Miocene Carbonate Microfacies Distribution of Tendehantu Formation, Mangkalihat Peninsula: Approach of Reservoir Potential using Outcrop Analogue*

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Abstract

The origin and sedimentary evolution of the Mangkalihat Peninsula, Kalimantan (Borneo), is still debatable and has attracted the attention of many geologists and explorationists. The petroleum system of the area is believed to have good potential, because it lies between the highly productive and prospective Kutai and Tarakan basins. It consists mainly of reef-associated carbonate rocks that are similar to the main reservoir rock types in the western-part of Indonesia. The objective of this research is to provide a detailed examination of the previously unstudied Miocene carbonate facies in this area. Based on field and petrographic analyses, this study shows that the microfacies distribution of the Tendehantu Formation consists of four microfacies as follows:

1) coralline-red algae boundstone
2) rhodolith-bioclastic rudstone - grainstone
3) bioclastic grainstone - mud-lean packstone
4) foraminiferal wackestone - floatstone.

The first two microfacies are considered to be deposited in the same environments, upper-middle reef front, with porosity of 10-25%. The depositional environment of microfacies 3 is suggested to be an upper forereef, while microfacies 4 is considered to be a lower forereef in the distal part of the carbonate margin, with porosities of 2-5%. These four microfacies together with mapping of the margin's morphology are used to interpret the depositional environment and construct a carbonate ramp model. The recognition of the four microfacies offers an additional tool to aid prediction of variations in reservoir potential in this area. Further seismic facies analysis is recommended to provide accurate thickness and lateral facies continuity that might not be possible to assess at the outcrop scale.

Introduction

Carbonate rocks contain more than 50% of oil and gas reserves around the world (Flügel, 2004) and account for a significant proportion of the world's giant fields. Reef and reef-associated carbonate deposits comprise a significant proportion of these reservoirs and occur most prominently in carbonate systems of Siluro-Devonian, Cretaceous, and Neogene age. Coral reef and related reservoir-prone deposits most commonly occur as thick to massively bedded boundstones in platform margins and in platform interior patch reef settings and as skeletal rudstones, floatstones, grainstones, and packstones interbedded with boundstones in foreslope debris. Reef deposits typically occur over relatively small areas ($1 – 10^2$ km^2) and range in thickness from meters to 1000 meters or more. The most common depositional pore types in reefs and reef-associated beds include interparticle, intraparticle, and moldic porosities, although these depositional pore systems may be extensively modified by post-depositional alteration (most notably dissolution, cementation, and dolomitization). Even though porosity in these reef-related reservoirs is typically very heterogeneous, they constitute some of the most prolific reservoirs in the world, including Indonesia. On Kalimantan Island (Figure 1), which is located in the western part of Indonesia, both oil and gas are produced from three syn-rift sedimentary basins, the Barito, Kutai and Tarakan basins. Recently, Kalimantan has accounted for 18% of Indonesia's oil production and 32% of its gas production, and the main reservoir of each basin is either siliciclastic or reef-associated carbonate rocks (Satyana et al., 1999). The study area, the Mangkalihat Peninsula, is located between two of the three prolific basins in Kalimantan and is believed to be a potential petroleum play. The aim of this study is to investigate the carbonate microfacies distribution and related reservoir potential based on field and petrographic analysis.

Geological Setting

Mangkalihat Peninsula is located at the eastern end of Kalimantan (Borneo) Island, and is physiographycally a highland that separates Kutei Basin in the south from Tarakan Basin in the north. Even though the area is part of Sundaland, the Mangkalihat High has a tectonic history that differs from other parts of Sundaland. Some previous authors interpret Mangkalihat as a micro-continent that originated from northern Gondwana and suffered rifting in the Late Jurassic and drifted toward the equator as a result of the opening of the Neotethys ocean (e.g., Satyana, 1999). The outcome of the opening of Neotethys can be inferred, based upon its tectono-stratigraphic structure, this being a zone of crustal accretion in southeastern mainland Sunda, comprising Meratus oceanic crust and Paternoster continental crust. A stratigraphic chart for the Mangkalihat Peninsula shows that the Tendehantu Formation (Tmt) is middle Miocene in age (Figure 2). The Tendehantu Formation belongs to the Mangkalihat High Cenozoic carbonate system that is believed to have good potential as a hydrocarbon reservoir in the East Kalimantan region. Wilson et al. (1999) reported the lithology of three exposed outcrop locations of Cenozoic carbonates which were deposited in a shallow-marine environment. The three carbonate outcrops of the Mangkalihat Peninsula have been reported respectively as: a) an extensive carbonate platform, b) some isolated bioherm, and c) reworked deposits along a platform margin. The succession is approximately 2000 ft thick, with benthonic foraminifera dominating much of the platform, but with corals and coralline red algae also as important constituents. Bedding of the outcrop successions is variable, but generally it strikes at about N120^{o}E, with a dip of 10-28 ^{o}SW. This study focused on the Tendehantu Formation successions located on the Antu Mountain (Figure 3).

Methodology and Data

Sixteen representative carbonate samples were collected from Antu Mountain and the surrounding areas. Detailed measured sections in the field were used to describe the facies and determine sample locations. Thin sections were prepared for all samples with blue epoxy to recognize the different porosity amounts and types. Staining analysis using red alizarin was performed to test for the presence of dolomite and non-carbonate minerals.

Microfacies Analysis

Detailed petrographic and micropaleontology studies of all the samples revealed four different microfacies present in the studied sequence:
Microfacies 1 (Figure 4a) - Coralline-red algae boundstone. This microfacies consists of in situ encrusting and binding red algae associated with head-forming coral. The presence of in situ encrusting red algae suggests that this microfacies formed a wave-resistant framework, and indicates a high-energy environment (Hussain and Al-Ramadan, 2009). Cementation by bladed-calcite cements is commonly found in thin section.
Microfacies 2 (Figure 4b, **c**, and **d**) - Rhodolith-bioclastic rudstone - grainstone, interpreted as talus. This microfacies is characterized by packstones composed of rhodoliths, brachiopods, benthonic foraminifera (*Lepidocyclina* sp.) and head-forming coral fragments, and contains grain sizes consistently larger than 2mm in size. This microfacies was also probably deposited in a high-energy environment. Cementation by meniscus and blocky-calcite cements is commonly found in thin section.
Microfacies 3 (Figure 4e and f) - Bioclastic grainstone - mud-lean packstone. The composition of this facies is greatly variable, consisting of skeletal and non-skeletal grains. The abundant presence of reworked shell fragments (foraminifera, bivalves) indicates high- to moderate-energy depositional conditions. Foraminiferal grainstones are also developed (Figure 4f). Cementation by blocky-calcite cements is commonly found in thin section .
Microfacies 4 (Figure 4g and h) - Foraminiferal wackestone-floatstone. The bioclasts are shell debris dominated by benthic foraminifera and rhodolith fragments. This microfacies may have been deposited in a low-energy forereef environment, based on the pervasive presence of micrite. The presence of the large foraminifera *Cycloclypeus* sp. and *Textularia* sp. indicates a forereef depositional environment (Bolli and Saunders, 1985).

Common Pore Types and Diagenetic Features in the Tendehantu Formation

Several different types of porosity were commonly observed in thin sections, including, from most to least common: interparticle, intraparticle, moldic, and vuggy (Figure 5a). The main diagenetic alterations include calcite cementation, dissolution, physical and chemical compaction, and dolomitization (Figure 5b).

Discussion

The depositional environment of the Tendehantu Formation is considered to have been an open shallow -marine, high-energy carbonate system. The presence of encrusting red algae may also support an interpretation of a high-energy depositional environment. Reworked debris of bioclastic shells are commonly found in the lower to upper forereef part, and the reworked materials are possibly derived from storm or wave processes. The increasing percentage of carbonate mud in thin section may be used to determine the depositional environment change from reef-front to lower energy forereef. Based on the microfacies distribution and 2D and 3D morphology of the platform (Figure 6a and b), there is a strong possibility that all the facies were deposited on a homoclinal ramp-margin (Figure 6c).

Diagenetic Sequence

The carbonates studied on the Tendehantu Formation, Mangkalihat Peninsula were mainly influenced by early marine phreatic, physical compaction and later chemical compaction and domolitization (Wilson et al., 1999). Early diagenetic effects include the microbial micritization of bioclasts. Marine phreatic bladed/ fibrous cements and meteoric phreatic blocky cements are well developed in these carbonates along the high energy ramp margin on the Mangkalihat Peninsula. Presence of meniscus cements indicates the meteoric vadose diagenetic environment. Chemical compaction caused by deep burial diagenesis can be observed by the presence of sutured grain contacts (Figure 7a) and also development of fracture filling by calcite may indicate the latest stage of diagenesis (Figure 7b).

Resevoir Potential

Low primary porosities (<5%) of the Tendehantu Formation occur in the low-energy facies, from the distal parts (forereef) of the ramp. In contrast, good primary porosities (up to 25%) were developed along the high- to moderate-energy zones of the ramp where little lime mud accumulated. Well developed shallow-marine phreatic cements are associated with extensive and high-energy seawater flushing along the margin that influenced the primary porosities development. The presence of abundant secondary porosities, however, suggests that the formation has attractive reservoir potential.

Conclusion

Four microfacies are recognized in outcrops of the Tendehantu Formation (middle Miocene) located at Antu Mountain. These microfacies comprise a succession of high- to low-energy, open shallow-marine depositional environments that were then cemented but later dolomitized during burial. The carbonate margin morphology in this study is successfully interpreted as a ramp margin, based on the microfacies types and distribution and on the platform morphology of the study area. Lithofacies and porosity results suggest that these rocks have a good reservoir potential.

Acknowledgment

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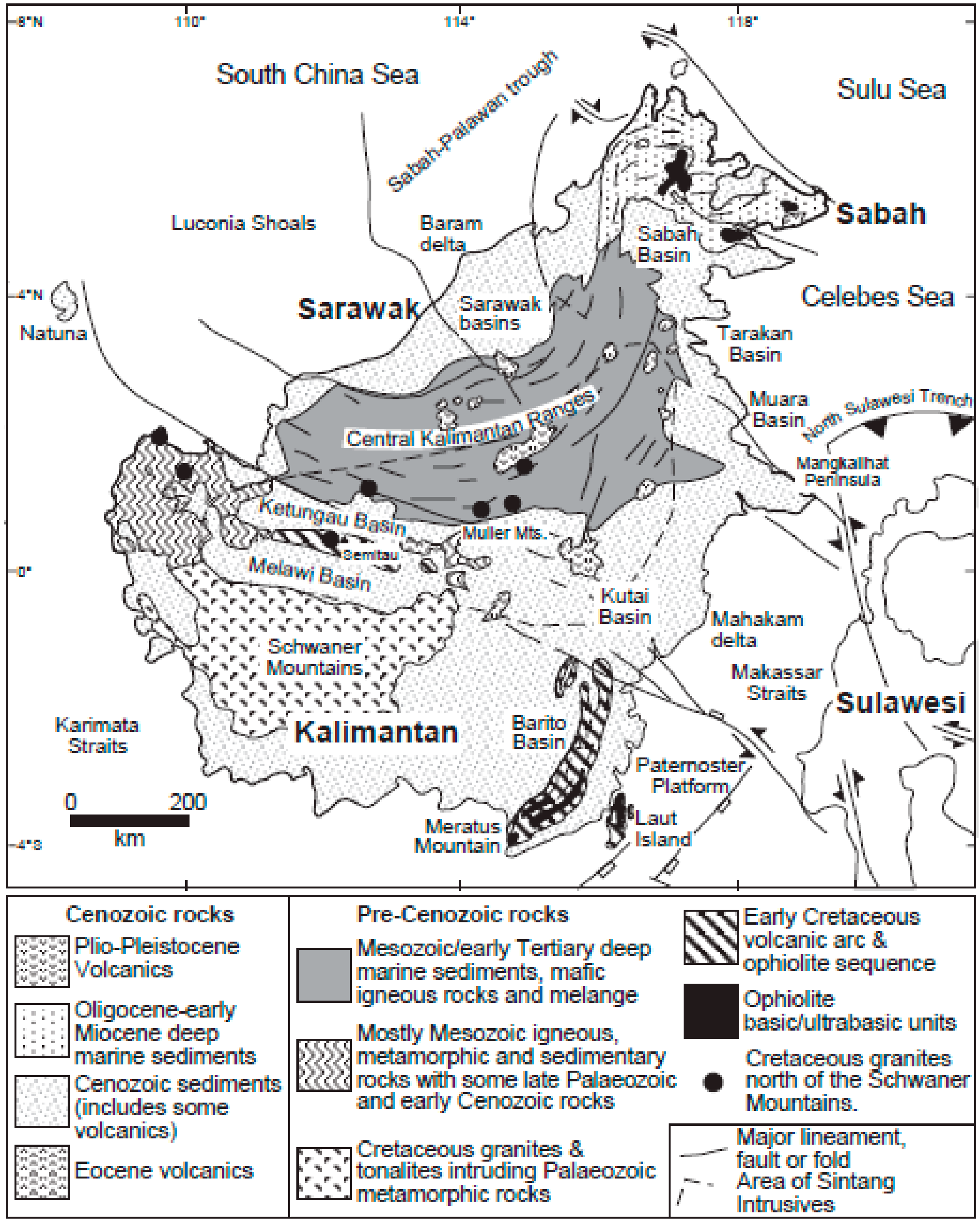

Figure 1. Generalized geological map of Borneo, showing surfical distribution of rock units and tectonic elements. (Wilson et al., 1999).

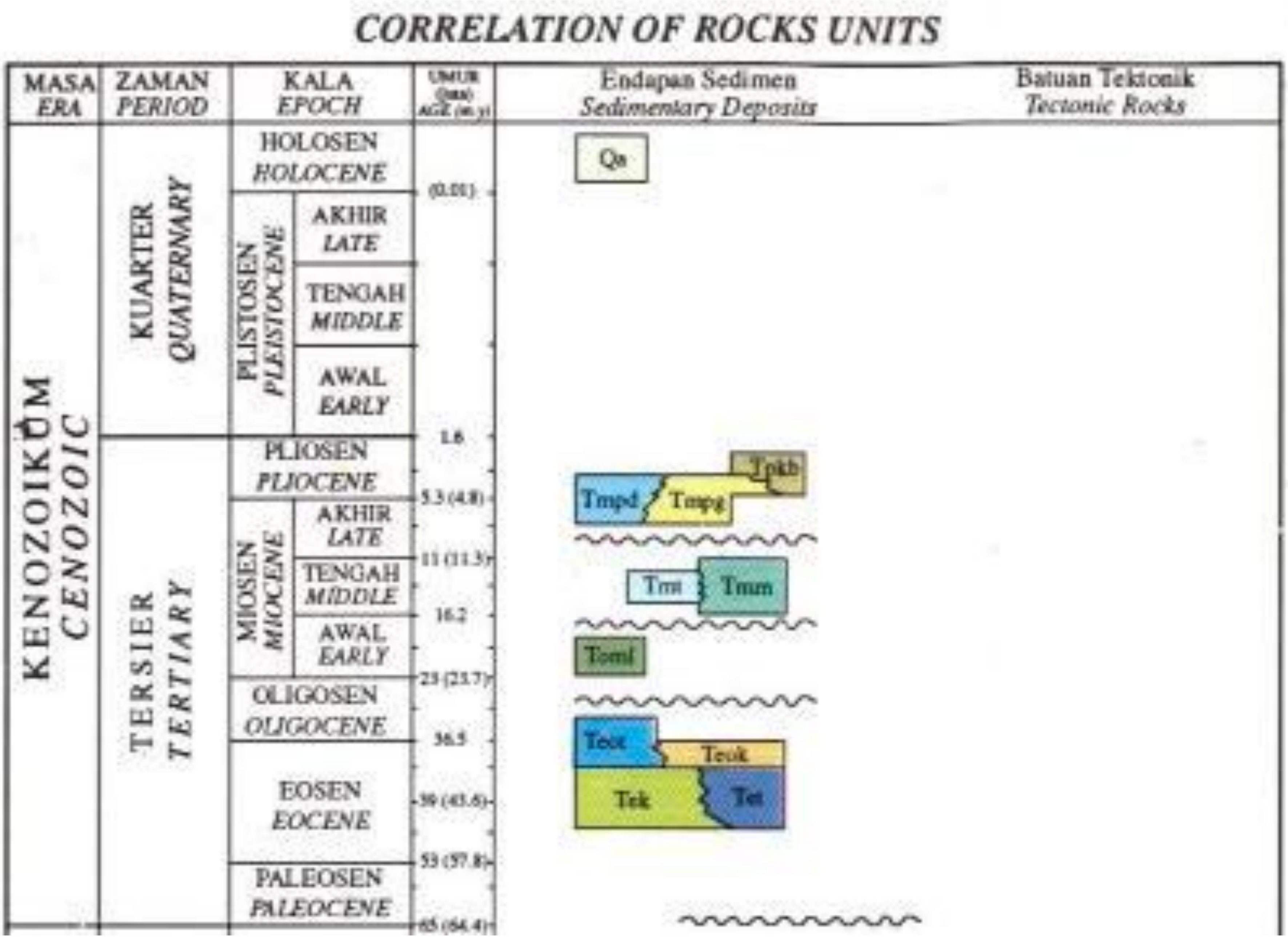

Figure 2. Stratigraphic chart of Mangkalihat Peninsula (Djamal, 1995).

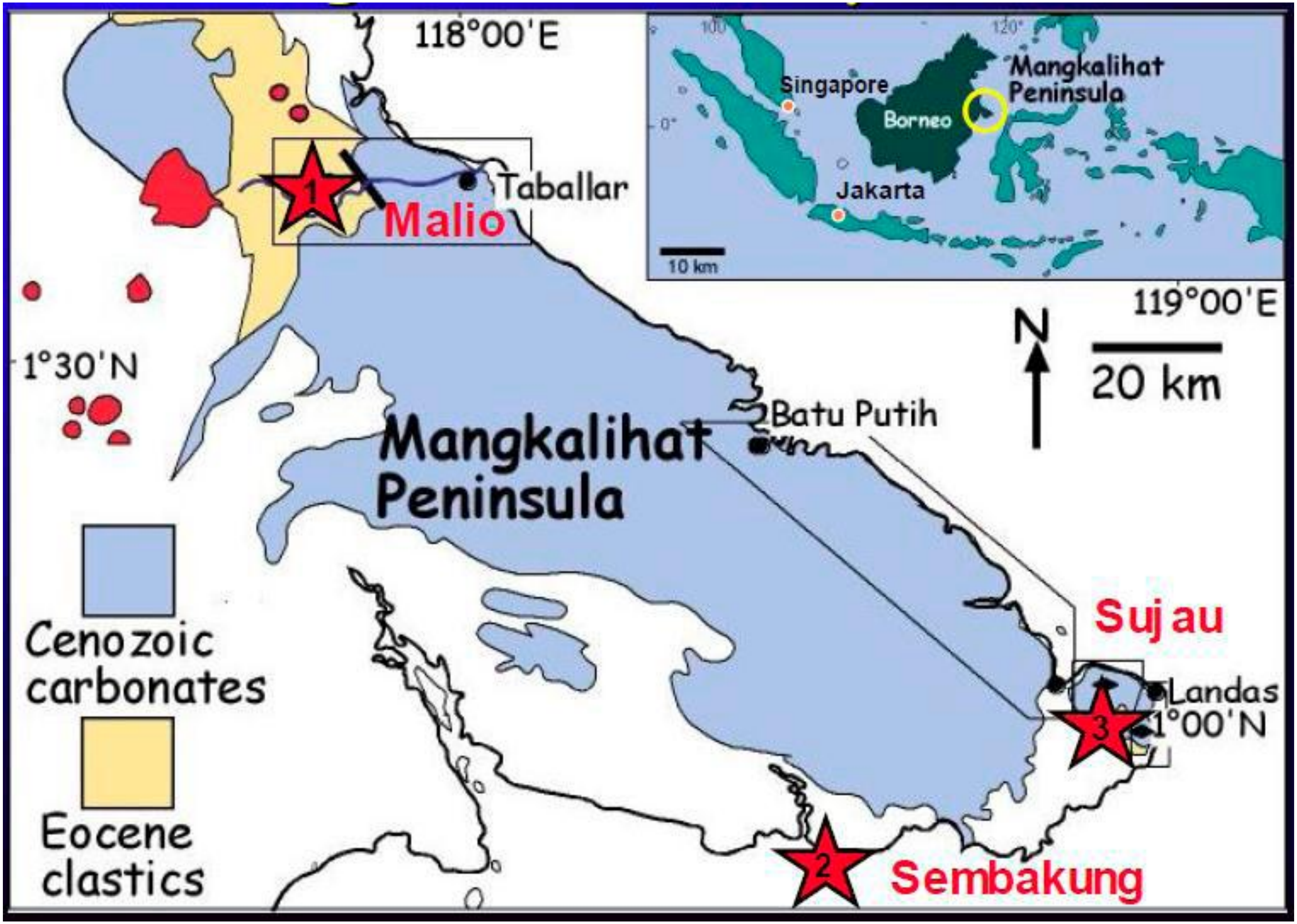

Figure 3. Outcrop locations and distribution of Cenozoic carbonate successions on the Mangkalihat Peninsula (Moss and Wilson,1998).

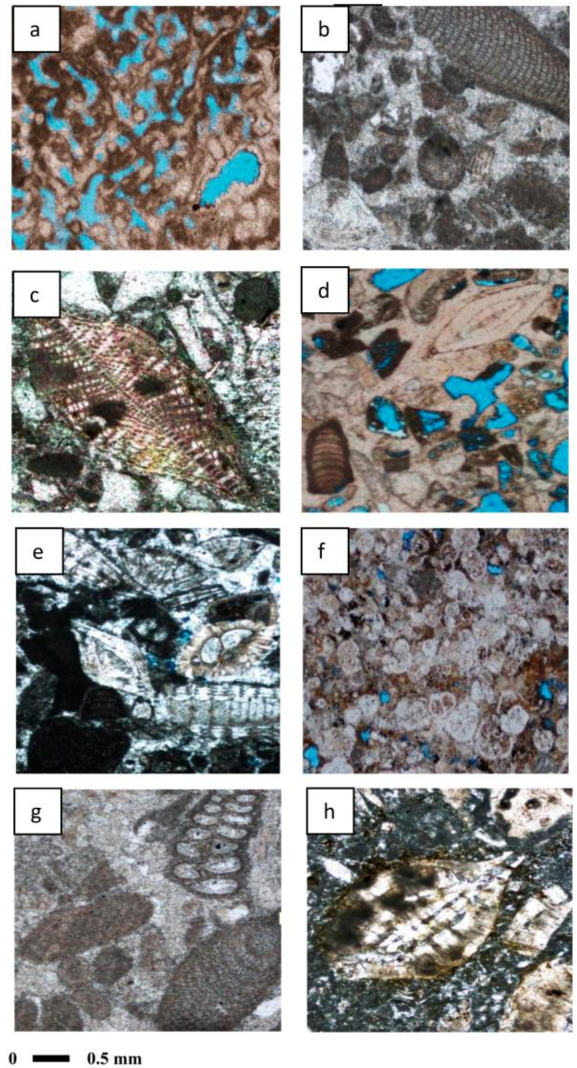

Figure 4. Thin section of the four microfacies. a. Reef-front boundstone, head-forming corals with a wackestone-packstone matrix containing primary interparticle porosity. b, c, and d. Reef-front bioclastic rudstone-grainstone, poorly sorted containing rhodolith fragments and benthonic foraminifera (e.g., *Lepidocyclina* sp.) with interparticle and intraparticle porosity. e and f. Proximal (upper) forereef mud-lean packstone, poorly sorted, containing rhodolith fragments and the benthonic foraminifera (*Amphistegina* sp.), also planktonic foraminifera, with a blocky cement. Primary interparticle porosity is partially occluded by sparite cement. g and h. Distal (lower) forereef foraminiferal floatstone with rhodolith fragments and benthonic foraminifera (*Cycloclypeus* sp.) and wackestone-packstone matrix containing very limited interparticle and intraparticle porosity.

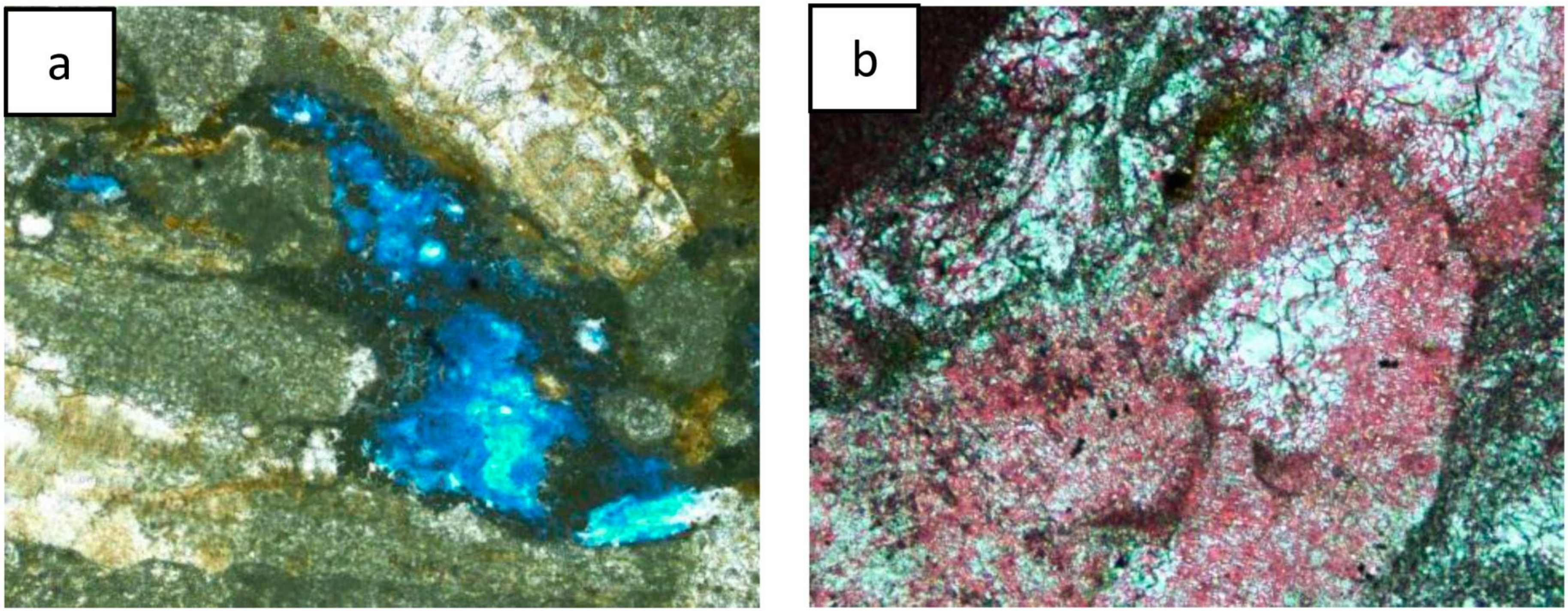

Figure 5. a.Vuggy porosity that can be observed in thin section of Tendehantu carbonate rocks. b. Dolomitization of the carbonate rocks of the Tendehantu Formation.

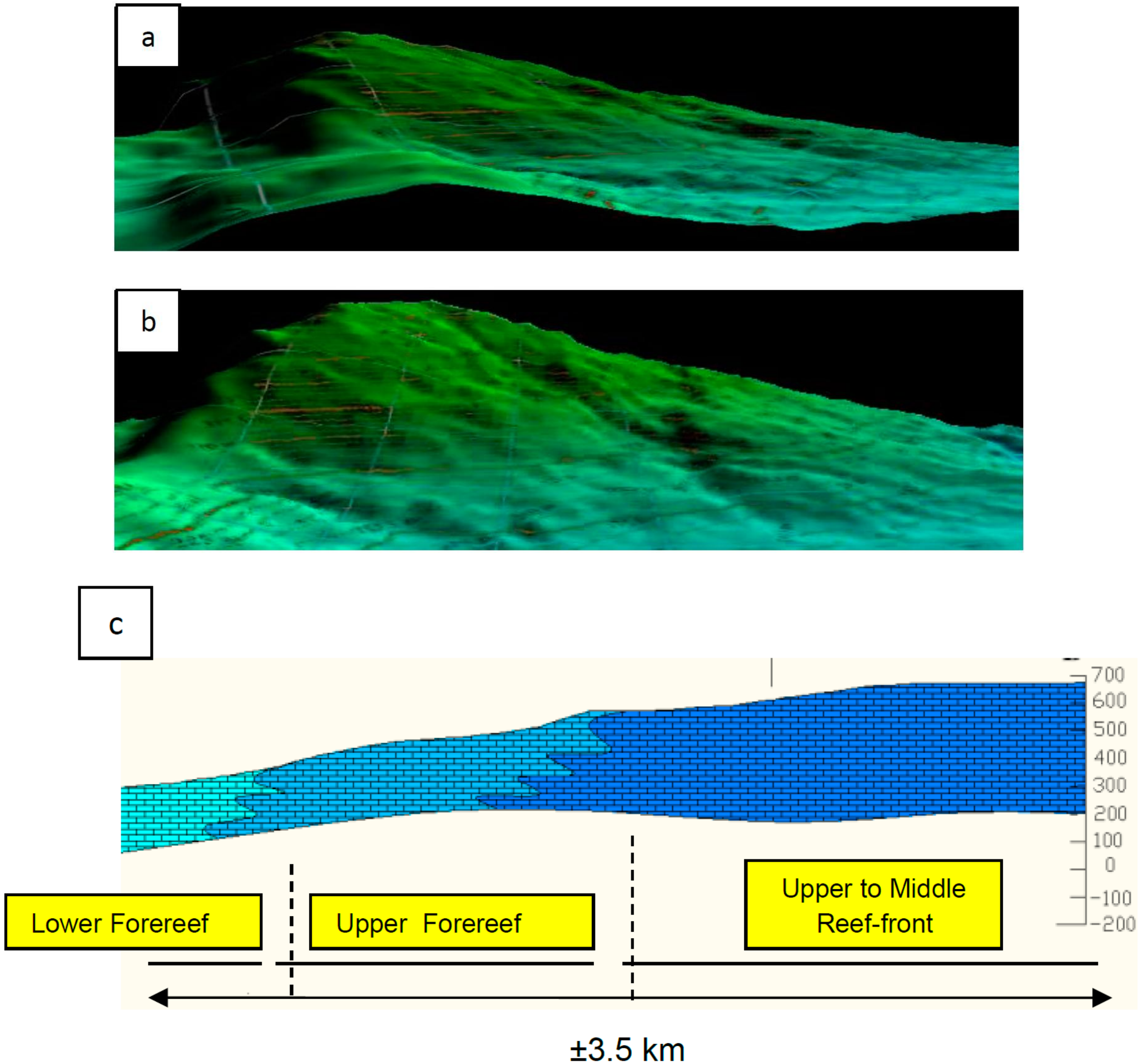

Figure 6. a and b. 3D morphology models of the Tendehantu Formation on Antu Mountain, also the platform morphology.c. Ramp-margin platform model constructed from the distribution of the four microfacies in the study area.

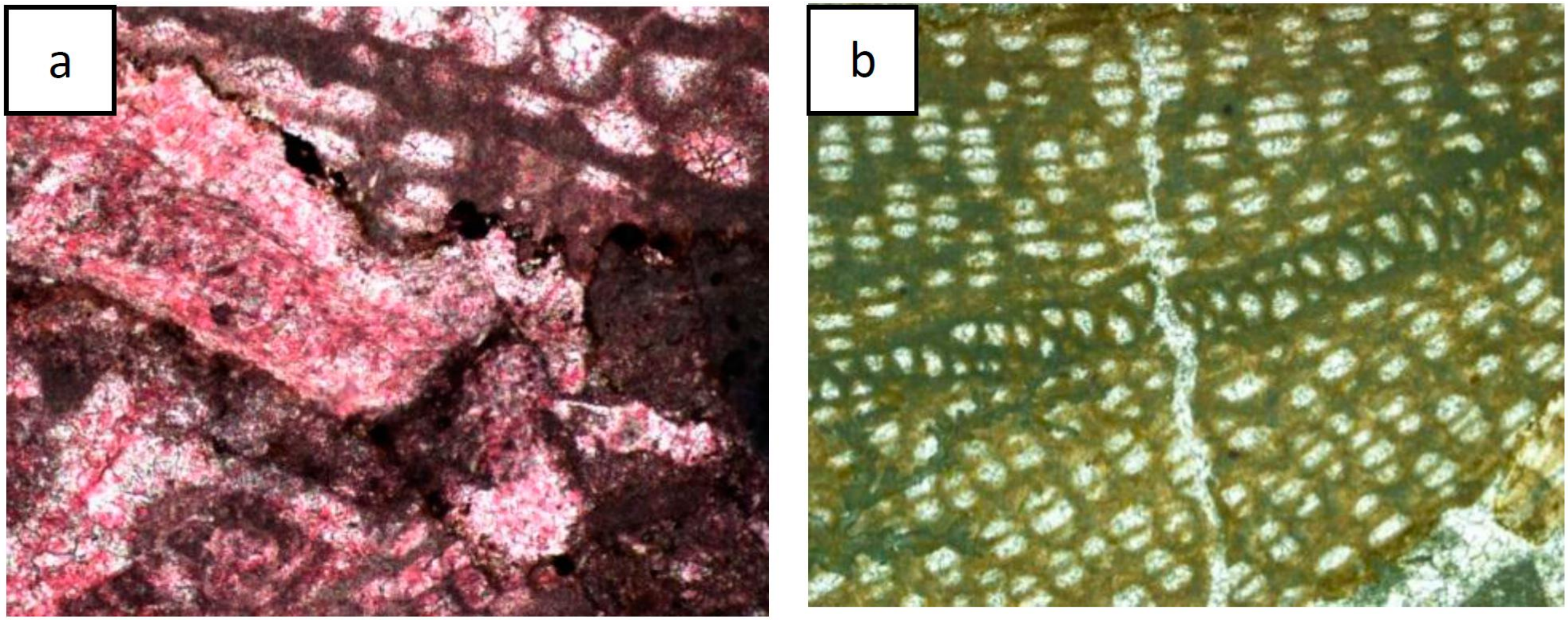

Figure 7. a. Suture grain contact between bioclasts, showing chemical compaction during deep burial diagenesis. b. Fracture filling by calcite in a bioclast grainy carbonate.