Diagenetic Effects on Reservoir Properties in a Carbonate Debris Deposit: Case Study in the Berai Limestone, "M" Field, Makassar Strait, Indonesia

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Abstract

After the drilling of four wells that successfully found gas, an unexpected dry well (NW-1) was encountered on what was thought to be the same trend in the "M" field, Paternoster Platform, Southeast Kalimantan – Indonesia. The "M" field is developed in carbonate slope debris reservoirs with gas accumulations within the Oligocene - Early Miocene Berai limestone (primary objective). The dry NW-1 well was a surprise as a previous study indicated that this was a favourable location to drill and the wireline from the well indicated a similar carbonate host. This study has shown that the Berai limestone has a complex depositional and stratigraphic framework and that it has experienced a multistage diagenetic and tectonic evolution. In order to reduce the risk in any future exploration drilling, this integrated study was done, using data from all the existing wells in the "M" Field, including the NW-1 well. This study incorporated all cores and developed a new understanding of the controls on the reservoir development based on the integration of petrography, stable isotope, and wireline log data. The dry NW-1 well was cemented earlier in its burial due to pervasive marine cementation, as evidence by the integration of thin section and isotopic data. In contrast, another well (M-4), containing a siginificant gas accumulation, experienced a longer diagenetic history a phase of later deeper burial leaching that significantly enhanced the reservoir quality of the Berai limestone in this well. This study defines a previously unrecognized non-meteoric origin for porosity development in down-slope Miocene carbonates. This creates a "greenfields" opportunity for exploration in similar settings locally and elsewhere in Indonesia and the Southeast Asia.

Keywords: Carbonate diagenesis, Carbonate debris, Stable isotope

1. Introduction

Carbonate reservoirs hold around 60% of the world's hydrocarbon reserves and account for 40% of total production (Chopra et. al., 2005). Diagenetic overprints in carbonates can completely change the pore structure and mineralogy. In its more extreme degrees, diagenesis can change mineralogy from aragonite/calcite to dolomite and completely dissolve original grains to form pores while the original pore space becomes filled with cement to form a completely inverted porosity distribution compared to the originally deposited sediment (Eberli et. al., 2003).

The "M" Field is situated in the Paternoster Platform, Southeast Kalimantan / Borneo in water depths of around 200 ft (Figure 1).

The study aims to explain why one of the wells (NW-1) in the Berai carbonate is dry compared to other four gas discovery wells within the Berai carbonate reservoir that is the "M" Field.

This study has shown that the Berai limestone has a complex depositional and stratigraphic framework and that it has experienced a multistage diagenetic and tectonic evolution. Therefore, the specific objective for this study is to look for, if any, a relationship between diagenesis with the reservoir quality.

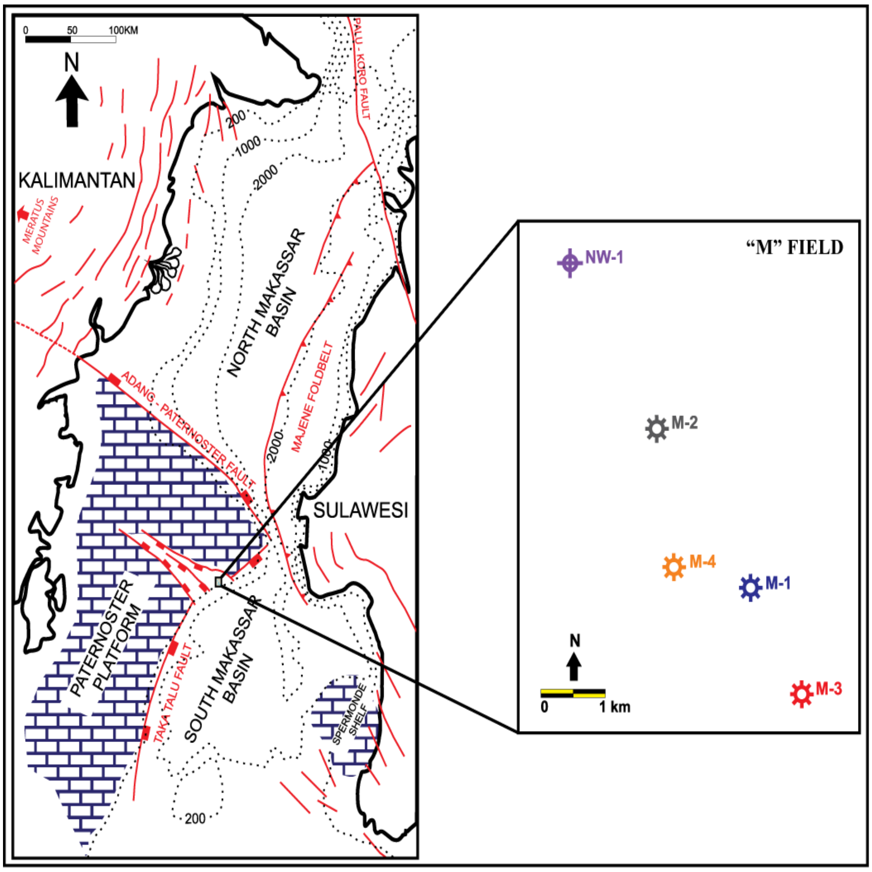

Figure 1. Location of the study area; Inset shows the relative position of the "M" field within this simplified regional geological map**.**

2. Methodology

The study was based on the digital dataset supplied by Pearl Energy and my own study, logging and sampling of cores. A suite of conventional wireline logs was available for all wells. Stratigraphic units were analyzed petrographically and geochemically using core material collected by me from the M-4 and the NW-1 well that includes the best recovery interval in of the Berai carbonate. A total of 102 ft of conventional core from 3 wells, M-3, M-4 and NW-1 wells, in the "M" Field were redescribed. Core plug measurement data, which was only available for M-4 and NW-1 wells, was used to know the porosity and permeability value.

Detailed thin section petrography provided the backbone of this study and, to date, 44 sections have been examined by me. These were impregnated with a high temperature blue-dye impregnated epoxy and stained with a standard alizarin-red S and potassium ferricyanide solution for carbonate mineral identification. All thin sections were observed in transmitted light optical microscopy. The main cementing phases and porosity types were described, and their abundance was visually estimated; the dissolution events were detected and the diagenetic sequence was reconstructed.

Stable carbon (δ13C) and oxygen (δ18O) isotopes were measured on 86 selected carbonate samples from the conventional core from three wells (M-3, M-4 and NW-1 wells). Stable isotope analyses were carried out on three sets of samples: carbonate matrix, limestone lithoclasts, and a calcite filled veins that had been handpicked using a dentist's drill and extracted as rock powder from the conventional cores. The isotope analysis was run using the facilities of Monash University, Melbourne. The stable carbon and oxygen isotope result use a ‰Vienna Pee Dee Belemnite (VPDB) scale. Coplen, 1988 published the standard conversion equation which is $\delta^{18}O$ (VSMOW) = 1.03091 * $\delta^{18}O$ (VPDB) + 30.91 which is used to convert the stable oxygen result from ‰ VSMOW to ‰ VPDB.

3. Results

3.1. Wireline log character

The gamma ray log response shows the carbonate section is present in all 5 wells, but, the character of the gamma ray log clearly differs in M-2 well compared to nearby wells to the southeast and the northwest.

The Berai carbonate section within the M-2 well has a different association of lithology which is more an intercalation of carbonate with shale whilst the other 4 wells show a blocky gamma ray pattern, implying a much more consistent, cleaner limestone of about 5 - 30 API (Figure 2).

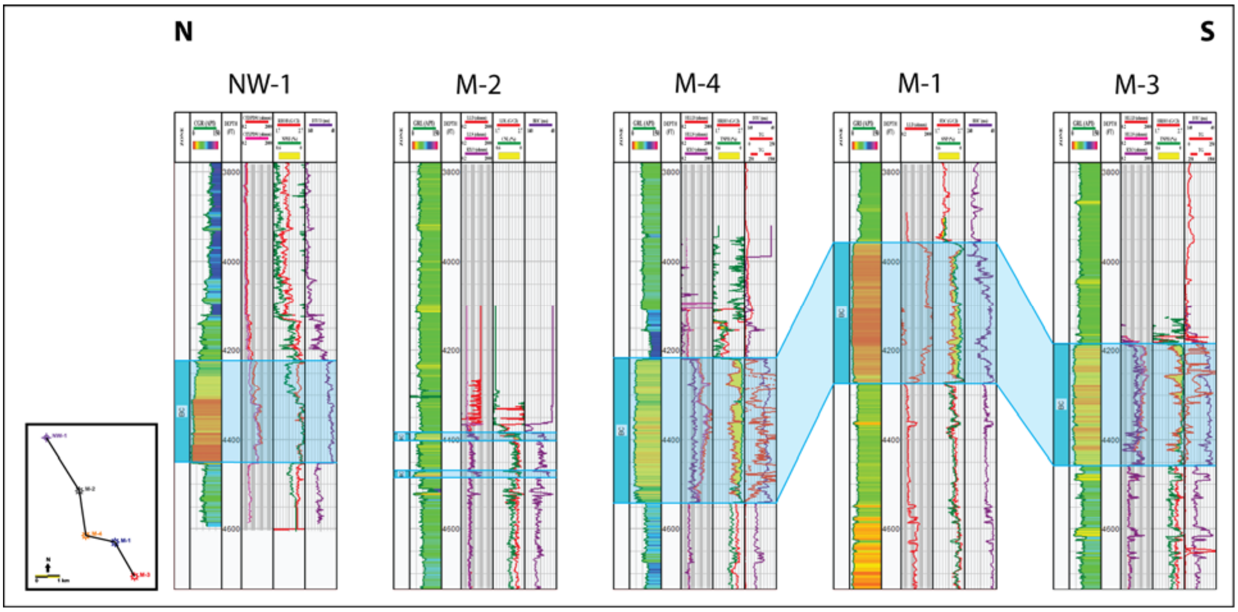

Figure 2. North to South correlation of Berai limestone within the "M" Field. It shows that the correlation cannot be carried from M-4 to NW-1 well because of the different gamma ray character.

3.2. Conventional cores

From the conventional cores combined with petrography observation, five lithofacies group was able to be identified and classified in both M-4 and NW-1 wells. The different lithofacies association between the 2 wells is there a more reefal association lithofacies within the NW-1 well, which clearly differs from the other 2 cored wells (M-3 and M-4). The M-3 and M-4 well consists of more mud and benthic forams with some placktonic forams than the NW-1 well.

Petrographic observation also helped to identify a different diagenetic cement association between the M-4 and NW-1 wells. The NW-1 well has a pervasive marine cement as shown in Figure 3, which clearly differs from the M-4 well.

Stable carbon and oxygen isotope result confirms the thin section observation, which indicates the longer diagenetic overprints present in the M-4 well whilst the NW-1 well shows a shorter time (Figure 4).

Spectral gamma log within the core interval was availabe for only the M-4 well. From the analysis, the gamma log signature has a poor correlation with the core-derived lithofacies. Therefore, the lithofacies derived from the core was not able to be applied to all the non-cored interval for all wells.

Likewise, the neutron and density log character illustrates the same poor correlation while trying to ditribute the core-derived lithofacies to the other well that do not have core.

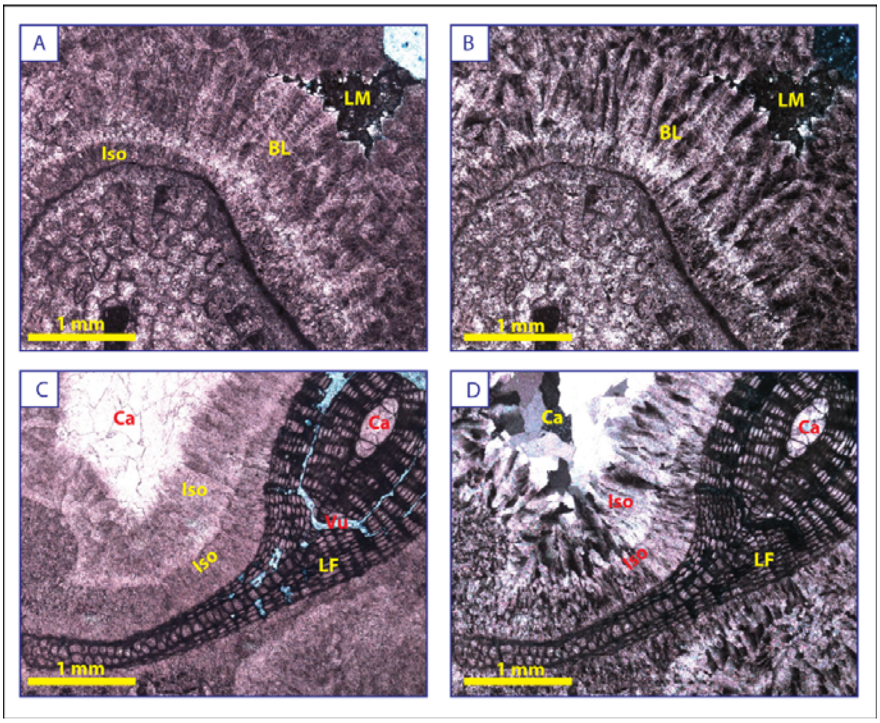

Figure 3. Photomicrographs showing the lithofacies, porosity and cement types found in the NW-1 well; A&B. Parallel and crossed nicols view of the bladed marine cement, C&D. Parallel & crossed nicols view of the marine cement, which shows the extensive development of multigenerational marine cement. RA: red algae, LF: larger benthic forams, Co: coral, Ca: calcite, Iso: Isopachous fibrous cement, Bl: bladed cement, Vu: vuggy, LM: lime mud. The scale bar is 1 mm.

4. Discussion

The evidence preserved of an early now replaced widespread aragonite cement type is abundant bladed calcite cement as shown in Figure 3. It is abundant in the NW-1 well, less so in the M-4. Within the M-4 well a longer, and probably deeper set of ongoing burial diagenetic overprint events took place (as evidence by the isotopic signatures), compared to the shorter and probably shallower marine-cement dominated diagenetic span preserved in the NW-1 well (Figure 4).

Unlike NW-1, these marine cement textures are relatively rare in M-4, implying a different early burial setting; perhaps indicating the sediments in M-4 were deposited in a deeper water setting, less subject to the early pore fluid cross flows that drive early marine cementation.

The diagenetic process which drove economic levels of porosity in the relatively-tight gas play reservoir in M-4 was deep burial leaching. It began in the lower parts of the shallow burial realm and continued well into the deep burial realm.

The different origins of the clast biota between these two wells may imply that their clasts were transported from geographically separate platforms. A summary of this new interpretation of the depositional environment for the "M" Field region is shown in Figure 5.

Table 1 and 2 are a summary of the Miocene carbonate characteristics within the region (Indonesia and throughout Southeast Asia) compared with those in the study area. These two tables indicates there is a new play opportunity for future exploration target within a debris flow set carbonate deposits.

This deeper water setting for the deposition of the host reservoir is so far unique in Miocene carbonate reservoirs in Indonesia and Southeast Asia and so, as mentioned earlier, defines a new play opportunity in Indonesia and throughout the SE Asian region.

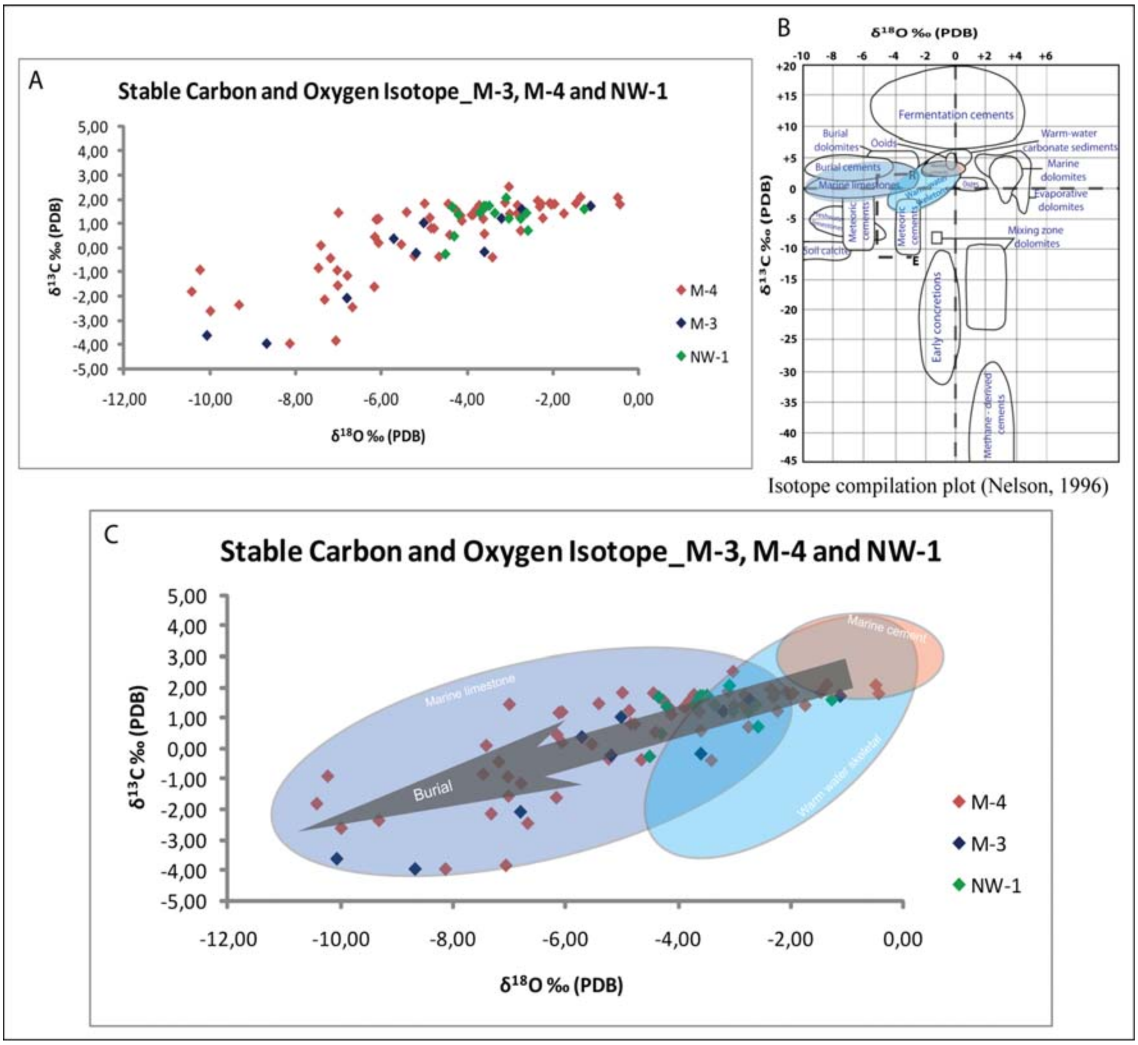

Figure 4. Stable carbon and oxygen isotope plots within the conventional core intervals for M-3, M-4 and NW-1 wells: A. The plot shows the distribution of the stable carbon and oxygen isotope data for the three wells, B. Modified Hudson's plot (isotope compilation plot) by Nelson 1996 as a reference for this study, C. The interpretation of stable isotope data plot; the arrow is an indication of the burial trendline.

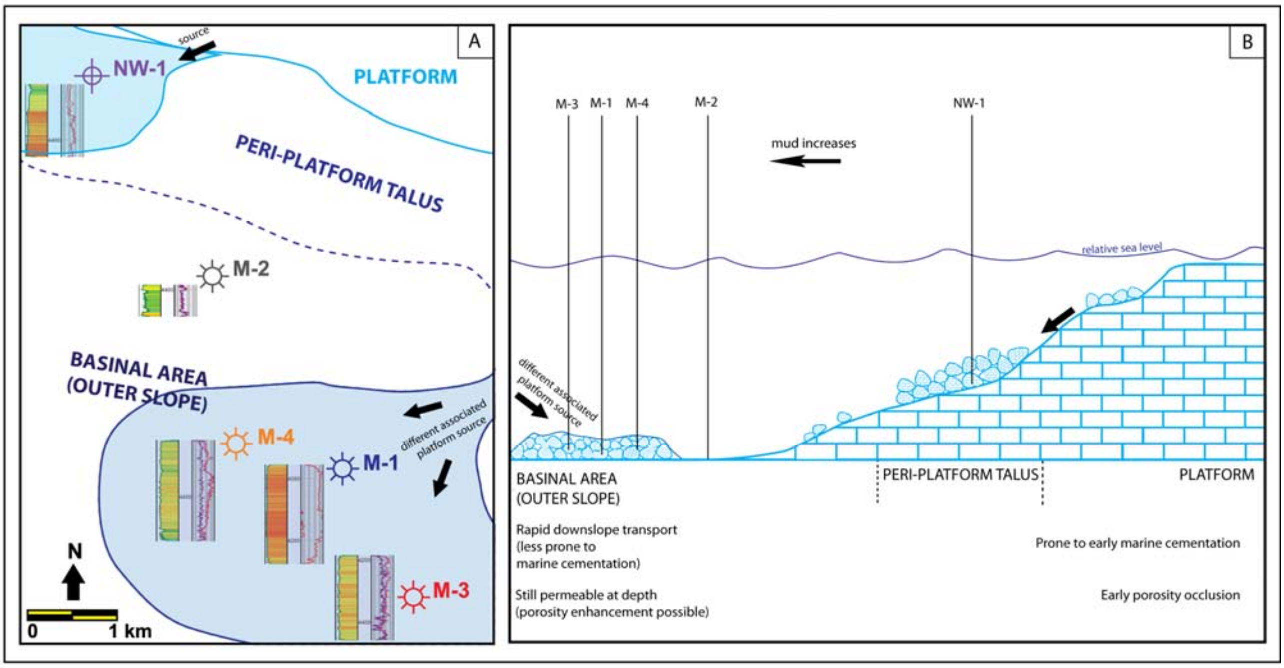

Figure 5. A depositional environment model for the "M" Field; It shows the relative position of the wells and the relative reservoir quality in a planar view and cross section

Table 1. Summary of characteristics of Miocene carbonate in Indonesia.

Platform	Location	Dominant biota and deposits	Carbonate Model	Factor-derived Best Porosity	Reference
Paternoster Platform (Berai Limestone in study area)	Southeast Kalimantan	Larger forams associated with benthic and planktonic forams, some area has more coral skeleton and red algae; bioclastic packstone - wackestone textures dominant	Carbonate debris flow system from the Paternoster platform which is believed to be comprised of some smaller platforms	Late burial leaching which enhances levels of secondary porosity	Pireno et. al., 2009; Pireno et. al., 2010; Study result
Tacipi Limestone	Sengkang Basin, Sulawesi	Coralgal planktonic foraminifera facies with wackestone or mudstone textures	Isolated carbonate buildups	Fresh water dissolution	Ascaria et. al., 1997
Kais Carbonate Platform	Salawati Basin, Papua	Bioclastic wackestone - packstone rich in planktonic forams in intra-Kais buildup; larger forams assemblages are fore-reef and back-reef forms	Carbonate buildups	Meteoric leaching	Satyana, 2003; Matsuda et. al., 2004; Livingstone et. al., 1992
Baturaja Limestone	Sunda Basin, Java	Corals, bivalves, echinoderms, shallow to deep water forams, some red and green algae, sponges and gastropods; Mudstone, wackestone, packstone, coral boundstone, and coral packstone	A rimmed carbonate platform	Meteoric fresh water leaching	Park et. al., 1995

Table 2. Summary of characteristics of Miocene carbonate in Southeast Asia.

Platform	Location	Dominant biota and deposits	Carbonate Model	Factor-derived Best Porosity	Reference
Paternoster Platform (Berai Limestone in study area)	Southeast Kalimantan, Indonesia	Larger forams associated with benthic and planktonic forams, some area has more coral skeleton and red algae; packstone to wackestone and rudstone textures are dominant	Carbonate debris flow system from the Paternoster platform which believed to be comprised of some smaller platforms	Late burial leaching which enhances levels of secondary porosity	Pireno et al., 2009; Pireno et al., 2010; Study result
Upper Zhujiang Platform (Liuhua Field)	Pearl River Mouth Basin, Offshore China	Benthic forams, red algae and corals; dominant wackestone and packstone, boundstone on reefal margin	Narrow and high relief platform	Deep burial dissolution (common vuggy porosity)	Sattler et al., 2004; Zampetti et. al., 2005
Luconia Platform	Offshore Sarawak, Malaysia	Benthic forams, red algae and corals; mudstone, wackestone, packstone, framestone, rudstone	A platform comprises of several isolated patch reefs	Deep burial leaching and dolomitization	Zampetti et al., 2003; 2004 in Fournier and Borgomano, 2007;
Malampaya Buildup	Offshore NW Palawan, Philippines	Benthic forams, red algae and corals; dominant wackestone and packstone and rarer grainstone on the inner shelf, boundstone on reefal margin	Isolated reef rimmed carbonate platform	Meteoric vadose dissolution (vuggy porosity)	after Grotsch et. al., 1999; Fournier et. al., 2004; 2005 in Fournier and Borgomano, 2007

5. Conclusion

The diagenetic overprint in the Berai carbonate section occurred across a shorter time frame within the NW-1 well than within the M-4 well. The early occlusion of porosity in NW-1 explains this di-fference, while the longer and deeper burial diagenetic overprint in the M-4 well explains why gas is present in this well but not the NW-1 well. The NW-1 well is significantly different in terms of the lithofacies and diagenetic overprint phases especially its narrower burial diagenetic band (as seen in its isotopic character). Its shallower depositional setting (compared to M4) explains its low porosity and permeability character. Porosity and permeability were lost in early diagenesis in this well due to pervasive marine cementation, porosity was never regained in this well during its deeper burial.

In contrast the M4 well was deposited as rudstones in a muddier deeper setting than NW-1 and probably was sourced from a muddier deeper platform compared to NW-1. It never experienced the pervasive early marine cementation seen in NW-1. It still retained sufficient remnant permeability on entering the deeper burial environment to allow later dissolution and the enhancement of reservoir quality in its Oligocene - Miocene Berai limestone section.

This new model of a non-meteoric origin for porosity development in down-slope Miocene carbonates creates a “greenfields” opportunity for exploration in similar settings locally and elsewhere in Indonesia. By knowing that there are several other producing fields in Southeast Asia, where the better reservoir intervals are a response to deep burial leaching, strengthens the likelihood of undiscovered hydrocarbons across the region. What is not known from the other regions of such burial-diagenetic related platform production is that the same set of deep burial processes can create reservoir quality in appropriate traps in deeper water carbonate debris aprons located some distance away from crestal positions (the typical seismically defined targets) in the Miocene carbonate platform of SE Asia.

6. Recommendation

1) Future core and core plug work should utilise stable isotope analyses as a standard tool in order to better define a

complete diagenetic history within the carbonate section.

2) The integration of core, stable isotope, petrographic, and wireline logs offers a better method of reservoir understanding and prediction. Even so, it would be even better to include the seismic data and so generate a more comprehensive regional result.

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