THE SHUTDOWN OF DIAGENESIS IN THE EARLY PLIOCENE GLOBIGERINID LIMESTONES OF THE MUNDU FORMATION AND IMPLICATIONS FOR POROSITY AND PERMEABILITY LEVELS (EAST JAVA BASIN, INDONESIA)

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Abstract

Globigerinid limestones, in the Madura Strait of Indonesia, as producing reservoirs are unique. This reservoir sediment was deposited and winnowed in a deepwater complex with substantial bottom current reworking. Although there is now more than 800 meters of overburden sediment and a strong tectonic overprint, as seen in seismic, this reservoir didn't experience significant diagenetic alteration. Early hydrocarbon emplacement ended the diagenetic process and preserved pristine intraparticle porosity with interconnection across foraminiferal punctae, so allowing connection between intrafossil and extrafossil porosity. The best reservoir quality occurs in globigerinid sands on Early Pliocene paleohighs where winnowing processes (bottom-current reworking) were stronger. Winnowing driven by bottom current reworking can result >40% porosity and excellent permeability. Partial destruction of reservoir quality is caused by micritization and rupture/collapse of foraminifera shells. There is strong evidence that the Pliocene collision of Southeast Asia and Australia plates drove changes in oceanic circulation and bottom current intensities in the Madura Straits area, via restriction then closure of the Indonesian Seaway. In the Pliocene deep water setting that was the Madura Strait, the restriction (prior to complete closure) drove more intense westward bottom currents and this was likely the driving force creating enhanced contourite currents that winnowed portions of the Mundu Fm. Once closure occured, bottom currents in the vicinity of the Madura Island trend weakened and 800 m of muddy seal sediments were deposited from suspension to form a regional seal. The improved understanding of the controls on this unique reservoir will allow improvements in future field development and an improved ability to predict the positions of possible future drilling targets in the Madura Straits and further a field.

Keywords: Globigerinid, intraparticle, bottom current rework, Madura Strait

1. Introduction

This study involves in Oyong Field, which was discovered in 2001, located in Madura Strait, Indonesia. The reservoir is the globigerinid limestone of the Mundu Formation. The Oyong structure, a 4 way dip closure, was successfully tested by the Oyong-1 discovery well and then better delineated by Oyong-2 and Oyong-3 wells in 2001. This study is focused in Oyong-2 and Oyong-3 wells because of availability of core data in these two wells (Figure 1).

Despite its relatively young age, the Mundu Formation constitutes a large gas reservoir, which until now shows as high success rate in terms of discoveries. The produced gas is associated with liquid hydrocarbons. This shallow gas is explained by reference to the fractionation character as being a product of vertical migration of a mixed oil and gas charge.

The globigerinid limestone host to the hydrocarbons was deposited in deep water complex in Early Pliocene. This high porosity has been preserved since its deposition time although there is now more than 800 m of thickness of overburden atop the reservoir.

2. Methodology

The use of carbon-oxygen isotope covariance is widely applied to understand diagenesis evolution of carbonate rocks. With this in mind, fifty samples from core were selected for C-O isotope determination and together with thin sections (from related plug trim ends) the samples were used to define depositional setting and the intensity of diagenetic alteration. Sixty meters total thicknesses of core from two Oyong wells were described in detail and compiled into standard facies groupings. Ten XRD samples were analyzed to confirm minerals identified in thin section. Rock property data from 165 core plugs were compiled to define poro-perm relationship with respect to facies definitions established in core.

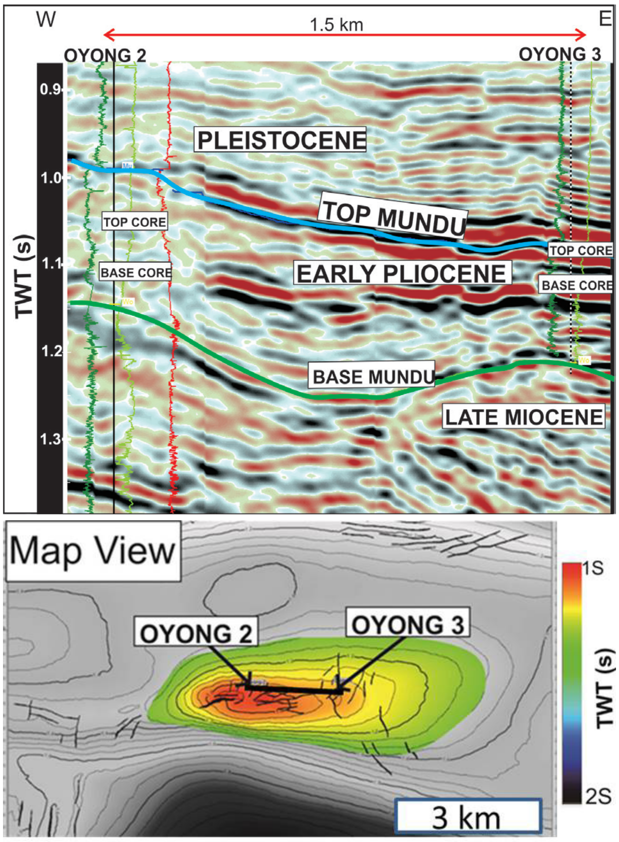


Figure 1. East-west seismic section showing the location of wells and cored intervals and map showing 4-way dip closure of Oyong

3. Regional geology

The Oyong field is located on the southern flank of the uplifted Madura Island trend. In the Madura Island trend, along the RMKS (Rembang-Madura-Kangean-Sakala) strike-slip fault zone, a Paleogene rift basin was inverted in the Early Miocene (N4-N5), and further uplifted again in the Middle Miocene (Bransden and Matthews, 1992). This tectonic history is important to stratigraphic development as the inverted zone then became a barrier to clastic sediment influx to the seafloor south of Madura Island trend. In the Pliocene the area about Oyong field was starved of clastic sediment and also remained a marine low, called the Randublatung low, which had deeper water depths than the surrounding areas of the NE Java Basin.

In the Early Pliocene in the Madura Strait, the Mundu Fm. was deposited as deepwater sediment fill, with thicknesses largely controlled by paleotopography. The crest of inversion was incised by several channels and the overlying strata were flat lying. The major sediment source was an uplifted zone in the northern part of the low and during a transgressive event was also supplied sediment carried into the area by westward-moving waters of the Pacific Ocean. In Oyong field, the relative position of Oyong-2 and Oyong-3 have not undergone significant change since Mundu deposition. The sediment above Mundu Fm. are characterized by onlap reflections with respect to the base Mundu Fm. which was a paleohigh since Late Miocene. Detail on structural style and structural evolution in Oyong field are discussed by Arifin (2016).

Understanding changes in oceanographic conditions in the Pliocene are very important to the understanding of deposition of the Mundu Fm. There is strong evidence that the collision of Southeast Asia and Australia plates drove changes in oceanic circulation and bottom current intensities via restriction then closure of the Indonesian Seaway, driven by northward movement of Australia were mostly complete by 4-3 Ma (Sato et al., 2008) This created the northward expansion of Western Pacific Warm Pool (Sato et al., 2008), so bringing colder water to the Indonesian archipelago from Pacific Sea. In the deep water setting that was the Pliocene Madura Strait, the restriction (prior to closure) drove more intense westward bottom currents and this was likely the driving force creating contourite currents, which winnowed portions of the Mundu Fm. on local highs on the deep sea floor. Once closure occurred, these more intense bottom currents no longer influenced bottom currents intensity in the vicinity of the Madura Island trend and a 800 m thick succession that is the muddy seal to the Oyong Field was deposited.

Even now, there is a strong steady current passing across the sea bed in the vicinity of Oyong field, flowing in NE-SW and NW-SE directions, with a mean speed of 11-30 cm/s. On the surface, the recent current is greatly affected by mixed tide energy, local winds and regional drift circulation (SE Monsoon and NW Monsoon). However, the modern average current speed is less than in the Pliocene, because of the closure of former Indonesian seaways, in response to the collision of the Australian and SE Asia plates.

4. Biostratigraphy analysis

Biostratigraphy indicates timing and paleonvironments and so is an important subject to discuss. Foraminifera and nannofosil datum and zonation are based on Lunt (2013), which provides the most updated time-scale zonation for Oyong Field. The consistent occurrence and in-situ FAD (First Appearance Datum) of Gt. tumida and LAD (Last Appearance Datum) of Discoaster quinqueramus across all wells defines the base of N18 (Early Pliocene) stage as the initial depositional timing to the Mundu Fm. This "N18 event" is also indicated by an abrupt lithology change from the shales and sandstones of Wonocolo Formation to the globigerinid limestone of Mundu Fm.

Planktonic to benthic ratios are consistently 70-80% or more (Figure 2). Benthic fossils are low in abundance, but high in diversity, and include deep marine calcareous benthic taxa andother deep marine arenaceous benthonic taxa are consistently recorded.

Interestingly, there is a consistent condensed section across all wells at 3 Ma(Figure which is resolvable also at the seismic scale. At the global scale, this "3 Maevent" ties to the final closure of Indonesian seaways and to an interval of global climate change (Sato et al., 2008).

This condensed section marks the start of local inversion and an increase in worldscale glaciation, it also defines the end of deposition of Mundu Fm. After the condensed section event there is an increasing abundance of Bulimina sp, this is a deep water benthonic transported milliolid association tied to deposition as the local environment become deeper.

There is a difference in rate of sedimentation between Oyong 2 and 3 well. A flattened gradient section in the "age vs depth" plot across the Oyong wells indicates a relatively rapid rate of sedimentation. Oyong 2 experienced a longer period of rapid sedimentation than Oyong 3. As discussed in more detail later, this difference likely indicates a different degree of winnowing overprint between sediments in Oyong 2 and 3.

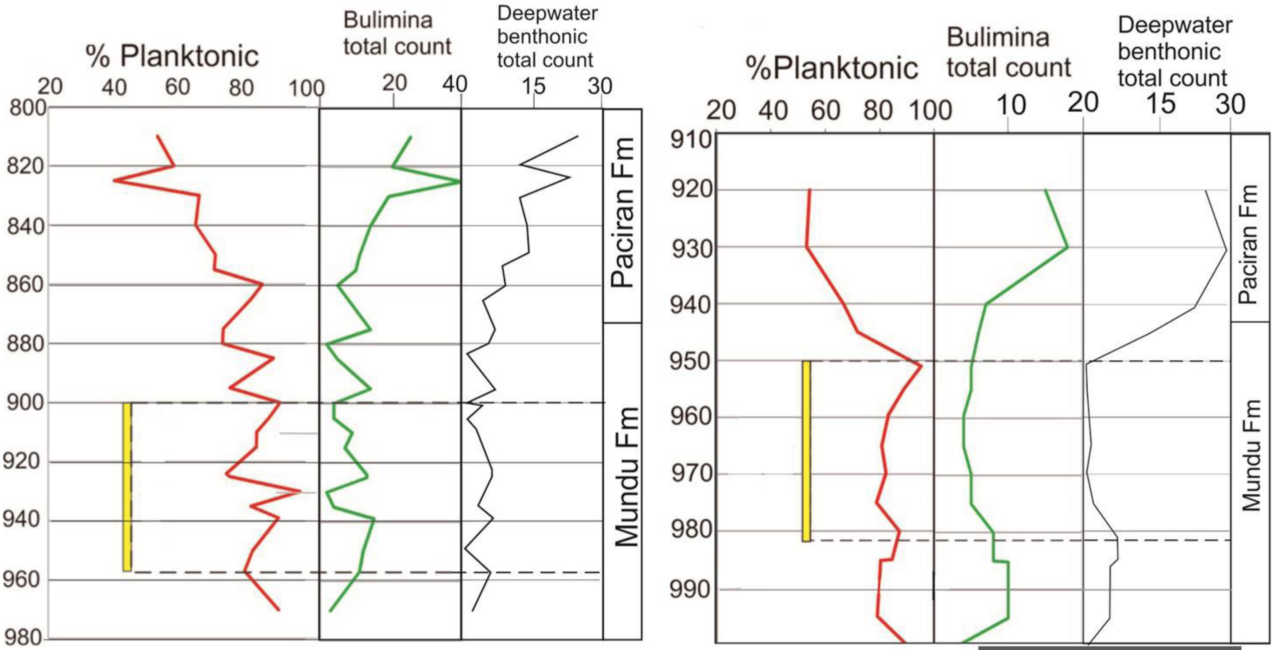
5. Facies and sedimentology framework

The internal sedimentary structure of Oyong core can be generally clustered into two main units; an upper and a lower units. The lower unit consists of a thoroughly-bioturbated packstone-wackestone, with common calcite cement, and some thin grainstone unit. The upper unit consist of cross-bedded packstone-grainstone containing common Ophiomorpha ichnofacies. There are consistent 5-8m-thick coarsening-upward parasequences in the cored interval. However, it should be noted that the entire cored interval in Oyong 2 wells is N18 in age, while the cored interval in Oyong 3 is N18-N19 in age.

Consistent detailed characteristics in the sedimentary structures in Oyong-2 and 3 are:

- Common thin mud layers through all core sections
- Some lenticular beds and cross laminations
- Cross-bedded limestones with rhythmic mud layer
- Cross-bedded glauconitic layers
- Sharp, non-erosional upper contacts

Most of the sedimentary structures listed above, which are illustrated in Figure 4, are interpreted as the product of deposition of traction currents or a combination of traction currents and suspension settling. However, due to intense bioturbation, the sedimentary grainstone intervals. A well oxygenated marine setting allows this



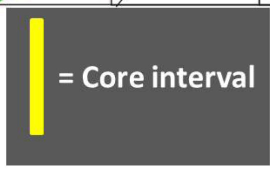


Figure 2. Biostratigraphy compilation from Corelab (2006). Left is Oyong-2 and right is Oyong-3

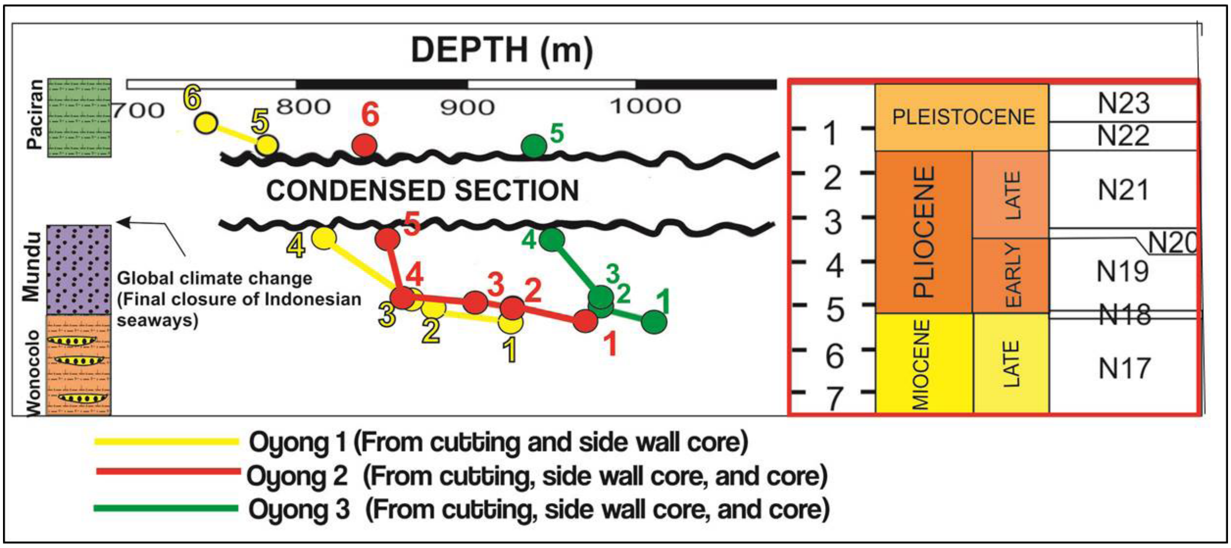


Figure 3. Condensed section in 3 Ma, marked the end of Mundu deposition

preservation of bioturbation regardless of water depth (Schiller et al., 1994).

6. Petrography

Thin sections clearly show the lack of diagenetic overprint in the globigerinid limestone of the Mundu Formation, The petrographic analysis also reinforces the depositional environment interpreted from core and define the results of fluid movement in the Oyong field. Intraparticle porosity within the foraminifera's living chamber dominates porosity throughout this entire reservoir interval (Figure 5). Most of the foraminifera's chambers are still well preserved along with test punctae and the body fossil aperture. In all of the thin section samples here are no reefal fragments present, such as coral and red algae, implying much of the coarser grained sediment is locally derived (a combination of planktonic and benthic fossils).

Some reworked benthic foraminifera contain glauconite in the chambers. This glauconitization requires a low rate of sedimentation before being subject to bottom current reworking (Schiller et al., 1994). Some glauconite is present as dispersed mud or partially cemented pellets and intergranular pores but is not present in the form of crystalline authigenic minerals (Figure 5). Across all samples glauconite is typically pore-occluding.

The amount of micrite in a sample is the most important parameter in terms of the development of reservoir quality. Winnowing of mud creates higher porosity and permeability in a sample. On the other hand, the absence of, or weak influence of winnowing current is tied to increases in the amount of mud. This tends to block intraparticle porosity connection and so reduce the permeability. Another significant parameter in terms of reservoir quality is the mechanical collapse of foraminiferal chambers due to overburden stress. This too lowers the level of storage porosity.

The size of an intraparticle pore throat in this reservoir depends on foraminifera test size, which can reach more than 100 μm. As a strong winnowing current hits the seafloor, the

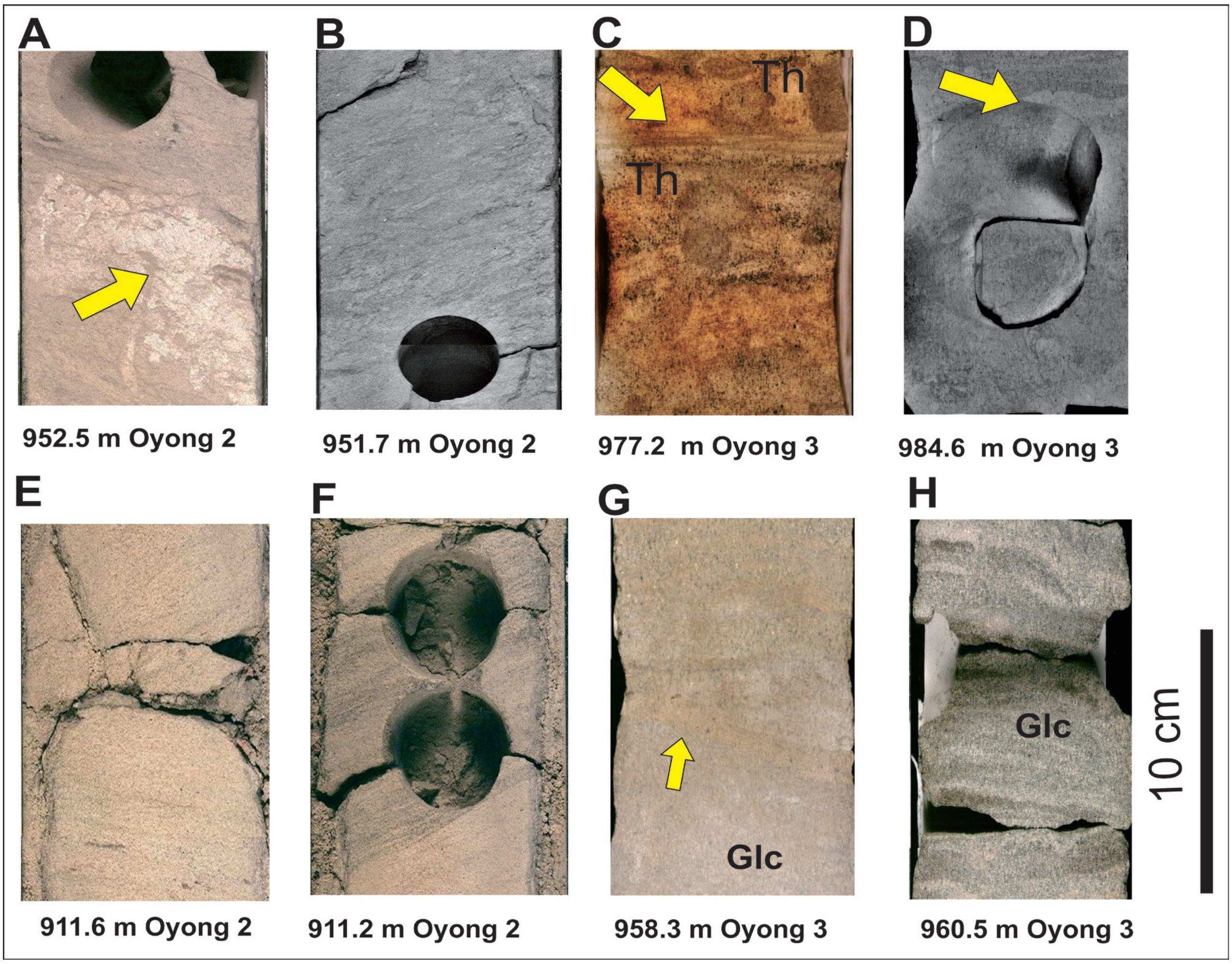


Figure 4. (A) Representative core features in Oyong wells (A) Calcite- cemented hardground (stratabound) form; (B) Mud drapes layers with low angle lamination; (C) Parallel lamination. Thallasinoides (Th) bioturbation with clay and glauconite filling usually occur in such grainstones. ; (D) Starved lenticular layer; (E) Cross-bedded grainstone with thin mud layer; (F) Low angle rhythmic mud layer, with sharp basal contact; (G) Winnowing surface with sharp contact between glauconite-rich (Glc) below to grainstone above; (H) Cross-bedded glauconitic (Glc) grainstone

larger foraminifera tend to remain behind, along with glauconite pellets in cross-bedded sands. The smaller forams and the mud are carried away by the currents.

What is most significant in terms of thin section observation of reservoir quality is that many of the foram tests are so little altered since deposition that the original punctae remain in the calcite structure of the body fossil. These numerous original holes in the foraminifera test remain today, and so allow free fluid communication between the interior and exterior of the foram test. Unlike most carbonate reservoir sediment worldwide, the ratio between total porosity and effective porosity approaches unity in these unusual biogenic reservoirs.

7. Stable isotopes

Stable isotope analysis also supports a lack of diagenesis evolution observed in thin sections in this globigerinid limestone. The range of δ18O PDB is -3 ‰ to 0.5 ‰ PDB and the range of δ13C is -2.3 ‰ to 1.3 ‰ PDB (Figure 6). These low values of carbon and oxygen preserve the initial conditions of seawater chemistry from the Early Pliocene.

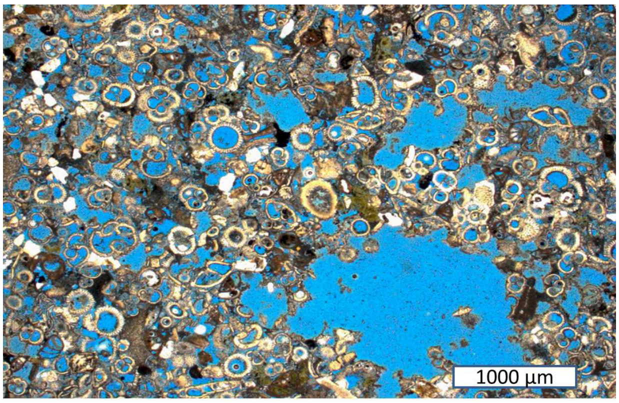


Figure 5. Evidence of lack cementation and lack of micrite in the well-winnowed reservoir allowing higher connection between intraparticle porosity since its deposition. Glauconite (Glc) is pore-throat occluding if present in intergranular pore.

Comparing this set of stable isotope values to published recent foraminifera isotope values in forams living in surface waters of modern NW Arabian Sea by Peeters et al. (2002), show an impressive overlap of the two plot fields (Figure 6 B). It seems there is no significant change of seawater temperature where these tropical globigerinids lived in Pliocene to the present. This overlap of stable isotope plot fields between modern and Pliocene populations shows that foraminiferal tests in the Oyong reservoirs have experienced little or no diagenetic alteration since first being deposited on the Pliocene seafloor. It also implies that the presence of overburden sediment, which can exceed 800 m and the associated tectonic stresses nave no influence the diagenetic evolution of the reservoir.

8. Porosity and permeability

The ratio between intraparticle porosity and all other type of porosity is 2:1 to 3:1. Aside from foram-associated intraparticle and interparticle porosity and minor vuggy porosity, other types of porosity appear minor but can play an important local role in reservoir deliverability. Pore space terminology used in this report follows the Lucia (1995) classification. However, the recognition of intraparticle connection in this reservoir prompted a modification of Lucia's classification. Lucia's (1995) classification describes the intrafossil porosity as separate-vug pore space and can only result in a lowered low permeability. Lucia (1995) only emphasizes the important of interparticle porosity in affecting the permeability. Lucia did not deal with a reservoir so little altered by diagenesis that the punctae remain open in the foram tests. Lucia (1995) stated that the separate-vug porosity can only increase the porosity without raising the permeability significantly. This is not the case in this reservoir because the intrafossil porosity is connected to interparticle porosity via open punctae and this gives a much higher permeability than predicted by the standard best fit Lucia transforms.

So, plotting porosity-permeability data in this reservoir to Lucia's texture aware subdivision classes gives an inappropriate result. The grainstone will be plotted in class-3 grainstone field in Lucia (1995) classification although the grainstone in Oyong field have significant connected intraparticle porosity

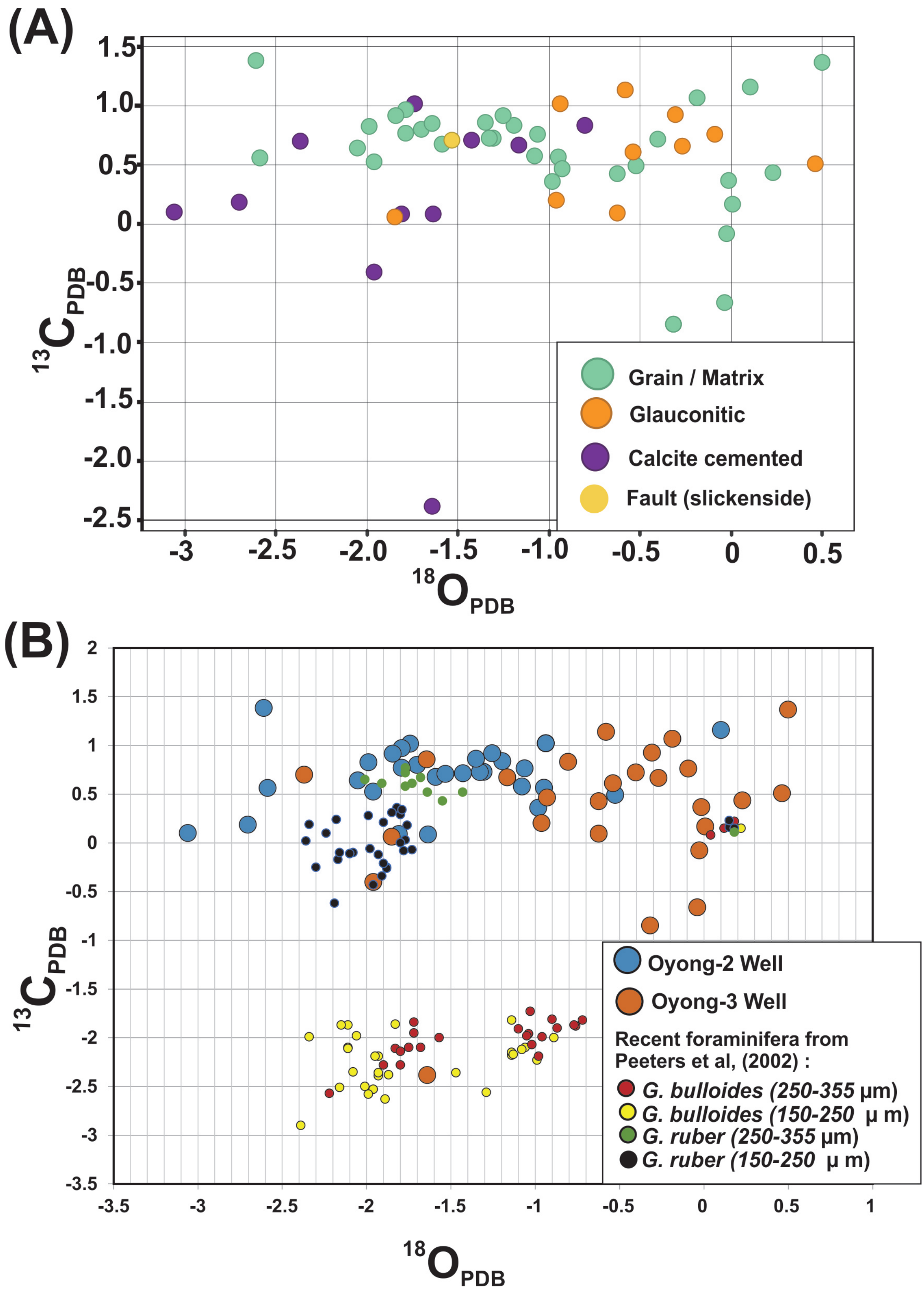


Figure 6. (A) Texture-aware C-O stable isotope plot in Oyong-2 and Oyong-3 wells; (B) Overlay of data plot of C-O stable isotope in Oyong wells with recent foraminifera in NW Arabian Sea by Peeters et al. (2002).

(Figure 7). Put simply the lack of diagenesis and the presence of open punctae means Lucia's predictive transforms grossly underestimate actual permeability.

The first step in better describing a correlation of porosity to permeability in this reservoir is to distinguish the hydraulic flow based on core data. The method introduced by Amaefule et al. (1993) is used to discriminate the hydraulic flow. This is very useful because the porosity in this reservoir is mostly fabric selective. As described by Amaefule et al. (1993), for any hydraulic unit, a log-log plot of of "Reservoir Quality Index," ," (RQI), which is equal to to 0.0314 $\sqrt{\frac{k}{\phi}}$ versus a "Normalized Porosity," (ϕz) , which is equal to/ ϕ(1-ϕ), should yield a straight line. The intercept of the unit slope unit with ϕz = 1, designated as the "Flow Zone Indicator," (FZI) is unique parameter for each hydraulic unit. The "Flow Zone Indicator" also incorporates the geological attribute of texture and mineralogy via the discrimination of distinct pore geometrical facies (Amaefule et al., 1993).

Based on core description, thin section, and FMI, the defined hydraulic units coincide with facies boundary seen in core. The FZI for wackestone, packstone, and grainstone is 0.161, 0.3356, and 0.9 respectively (Figure 7). Higher FZI means higher reservoir quality, this corresponds to the grainier globigerinid limestone intervals where the interparticle mud has been washed away by winnowing current.

This correlation of FZI with facies boundary can be used for permeability prediction in uncored well by substituting the FZI value to porosity-permeability equation by Amaefule et al. (1993):

$$k = 1014\ (FZI)^2 \frac{\emptyset^3}{(1-\emptyset)^2}$$

where k=milidarcys, $\emptyset$ = porosity in fraction. The use of this equation can be seen in Figure 7 C.

9. Validation of hydraulic units

Using petrography to validate the hydraulic units gives a critical understanding to predicting permeability in Oyong Field (Figure 8). Along the hydraulic flow unit line, the amounts of micrite heavily control the permeability. Besides being a poorly-winnowed rock, the degree of bioturbation also controls the degree of matrix.

Interparticle porosity plays an increasingly significant role as the winnowing current became stronger and more and more mud was washed away. Increases in foraminifera size in the more intensely winnowed sediment also give higher interparticle porosity.

However, the hydraulic unit zone trend defined earlier does not fit very well with the addition of interparticle porosity via winnowing as the permeability rises significantly and departs the predicted trend (Figure 8). In terms of hydraulic response, a large foram with high levels of preserved internal porosity probably has the erosional current threshold equivalent to that of a silt particle, not a coarse sand.

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11. References

Amaefule, J.O., Altunbay, M., Tiab, D., Kersey, D.G., 1993, Enhanced Reservoir Description : Using Core and Log Data to Identify Hydraulic (Flow) Units and Predict Permeability In Uncored Interval/ Wells: Society of Petroleum Engineers, SPE 26436, p1-16.

Arifin, M.T., 2016, Reservoir Characterization using Seismic Attributes and Seismic Inversion in a Globigerina Limestone Reservoir, Madura Strait, Indonesia: M.Sc Research Report, Petroleum Geoscience, Chulalongkorn University, Bangkok.

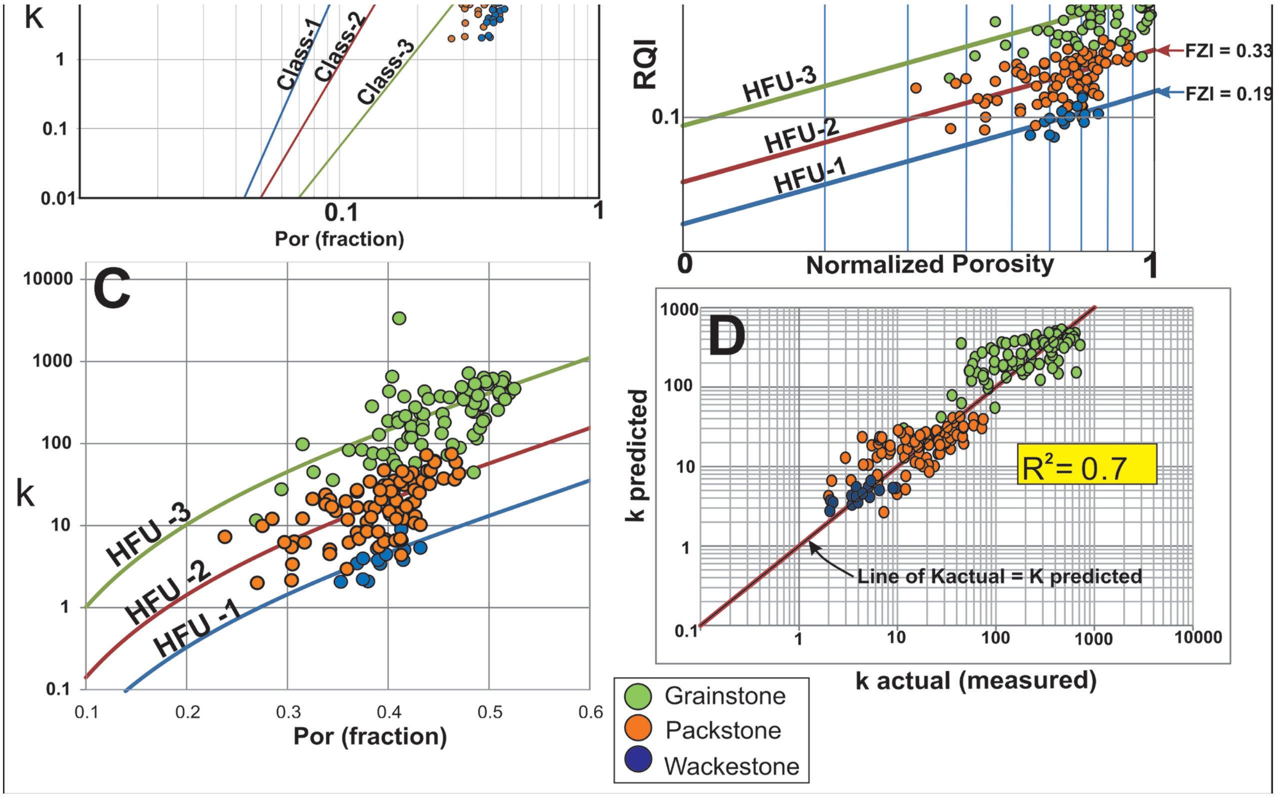

Figure 7. (A) Plot of porosity-permeability data, overlain on Lucia's subdivision classes (1995), places the globigerinid limestone grainstone in class-3 of the Lucia classification. This is inappproate since the globigerinid limestone has high levels of interconnected intraparticle porosity that a class-3 grainstone of the Lucia classification doesn't accomodate; (B) log-log plot of RQI and normalized porosity give a definition of FZI and hydraulic units on each facies boundary; (C) Porosiy-permeability plot in semi log plot with each hydraulic flow units; (D) Using hydraulic unit equation with FZI, permeability can be predicted with R2 = 0.7

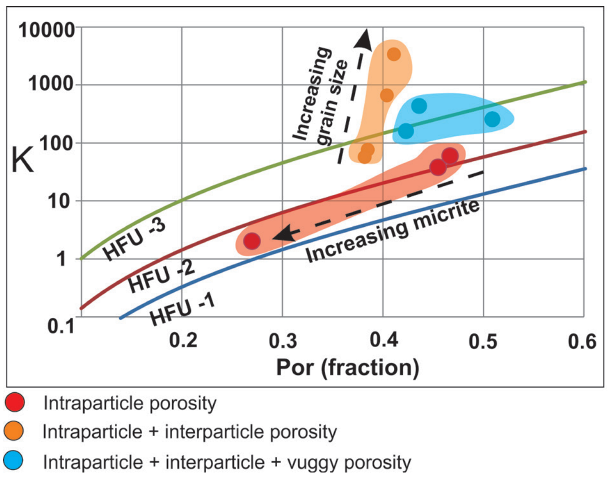

Figure 8. Validation of hydraulic units with petrography description. Increasing micrite will lower the permeability, increasing grain size will raise permeability significantly in the addition of the presence of interparticle porosity, and presence of vuggy porosity will add more porosity and permeability

Bransden, P.J.E., Matthews, S.J., 1992, Structural and Stratigraphic Evolution of the East Java Sea, Indonesia : Proceedings 21st Indonesian Petroleum Association Annual Convention, 21, p. 417-453, Indonesian Petroleum Association, Jakarta, Indonesia.

Lucia, F.J., 1995, Rock-fabric/petrophysical Classification of Carbonate Pore Space for Reservoir Characterization: AAPG Bulletin, v.79, no.9, p.1275-1300.

Lunt, P., 2013, The Sedimentary Geology of Java : Indonesia Petroleum Association, p.224-292.

Lunt, P., 2013, The Sedimentary Geology of Java : Indonesia Petroleum Association, p.224-292.

Peeters, F.J.C., Brummer, G.A., Ganssen, G., 2002, The Effect of Upwelling on The Distribution and Stable Isotope Composition of Globigerina bulloides and lobigerinoides ruber (planktic foraminifera) in Modern Surface Waters of the NW Arabian Sea: Elsevier, Global and Planetary Change 34, p. 269–29.

Sato, K., Oda, M., Chiyonobu, S., Kimoto, K., Domitsu, H., Ingle, J., 2008, Establishment of the western Pacific warm pool during the Pliocene : Evidence from planktic foraminifera, oxygen isotopes, and Mg/Ca ratios : Elsevier, Paleogoegraphy, Paleoclimatology, Paleoecology 265, p.140-147.

Schiller, D.M., Seubert, B.W., Muskiki, S., Abdullah, M., 1994, The Reservoir Potential of Globigerinid Sands in Indonesia : Proceedings 23rd Indonesian Petroleum Association Annual Convention, p. 189-212, Indonesian Petroleum Association, Jakarta, Indonesia.