DEPOSITIONAL AND DIAGENETIC CHARACTERS OF SEDIMENT IN THE "D" PROSPECT EAST JAVA, INDONESIA: INTEGRATION OF ROCK PROPERTIES AND ISOTOPES AS AN EXPLORATION TOOL

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Abstract

The two wells in "D" Field, D-2 and D-3, from offshore Indonesia, have distinct depositional and isotopic signatures, implying they experienced distinct diagenetic histories. The neutron-density log is used to distinguish specific features that occur in the carbonate interval, with higher porosity generally tied to vuggy fractured zone. Core plug measurements show higher values in well D-3 compared to well D-2. Measurements of stable C-O isotopes from core in both wells are used to define the diagenetic history and the constrasts between the two wells. This differentiation can affect the economic value of the carbonates in the two wells. Carbonates in the D-2 and D-3 wells have distinct isotope signatures, implying they have experienced distinct diagenetic histories and for a classic "T"trend made up of a burial trend and a meteoric mixing trend. Most of the carbonate sampled in the D-2 well shows a typical burial re-equilibration response, related to carbonate dissolution and re-precipitation from pore fluids with increasing temperatures associated with increasing burial depths (the upper arm of the "T"). There are another group of samples in the D-2 well that show a second trend of increasingly negative carbon values that constitute the subvertical arm of the "T". These "second trend" samples are typically from zones of leaching, fracturing and dissolution. In contrast, there is no burial trend seen in the isotope results of the D-3 well. Carbonates in the D-3 well are grainier and more heavily overprinted by the effects of calcite recrystallisation and leaching. The isotope results suggest the grainier sediment interval sampled in the D-3 well acted as an aquifer that carried deeply-circulating meteoric waters, which in turn drove a more pervasive diagenetic overprint in this well compared to the muddier section in D-2. It may be that carbonates in the D-3 well were better connected to an aquifer source, tied to the exposure surface induced by the Miocene uplift and the resulting unconformity.

Keywords: kujung carbonate, "T" trend, burial, meteoric, isotope.

1. Introduction

This report is a detailed depositional and diagenetic study of Oligocene-Miocene carbonates within "D" Field, Madura Strait, Indonesia (Figure 1). The study focuses on integration of rock properties with Carbon-Oxygen (^{13}C and ^{18}O) stable isotopes measurements.

For this study, company-supplied data from two wells with core and allowed the author to relog and sample both sets of cores, namely; D-2 and D-3 wells. Both wells penetrated the Oligo-Miocene interval. There are significant differences in rock properties between the wells, especially in their porosity-permeability values. The D-3 well contains a better quality reservoir in terms of both pore space and pore throat diameters. This difference is supported by oil staining, which is visible on almost all the core from the D-3 well.

So, are the differences related to different style of diagenesis? Or does the local unconformity above the cored interval in both wells explain the different porosity and permeability development. A previous study on the nearby Oyong Field, hosted in Late Miocene carbonate and located above the unconformity, showed that there the reservoir was liitle effected by diagenesis and preserved high levels of primary porosity of up to 60% and hundreds of milidarcies permeability (Tampubolon, 2016).

2. Methodology

Core from the two wells were re-described by me, and these new descriptions, along with the results of sampling for carbon and oxygen isotopes, were integrated with available core data. The recovered intervals in both D-2 and D-3 wells

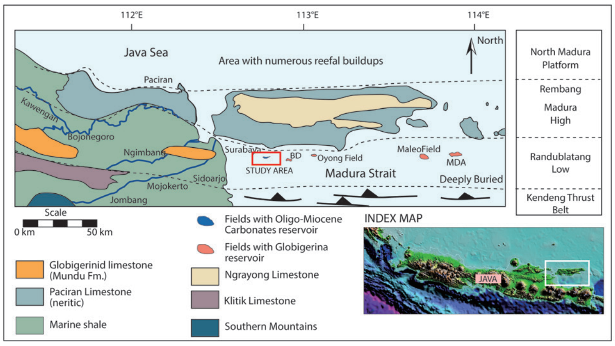

Figure 1. Study area is located in Madura Strait, lies on the Randublatung Low.

come form the Kujung carbonate (Oligocene-Miocene interval). Core plug measurements were tied to the re-logged outputs and the isotope data to better understand porosity and permeability behaviour.

Detailed thin sections reports that has been described by the company were used to integrate the isotope results with the porosity and permeability section.

Stable carbon □ ^{13}C and oxygen □ ^{18}O isotopes values were determined on 220 carbonate samples selected in this study from the available conventional core in the D-2 and D-3 well. Stable isotope analyses were carried out on 10 sets of classified textures: matrix, stylolitized matrix, dark grey mud, crystal calcite, brecciated fragment, cemented pore, bioclasts (algal, coral), calcite lining, cemented fracture/vein and vug. The carbon isotope results were reported in the ‰Vienna Pee Dee Belemnite (VPDB) scale, while the oxygen isotope results were reported in the ‰Vienna Standard Mean Ocean Water (SMOW) scale, which then was converted to the ‰VPDB international standard scale, as this PDB scale is generally used for geological studies. Coplen, 1998 published a standard conversion equation which is □ ^{18}O (VPDB) = (SMOW) - 30.91 / 1.03091.

3. Wireline

3.1 Wireline Log Character

The D-2 log shows a lightly serrated pattern compare to D-3 which is more blocky up to several hundred meters thick. Based on Sharaf et.al. (2005), the Kujung interval can be up to 770 m thick.

The carbonate section in D-2 has different association of lithologies with more intercalated carbonate and shale, while D-3 has a blockier gamma pattern that is composed dominantly of carbonate with little or no shale

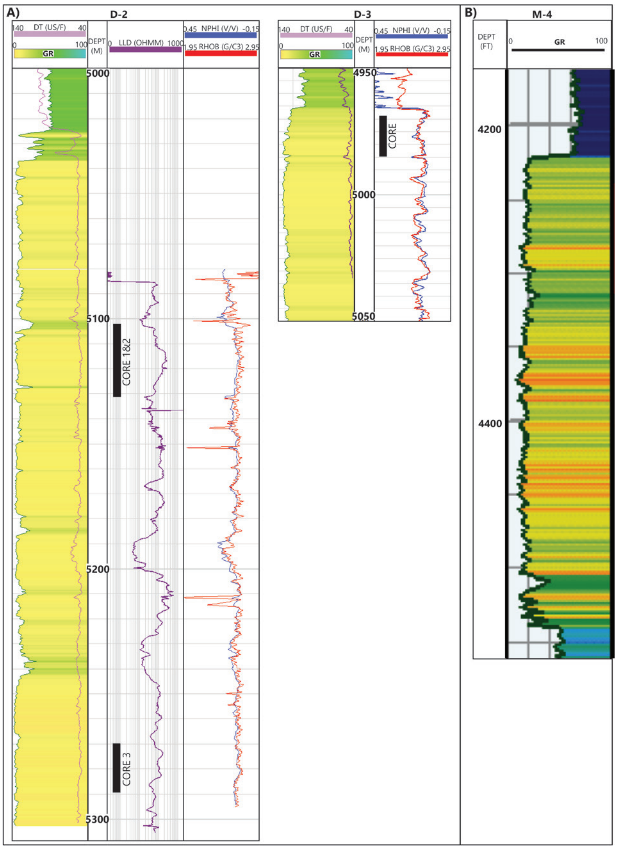

Figure 2. A) Wireline log on D-2 and D-3 wells. B) M-4 well (Tanos, 2011) shows similar pattern with D-2 well.

(Figure 2A). The thickness of intercalated shales varies from 5cm to 1m. The M-4 well(Tanos, 2011) also penetrated a Berai carbonate section with a similar age to the Kujung Fm., but is located in Southern Kalimantan. The M-3 well also has a similar gamma pattern to D-2 (Figure 2B) as as will be seen later later has a similar isotope trend.

3.2 Porosity Log vs Core Porosity-Permeability

The neutron-density log in the D-2 well shows a relatively poorer porosity compared to D-3. Likewise with the core plug measurements; D-2 generally has lower values, around 1 to 9% porosity, compared to D-3,which has higher values ranging from 4 to 26% porosity.

When the porosity to permeability measurements are plotted and clustered, potential flow units can be seen: Good porosity with low permeability and low porosity with good permeability which reflected by subvertical trend. Another one is good porosity with good permeability which represented by a linear trend (Figure. 3). Also, there is a plotted zone with poor porosity and poor permeability that I will not use in the study. All the appropriately shaded zones are illustrated in Figures 4 and 5 along with the corresponding photomicrographs. The good porosity with low permeability zone at depth 5123-5126m in the D-2 well comes from where the limestone matrix is partially replaced by dolomite and minor secondary mouldic porosity. The low porosity with good permeability zone at depth 5108-5110, 5112-5118 and 5119-5121 m in the same well comes from a zone of recrystallized mud with open microfractures. Unfortunately, the good porosity with good permeability zone at a depth 5286-5288m has no thin section as a reference.

In the D-3 well, the good porosity with good permeability zone at depths of 4974.32-4975.25m and 4977.7-4979m is from matrix that is completely dolomitised, with a combination of intercrystalline porosity, vugs and open fractures. While the low porosity with good permeability zone at depth 4971-4972m, 4975.5-4976.5m and 4979.8-4978.8m in the same well comes from matrix with abundant recrystallized mud and open fractures with intercrystalline pores.

4. Full Core Data

4.1 Core Descriptions

Based on the observation that I completed for the core section, I used Dunham (1962) classification combined with the majority occurance in biota to distinguish each facies. There are several facies that can be divided into each well below.

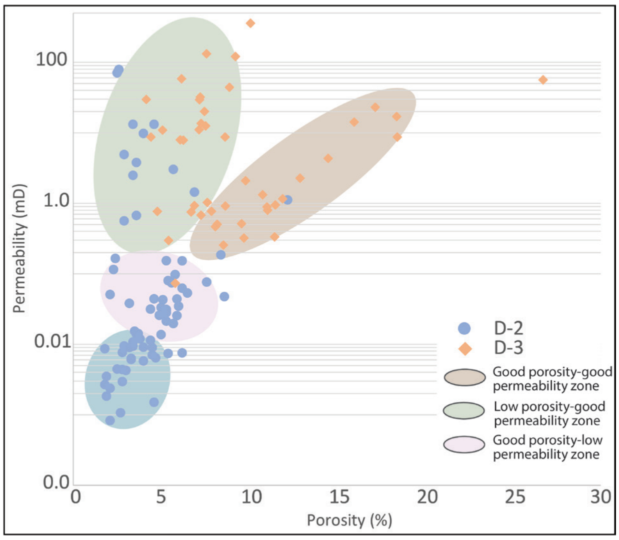

Figure 3. Crossplot porosity-permeability measurements show D-3 well has better quality than D-2 well and can be divided into some flow units.

Core Facies of D-2 Well

The available core in this well mostly consists of two main parts, these are core 1 and 2 from 5105 m to 5131.3 m, and core 3 from 5270 m to 5288.7 m. Each part reflects the carbonate related to mound facies on core 3 at the base, and carbonate related to off-mound facies in core 1 and 2 in the upper part. I classified the bottom portion as Coralline-Algal Reef Boundstone. This interval mainly consists of binding and encrusting alga, coral and some sponges. The upper part consists of bedded of mud dominated mudstone-wackestone and grainier packstone and grainstone. There is also a minor layer of dolomitic limestone in the lower part of core 2 (at depth 5131 m). At the position of the shallower part of this well, the muddier limestone may pass through multiple diagenetic stages (burial and uplift stage) compared to the mounded facies in the lower part. It alternates from the burial stylolitized phase to cross-cutting fractures that formed during uplift. While in contrast the mounded facies in the bottom part, shows some stylolites, less fractures and some minor leaching.

Core Facies of D-3 Well

The available core in this well ranges from 4969 m to 4984 m. This interval shows 2 main facies, 1) mud-dominated wackestone-packstone from 4984 m to 4977 m and 2) boundstone facies above the mud-dominated unit, from 4977 m to 4969 m. Fractures are common in the lower part and some stylolites occur in the upper part. Leached vuggy features are also common. Those features relate to meteoric diagenesis as discussed in more detail in the isotope section.

5. Stable C-O Isotopes

Stable isotope values reflect rock-water interactions and fluid evolution during progressive carbonate rock cementation, recrystallization and re-equilibration of $CaCO_3$ minerals in a progressively higher temperature regime (during burial), and other post depositional factors that control the composition of carbon □ ^{13}C and oxygen □ ^{18}O values (Laya, 2015). Changes in isotope values are useful for carbonate reservoir characterization, understanding the various diagenetic stages, and the relationships to porosity-permeability development via recognising clustering/trends in C-O plots.

Carbon and oxygen stable isotope analyses were run on 230 powder samples collected from available conventional core and core plugs. Bivariate plots of carbon □ ^{13}C and various diagenetic paleo-environments that were oxygen □ ^{18}O are a common way to recognize the responsible to carbonate formation (Nelson et. al., 1996). This study uses a modification of the original Hudson plot by Nelson et. al. (1996) in order to define the paleo-diagenetic environment preserved in the two wells.

The bulk stable isotope data of the D-2 well, range from 2.49‰ to -6.6‰ PDB for□ ^{13}C and -7.56‰ to -0.78‰ for □ ^{18}O. For the D-3 well, the range is from -5.7‰ to -0.5‰ for ^{13}C and -6.16‰ to -0.98‰ for □ ^{18}O (Figure 4A).

Data in a C-O plot in this study give a classic "T" shape, and this is typical of many Tertiary carbonate reservoirs in Indonesia (Figure 4A). That is, a "T-trend" is made up of two separate trends in the C-O isotope plot, namely 2 well are clustered into the burial trend, while the majority data from D-3 well are clustered into the meteoric mixing trend. Except for some points, if we look more detail on D-2 shows a minor meteoric mixing trend too.

The burial trend is characterized by increasingly negative oxygen values due to elevated temperatures of the burial fluids. At the same time the carbon value has slightly decreased with increased temperature during the burial. This is because tion of bicarbonate atoms in it diagenetic fluids, and carbon, unlike oxygen, is

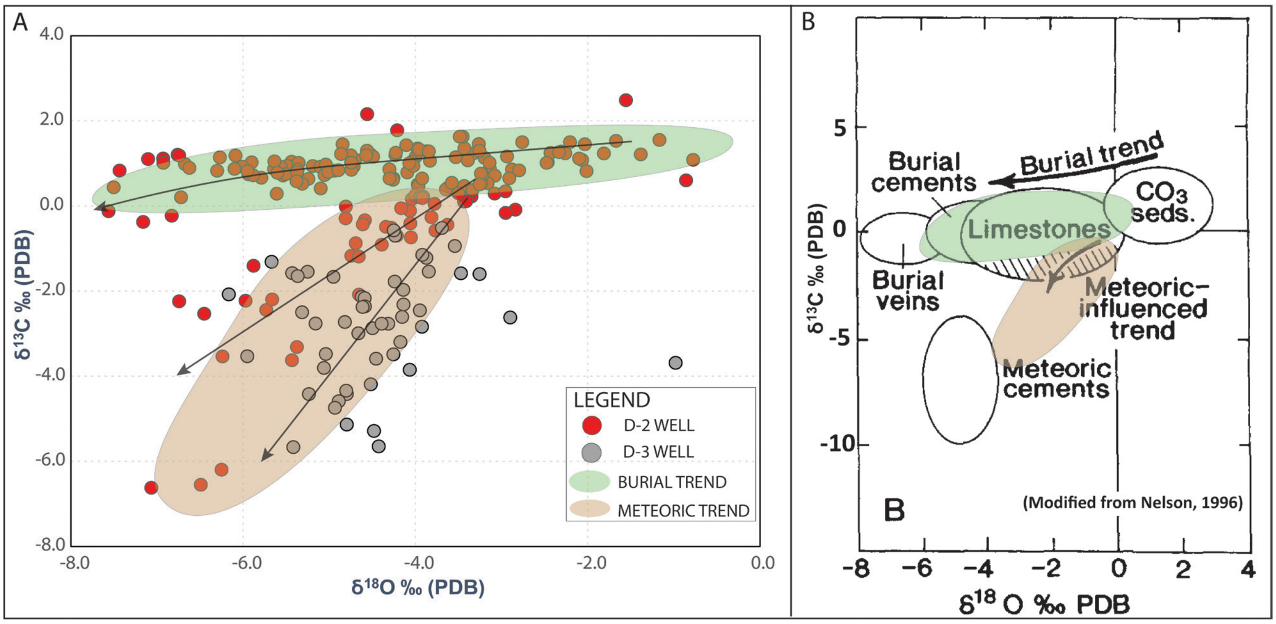

Figure 4. A) Stable C-O isotope plot shows "T" curve made by burial and meteoric trend. B) Overlie to Nelson (1996) plot, the data matches to burial and meteoric-influenced trend.

not siginificantly fractionated by increasing temperature. Those carbon values mostly come from the marine cementation products such as calcite linings, ealy drusy calcite crystals and also the later burial recystallisation of matrix.

Some more negative carbon values in D-3 well are tied to samples collected around cross-cutting stylolites, with additional samples coming from dark grey mud/clay seams (Figure 5). Some of the negative carbon trend may reflects an increased input from locally-derived organic carbon. However, few samples with more negative cabon values in D-3 come from calcite and dolomites tied to zones of leached vuggy porosity. This secondary leached porosity association is most obvious in samples from D-3 and these are interpreted as belonging to the meteoric mixing trend. These calcites likely formed during the entry of meteoric waters, at a time perhaps related to uplift and exposure of the Berai carbonates in the D-3 well.

Comparing to the global isotope compilation and crossplot by Nelson (1996), the data over the 2 wells spread across fields defined

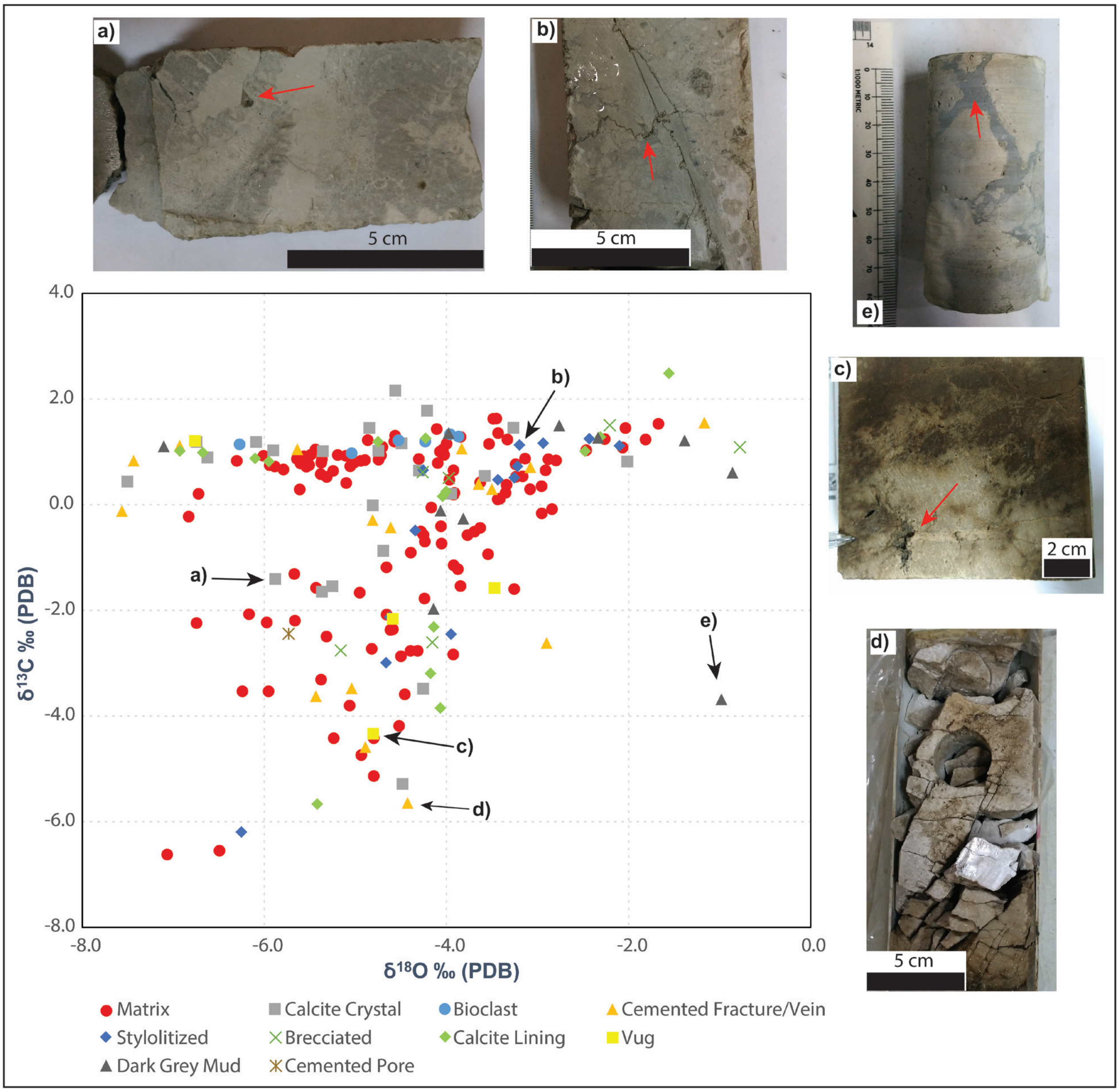

Figure 5. Stable C-O isotope plot in both well shows relationship with its diagenetic textures.

by Nelson as marine limestone, warm water skeletal, and meteoric cements, confirming that the carbonate grains in both wells have experienced are least 2 sets of diagenetic fluids (marine burial and meteoric; Figure 4B).

These isotope results are compared to another similar carbonate interval age (Oligocene - Miocene age) in Indonesia. The study also compares the result from the younger interval above the unconformity (Figure 6). Most of the D-2 samples overlay the burial trend that occur in slope carbonates in Makasar Strait (Tanos, 2011). In contrast, the comparison with platform carbonate in South Kalimantan (Laya, 2015) does not match. Kujung carbonate in this studyshows lesser affect of compacted basinal shales that bring organic rich fluids that give lowered or more the negative carbon value in the carbonate precipitates. The comparison plot also indicaste that the carbonate under the unconformity in the study area has undergone at least 2 stages of diagenesis, compared to a previous nearby study by Tampubolon (2016), that shows the younger interval above the unconformity has not experienced significant diagenesis (Figure 6).

6. Discussion

6.1 Stable C-O Isotopes Corresponds to Porosity and Permeability

As the D-2 samples are deeper than D-3, this condition may have bathed in hotter fluid and so will give more negative □ ^{18}O. Compare to D-3 that experienced the cooler fluid during the burial stages. Porosity occlusion was widespread in the burial stage. The micrite envelopes rimming the grains are follow by dissolution and precipitation of calcite spar. This is related to the majority of samples with calcite pore linings and calcite crystal that plot as the burial trend. A similar trend is seen in some samples from core 3 of D-2 well.

Partly collapsed components/grains and abundant lining contacts between grains indicate ongoing burial diagenesis. This is followed sometimes by a influx of Mg-rich fluids forming a stratiform dolomitic carbonate. This happen in D-2 at depth 5131m, while in the D-3, it forms a dispersed dolomite that fills some pore spaces.

The next stage is uplift, this brings all the carbonates into the telogenetic (meteoric) realm. It will move slightly narrower value in □ ^{18}O, but will create more negative □ ^{13}C value. During this stage, enhanced mouldic and vug porosity is created. Followed by fracturing and ongoing stylolitisation that creates an interconected vug porosity facilitating fluid flow. The upper part of D-2 has more permeability flow as it is morefractured. In D-3, leached vugs are more common, creating more porosity and permeability.

In the (Figure 5e), it plots a point with textures of dark grey mud/clay seams. The depletion in □ ^{13}C and the relative enrichment in □ ^{12}C can be explained by the impact of isotopically light meteoric water and light soil zone CO_2 (Immenhauser et al., 2002; Weidlich, 2010). This also indicates that the upper part of the wells are better connected, that then allowed meteoric waters to moove more deeply into the system.

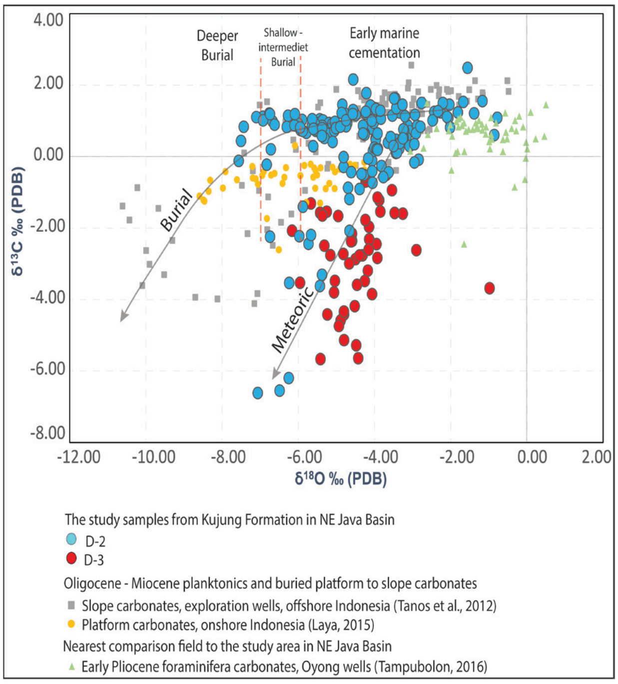

Figure 6. Comparisons to similar age interval in Indonesia (platform to slope carbonates) and younger age that has less-effect of diagenesis.

7. Conclusions

Carbonates in the D-2 and D-3 wells have distinct. Most of the carbonate sampled in the D-2 well shows a typical burial re-equilibration response, related to carbonate dissolution and re-precipitation from pore fluids with increasing temperatures associated with increasing burial depths (the upper arm of the “T”). There are another group of samples in the D-2 well that show a second trend of increasingly negative carbon values that constitute the subvertical arm of the “T”. These samples are typically from zones of leaching, fracturing and dissolution. In contrast, there is no burial trend seen in the isotope results of the D-3 well. The core description shows carbonates in the D-3 well grainer and more heavily overprinted by the effects of calcite recrystallisation and leaching. The isotope results suggest the grainier sediment interval sampled in the D-3 well acted as an aquifer that carried deeply-circulating meteoric waters, which in turn drove a more pervasive diagenetic overprint in this well compared to the muddier section in D-2. It may be that sands in the D-3 well were better connected to an aquifer source, tied to the exposure surface induced by the Miocene uplift and the resulting umnconformity.

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