Porosity Creation of the Baturaja Formation by Meteoric and Burial Diagenesis: Study Case in Northwest Java Basin, Indonesia
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Abstract
Porosity in carbonate rocks is mostly diagenetic in origin which adds complexity in classifying and quantifying porosity system. Pore type distribution, characterization and analysis allow for more detailed reservoir models for optimum production of the mature oil field. This is also the case for the Early Miocene Baturaja Formation in Melandong area, onshore Northwest Java Basin, Indonesia. The Melandong area is a part of a series of half-grabens bounded by north-south trend of deep seated normal faults formed in the Eocene-Oligocene that was later re-activated in the Late Miocene-Pliocene. In the Early Miocene, the Baturaja Formation was deposited displaying slightly thinning in the inter-mounds depositional area but shows thicker strata characterizing a shallower carbonate mound, on the Pamanukan High.

Aims of the study are to characterize different types of porosity and propose its origin for the Baturaja Formation. Porosity in the formation was dominated by moldic and vuggy that were previously interpreted as meteoric-derived through the dissolution of aragonitic skeletal grains and lime muds. Detailed petrography, including micro-image analysis, combined with stable isotope geochemistry and trace element analysis to determine the diagenetic processes of the Baturaja Formation are used. Three-dimensional pre-stack time migration (PSTM) seismic data, well-logs, and samples from conventional and side-wall cores from seven wells were used. In addition, we constructed a diagenetic model to identify the spatial and temporal influence of these processes that created the diagenetic history. Two possible scenarios of the origin of this dominant dissolution porosity in the Baturaja Formation: 1) meteoric dissolution and 2) burial dissolution based on CO2 degassing. The dissolution processes creating porosity for the red algal-large benthic foraminiferal rich facies of packstone-grainstone in the middle ramp setting. In addition, areas adjacent to major deep-seated faults are proposed to have more porosity created by burial acidic gases. Interpreting and understanding of the diagenetic processes are essential to describe and predict pore heterogeneity trends for hydrocarbon exploration and production. Pore type distribution, characterization, and analysis, shown by this study, allow for a more detailed reservoir models for optimum production and development phases of the mature oil field.

Keywords: Baturaja Formation, Diagenesis, Meteoric, Burial Diagenesis.

Introduction
Carbonate rocks are formed mainly from biochemical and biological process in primarily marine environments and they are prone to rapid diagenetic alteration that can change their mineralogy pore type and pore size. Porosity in carbonate rocks is mostly diagenetic in origin which adds complexity in classifying and quantifying porosity system (Choquette and Pray, 1970; Tucker and Wright 1990). Interpreting and understanding of the diagenetic processes are essential to describe and predict pore heterogeneity trends for hydrocarbon exploration and production (Longman, 1980). Pore type distribution, characterization and analysis allow for a more detailed reservoir models for optimum production and development phases of the mature oil field. This is the case for the Early Miocene Baturaja Formation, one of the main reservoirs in the NW Java Basin, Indonesia. This carbonate succession can be divided into lower, middle shale, and upper members in the study area.

Melandong field (Figure 1) is indicted by the extensive moldic pores forming fabric-selective dissolution texture within the mound area developed on paleotopographic high. In addition, burial dissolution processes could be applied to the moldic and vuggy pores i.e. by deeply originating aggressive fluids (Choquette and James, 1987; Machel, 2005; Shen et al., 20016). Such stylolite enlargement partly filled by calcite cements is an evidence for the burial dissolution processes by mantle- and magmatic-derived CO2. Deep-seated faults in the Melandong area were the likely updip pathways for the delivery of this acidic gas.

There could be two possible scenarios of the origin of this dominant dissolution porosity in the Baturaja Formation: 1) meteoric dissolution or 2) burial dissolution based on CO2 degassing originated in the mantle and moving upwards through deep-seated faults. The deeper inter-mound areas adjacent to major deep-seated faults is likely contain reservoirs with abundant burial dissolution-derived porosity. The dissolution processes leached the red algal-large
benthic foraminiferal (LBF) rich facies of packstone-grainstone in the middle ramp setting. In addition, areas adjacent to major deep-seated faults are proposed to have more porosity created by mantle-derived acidic gases to dissolve the rock and create secondary porosity.

Data and Method
Petrography was used combined with inorganic geochemistry in addition to three-dimensional PSTM seismic, core, and well log interpretations to determine the diagenetic processes of the Baturaja. In addition, we constructed a diagenetic model of the Baturaja Formation to identify the spatial and temporal influence of these processes that created this diagenetic history. These new ideas of the origin of the porosity in the Baturaja Formation may have implications on play concepts and prospect evaluation for hydrocarbon exploration in other Early Miocene carbonate sections.

Result and Discussion
We described six facies in the Baturaja Formation (Figure 2): coral floatstone-rudstone (CFR); rhodoid-LBF floatstone-rudstone (RFR); rhodoid/red algal-LBF packstone-grainstone (RPG); red algal-LBF mudstone-wackestone (RLW); very fine glauconitic quartz sandstone (GQS); and shale (SHL). Dolomite occurs as a minor portion (observed in less than 2%) of the succession, occurring primarily in partially dolomitized samples of mudstone-wackestone of RLW facies.

The predominant porosity types for the succession are moldic (or biomoldic) and vuggy porosity in 74% of samples (Figure 3). Intraskeletal, interparticle, intercrystalline, microporosity, fracture and enlarged stylolite porosities are minor to rare. Total porosity of the Baturaja Formation from the image analysis shows 0.2 to 44.8% with an average of 12.5%. Extensive moldic and vuggy porosity occurs in CFR, RFR, RPG, and RLW facies from the B-1, P-1, C-1, J-2, and K-1 wells (Figures 5, 6).

A series of diagenetic events in a paragenetic sequence (Figure 4) was identified that define diagenetic environments and the evolution of the porosity in the Oligocene-Miocene succession through time. This paragenetic sequence was created to help identifying porosity creation stages. The earliest stage of diagenesis occurred shortly after the deposition of the succession and is characterized by marine cementation–micritization. These processes were followed by early meteoric diagenesis in vadose and phreatic realms. Sea-level fluctuations were clearly significant in the early stages of diagenesis especially in upper part of the succession and at the crest of the mounds. In contrast, the late-stage diagenesis is thought to have occurred in the burial diagenetic settings. These burial diagenetic events resulted in compaction, fracturing, pressure solution, burial dissolution, calcite cementation, and silification.

The Baturaja Formation has a quite simple burial history that after deposition, this succession was buried to the burial diagenetic setting after its deposition to Recent. Consequently, there are two possible scenarios of the origin of the moldic and vuggy dissolution porosity in the Baturaja Formation (Figure 7): 1) dissolution in meteoric setting or 2) burial dissolution based on CO2 degassing from mantle through deep-seated fault conduits.

In spite of this meteoric evidence there were variations of CO2 content in gas production: 92% from B-1 production data at the mound area and 80% and 16% for S-1 and J-2 wells within the inter-mound areas. High CO2 abundance could be related to several sources, including decomposition of organic material from biogenic processes, thermal breakdown of kerogen, mantle degassing, and metamorphic mineral reactions (Dai et al., 1996; Cooper et al., 1997; Noble et al., 1997). Data from a nearby well (PMK-2 with ~100% CO2) at the Pamanukan High, located less than 3 km from our study area, has a mantle source of CO2 from 3He/4He analysis (Cooper et al., 1997) and can be an analog to our data. Additionally, the position of the wells in the Melandong area is adjacent to deep-seated basement-involved faults (B-1 and J-2 wells) and magmatic intrusion-related faults (S-1 well) that could be correlated to a mantle- and magmatic-degassing interpretation. Additionally, radial faults around the S-1 well might be supplementary conduits for CO2 gas expulsion from the magmatic intrusions and contribute to diagenetic fluids. The CO2 gas likely affected carbonate sequences and significantly decreased the pH of diagenetic fluids and made corrosive brines that promoted the burial dissolution to create and expand pores. The dissolution in this burial setting likely result in non-fabric selective dissolution textures. The very similar products of moldic and vuggy porosity might be produced by two distinctive processes of burial and meteoric dissolutions.

Conclusions
The Baturaja Formation has mixed porosity (moldic and vuggy) that was created by two main episodes: meteoric and burial processes, based on the following points:

1. Paragenesis for the Baturaja Formation succession in NW Java Basin, Indonesia shows marine diagenetic processes that were followed by occasional subaerial exposure events to meteoric
settings. Rapid changes of diagenetic environments for these early events were clearly significant for the porosity creation, especially at the vadose meteoric zone. The late-stage burial diagenesis resulted in significant burial dissolution.

2. Porosity types are dominated by moldic and vuggy secondary porosity. More abundant moldic pores in the carbonate mound area are related to the fabric-selective meteoric dissolution of ellipsoidal shaped of perforated LBF and red algae whereas slightly equal portions of moldic and vuggy pores occurred in the inter-mound area related to non-fabric selective burial dissolution.

3. The Baturaja Formation has prolific hydrocarbon reservoirs where its porosity system was widely interpreted previously by strong meteoric-dissolution events. Occasional meteoric exposures of the succession, for both lower and upper members, are indicated by the extensive dissolution of moldic and vuggy pores, within the mound area. In the deeper inter-mound areas, burial dissolution might dominate porosity creation by dissolution of the rock volume by mantle-derived CO2.

4. The burial dissolution model emerges as an inter-mound exploration concept focusses on the muddy middle ramp setting. An area with the deep-rooted faults has a larger probability to have mantle-derived CO2 to dissolve the rock and create secondary moldic and vuggy pore spaces.

References
Cooper et al., 1997

Figure 1. a. An Indonesian map showing structural features (subduction zones, strike-slip faults) and the Sundaland block as southeastern promontory of the Eurasian Plate. Shaded relief map, coastal line and country boundaries were taken from the GeoMapApp (http://www.geomapapp.org). Structural features were modified from Hall (2002). b. The Melandong field is located at the NW Java area, a prolific hydrocarbon basin. c. A basemap of 3D seismic (red rectangle) and wells data from the Melandong field.


Figure 3. a. Moldic porosity (red arrows) is likely produced by fabric-selective meteoric dissolution. Sample from B-1. b. Vuggy porosity (red arrows) from J-2. c. Similar vuggy porosity (red arrows) that cross-cut partially leached skeletals and calcite cements. Sample is from K-1 well. Burial dissolution by CO2 was likely responsible for producing non-fabric selective pores in b and c.

Figure 4. Schematic paragenesis of the Baturaja Formation. Diagenetic events for the succession can be classified to early and late diagenesis. Marine and meteoric diagenesis are categorized as early events whereas burial diagenesis is late process.
Figure 5. Traverse seismic section through the wells. Relatively N-S growth and normal faults are shown that evolved to strike-slip faults with distinctive flower structure. Possible magmatic intrusion or uplifted fault block is identified based on the positive intruded morphology beneath S-1 well. CPN sub-basin is located at the inter-mounds deeper depositional area. Zoom in cross-section in the red box is shown for the Figure 2.7. Red arrows point to downlapping reflectors. PMK: Pamanukan, CPN: Cipunegara, KDH: Kandanghaur, BSMT: basement, VJTB: Jatibarang Formation, TAF: Talang Akar Formation, BRF: Baturaja Formation, MFS: Maximum Flooding Surface, UCBL: Upper Cibilakan Formation, PRG: Parigi Formation, CSB: Cisubuh Formation, div: divergent reflectors.

Figure 6: a. Well-to-well correlation of B-1, J-2, and K-1 to show physical (GR and effective porosity/PHIE) and geochemical (stable isotopes and trace elements) properties within two different morphologies: carbonate mound and inter-mound areas. Normal faults are shown to indicate structural control to the rock properties. B. Vuggy and moldic distribution for the three wells based on the roundness of the pore geometry. The B-1 well shows domination of moldic pore type while J-2 and K-1 wells have slightly similar distribution of moldic and vuggy porosity.
Figure 7: Amplitude slice map created by 0 to 10 ms window below the top Baturaja Formation horizon showing possible porosity distribution in the study area. Green polygon shows the direction of 3D model in b. b. Vertical conduit model for mantle- and magmatic-derived CO2 affecting this deep buried succession. Moldic and vuggy porosity was created by the dissolution of the rock volume by this acidic gas.