New Insight of Surface and Subsurface Sedimentology of Salodik Group, Banggai Basin

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Abstract. The research area is situated in the Eastern Arm of Sulawesi, Banggai Basin. The complexity of geological components in Sulawesi greatly affects the pattern of sedimentary rocks. Certainly, these conditions have implications of the petroleum system in this basin. The characterization of carbonate rock in the Banggai Basin requires the integration of multi-disciplines in order to conduct reservoir characterization on a detailed scale. This study focuses on integrating surface to subsurface sedimentology aspects to evaluate the reservoir characterization. The two methods are used to analyzed, the surface field observation and subsurface study. These methods will then be assisted by several methods, such as petrographic analysis, XRD and SEM, biostratigraphic analysis, and routine core analysis. The outcrop sampling is carried out in the northward and subsequently integrated with subsurface in the southward (Tiaka-Tiara Field). In the surface area, Tomori Formation has two part, Lower Tomori Formation is composed of Large Foram-Red Algae facies with deposited inner-middle sublittoral. Wherein, Upper Tomori Formation is composed of planktic-large foram packstone-wackestone with deposited Middle-Outer Sublittoral and skeletal packstone-wackestone with deposited Inner-Middle Sublittoral. Minahaki Formation is overlying of Tomori Formation, there are two facies namely large foram packstone-mudstone with deposited at Middle Sublittoral-Upper bathyal and skeletal packstone-wackestone with deposited at Inner-Middle Sublittoral. The youngest formation of the Salodik Group on the surface is Mentawa Formation where this member is reefal facies. On the subsurface, the Salodik Group consists of Tomori Formation, Matindok Formation, and Minahaki Formation. The Tomori Formation was deposited at Bathyal-Inner shelf with mudstone-grainstone facies and slightly dolomite. Younger than Tomori Formation on the subsurface is calcareous sedimentary rocks, known as Matindok Formation. The Minahaki Formation was directly overlying the Matindok Formation in the transgressive phase.
1. Introduction

This study is situated in the Banggai Basin, more precisely in the Eastern Arm of Sulawesi (Figure 1). The surface study was conducted in Luwuk, several geological traverse in Batui, Nambo, Teletubbies, Salodik, Balantak, Pagimana, Kauru, Bolaang, Bangketa, Batutambung and Peleng area. During Late Neogene, Luwuk has been recognized to be formed under obductional tectonic where the East Sulawesi Ophiolite Complex thrust southward over the Banggai-Sula microcontinent [1]. Whereas, subsurface area in the Tiaka-Tiara Field the southward from surface geological mapping area. Sulawesi Islands in the middle part of Indonesia are composed by collision of geological provinces and have been modified by post-collision releasing tectonic [2]. Banggai Basin is Mio-Pliocene foreland basin which is the prolific basin [3]. The Banggai Sula Basin, which is composed of micro-continent origin from Australian [4], produces the present of petroleum system and has been proven as a hydrocarbon producer. Banggai-Sula was not separated from New Guinea, but belonged to Sula Spur [5]. Collision of two macroplate blocks, Buton-Tukang Besi and Banggai-Sula with eastern part of this island initiate Neogene orogenic in Sulawesi [6]. Reconstructed the microcontinents from Papua ‘Bird’s Head’, their transforms to the west, and collisions with Eastern Sulawesi ophiolite. These collisions caused foremost edges of micro-Buton-Tukang Besi and Banggai-Sula are pushed down below the ophiolite, causing ophiolite merge into microplate blocks. Furthermore, as an impact of collision, Central Sulawesi metamorphic belt forced to the west over Western Sulawesi and uplifted to form mountain range scaled almost 3000 meters [7]. There are some previous researches in Banggai Sula Basin both on the surface and subsurface. On the surface area, tertiary limestones was named the Salodik group, aged Early Eocene until Middle Miocene. While, subsurface research explains the Salodik Group into specific formations including Tomori Formation, Matindok Formation, Minahaki Formation, and Mentawa Member. Stratigraphy in the Eastern Sulawesi associated with two different depositional periods; first, it represents a series of continental edge translation before the collision, and second, represents a series of *flysch-molasse* sediments sequence in foreland basin, which is deposited in front of thrust fault migration to the east after the collision occurred. Platform carbonate sequences from Minahaki and Tomori Formation have been identified from Middle to Late Miocene (before collision), that overlain by post-collision sediment sequences from Pliocene-Pleistocene Sulawesi Molasse Group and among of them are separated by hiatus of unconformity. Entire carbonate member from Mentawa, Minahaki, Matindok, and Tomori Formation are known as Salodik Group. Basement of Banggai-Sula micro-continent consists mostly of schist and granite from the Permo-Triassic era [8].

![Figure 1. The study area (red box), Eastern Arm of Sulawesi [9]](image-url)
Comparison of surface and subsurface stratigraphy are represented in Figure 2. Distribution of Mesozoic sediments is restricted in eastern area from the line extending from northwest to southeast through Eastern Peleng and Middle Banggai in the east of Selue Besar. In the west of this line, Tertiary and Quaternary sediments overlay straight above Palaeozoic basement. In far east, Early Jurassic coarse clastic is poorly developed although the thicker sequences occur again in Sulawesi. The basement is locally overlain by Eocene-Oligocene clastic and thin basalt carbonate, and regionally by thick part of Miocene carbonate and clastic. Tomori Formation, basically aged Early Miocene, largely consists of shallow marine bioclastic limestone, dolomite in some areas, with claystone and coal.

Figure 2. Stratigraphy comparison of surface & sub-surface Banggai-Sula Microcontinent, modified [10].

2. Data and Method

The geological surface mapping has a total of 166 observation locations, consist of 19 observation locations on Batui Traverse, 32 observation locations on Nambo Traverse, 20 research locations on the teletubbies travers, 18 research location on the salodic travers, 28 locations on Balantak Traverse. Whereas, 13 wells and 3D seismic were observed on the subsurface to determine subsurface sedimentology and stratigraphy condition. The two methods are used to analyzed, the surface field observation and subsurface study. These methods will then be assisted by several methods, such as petrographic analysis, XRD, SEM, biostratigraphic analysis, and routine core analysis. The outcrop
sampling is carried out in the northward (Luwuk) and subsequently integrated with subsurface in the southward (Tiaka-Tiara Field). The purposes of this research is to give comprehensive and detail analyzed including stratigraphic sequence of sedimentary rocks, carbonate facies, diagenesis, and paleogeographic model. Determination of carbonate facies used classification of Dunham (1962), the pore type classification is identified according to definition set by Choquette and Pray (1970), and diagenesis regime was interpreted based on Tucker (1991) classification and scheme.

3. Result and Discussion

This research is focused on surface to subsurface study of Salodik Group carbonate facies. In order to get a comprehensive result, this research had done a few analyses, including determination of surface condition of Salodik Group into specific formations based on biostratigraphic and petrographic analysis, determination of thrust faults and geomorphology, interpretation of facies map and stratigraphic sequence of each formation, reconstruction of paleogeography, and diagenesis and characterization of carbonate facies analysis.

Surface Field Observation

This study has 19 observation locations on Batui Traverse, 32 observation locations on Nambo Traverse, 20 research locations on the teletubbies traverses, 18 research location on the salodic travers, 28 locations on Balantak Traverse (Figure 3).

Batui Traverse is located around 80 kilometers from Luwuk City, Banggai Regency, Central Sulawesi. There are four imbricate thrust faults, interpreted based on biostratigraphic and lineament analysis. These faults are causing Upper Tomori Formation exposed and Minahaki Formation shortened. Based on petrographic and biostratigraphic data, Upper Tomori Formation is exposed on BAT-1A. Large foraminifera packstone facies is exposed, with large foraminifera species such as Heterostegina borneensis, Lepidocyclina sp., and Miogypsinoides sp. This section is deposited at middle sublittoral based on the presence of Amphistegina sp, Cycloclypeus sp, Heterostegina sp, and Lepidocyclina sp. It has predominant Minahaki Formation large foraminifera packstone – mudstone facies. Abundant planktonic foraminifera i.e. Globorotalia sp and Globigerinoides sp are occurred at BAT-1B, BAT-6, and BAT12. Whereas, corals, mollusks, and echinoids are present in small amount. Minahaki Formation in this section is deposited at middle sublittoral – upper bathyal paleoenvironment.

Nambo Traverse covers 31 observation locations in 4 different formations, divided into Eq. Nambo Formation, Eq. Upper Tomori Formation, Eq. Mentawa Formation, and Quaternary Reef Coral. Distribution of Eq. Nambo Formation was interpreted based on occurrence of bellemnites at NAM-20 and Late Cretaceous age determination at NAM-21. Packstone – wackestone facies is dominant, while grainstones and dolostone are also present at NAM-24 and NAM-22. Planktonic foraminifera are quite common at NAM-24. Nambo Formation is deposited at inner – middle sublittoral. Eq. Upper Tomori Formation is dominated by skeletal packstone – wackstone facies. The skeletals are varied, including large benthonic and planktonic foraminifera, corals, echinoids, brachiopods, and mollusks. Eq. Mentawa Member in Nambo Traverse is dominated by reefal packstone facies. Organisms that found on this section are corals, benthonic foraminifera, and planktonic foraminifera.

Teletubbies Traverse covers 19 observation locations in 2 different formations. Based on biostratigraphic, petrographic, and lineament analysis, formations divided into Lower Tomori Formation and Quaternary Reef Coral. Lower Tomori Formation are covered with Large Benthonic Foraminifera – Red Algae Packstone Facies. Large benthonic foraminifera, such as Amphistegina sp and Alveolina sp. It was determined to be deposited at inner sublittoral.

Salodik Traverse is located within 28 kilometers from Luwuk City. This area covers 15 observation locations and four formations, including Eq. Lower Tomori Formation, equivalent Upper Tomori Formation, equivalent Poh Formation, and equivalent Kintom Formation. Equivalent Lower Tomori Formation is dominated by Large Benthonic Foraminifera – Red Algae Packstone. Large benthonic foraminifera, such as Alveolinela sp and Amphistegina sp, milliolids, and red algae are dominant.
Dolostone was also found at SAL-1. Based on occurrence of abundant millioids and other large benthonic foraminifera, especially *Alveolinela* sp at SAL-3.

Located within 100 kilometers from Luwuk City, Balantak Traverse covers two traverse and other observation locations outside traverse lines. Four formations were determined at Balantak area, including equivalent Upper Tomori Formation, equivalent Minahaki Formation, equivalent Mentawa Member, and Quaternary Reef Coral. Equivalent Upper Tomori Formation at Balantak Area predominant skeletal wackstone facies. Organisms are varied, red algae, large benthonic foraminifera, coral debris, and planktonic foraminifera are present. Equivalent Minahaki Formation in this area is dominated by skeletal packstone – wackestone facies. Planktonic foraminifera are rarely found, while shallow marine benthonic foraminifera, i.e. *Amphistegina* sp and *Lepidocyclina* sp, red algae, coral, and echinoids are common. Based on organism occurrences, equivalent Minahaki Formation in this area was deposited at inner – middle sublittoral. Reefal packstone – wackstone facies is dominant on equivalent Mentawa Member of Balantak area. Shallow benthonic foraminifera, i.e. *Amphistegina* sp and *Cycloclypeus* sp, red algae, mollusks, and coral debris are present.

**Figure 3.** Study area, traverse, cross Section, geological map, outcrop, and petrographic analysis of Batui traverse, Nambo traverse, Teletubbies traverse, Balantak traverse, and Salodik traverse.

**Subsurface Observation**

The data is used for sedimentology and stratigraphic analysis on the subsurface is well log and core data (Figure 4). To find out the sediment distribution in subsurface (Tiaka-Tiara field), related with well log data correlation and 3D seismic interpretation, furthermore the well log data also controlled with the core data to get a good confidence level. Their analyzed is intended for interpretation of lithofacies types, vertical sequence, and facies association. Biostratigraphic interpretation of the Tiaka-1, Tiaka-2, Tiaka-3, Tiaka-7st2, and Tiaka-13 are based on the compilation of the foraminifera and calcareous nanoplankton analysis. Tiaka area composed of 13 wells, there are 5 wells has micropaleontological data from North to South.

In Tiaka-1, interval 5620-6560 ft was interpreted the Late Miocene and it is attributed to zone N17-N15 based on present of *Globorotalia tumida plesiotumida*, *Globorotalia ocastaensis*, *Globorotalia merotumida*, *Globorotalia continuosa*. Moreover, this interval also present calcareous nanofossil which is attributed to zone NN11-NN9 based on presence of *Discoaster neohamatus*, *Discoaster quinqeramus*. Interval 6560-7500 ft is interpreted Middle Miocene-Late Miocene and it is attributed to zone N15-N9 based on the present *Globorotalia continuosa*, *Globogerina nephentes*, *Globorotalia siakensis*, *Sphaeroidinella subdehicens*, *Globorotalia foshi*, *Globorotalia praefoshi*, *Globorotalia*
pheriperoronda, Orbulina suturalis. Moreover, this interval also present calcareous nannoplankton which is attributed to zone NN5-NN9 based on the present of Discoaster neoahamatus, Discoaster hamatus, Catinaster coali tus, Discoaster exilis, Sphenolithus heteromorphus. The lithofacies is wackestone to packstone, have dark yellowish gray and very pale orange color. Predominantly faunal is planktonic foraminifera, but also presents a small amount of benthic foram. Stylolite and microstylolites are common. Porosity is secondary interparticle and moldic. Porosity varies with the degree of winnowing and compaction.

In Tiaka-2, Interval 6110-6180 is interpreted as Late Miocene carbonate based on the present of Globogerinoides quadrilobatus triloba, Orbulina universa, Globigerina nepentes, Globorotalia plesiotumida, sinistrally coiled G. menardii. Interval 6630-7090 ft composed of benthic foram Eponides praecinctus, Amphistegina sp, Lepidodona sp, Miogypsina sp. Whereas, planktonic foram presence namely Globogerina sicanus and Praeorbulina transitoria (6700-6730 ft) there is concluded Middle Miocene in age. Interval 7348-7350 ft predominant coral packstone/grainstone. While, Interval 10880-10940 ft has distinctive benthic foram namely Nummulites sp, Lacazinella aff, reicheli. Then, it was concluded this interval was interpreted Oligocene in age.

In Tiaka-3, is repeat sequence between overthrust sequence and subthrust sequence. There is difference age in each formation in the overthrust and in the subthrust. Interval 7538-8394 ft & 9244-9837 ft in the overthrust are interpreted as Late Miocene carbonate and equivalent Minahaki Formation. It is attributed to zone N16-N17 based on presence of Globorotalia acostaensis acostaensis and Globorotalia merotumida. Moreover, this interval also present calcareous nannoplankton which is attributed to zone NN11-NN12 based on presence of Discoaster quinqueramus. Whereas, in the subthrust Minahaki Formation is attributed to zone N17 (foram) based on presence of Globorotalia plesiotumida and attributed to zone NN11-NN12 based on present of Discoaster quinqueramus. Zone N16 in the sub-thrust sequence is missing due to cut by thrust fault plane. Interval 8771-9016 ft is interpreted as Early Miocene carbonate and it is attributed to zone N7-N8 based on presence of Globogerinatella insueta and Globogerinoides trilobus. This interval consists of coral framestone interbedded floatstone and wackestone/packstone. Then, this interval also present calcareous nannoplankton which is attributed to zone NN4 based on present of Helocopsphaera ampliaperta. Whereas, interval 10234-10967 ft in the subthrust is attributed to zone N4-N8 (foram) based on present of Globogerina primordius, globorotalia kugleri, Globigerinoides primordius, globigerinatella insueta. Then, this interval also present calcareous nannoplankton which is attributed to zone NN1-NN4 based on presence of Triquetrorhabdulus carinatus, Sphenolithus belemnos, Helicopsphaera ampliaperta.

In Tiaka-4, interval 6345-6865 ft predominantly packstone-grainstone occasional wackestone, calcite spar restricting porosity, trace dolomite, abundant skeletal fragments from coral. Whereas, Interval 8014 ft marked as top Tomori Formation. They have grey color, occasionally white, very hard, angular, wackestone/mudstone, slightly argillaceous, occasionally very fine fracture with crystalline calcite spar, occasionally stylolite, common skeletal benthic foram, crystallized algae, and visible secondary porosity.
Figure 4. Wireline log and core data of Tiaka-1, Tiaka-2, and Tiaka-3 which show Minahaki and Tomori Formation

4. Conclusion

1. Based on the surface data Salodik Group is dominated by benthic foram packstone to wackestone and slightly dolostone which deposited in Middle Eocene-Middle Miocene. Biostratigraphic data reveal that the Salodik Group consists of Lower Tomori Formation, Upper Tomori Formation, Matindok Formation, Minahaki Formation, and Poh Formation. The depositional environment of Salodik Group is Inner sublittoral-Upper bathyal.

2. Subsurface identification reveals several critical sedimentology aspects, that are the Salodik Group is deposited in Early Miocene-Late Miocene, with inner shelf-Outer Bathyal depositional environment. Significant differences of Salodik Group ages at surface and subsurface.

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