the importance of microporosity and leaching in Yadana and how it is tied to the joining of intercrystalline pore throats in recrystallized micritic calcite and dolomite. This microporous network joins up the moldic porosity (Figure 17), so creating a greater proportion of effective class III porosity in Yadana field (Warren, 2008).

In contrast, the Middle Miocene carbonate reservoirs in study area plot as low-end class I and II grainstone to packstone. Initially these grainy sediments possessed good as the results from RCA and petrographic analysis show, the same sediments now retain low and only isolated-vug porosity with very low permeability, due to ongoing regional porosity loss, indicative of deeper and more pervasion diagenesis.

Next, isotope signatures of the study area are compared to isotope plots from similar-

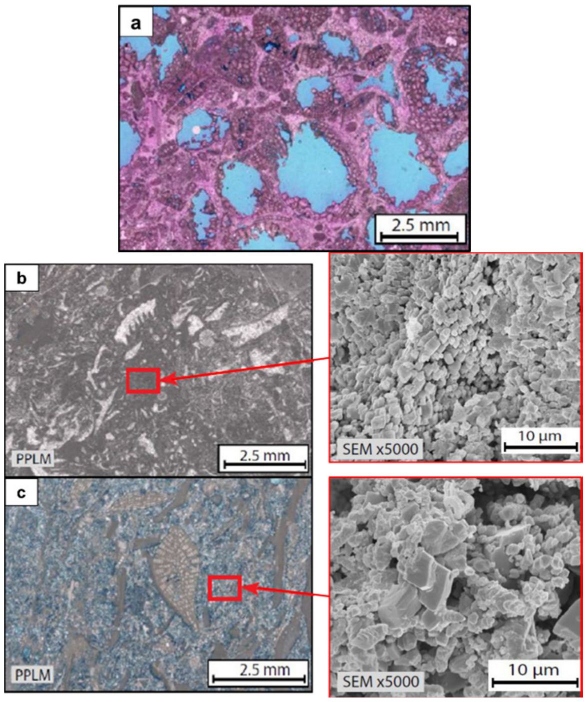


Figure 17: Thin-section photographs of Carbonate reservoir at Yadana field showing the main porosity types: (a) moldic, (b) microporosity and (c) enlarged microporosity with SEM images.

age upper slope carbonates in hydrocarbon-bearing exploration wells, offshore Indonesia(Figure 18; Indonesian data from

Laya, 2015). The oxygen values of the Indonesian data overlap the Yadana and study area ranges but are less than the value of -10‰ that defines hydrothermally influenced samples. The Indonesian data consist of two trends; 1) a cooler burial trend (oxygen values >-6‰) and, 2) a more steeply sloping catagenic trend (oxygen <-6‰, and carbon <0‰) tied to warmer fluids, with increasing hydrocarbon entrainment in the crossflowing fluids.

Final observations and interpretations are listed below;

1) The general trend of sampled Oligocene – Miocene carbonates in the SE Asian region, range from -10.0‰ to 3.0‰ in $\delta^{18}O$ and show the most negative oxygen values (less than -10.0‰) when influenced by volcanic or hydrothermal fluids.

2) Diagenesis can influence reservoir quality and well performance much more than patterns defined in the depositional environment.

3) The Oligocene – Miocene carbonate with $\delta^{18}O$ values more than -8.0‰ in the study area and at Yadana have the potential to flow or produce hydrocarbons.

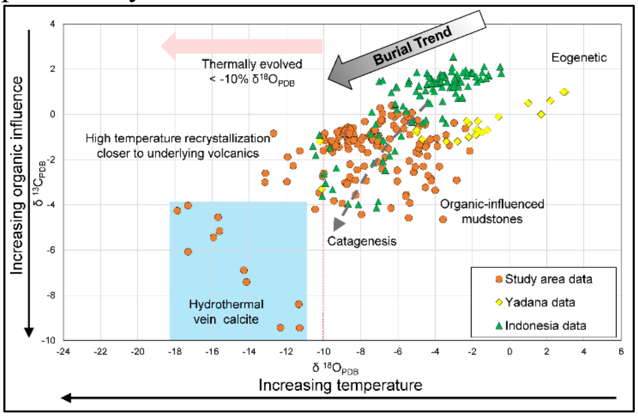


Figure 18: $\delta^{18}O$ and $\delta^{13}C$ plot from the wells in study area, compared to Late Oligocene – Early Miocene Yadana carbonate, offshore Myanmar and upper slope carbonate in Oligocene – Miocene carbonates, offshore Indonesia (Laya, 2015).

5. Conclusions

When Middle Miocene carbonates in the study area are compared to Late Oligocene – Early Miocene Yadana field, they have distinct isotope signatures, implying they have experienced different diagenetic histories. Most of the carbonate samples in study area shows a typical burial re-equilibration response, related to carbonate dissolution and re-precipitation /recrystallization from pore fluids with increasing temperatures tied to increasing burial depths. Most samples in the study area now show largely occluded porosity and permeability in these Middle Miocene carbonate sediments. In contrast, the Yadana isotope data show its reservoir rocks are less diagenetically evolved and indicate shallower burial, with cooler burial fluid temperatures. There is a less pervasive diagenetic shutdown of porosity and permeability in Yadana Field.

The isotope results suggest sediments in the study area are in part influenced by calcites precipitated from circulating hydrothermal waters moving through volcanic rock beneath the Middle Miocene carbonate interval, and by regional burial-driven limestone recrystallize-ation, which has significantly decreased the potential reservoir quality.

A study of depositional indicators differentiates primary lithofacies and define the location of potentially good primary porosity. But, in all the sampled carbonates, burial diagenesis has overprinted and destroyed almost all of the initial porosity in the grainier lithofacies.

Overall there is a regional trend of diagenesis altering reservoir character in Oligocene – Miocene Yadana, as reflected in isotope trends in shelf and slope carbonates across south-east Asia. Burial occlusion of porosity is defined by a regional isotope burial trend, which can be used to relate relative calcite cement temperature and the rock's ability to preserve reservoir properties. So, whenever the relationship between $\delta^{13}C$ and $\delta^{18}O$ isotope values become more negative, the porosity is lowered. Locally, where $\delta^{13}C$ and $\delta^{18}O$ isotope values are more positive, it is likely the porosity is preserved or created, and reservoir potential of the carbonates increases.

6. Recommendations

Future exploration or appraisal well should utilize stable isotope analyses as a standard tool in order to better define a complete diagenesis history within the carbonate reservoir and so help focus exploration into regions with appropriate diagenesis that can enhance poroperm (due to burial diagenetic slowing, associations with early hydrocarbon emplacement, shallow burial, fracturing and burial leaching).

Hydraulic fracturing in carbonate reservoirs would likely improve recovery in some low flow wells in the study area, if matrix porosity retains sufficient volumes to economically flow.

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8. References

Anonymous, 2013, Core description report for PTTEP by GEN Labs (September 2013), 99 p.

Chakraborty, P.P., Khan, P.K., 2009. Cenozoic geodynamic evolution of the Andaman-Sumatra subduction margin: current understanding. Isl. Arc 18, 184-200.

Eberli, G. P., F. S. Anselmetti, C. Betzler, J. H. Van Konijnenburg, and D. Bernoulli, 2004, Chapter 45 10: Carbonate platform to basin transitions on seismic data and in outcrops: Great Bahama Bank and the Maiella Platform margin, Italy, in G. P. Eberli, J. L. Masaferro, and J. F. Sarg, eds., Seismic imaging of carbonate reservoirs and systems, American Association of Petroleum Geologists Memoir 81, p. 207– 250.

Khan, P.K., Chakraborty, P.P., 2005. Two-phase opening of Andaman Sea: a new seismotectonic insight. Earth Planet. Sci. Lett. 229, 259-271.

Khumputorn, M., 2019, internal presentation, PTTEP (May 2019).

Laya, K. P., 2015. Diagenesis and Petrophysical Rock-Type Study Of Oligocene BeraiCarbonate Platform, Central Kalimantan: Implications For Depositional and Reservoir Models. Bulletin of Earth Sciences of Thailand, Vol. 8, No. 2, 44-52.

Lee, T.-Y., Lawver, L.A., 1995. Cenozoic plate reconstruction of Southeast Asia. Tectonophysics 251, 85-138.

Morley, C.K., 2002. A tectonic model for the Tertiary evolution of strike-slip faults and rift basins in SE Asia. Tectonophysics 347, 189-215.

Morley, C.K., 2013. Discussion of tectonic models for Cenozoic strike-slip fault affected continental margins of mainland SE Asia. J. Asian Earth Sci. 76, 137-151.

Mueller, J., 2004, Myanmar places offshore prospects in the spotlight: Offshore Engineer.

Nelson, C. S., and A. M. Smith, 1996, Stable oxygen and carbon isotope compositional fields for skeletal and diagenetic components in New Zealand Cenozoic nontropical carbonate sediments and limestones: a synthesis and review: New Zealand Journal of Geology and Geophysics, v. 39, p. 93-107.

Racey, A., Ridd, M.F., 2015. Petroleum geology of the Moattama region, Myanmar. In: Racey, A., Ridd, M.F. (Eds.) Geological Society of London Memoir, vol. 45, pp. 63-81.

Thornton, S.E., 2015, The history of petroleum exploration in the union of Myanmar: AAPG-SEG ICE, Melbourne, 33 p.

Warren, J. K., 2008, Carbonate concepts and their applications in the search for shoal-water carbonate, offshore Myanmar. Internal report, PTTEP (November 2008), 44 p.