A fully integrated approach through petrophysical analysis, hydraulic flow units and seismic inversion to map good quality flow unit of globigerina limestone gas reservoir in C field, Madura Straits

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Abstract. The common problem for reservoir characterization usually related to understanding of vertical and lateral heterogeneity of reservoir. Understanding the vertical reservoir heterogeneity generally can be solved based on petrophysical analysis combined with hydraulic flow unit analysis result. HFU’s analysis based on indicator of flow zone which reflect to rock quality that influenced by the mineralogical composition and texture of lithology. Whereas to understand the lateral heterogeneity, generally solve based on the quantitative seismic analysis as results from model based seismic inversion. The purpose of this study is to determine the lateral good flow unit distribution so that the development well placement and targets can be optimized. The petrophysical results obtain 370.5ftMD gross thickness with net pay = 346.0 ftMD, NtG = 93.4 %, Vclay = 6.9 %, Phie = 38.7 %, permeability = 22.6 mD and Sw = 46.6 %. From hydraulic flow units results obtain five flow units with the fifth flow unit has best quality. Characteristics of the fifth flow unit has FZI = 0.727, Vclay = 3.9 %, Phie = 45.1 %, Permeability = 229.6 mD and Sw = 31.1 %, with grainstone as dominant lithology. The good flow units have AI value 3600–4300 gr/cc*m/s and have lateral distribution relatively Northwest–Southeast. Going to the crest of structure, the thickness of good flow unit will be thinner because it is truncated by the fault.

Keywords: Petrophysical analysis, hydraulic flow unit, flow zone indicator, model based inversion

1. Introduction
One of the most widely spread reservoirs in Madura Strait PSC is coming from Mundu–Selorejo sequences. This reservoir is mainly produce biogenic gas, which contain methane more than 96 % [1]. One of the well were drilled in 2012 and success found gas in Globigerina Limestone reservoir. Globigerina Limestone reservoir is bio-elastic carbonate reservoir defined by heterogeneities in reservoir quality and performance due to the highly varied processes that affects the formation of pore.
Reservoir characterization has always been crucial to identified reservoir quality heterogeneity. A successful reservoir characterization estimation effort has three steps which is petrophysical analysis, hydraulic flow units and seismic analysis. Well-log analysis and petrophysical evaluation provides lithology, porosity, clay volume, grain size, water saturation, and permeability as main output. Hydraulic flow units provide the basic input for the generation of different lithology classes. Flow units are illustrated as continuous reservoir zones with high, intermediate, and low values of porosity and permeability with correspondingly lower capillary resistance to fluid flow [2]. Seismic data inverted into elastic attributes and geologic interpretations offer a different scale and spatial coverage of the data. Seismic data is a yield from a forward modelling applying earth reflectivity series, convolved with source signal or wavelet to generate the seismic trace [3]. Seismic inversion is an inverse way to obtain earth layer model that shows the subsurface geological information. Due to seismic trace are bandlimited, so to do seismic inversion need low frequency component to recover and create absolute acoustic impedance [4]. By using seismic inversion result, the lateral distribution of good flow unit could be obtained. Ultimately, we share the lithology unit estimate with the uncertainty related to our prediction. The practical aspects of this workflow are elaborated in the explanation below.

Based on gas geochemistry study, the genetic type of natural gas has been identified in the C Structure area is biogenic gas. The biogenic gases were sourced by the Miocene to Pleistocene Claystone or fine grained which interbedded with reservoir. Regionally, the main reservoir targets for Pliocene plays are the Mundu-Selorejo Sequence (Globigerina Limestone). It consists of bioclastic facies limestone, characterized by the abundance of Globigerina foraminifera. Major porosity types encountered in this sequence are intra-particle porosity within foraminifera shell and inter-particle porosity (between foraminifera). The pelagic shales of the Lidah Sequence act as an effective regional seal for Mundu–Selorejo Sequence (Globigerina Limestone) play [5]. The C Structure is a 4 way-dip closure, cut by normal faults with NE–SW trend. The hydrocarbon charge in the field through methanogenic process was highest in Late Miocene to present with claystone marine shelfal environment (mid - outer neritic). Migration is believed comes from Early-Late Pliocene reservoir. Biogenic gas generation and migration in C Field is interpreted as a constant process, taking place from the time of deposition continuously in Early Pliocene. Its process will stop until source material exhausted or the aerobic methanogenesis temperature threshold (75–80 °C) exceeded or the burial depth reached approximately 3,000 ft. The biogenic gas interpreted migrated laterally through carrier beds from surrounding area which has sufficient TOC (> 0.5 %), might be intra-shale or siltstone of Early-Late Pliocene sediment, charging the reservoir which is believed relatively close to the trapping structure. Detail petroleum system is shown in figure 1 [1].

Core data sets from laboratory results include vertical and horizontal permeability, porosity, grain density, petrography (SEM, XRD and Thin Section), formation resistivity, and capillary pressure. Core permeability analysis applied in this research refers to the horizontal permeability values. Fifty thin sections were picked up from the accurately chosen, representative rock and pore types in the cores to define reservoir facies and genetic pore types from different position [5]. Various rock types study can be identified using permeability - porosity cross plots to create relationship. Facies were categorized by applying the traditional Dunham classification, which underlines the depositional texture: grain supported versus mud supported. Based on Dunham’s classification, the carbonate rock has more diffused clouds indicates the other main parameters as permeability control. High porosity in carbonates can be noticed that does not always cause rise to high permeability. The phenomenon is well known as poor connectivity of the inter-particle and or vugs. However, the clusters of points which represent carbonate classification for each reservoir are not totally distinct from each other [2].

2. Methodology
Reservoir characterization related to understanding of vertical and lateral heterogeneity distribution of reservoir. Understanding the vertical heterogeneity of reservoir generally based on petrophysical
analysis combined with hydraulic flow unit analysis. HFU’s analysis based on indicator of flow zone which reflect to rock quality that influenced by the mineralogical composition and texture of lithology.

Wireline logging is a study of acquiring physical properties of rocks during drilling of a well. The purpose of logging is to obtain petrophysical output such as porosity, permeability, and water saturation. Wireline logs tell about the fluids content in the pores. Petrophysical parameters such as formation water resistivity (Rw), and true resistivity (Rt) are evaluated to produce water saturation (Sw). Petrophysical analysis main objectives are to transform well logs information into reservoir properties such as minerals volumes and fluids content in the invaded and un-invaded zones [2].

Clay volume is the first step to be measured by applying a combination of Gamma ray (GR) and Neutron-density logs. Complex lithology procedure has been used to analyze minerals, porosity and water saturation. Neutron-density log use to estimate porosity and deep resistivity log for water saturation. Analysis of C–I well applied appropriate petrophysical parameters and formula for clastic carbonates and validated with core data.

Based on petrophysical result and core porosity versus core permeability cross-plot, hydraulic flow units (HFUs) research is performed quantitatively. It will provide systematic information about the ability of reservoir to flow the fluid content. HFU analysis technique has been introduced by Amaefule, J.O., and Mehmet Altunbay. (1993) by calculating indicator of flow zone indicator from pore volume to solid volume ratio \( \Phi_z \) and reservoir quality index (RQI) [6]. From FZI values, samples can be classified into different HFUs. Samples with similar FZI value will have same HFU. Each HFU on a log-log cross plot between RQI vs normalized porosity index will result in a straight line with a specific unit slope. The intercept of each unit slope with \( \Phi_z = 1 \), designated as FZI is a unique number for each HFU [7]. Data points that plot along a constant FZI displays an identical flow quality across a wide range of pore-perm values. Therefore, these ratio lines can be applied as a scale to assess and rank petrophysical rock types by quality. The hydraulic flow unit quality is controlled by type of pore geometry as a function of mineralogy (abundance, morphology, type, and location relative to pore throat) and texture (packing, grain shape, grain size, sorting, and packing).

Figure 1. Petroleum system in Madura strait PSC.
Understanding the lateral heterogeneity, generally based on the quantitative seismic analysis as results from model based seismic inversion. To complete this research, several data has been utilized including 3D post stack data. Well quality control of wireline logs data is significant for high quality reservoir characterization, since the well logs data used for well seismic tie, estimation of wavelet, building low frequency model, calibration of seismic velocity, and time to depth conversion [10]. After top and bottom reservoir validity, some seismic horizons then be taken to construct the gas reservoir container and there are several output surfaces that will serve as the input for low frequency modeling. The non-uniqueness issue had been minimized by applying another horizon above top and below base reservoir target [8]. The wavelet also had been analyzed and resumed of which wavelet is the most appropriate. The limitedness of seismic bandwidth, particularly at the low frequency content, made the impedance model contained the relative value of P-impedance. To apply the geological trend into the final model, it is required to apply the low frequency modeling as an initial model during the inversion process [9].

3. Results and discussion

3.1. Petrophysical result
Total one well have complete quad combo conventional log responses such as gamma ray, resistivity, neutron, density, compressional and shear velocity. After loading and checking of all wireline logs data, it was observed that most of the wireline logs are aligned in depth, so does not need any depth shift. The effects of tool position, tension, current fluctuation, cycle skipping, have been understood by carefully. The corrected and conditioned wireline logs data must be assured with quality control methods. Therefore, in this study, several cross-plots have been used to quality control of the conditioned data as shown in figure 2. Final petrophysical output of C-1 well are shown in figure 3.

![Figure 2](image-url)
Figure 2. Wireline crossplots, (a) Neutron vs Density, (b) Deep resistivity vs Density, (c) Deep resistivity vs Compressional velocity, (d) Pickett plot, and (e) Core porosity vs Density.
The petrophysical results obtain 370.5 ft gross thickness with net pay = 346.0 ft MD, NtG = 93.4 %, Vclay = 6.9 %, Phie = 38.7 %, permeability = 22.6 mD and Sw = 46.6 %.

3.2. Hydraulic flow units
From the geological and petrophysical aspect, HFU analysis in Globigerina Limestone reservoir was carried out. The HFU analysis results were used to identify reservoir quality in the reservoir. Each rock type is identified as unique of rock which consist pore geometry, composition of mineralogical and is corresponded to a particular specific fluid-flow characteristics. The first step by applied porosity permeability cross plot from routine core analysis to classify each reservoir rock type. Then, each rock type classification compared with visual porosity and rock fabric character from microscopic studies. For mineralogical and textural characteristics of each unit determined from petrographic data (XRD, thin section photography and SEM). Capillary Pressure from air brine (ABCP) or High Pressure Mercury Injection (HPMI) analysis was run to confirm each rock type. Capillary pressure curves behavior will represent the information from thin sections and SEM. However, in this study five flow units was identified (HFU1 to HFU5) with specific mineralogy, pore geometries, and fluid-flow characteristics as shown in figure 4. HFU5 is the best rock quality with characteristic has FZI = 0.727, Vclay = 3.9 %, Phie = 45.1 %, Permeability = 229.6 mD and Sw = 31.1 %, with grainstone as dominant lithology.

3.3. Model based inversion
Inversion analysis is required to confirm how good the correlation of the final model will be when placed side by side against the original well log. This implies that the inversion parameter is quite good and enabled to continue to the inversion process. Best straight line that match in P-impedance cross plot is the key to obtain a reliable final model based seismic inversion result. Applying some horizons as lateral guidance enabled the impedance model to be more acceptable geologically.
In the case of seismic inversion resolution, the layer thickness is typically within ¼ of the wavelength. This implies that the velocity and density assumed within each layer reflect an absolute value within the effective media. The seismic accuracy inversion can be integrated using the well log data by deriving an error filter that will conform to the expected accuracy of the seismic data. As shown in figure 5, the good flow units have AI value 3600–4300 gr/cc*m/s and have lateral distribution relatively Northwest - Southeast. Going to the crest of structure, the thickness of good flow unit will be thinner because it is truncated by the fault.

Figure 4. Hydraulic flow unit result and good flow unit will be mapped.

Figure 5. Flow units distribution as model based inversion result.
4. Conclusion
A detailed petrophysical analysis has been carried out for reservoir characterization of Globigerina Limestone reservoir and the results obtain 370.5 ftMD gross thickness with net pay = 346.0 ftMD, NtG = 93.4 %, Vclay = 6.9 %, Phie = 38.7 %, permeability = 22.6 mD and Sw = 46.6 %.

The determination of reservoir rock type in an un-cored interval will have high uncertainty. To reduce the uncertainty of rock-type analysis the integration of core, conventional open-hole logs and geological data was done in a wise. Total five HFUs and fifth HFU (HFU#5) is the best reservoir quality which has characteristic of FZI = 0.727, Vclay = 3.9 %, Phie = 45.1 %, Permeability = 229.6 mD and Sw = 31.1 %, with grainstone as dominant lithology.

The good flow unit form 3967–4000 ftMD, has P-Impedance value 3600–4300 gr/cc*m/s and have lateral distribution relatively Northwest - Southeast. Going to the crest of structure, the thickness of good flow unit will be thinner because it is truncated by the fault.

Acknowledgments
The author would like to thank Husky-CNOOC Madura Ltd. for permission and support to publish data and analysis result. The author would also like to thank Universitas Indonesia for the research funding by the PIT 9 Research Grant with the contract number NKB-0017/UN2.R3.1/HKP.05.00/2019.

References
[1] Saputra R 2013 Seismic Trace Analysis on Bright Spot Feature in Relation to Direct Hydrocarbon Indicator and Gas Saturation in the Globigerina Formation, Madura Strait, East Java Basin (Jakarta: Universitas Indonesia)
[2] Donaldson E and Tiab D 2004 Petrophysics Second Edition Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties (United States: Gulf Professional Publishing)
[3] Cooke D and Cant J 2010 CSEG Recorder 35, available at https://csegrecorder.com/articles/view/model-based-seismic-inversion-comparing-deterministic-and-probabilistic
[4] Russell B H 1988 Introduction to Seismic Inversion Methods (United States: Society of Exploration Geophysicists)
[5] Amaefule J O Altunbay M Tiab D Kersey D G and Keelan D K 1993 Enhanced Reservoir Description: Using Core and Log Data to Identify Hydraulic (Flow) Units and Predict Permeability in Uncored Intervals/Wells (Texas: Society of Petroleum Engineers)
[6] Chekani M and Kharrat R 2012 Petrol. Sci. Technol. 30 1468-85
[7] Sukmono S 2000 Seismik Inversi untuk Karakterisasi Reservoir (Bandung: Department of Geophysics Engineering, Institut Teknologi Bandung)
[8] Sukmono S 2002 Seismic Inversion and AVO Analysis for Reservoir Characterization (Bandung: Department of Geophysics Engineering, Institut Teknologi Bandung)
[9] Simmons J L and Backus M M 1996 Geophysics 61 1575-948