Jurnal Geologi dan Sumberdaya Mineral Vol. 23 No. 3 Agustus 2022 hal. 189-196

Geo-Science

Jurnal Geologi dan Sumberdaya Mineral
Journal of Geology and Mineral Resources
Center for Geological Survey, Geological Agency, Ministry of Energy and Mineral Resources
Journal homepage: http://jgsm.geologi.esdm.go.id
ISSN 0853 - 9634, e-ISSN 2549 - 4759

Depositional Facies Model and Reservoir Quality of Paleogene Limestone in Labengki Island, Southeast Sulawesi

Model Fasies Pengendapan dan Mutu Reservoir Batugamping Paleogen di Pulau Labengki, Sulawesi Tenggara

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Naskah diterima: 20 Mei 2020, Revisi terakhir: 26 Agustus 2022, Disetujui: 31 Agustus 2022, Online: 31 Agustus 2022
DOI: http://dx.doi.org/10.33332/jgsm.geologi.v23.3.189-196

Abstract - Eastern Indonesia has become an attractive venture for hydrocarbon exploration since 10 years ago. The discovery of hydrocarbon from Miocene carbonate of Tondo Formation has opened a new opportunity and hopes in the Southeast Sulawesi region. Can we find other potential reservoirs in Southeast Sulawesi? In this study, we assess and reconstruct the depositional model and the reservoir quality of the Paleogene Tampakura Formation in Labengki Island, Southeast Sulawesi. This field observation and petrographical study revealed that: (1) Tampakura Formation comprises mainly of grainstone, boundstone and floatstone with minor packstone and dolomitic wackestone/mudstone, (2) Tampakura Formation was deposited mainly in wide carbonate sand shoals and reef margin belt of rimmed carbonate shelf, (3) Boundstone and floatstone facies could be the best reservoir candidate in the region since they show extensive porosities development of cavernous and fracture porosity, (4) Dolomite cementation has deteriorated the reservoir quality of packstone which was deposited in platform interior-restricted marine, (5) Extensive calcite cementation in grainstone facies has reduced the reservoir quality of Tampakura Formation. However, locally, solution enlarged fracture porosity may have enhanced it. We suggest that post collision event of Late Oligocene - Early Miocene between Australian-originated microcontinent and ophiolite complex was highly responsible to create cavernous porosity. The collision resulted in the folding and uplifting of Tampakura Formation to the subaerial exposure. The carbonate strata were exposed to the surface developing a cavernous porosity and potentially becoming the best reservoir candidate for the next exploration target.

Keywords: Carbonate facies, Kendari Basin, reservoir quality, Tampakura Formation.

***Abstrak** - Wilayah Indonesia timur dalam sepuluh tahun belakangan telah menjadi target baru yang menarik dalam eksplorasi hidrokarbon. Penemuan hidrokarbon di batugamping Formasi Tondo berumur Miosen telah membuka sebuah kesempatan baru dan harapan di kawasan Sulawesi Tenggara. Dapatkah kita menemukan potensi reservoir lainnya di Sulawesi Tenggara? Pada studi ini, kami akan menganalisis dan mengkonstruksi model pengendapan karbonat dan kualitas reservoir Formasi Tampakura berumur Paleogen di Pulau Labengki, Sulawesi Tenggara. Pengamatan lapangan dan analisis petrografi memberikan beberapa kesimpulan, yaitu: (1) Formasi Tampakura utamanya terdiri dari grainstone, boundstone dan floatstone dengan sedikit packestone dan dolomitic wackestone/mudstone, (2) Formasi Tampakura diendapkan pada paparan karbonat dengan beting pasir karbonat dan terumbu yang lebar, (3) Fasies Boundstone dan Floatstone memperlihatkan kualitas reservoir terbaik ditandai dengan pembentukan porositas rekahan dan porositas gua, (4) Sementasi dolomit memperburuk kualitas reservoir pada fasies packstone yang terendapkan pada platform interior-restricted marine, (5) Sementasi kalsit yang ekstensif menurunkan kualitas reservoir pada fasies grainstone. Meskipun demikian di beberapa tempat, solution enlarged fracture meningkatkan porositas pada grainstone. Kami mengusulkan bahwa tumbukan yang terjadi pada Akhir Oligosen hingga Awal Miosen berpengaruh besar terhadap pembentukan porositas gua/karst sebab even tektonik tersebut melipat dan mengangkat formasi tampakura ke darat/subaerial. Perlapisan karbonat yang tersingkap ini membentuk porositas gua (cavernous porosity) dan menjadikan Batugamping Tampakura potensial untuk target eksplorasi selanjutnya.*

***Katakunci:** Fasies karbonat, Cekungan Kendari, mutu reservoir, Formasi Tampakura.*

INTRODUCTION

The increasing demand on oil production in Indonesia has shifted the conventional hydrocarbon exploration from mature fields on western Indonesia to the frontier fields in eastern Indonesia. Satyana (2017) listed several oil and gas fields in Eastern Indonesia which have produced hydrocarbon, for instance Flamingo, Evans Shoal, Wiriagar deep field in Bintuni Basin. He argued that many proven petroleum systems in the eastern Indonesia region has been associated with the drifting and collision of Mesozoic Australian passive margin sediments with other terrain in Cretaceous and Paleogene.

Tampakura Formation is Paleogene limestone which was deposited in Kendari Basin, Southeast Sulawesi. The geology of Southeast Sulawesi has been studied by many authors (e.g. Rusmana *et al.*, 1993; Surono 1994, 1997; Panggabean & Surono, 2011; Surono, 2013) and yet no publication emphasized on paleogene carbonate of Tampakura Formation.

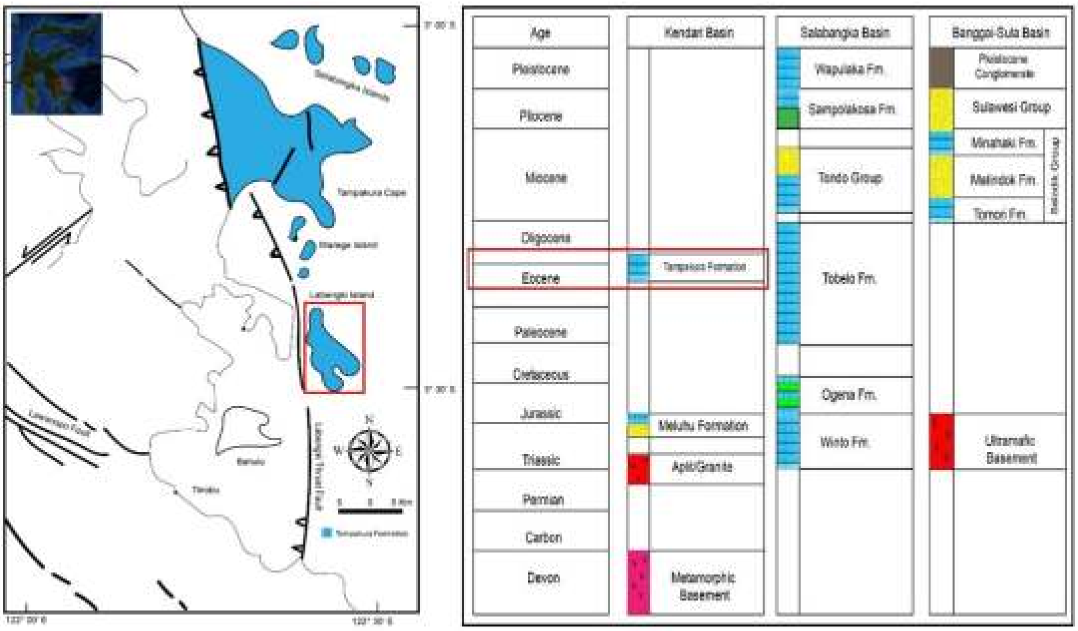
In this paper we examine and reconstruct the carbonate depositional model of Tampakura Formation in Labengki Island, Southeast Sulawesi. The reservoir quality will be discussed to determine which facies can be the best reservoir candidate for the exploration target in the region.

GEOLOGICAL SETTING

Labengki Island is located in Southeast Sulawesi (Figure 1a). Sulawesi region is a complex triple junction plate convergence between Indian-Australian, Pacific and Eurasian plates which represents the most complex tectonic setting in Indonesia.

Sulawesi can be divided into three geological provinces: (1) the Western volcanic arc province; (2) the eastern ophiolite complex province and (3) Australian-originated microcontinental fragments province (Martosuwito, 2012). Two main geological provinces cover the Southeast Sulawesi: the eastern ophiolite complex and the microcontinental fragment. The Eastern ophiolite complex comprises of lherzolite, harzburgite, dunite, wehrlite, gabbro, serpentinite and pelagic sediment of Matano Formation (Surono, 1997). Mubroto (1998) suggested that the formation of this ophiolite complex is in Late Cretaceous age which later underwent 60° clockwise rotation.

The ophiolite was formed in both mid- oceanic ridge and oceanic plateau which might be originated from the Pacific Plate (Kadarusman *et al.*, 2004). The ophiolite complex provinces overthrusted the Australian-originated microcontinent fragment. This Australian-originated microcontinental fragments comprises metamorphic basement (with local granitic intrusion), siliciclastic and carbonate rocks.



source:modified from Indonesian Basin Summaries (2006); Surono (2013).

Figure 1. Distribution of Tampakura Formation and major structures in the Southeast Sulawesi (modified from Surono, 2013). Location map of the study area is shown in the red box (b) Regional stratigraphy diagram of Kendari Basin and its adjacent basin.

Kendari Basin comprises metamorphic basement, Triassic-Permian intrusive granite, Meluhu Formation and Tampakura Formation (Figure 1b). The basement rocks of Southeast Sulawesi continental terrane is metamorphic rock and locally found granitic intrusion. This metamorphic rock is unconformably overlain by Late Triassic Meluhu Formation. Meluhu Formation can be divided into three members which are Toronipa Member (sandstone dominated), Watutalaboto Member (mudstone dominated) and Tuetue Member (intercalation of sandstone and limestone). Meluhu Formation is overlain by Tampakura Formation. The contact between these two Formations is unconformable. Tampakura Formation was formed in Eocene-Early Oligocene. This formation dominated by carbonate rocks which deposited in a rimmed shelf. (Martosuwito, 2012). The formation comprises wackestone, packstone, grainstone with minor framestone. Locally, the carbonate sequence is intercalated with siliciclastic mudstone.

SAMPLES AND METHODS

The reconstruction of carbonate depositional model in this paper was based on petrography analysis of thin sections and field study. The carbonate rocks classification used is based on Dunham (1962) classification with a modification of Embry & Klovan (1971). Outcrop description and measurement were taken in several location in Labengki Island. Ten samples were picked in different outcrops and later were analyzed using optical petrography microscope.

Microfacies of each sample were analyzed and described for type of grains (skeletal/non skeletal), grain size, sorting, porosity type (if any), dolomite content and/or other minerals based on Flugel (2004). Carbonate depositional conceptual model of Tampakura Formation was constructed based on this microfacies association.

RESULT AND ANALYSIS

Outcrop Observations

Tampakura Formation are characterized by grainstone, floatstone, boundstone with minor packstone and dolomitic wackestone/mudstone. Ooidal grainstone occurs as well-bedded strata and commonly shows cross-bedding structure (Figure 2a). These are common in western and northern part of the island. High dolomitization index can be found specifically in the muddy limestone (Figure 2b) in the southern part of the island. However, some boundstone were partly dolomitized with variable degree of dolomitization. Locally, chert (Figure 2c) were found abundant in the western part of Labengki Island. Laminated stromatolite boundstone distributed mainly in the southern and western part of the Island (Figure 2d).

Wackestone and mudstone are common in the southern part of the Labengki Island. They intercalate with thinly bedded packstone and sometimes grainstones. Porosity types which can be observed in the outcrop are as moldic porosity, solution enlarged fracture porosity, cavernous porosity and fracture porosity.

Moldic pores are more common in packstone (Figure 3a). Bivalves or brachiopod shells may have been dissolved and leaving the moldic pores empty. Most mega pore spaces in Tampakura Formation are related to the touching vugs porosity. Solution-enlarged fracture porosity (Figure 3b) developed locally in grainstone facies, whereas cavernous and fracture porosity were mainly observed in floatstone and boundstone facies (Figure 3c and 3d). Fracture filling minerals are absent in most cases.

Red-bedded limestone were found locally intercalated with boundstone facies. These red bedded limestones may indicate that iron-rich limestones bedded were oxidized during subaerial exposure of the limestone. The occurrence of red bedded limestone along with cavernous porosity of the boundstone corroborate the notion of subaerial exposure of Tampakura Formation.

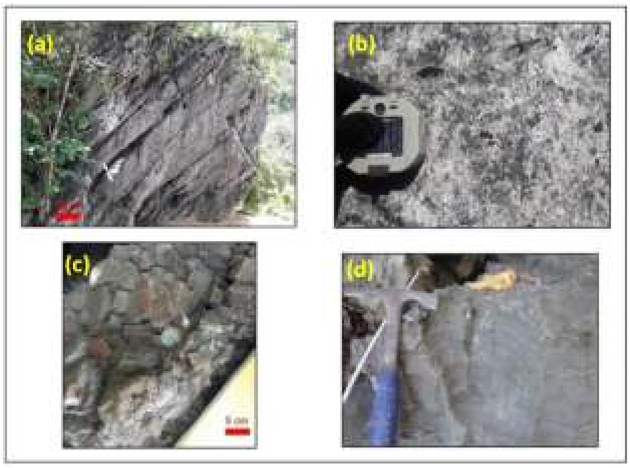


Figure 2. Field photographs showing: **(a)** Cross-bedding in grainstone facies. These beds thickness ranged from 0.5-1.5 meters. **(b)** Close-up view of coarse dolomite crystal. **(c)** Cherty limestone in the western part of Labengki Island **(d)** Laminated stromatolite in boundstone showing laterally-linked hemispheroid.

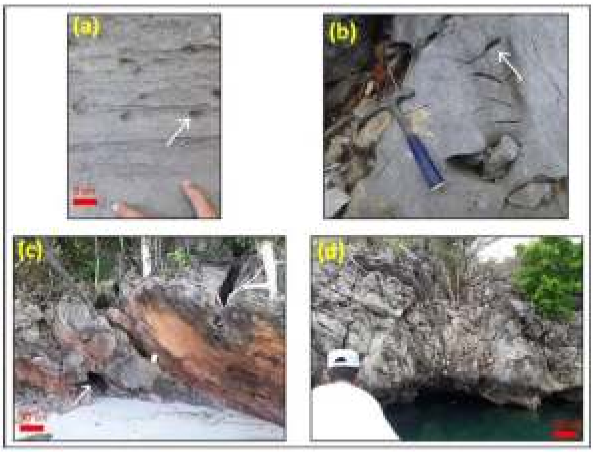


Figure 3. Field photographs showing **(a)** Close up view of moldic porosity in packstone facies. Note that dissolution of grains leaving non-touching vugs empty. **(b)** Solution enlarged fracture in ooidal grainstone. **(c)** Cavernous porosity developed in boundstone facies. Reddish bed probably indicating oxidation after the carbonate exposed to the surface. **(d)** Highly fractured zone in boundstone facies. Note that the fracture occurred along with cavernous porosity.

Petrography

Limestone of Tampakura Formation can be divided into 6 microfacies. Parameters and trends of each microfacies were specifically shown in Figure 5.

Dolomitic Packstone (LF-1)

This microfacies is commonly distributed in the southern part of the Labengki Island which are characterized by abundant dolomite matrix with minor quantity of milliolid, gastropod and brachiopod. Dolomitization has obscured many of skeletal grains (Figure 4a). Dolomite crystals act as replacement of carbonate mud. Dolomites shape are euhedral-subhedral rhombic with crystal size ranged from 60-100 µm. In Flugel (2004), this microfacies is classified as SMF-3.

The presence of milliolid in carbonate may indicate a low energy environment (Zieglar, 2001; Deville de Periere et al., 2017). Additionally, the carbonate mud had been replaced mostly by the dolomite, thus it was interpreted that this facies was deposited below fair weather wave base (FWWB) in the low energy environment which later diagenetically replaced with rhombic dolomite. Low to moderate fauna diversity may indicate a semi- restricted environment, probably relatively intermediate salinity. Therefore, we interpret this facies was deposited in platform interior – lagoon, restricted marine (Flugel's Standard Facies Zone 8)

Bioclastic Floatstone (LF-2)

This facies comprises of whole fossil, unbroken shell of brachiopod, planktonic foraminifera and peloid with minor echinoid (Figure 4b). The matrix of this facies is wackestone. Dolomite content on this facies is only 5%.Grains are poorly sorted with grain size ranged from silt to very coarse sand. Fracture index is low. This facies belongs to SMF-8 based on Flugel Standard Microfacies Model (2004). We interpret that the floatstone was deposited in Platform Interior-Open Marine (Flugel's Standard Facies Zone 7)

Pelloidal-Algal Floatstone (LF-3)

The grains are dominated by calcareous algae fragment, coral and peloids with minor benthic foraminifera and brachiopod. Laminated stromatolite boundstone (Figure 4c) occasionally found in this facies. The matrix of this facies is packstone. No dolomite found in this facies. Grains are poorly sorted with grain size ranged from silt to medium sand. Fracture index is moderate and they are partly filled with calcite. This facies is classified as SMF-8 which is interpreted to be deposited in platform interior - open marine (Flugel's Standard Facies Zone 7).

Dolomitic Coral Boundstone (LF-4)

The main constituent grains of this facies are corals and calcareous algae and minor quantity of echinoid, bivalve and peloids (Figure 4d). Broken bivalve fragments may indicate a high energy energy environment where wave/current controls the deposition. The presence of tabulate corals indicate a shallow marine within photic zone (Scholle and Scholle, 2003). Dolomite content on this facies is very high that can range from 60-90 %.

Fine dolomites are very common with perfect rhombic shape. Grains are well sorted and the fracture index of this facies ranged from low to medium. Blocky calcite minerals filled the fracture. This facies are classified as SMF-7. We interpret this facies deposited in reef margin complex (Flugel's Standard Facies Zone 5).

Ooidal Grainstone (LF-5)

Grainstone facies is dominated by ooids and intraclast (Figure 4e) with minor quantity of gastropod, echinoid, bivalve and benthic foraminifera. Grains are moderately sorted with size ranged from medium to coarse sand. Fractures are very common and may often cross cut each other. Blocky calcite cements partly filled the fracture. This microfacies is classified as SMF-15C.

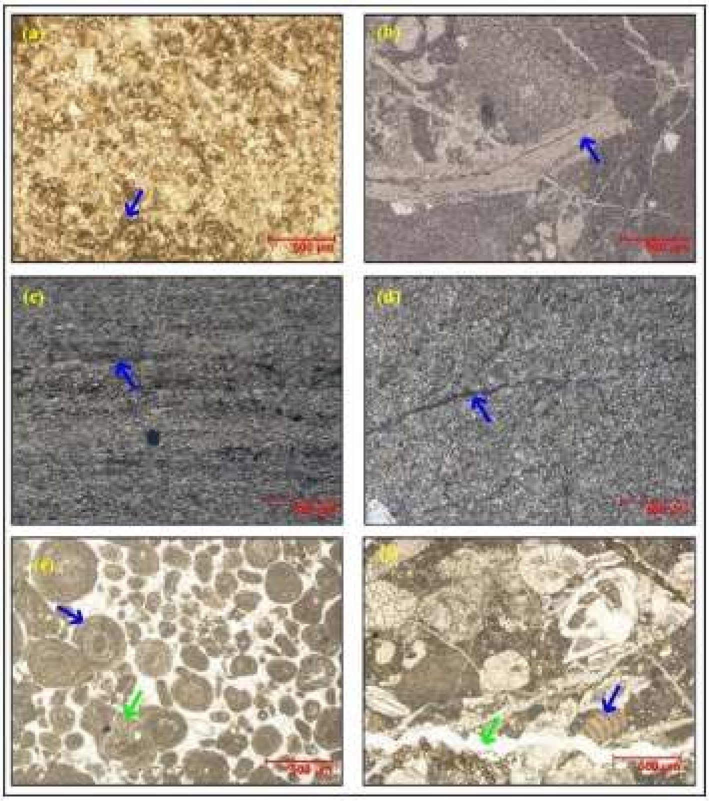


Figure 4. Optical micrographs showing: **(a)** Fine to medium dolomite crystals in LF-1. These dolomites replaced the carbonate mud. **(b)** Large bivalve in Floatstone of LF-2. Benthic foraminifera and gastropods floating in mud matrix. **(c)** Laminated stromatolite in Boundstone of LF-3. These microbes trapped mud and other skeletal grains. **(d)** Dolomitic Boundstone of LF-4. Note that wispy seams (blue arrow) filled with carbonate mud. **(e)** Ooid grain (blue arrow) and intraclast grain (green arrow) in grainstone of LF-5. Some ooid grains are deformed suggesting mechanical compactional. **(f)** Red algae (blue arrow) and jagged stylolite (green arrow) in packstone of LF-6. Some benthic forams also occurred in this facies.

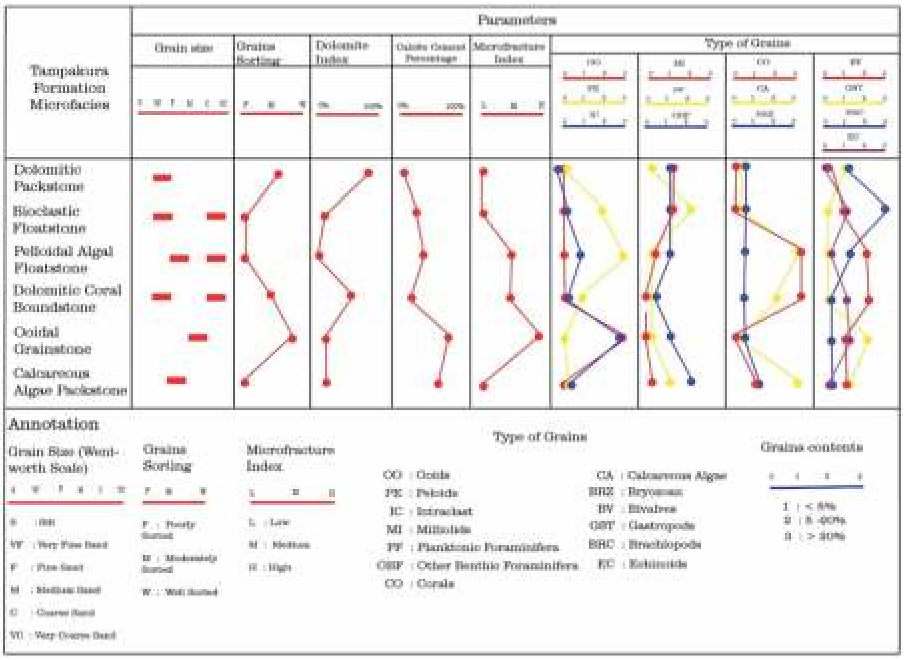


Figure 5. Line charts showing parameters and trends which were used to characterize and analyze each microfacies of Tampakura Formation.

The grainstones are interpreted to be deposited in high energy environment, which was indicated by the absence of lime mud, typically in the shoal/beach-barrier island complex (Flugel's Standard Facies Zone 6). This interpretation is also supported by the absence of bioturbation feature. In high energy environment, bioturbation may not be well developed due the wave/current activity.

Calcareous Algae Packstone (LF-6)

This facies is distributed massively in the northern Labengki Island along with Coral Boundstone Facies. This facies is characterized by abundant calcareous algae and benthic foraminifera with minor broken shell of corals fragments, bryozoan, gastropods and bivalve (Figure 4f). The grains are moderately sorted with grains size ranged from fine to medium sand. Fracture index is very low. Dolomites are absent, if presents, the quantity would not be greater than 2 %. This microfacies is classified as SMF-4 based on Flugel's Classification (2004).

Considering high diversity of fauna assemblage, this facies may have been deposited in nutrient rich environment with an open circulation. Additionally, the presence of red algae may imply the salinity of the water ranges from 33-42 ppt (low salinity environment). Branching red algae may indicate a moderate energy environment (Scholle & scholle, 2003). We interpret this facies to have been deposited in platform Slope (Flugel's Standard Facies Zone). 4)

DISCUSSION

This study revealed that Tampakura Formation was deposited in rimmed shelf with wide belt of carbonate sand shoals-reef margin facies (Figure 6). This wide facies belt may indicate extensive lateral distribution of potential reservoir for the next exploration target. Labengki Island provides a good example of rimmed shelf of Eocene- Oligocene Carbonate in Eastern Indonesia. These carbonates can be used as analogue for the subsurface strata with careful consideration.

Although we did not find any significant pores under optical microscope, field study suggests porosity development mostly governed by subaerial exposure. The collision between microcontinental terrain and ophiolit in Southeast Sulawesi occurred at Late Oligocene to Early Miocene (Surono, 2013). The collision folded and uplifted the Tampakura Formation to the subaerial exposure.

In this study, we observe that boundstone and floatstone could be the best reservoir candidate in the region since they showed significant porosity development such as fracture porosity and cavernous porosity. These porosity types were classified as touching-vuggy porosity. Lucia (2007) suggested that touching vugs can increase permeability well above the interparticle porosity systems.

Grainstones and packstones in Tampakura Formation are severely cemented with calcite. Calcite cements occur in intraparticle and interparticle pore space. Locally, grainstone facies show solution- enlarged fracture porosity. Some moldic pores were observed occasionally in packstones, but in many cases they are lack of visible/macroporosity.

Enos & Sawatski (1981) suggested that porosity of grainstone in its original depositional environment was in the range of 40-50 %. Their study was based on recent carbonate sediments in T-Carbonate Factory of Bahama Reef which can be assumed to be analogous Tropical Carbonate Factory in Southeast Asia.

It is suggested that diagenesis controlled the porosity evolution of this grainstone and packstone facies of Tampukura Formation. Diagenesis could have reduced the porosity value of original grainstone sediment by cementation process. The timing of calcite cement formation is still unknown and will be further studied.

Dolomitic packstone of Tampakura Formation has low reservoir quality. Dolomitization requires hydrology flow to introduce magnesium to the carbonatesystem (Lucia, 2007). Dolomitization in Tampakura Formation have occurred mainly in muddy limestone and some cases in boundstone and packstone.

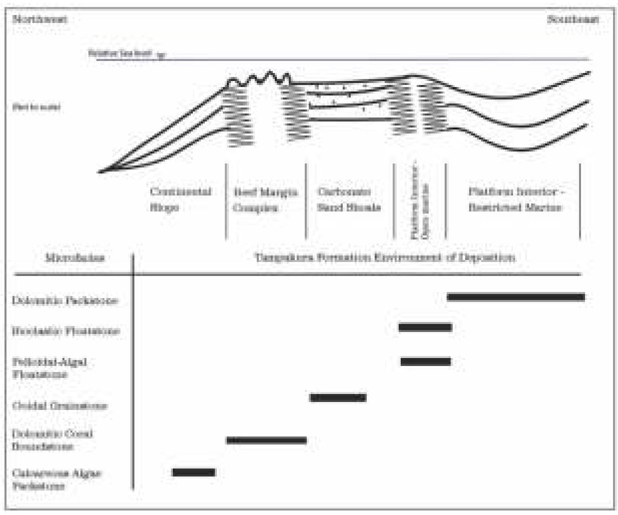


Figure 6. Schematic cross-section showing paleo-depositional environment of Tampakura Formation. Note the wide reef margin – carbonate sand shoals belt protecting the platform interior.

Surono (2013) suggested that the formation of dolomite in Tampakura Formation was controlled by the reflux of Mg-rich sea water in lagoon. However, the occurrence of dolomite in shelf facies of Coral boundstone may suggest that the dolomitizing fluid flows down offshore to the shelf. We propose that dolomitization of Tampakura Formation may have occurred in the mixing zone. Dolomitization in mixing zone occurred in the mixing of meteoric and phreatic waters along the margins of the platform and under islands (Lucia, 2007).

CONCLUSIONS

Tampakura Formation was deposited in rimmed carbonate shelf with extensive development of high energy facies (reef margin complexes and carbonate sand shoals) mostly in the northern part of the island. Tampakura Formation composed of grainstone, boundstone and floatstone with minor packstone and dolomitic wackestone.

Boundstone and floatstone facies show the best reservoir quality which were associated with touching-vuggy porosities (fracture porosity and cavernous porosity).

Although some grainstones were highly cemented by calcite, locally they developed solution-enlarged fracture porosity. On the other hand, packstone facies developed some minor moldic porosity.

Dolomitization of boundstone and packstone are expected to enhance the porosity of Tampakura Formation. Packstone deposited in Platform Interior-restricted marine could have undergone extensive dolomite cementation and this process would deteriorate the reservoir quality.

ACKNOWLEDGMENTS

We would like to show appreciation and gratitude to all people who were involved in the writing of this paper. Funding for this research was provided by Geological Survey Agency of Indonesia as part of Southeast Sulawesi Hydrocarbon Play Appraisal Project. We thank the anonymous reviewers for their careful reading of our manuscript and of insightful comments and suggestions.

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