Sedimentology and Characteristics of Pliocene Shallow Marine Carbonate as Reservoir Alternative Based on Outcrop Analogue in Madura and Puteran Island, Northeast Java Basin*

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Abstract

Hydrocarbon exploration in Northeast Java Basin has Pliocene Globigerinid Limestone – a deep-water facies – as one of its main reservoirs. New play concept is highly expected, especially in carbonate reservoir that involves facies varieties within a depositional system. Detailed sedimentology study was accomplished based on field stratigraphy measurement to suggest reservoir alternative and figure out the reservoir characteristic (porosity and permeability) by petrography and mercury intrusion porosimetry.

Stratigraphy measurements show lateral facies distribution with inter-fingering contact of the exposed Pliocene carbonates in Madura to Puteran Island. The facies variations are defined by grouping some facies into certain association with different characteristics. The first is coarsening upward sandy bioclastic floatstone intercalated by paleo-soil interbeds (fringing reef facies, 7-22 % moldic, intra-grain, vuggy, and fracture porosity). The facies contains quartz fragment from erosion of Ngrayong Fm. along with abundant macrofossils and branching coral clasts. The second is bioclastic wackestone – floatstone (lagoonal facies with 22-40 % vuggy, channel, and inter-grain porosity and 4877 mD permeability). It is coarsening upward with some brachiopods and pelecypods. Next is massive coralline framestone – rudstone (carbonate build-up with 2-4 % moldic porosity). It consists of 40-70 cm beds and is made of massive corals and algae. The last is foraminifer grainstone – rudstone (reefal limestone – fore reef facies with 22-28 % vuggy, channel, and moldic porosity and 355 mD permeability) dominated by larger forams.

Those characteristics of Pliocene carbonates facies are generally controlled by dissolution process, but petrography analysis shows that depositional texture (product of depositional environment and mechanism) is the main influence. Grain supported foraminifer grainstone – rudstone facies acts as reservoir alternative in the area. Its good property is controlled by depositional environment with active current where this facies was formed (fore-reef that is directly influenced by oceanic current). The dominant composition of big foraminifers associated with red algae and some planktonic foraminifer indicate that study area has a more complex reef system than just deep-water facies, which caused only small composition of carbonate mud. This facies is more widely distributed compared to the others, and interpreted to continue in the subsurface area.

Introduction

Northeast Java Basin is one of the most prolific hydrocarbon basins in Indonesia. It is part of the back arc basins developed around the margins of the Sunda Shield, from North Sumatra to Central Sulawesi. Onshore East Java is well explored and has been producing oil since the late 19th century. Exploration of the East Java Sea began in the early 1970's and has proven significant gas reserves (including Pagerungan and BD), and a number of currently sub-economic oil and gas finds.

Until today, hydrocarbon exploration in Northeast Java Basin has Pliocene Globigerinid Limestone – a deep-water facies – as one of its main reservoirs. New play concept is highly expected, especially in carbonate reservoir that involves facies varieties within a depositional system. A field study is brought up to conduct a stratigraphic measurement and rock sampling in study area to later analyse if there are other reservoir alternative, especially within Pliocene carbonates interval. This study covers most Madura Island, which was divided into three works area: the western, central, and eastern area. From the regional geology point of view, the study area include in the easternmost Rembang Anticlinorium of Northeast Java Basin.

Regional Geology

East Java Basin is one of the most prolific basins in Indonesia. It contains thousands meters of tertiary sedimentary sequence. The sequences have a good potential of hydrocarbon source rock and reservoir rock, the two most important elements of a petroleum system and were reported in almost all stratigraphic levels from Eocene to Pliocene. Those mainly are the Eocene Ngimbang clastics and carbonate, Miocene Ngrayong clastics and carbonate, Pliocene Kawengan carbonate and clastics.

Study area is located on the southeast edge of the Sundaland craton which basements are Cretaceous and Early Tertiary mélange. East Java Basin is a back-arc basin, which is bounded to the south by a young east-west trending Quaternary Java volcanic arc. Northern boundary is NE-SW trending Masalembo High, to the west is bounded by Karimunjawa Arch, and passes eastwards into the deepwater Lombok Basin. It covers an area of approximately 50,000 km^2. The major part of this basin at present forms the onshore of East and Central Java, and Madura Island, while the rest lies offshore below the Java Sea. Three major distinctive structure provinces can be identified in the East Java Basin such as Northern Platform, Central High, and Southern Basin (Figure 1).

Stratigraphy

In the Madura Island, Situmorang (1983) composed stratigraphic column (Figure 2) which can be described from oldest to youngest as follows:

1. Tawun Formation

This formation consists of claystone with sandstone intercalation, limestone, and conglomerate. Foraminifera, mollusk, and coral are identified within this formation. Based on fossils assemblage, it is interpreted that this formation was deposited in shallow, outer shelf of an open marine environment during Early to Middle Miocene in age. Thickness of this formation is ranging form 650 to 1500 m (Pringgoprawiro, 1983).

2. Ngrayong Formation

This formation consists of sandstone with claystone intercalation, marl, and orbitoidal limestone. Ngrayong Formation was deposited conformable overlies the Tawun Formation. The sandstones are red to yellowish red in color, showing a soft sediment deformational structures and scattered vertical burrows of *Ophiomorpha*. The occurrence of ripple mark and gypsum crystals at the lower part of this formation indicates that this unit was at first deposited in an intertidal environment (red sandstones) then deepened into the middle shelf environment which produced orbitoidal (*Cycloclypeous*) limestone (Burgon et al., 2002). Based on paleontological analysis, this formation indicates N9-N12 (Middle Miocene) in age. From geological section, the thickness of Ngrayong Formation is about 300 to 500 m.

3. Bulu Formation

Bulu formation overlies the Ngrayong Formation and is widely distributed in Rembang Anticlinorium. It consists of alternation of calcarenite with sandy marl. In Madura, this formation is found narrowly in the northern part with east-west trending, with thickness of about 200 m. Foraminifera fossils found within this formation are including *Lepidocyclina sp*., *Cycloclypeus sp*., *Operculina sp*., *Orbulina universa*, *Textularia sp*., *Hastigerina sp*., *Miliolid*, and *Globigerinoides sp*. (Azis et. al, 1993). These fossils indicate late Middle Miocene age and shallow marine of depositional environment.

4. Pasean Formation

This formation consists of an alternation of sandy marl with clayey limestone and sandy limestone and was deposited conformably over the previous formation. Sandy marls and limestone of this formation are well bedded and containing many foraminifera fossils, such as *Lepidocyclina rutteni*, *Lepidocyclina sp*., *Cycloclypeus sp*., *Operculina sp*., *Orbulina universa*, *Globigerinoides obliquus*, *Globigerinoides sp*., *Hastigerina sp*., *Brizalina sp*., *Tritaxia sp*., *Univegerina spp*., *Eponides sp*., *Robulus sp*., *Ammonia sp*., and *Nonion sp*., (Azis et. al, 1993). Based on those fossils assemblage, this formation is suspected was deposited in shallow marine (inner sub-littoral) environment and indicating Late Miocene in age.

5. Madura Formation

Sandy limestone interbedded with marl and massive limestone is the main component of the Madura Formation. Madura Formation is widely distributed in the northern and southern part of Madura Island. This formation has thickness of about 100 - 250 m. It was deposited unconformably over the Bulu Formation during Late Miocene to Pliocene age.

6. Pamekasan Formation

This formation consists of claystone, quartz sandstone, and conglomerate. Pamekasan Formation occupies gently hills on the southern part of Madura Island. It has thickness of about 250 m. The fossil assemblage indicates shallow marine (littoral) depositional environment and Pleistocene age (Azis et al., 1993).

7. Alluvium Deposit

Sand, clay, mud, pebble, and cobble of fluvial, coast, and swamp deposits are the general composer of alluvium deposit in Madura area. They are widely found in coastal area with indication of fluvial, wave, and wind influence in sedimentation.

Methodology

This study was conducted in the onshore of Madura and Puteran Island, Northeast Java Basin. The research aims to figure out if there are upside reservoir potential that can be utilized in the petroleum, play within the basin, which is one of the mature and proven basins in Indonesia. The appraisal used in this research consists of literature overview about the basin and surface data collecting including making outcrop measured section by using Jacob staff and rock sampling. Measured stratigraphic sections (MS) were conducted in areas containing exposures of sedimentary rocks. Rock samples were taken systematically at some representative parts of the section to be further analyzed in the laboratory (paleontology and petrography). The combination of thickness and sedimentological features observed in the MS with the result of laboratory analysis (including porosity and permeability) were finally utilized to define the characteristics of Pliocene carbonates as the reservoir alternative in the study area.

Study Result

Structural Geology of Study Area

Northeast Java Basin has three major distinctive structural provinces that have been controlled by tectonic evolution in this region; there are the Northern Platform, Central High, and Central Deep (Satyana and Purwaningsih, 2003). Madura and Puteran Island were located in Central High area, which associated with Rembang – Madura - Kangean (RMK). Madura and Puteran Island are located in Rembang – Madura - Kangean (RMK) zone controlled by major E-W trend of striking wrench zone (Manur and Barraelough, 1994). The rifting in Northeast Java Basin began due to NW subduction during Early Cretaceous along SE Kalimantan with oceanic plate (PND). The subduction trend has been shifted to southward in Eocene and reactivated in Early Miocene (PND, 2006). Reactivation during Neogene lead to widespread inversion and caused uplift of the older graben (both of Early Cretaceous NE-SW and Eocene E-W), produced major E-W trend of striking wrenching (PND, 2006) to represent a major sinistral shear zone (Manur and Barraelough, 1994). Based on observation in the field, several major thrust faults and anticlines as the product of Neogene inversion are mostly found in Miocene Ngrayong sandstone.

Stratigraphy of Study Area

In regional stratigraphy of Northeast Java Basin, several authors have known Pliocene carbonate deposits as Selorejo Formation in Rembang and Randublatung zones (Musliki et al, 1996) or Sonde Formation in Kendeng zones (Harsono, 1983 in Musliki and Suratman 1996) but generally as Pliocene Globigernid Limestone. Actually, Pliocene carbonate or Globigernid Limestone is representative of highly porous carbonate, and is composed by a high abundance of planktonic foraminifera *Globigerina*. The outcrops of Pliocene carbonate are also extensively exposed throughout north and south flank of onshore Madura to Puteran Island in the east. Based on GRDC map (1992), Pliocene carbonate deposits in Onshore Madura to Puteran Island were formally named as Madura Formation.

Based on observation supported by sedimentological analysis by thin section, the outcrops of Pliocene carbonate in onshore Madura to Puteran Island did not included facies of Globigernid limestone but wide variety of carbonate facies. The variations from the north to the south were interpreted to be deposited in transition -shallow marine until deeper marine facies. In regional stratigraphy, Pliocene carbonate in Onshore Madura to Puteran Island overlie conformably on top of Pasean Formation (Late Miocene) and covered by Pamekasan Formation (Pleistocene) (GRDC,1992). Stratigraphy measurements in Onshore Madura to Puteran Island show lateral facies distribution with inter-fingering relationship of the exposed Pliocene carbonates. All facies are defined by grouping based on characteristics of lithology (depositional texture, composition, fossils, sedimentary structure) and sedimentology, into four group facies:

A. Coarsening Upward Sandy Bioclastic Floatstone Intercalated with Paleo-Soil Interbeds

The facies of sandy bioclastic floatstone is very muddy and distributed along north flank of Madura Island from West until Central Madura. This facies is composed dominantly by carbonate muds with light brown in color, coarsening upward and highly abundance of macro fossils such as as gastopod, pelecypod, unidentified fragments, burrows of pelecypods and many branching coral clasts (external mold of *acropora* sp.?). These fossils are insitu but the fragmentsof unidentified valveand branching coral clasts, have been interpreted as exitu fossils (Figure 3).

Several quartz grains (fine sand size) have been identified and have irregular bedding. Between its beds is intercalated by paleo – soil that has been identified by the texture characteristic very loose and composed by some quartz grains. The fine quartz fragments probably came as product of erosional process of Miocene Ngrayong quartz sandstone.Based on thin section, this facies has 7-22 %porosity in moldic, intra-grain, vuggy, and fracture poretype.

The facies of sandy bioclastic floatstone was deposited in complex of fringing reef in low energy, shallow and warm condition which is showed with high abundance of benthic fossil such as gartropod and pelecypod, associated with their burrow in muddy limestone. This facies was deposited near with both of terrestrial and reef complex that more deeper or more far from terrestrial, because infux of fine quartz grain and fragment of branching coral also preserved. Intercalated of paleo-soil was indicated the abruptly local changed of sea level as impact of tide effect.

B. Bioclastic Wackestone – Floatstone

The facies of bioclastic wackestone - floatstone facies have been found in south flank of Madura. Distributed from West Madura until East Madura. This facies composed dominantly by carbonate mudswith light cream in color and highly abundance of larger benthic foraminifera (*Cycloclypeus sp.*, *Amphistegina sp*.) and associated with fragment of red algae, small planktonic foraminifera, mollusc valve, quartz grain, high abundance of inner mold of braciopod fossils and micrite. Inner mold of braciopod fossils has been identified as insitu type. Several part intercalated with wackestone facies that is composed also by larger benthic foraminifera. Based on thin section, this facies has 23 – 40 %

porosity by visual identification in vuggy, channel, and inter-grain pore type and 20,03% porosity with 4877 mD permeability on mercury intrusion porosimetry.

The depositional environment of bioclastic wackestone – floatstone is lagoonal area which its has been shown by high abundance of insitu inner mold bracipod fossils that were lived in trasistional and closely area. Muddy limestone showed texture of low energy condition and associated with larger benthic foraminifera. Major species of larger benthic foraminifera indicated shallow marine and still located in transition area which influx from terrestrial can be preserved also. Several fragments of red algae has been identified and showed transportation mechanism from near area which is more active and high energy that could be is environment of reef complex (Figure 5).

C. Massive Coralline Framestone – Rudstone

The facies of massive coralline framestone – rudstone actually is composed by similar composition but different size. This facies has been found locally in West Madura, Central Madura until East Madura. The main composition is massive coral and very thick in framestone facies. Massive coralline framestone – rudstone facies have greyish black color and sharp contact between beds but have been recrystallized extensively by diagenetic process. Based onvisual determnation in thin section, this facies has 2-4 % porosity in moldic pore type.

The facies of massive coralline framestone – rudstone was clearly deposited as part of reef complex but need more evidence to identified it as part of barrier reef. Massive coral associated with coral fragments intercalated between its has been indicated that this facies was deposited in high and active energy condition, far away from terrestrial because the composition lack of silisiclastic. Bedding as evidence of sedimentary structure showed control of traction current, so this facies was deposited in flank of reef complex (Figure 4).

D. Foraminifer Grainstone – Rudstone

The facies of foraminifera grainstone - rudstone is widely distibuted with realtively NE-SW trendin Puteran Island and continue to East Madura. Actually, the major condition of its primary texture is difficult to identified. Primary texture of this facies has been changed to be chalky limestone by leaching intensively. In eastern part of Puteran Island, has been exposed this facies with good preserved and can be identified. This facies is composed dominantly by larger benthic foraminifera (*Amphistegina* sp., *Miogypsinoides* sp., *Textularia* sp., *Martinottiella communis*) and barren of small planktonc foraminifera (Figure 6).

Several beds has associated with fragment of coral, inner cast of pelecypod and gatropod fossils.Others composition are unidentified valve (probably benthic foraminifera), coral fragments, algae fragments, and micrite.This facies actually a little bit loose and slightly carbonate mud contain. Based on visual determination with thin section, this facies haspore space around 30 - 36% from moldic type and based on mercury intrusion porosimetry showed 22-28 %porosity and 355 mD permeability.

The facies of grainstone – rudstone was interpreted to deposited in deeper marine environtment. Actually this facies is not same with Globigerinid limestone because comparison between the composition and texture is signifacantly different. Based on the composition, major fossils were reef builder and associated with pelecypod and gastropod fossil. Depositional environtment of this species is more deeper than shelf, more active and moderate energy area because slightly carbonate mud still preserved.

Discussion

The characteristic of Late Pliocene carbonate in onshore Madura to Puteran Island is totally different comparing to facies characteristic of Globiigerinid limestone. Based on obeservation in onshoreMadura to Puteran Island, has been identified 4 major depositional facies with inter-fingering relationship to each others.From north to the south flank in onshore Madura to Puteran Isand, all of facieses which its composed Pliocene carbonate are coarsening upward sandy bioclastic floatstone intercalated with paleo-soil interbeds, bioclastic wackestone – floatstone, massive coralline framestone – rudstone, and foraminifer grainstone – rudstone.Actually, the characteristic of Globigerinid limestone has been identified in several hydrocarbon field in southern part especially in offshore Madura Strait,which is probably have inter-fingering relationship to others (Figure 7).

Modelling for depositional environment of Pliocene carbonate in Onshore Madura to Puteran Island is built by collaborated the control of paleo-topographic with lateral distribution model of Pliocene carbonate.The reconstruction model of Pliocene carbonate depositional environtment showed the trend of lateral distributiion relatively E-W with lateral changingto other depositional facies relatively from the north to the south and continue to offshore area in along southern part of Madura to Puteran Island. Several explorationwells such as Maleo-1 and Maleo-2 in Maleo gas field, have shown Globigerinid limestone that high porous and good permeability as the reservoir target and produced gas (Triyana *et al.*, 2007).

The changing of depostional facies of Pliocene carbonate was an significant implication from factors that controlled it such as depositional characteristic such as influx of terrestrial material, temperature, depth, salinity, depositional energy, current type and others within it.All of this factors implied to the variety of carbonate depositional environement that were developed in onshore Madura to Puteran Island.From the north flank, the complex of fringing reef facies showed low – moderately energythat produced it and the depositional energy was decreased to develop and deposite lagoonal facies. Continue more to the south flank of onshore Madura Island, th barrier reef facies was deposited in depositional energy that more higher and active. The condition was changed gradually more moderately energy to deposited deeper marine facies in onshore Puteran Island.The explanation of heterogeneous facies and model of depositional environment in onshore Madura to Puteran Island have been controlled by paleo-topography that was formed during Pre-Pliocene until Pliocene and influx of sediment supply from terrestrial.

The stratigraphic correlation of several lithology logs with supported by sedimentology analysis allow for the interpretation of Pliocene carbonate and correlated to eustatic sea level and local tectonic that had significant iinfluence to explain the architecture of depositional environtment and their geomerty. Eustatic sea level during Pliocene was relatively falling (Sloss, 1963 in Walker, 1992) but influenced from local tectonic more significant to controlled of paleo topography forming.Onshore Madura to Puteran Island was a shallow marine with open marine to the south and probably also to the north, because uplift and activated of RMKS from inversion of Northeast Java Basin in Pliocene. Forming of flower structure and rising Madura Island controlled the paleo-topography which in center to the north flank developed shallow marine and near with terrestrial where is Miocene Ngrayong sandstone was exposed. Some quartz grain as product of erosional process in exposed Ngrayong were deposited relatively far and deposited in fringing reef environment. facies formed are coarsening upward sandy bioclastic floatstone intercalated with paleo-soil interbeds.Some fragments of branching coral (their long is relatively 10-13 cm) also preserved as the evidence of finging reef along the north flank of Madura Island.

Onshore Madura to Puteran Island were interpreted tilting to the south and supported by the evidence of lagoon environment along central Madura that widely distributed from West to East Madura but wasn't in Puteran Island. This facies is very muddy with high abundance of brachiopod fossils indicated closely are to open marine and relatively mode deeper than in the north.Continue to the south, massive coral as part or flank of barrier reef complex is the boundary and helped forming of lagoonal environment in the north of it.Puteran island is the place to showed the last key of variety facies of Pliocene carbonate in study area which has shown foraminifer grainstone – rudstone but totally different with the characteristic of Globigerinid limestone. This facies was interpreted as reefal facies in deeper marine environment but still associated with reef complex as distal part of the reef flank. High abuncane of larger benthic formainifera, associated with fragment of red algae and some pelecypod and gatropod fossils have shown the association of reef builder. Southern most to offshore Madura Strait, Triyana *et al.* (2007) showed the presenced of truly Globigerinid limestone. This evidence helped to completed the series of Pliocene carbonate that was developed in onshore Madura to Puteran Island that controlled by fault movement.

Summary

The characteristics of Pliocene carbonates facies are generally controlled by dissolution process, but petrography analysis shows that depositional texture (product of depositional environment and mechanism) is the main influence. Grain supported foraminifer grainstone – rudstone facies acts as reservoir alternative in the area. Its good property is controlled by depositional environment with active current where this facies was formed (fore-reef that is directly influenced by oceanic current). The dominant composition of big foraminifers associated with red algae and some planktonic foraminifer indicate that study area has a more complex reef system than just deep-water facies, which caused only small composition of carbonate mud.

Acknowledgement

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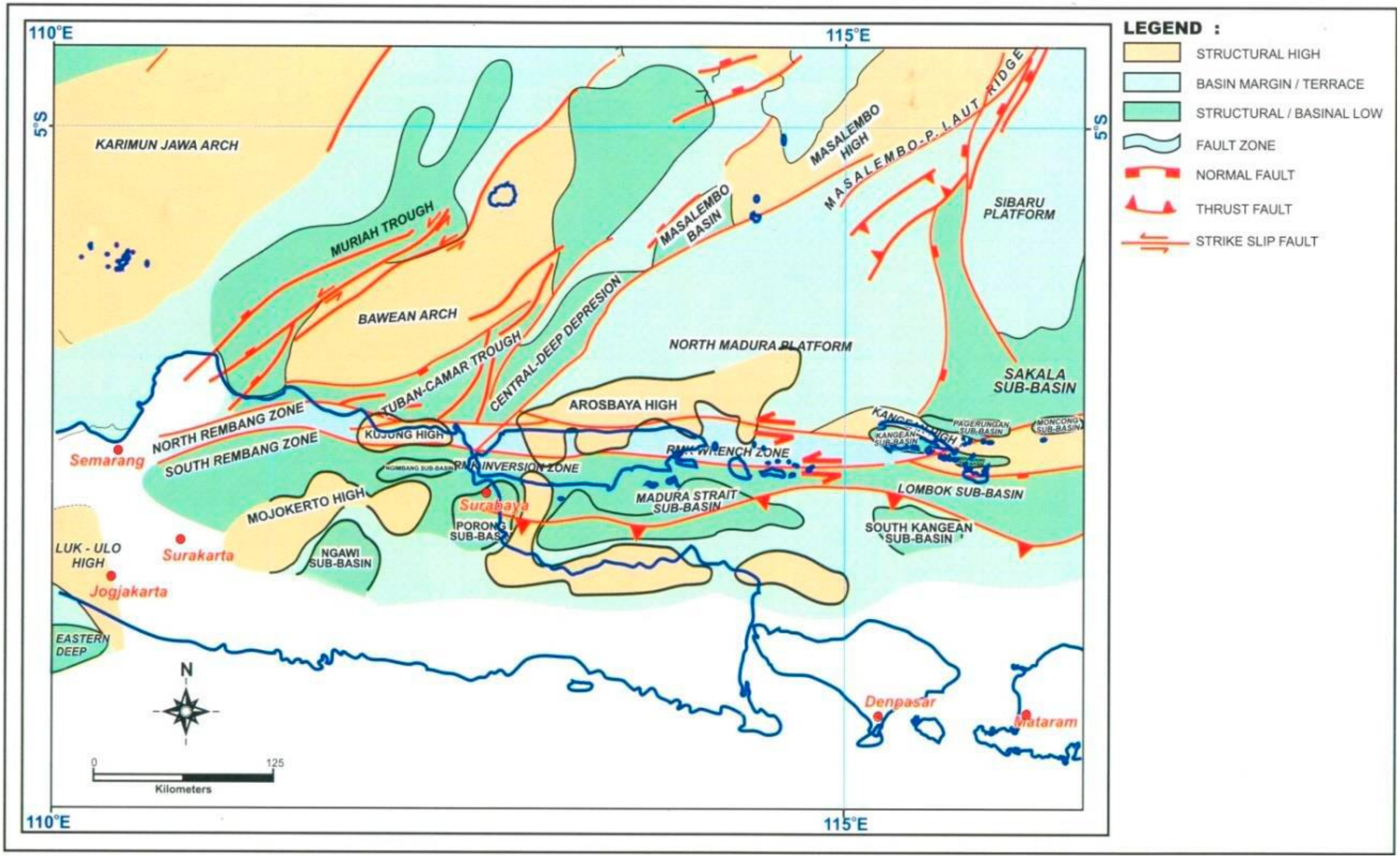

Figure 1. Structural configuration of East Java Basin (Bransden and Mathews, 1992).

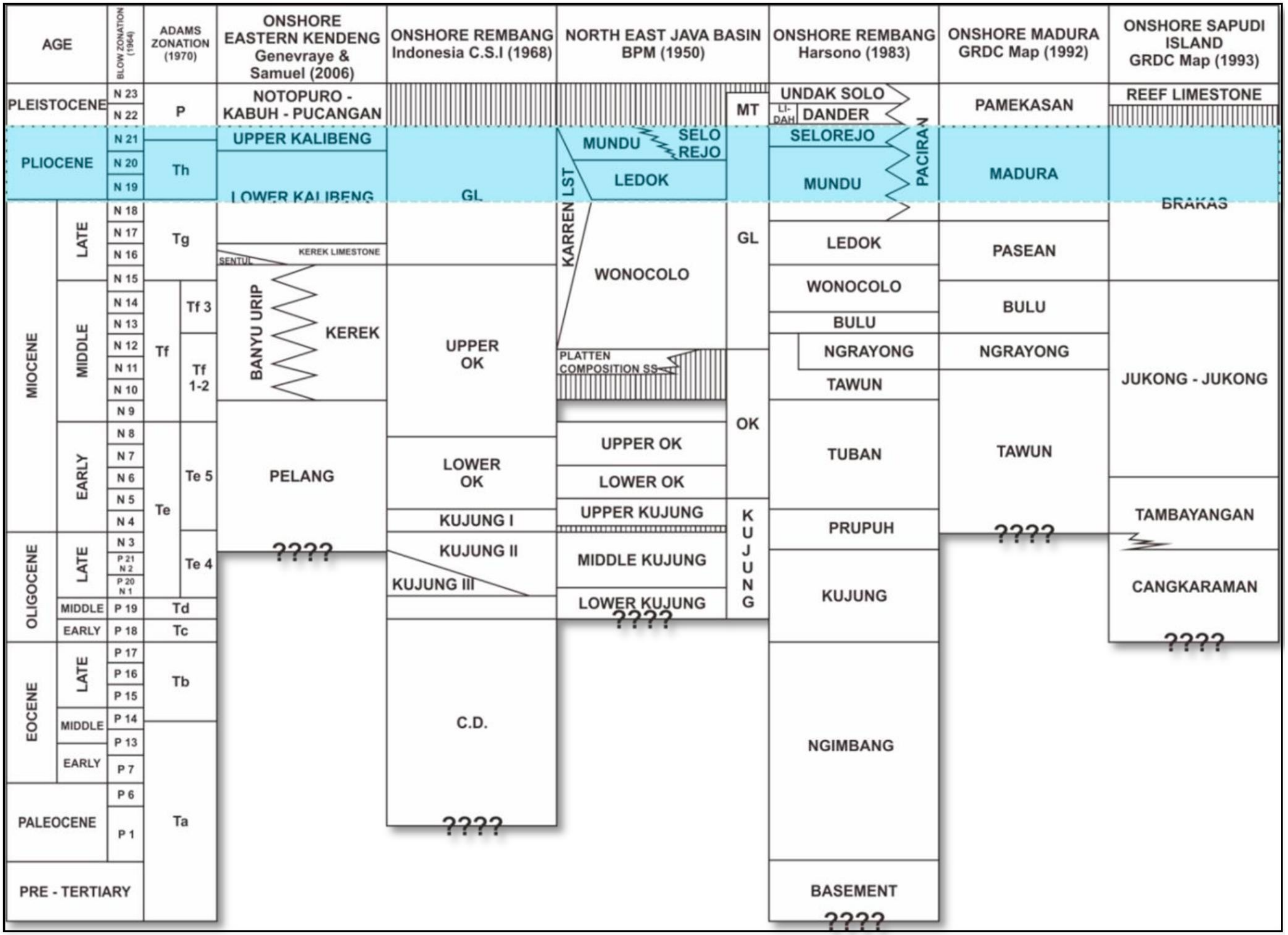

Figure 2. Regional stratigraphy of study area and its equivalency with others area in Northeast Java Basin (compiled from many sources).

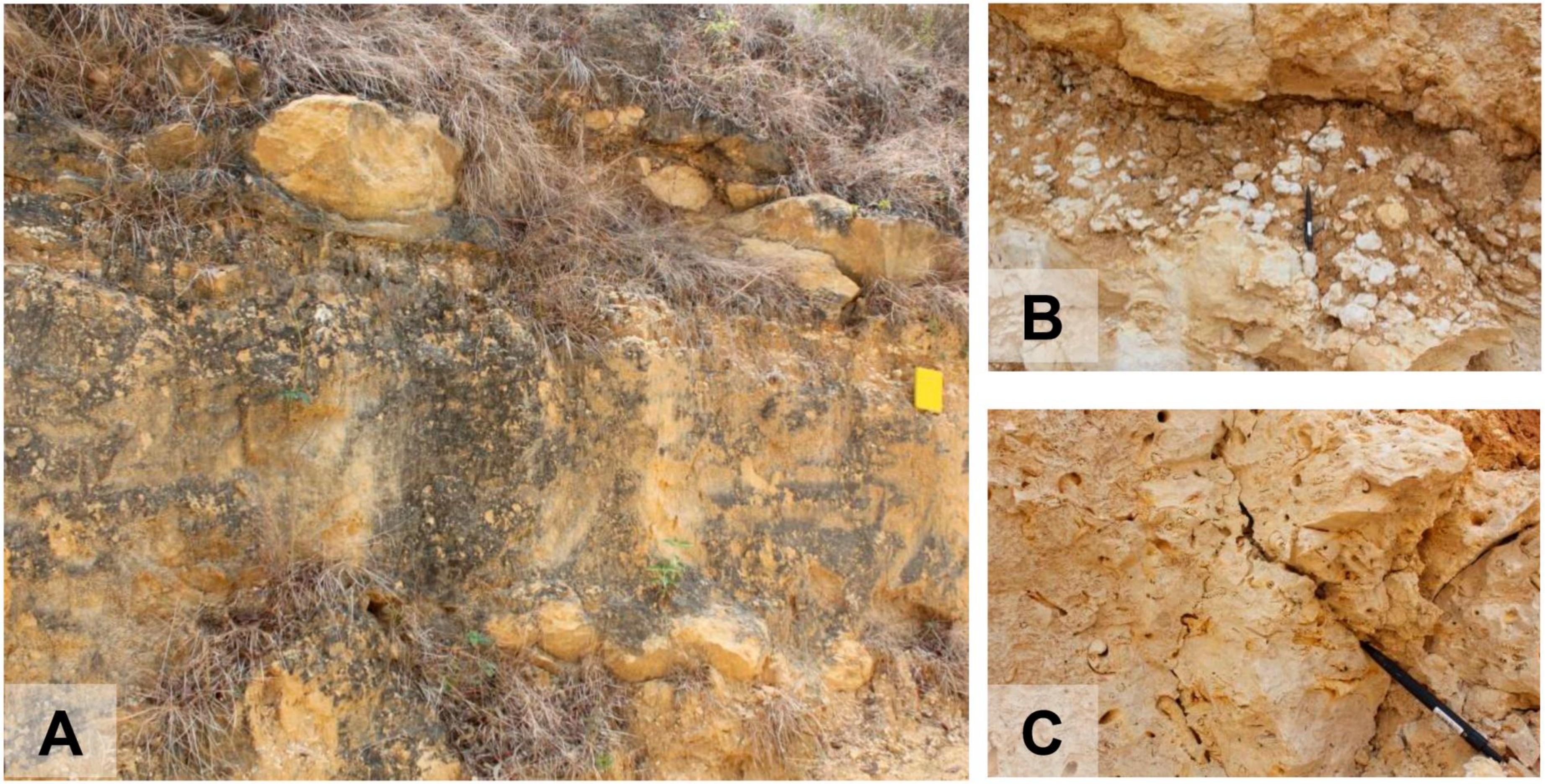

Figure 3. Outcrop of coarsening upward sandy bioclastic floatstone intercalated by paleo-soil interbeds as fringing reef facies.

Figure 4. Outcrop of massive coralline framestone – rudstone as carbonate build-up (complex of barrier reef) facies.

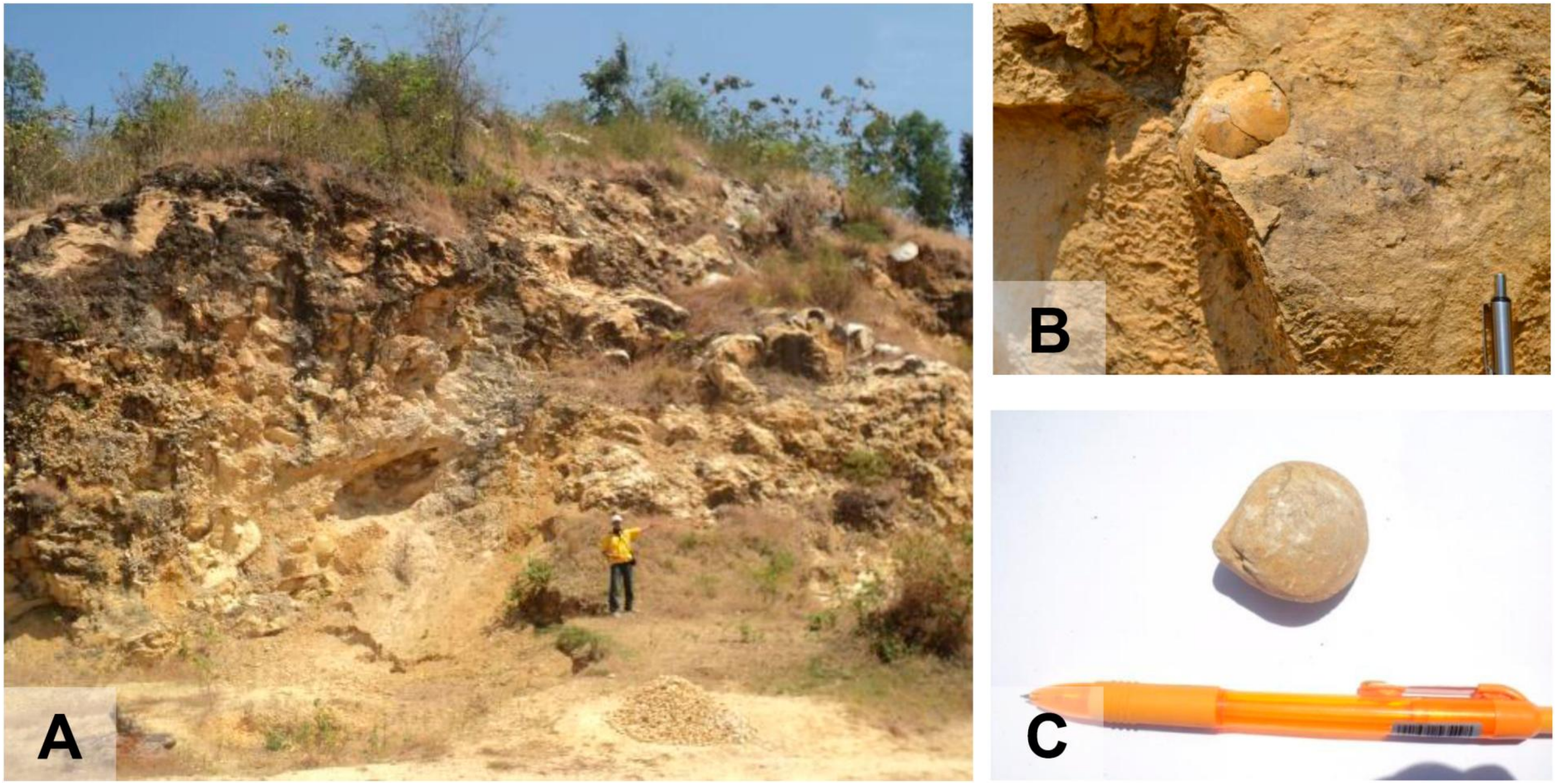

Figure 5. Outcrop of bioclastic wackestone – floatstone as lagoonal facies.

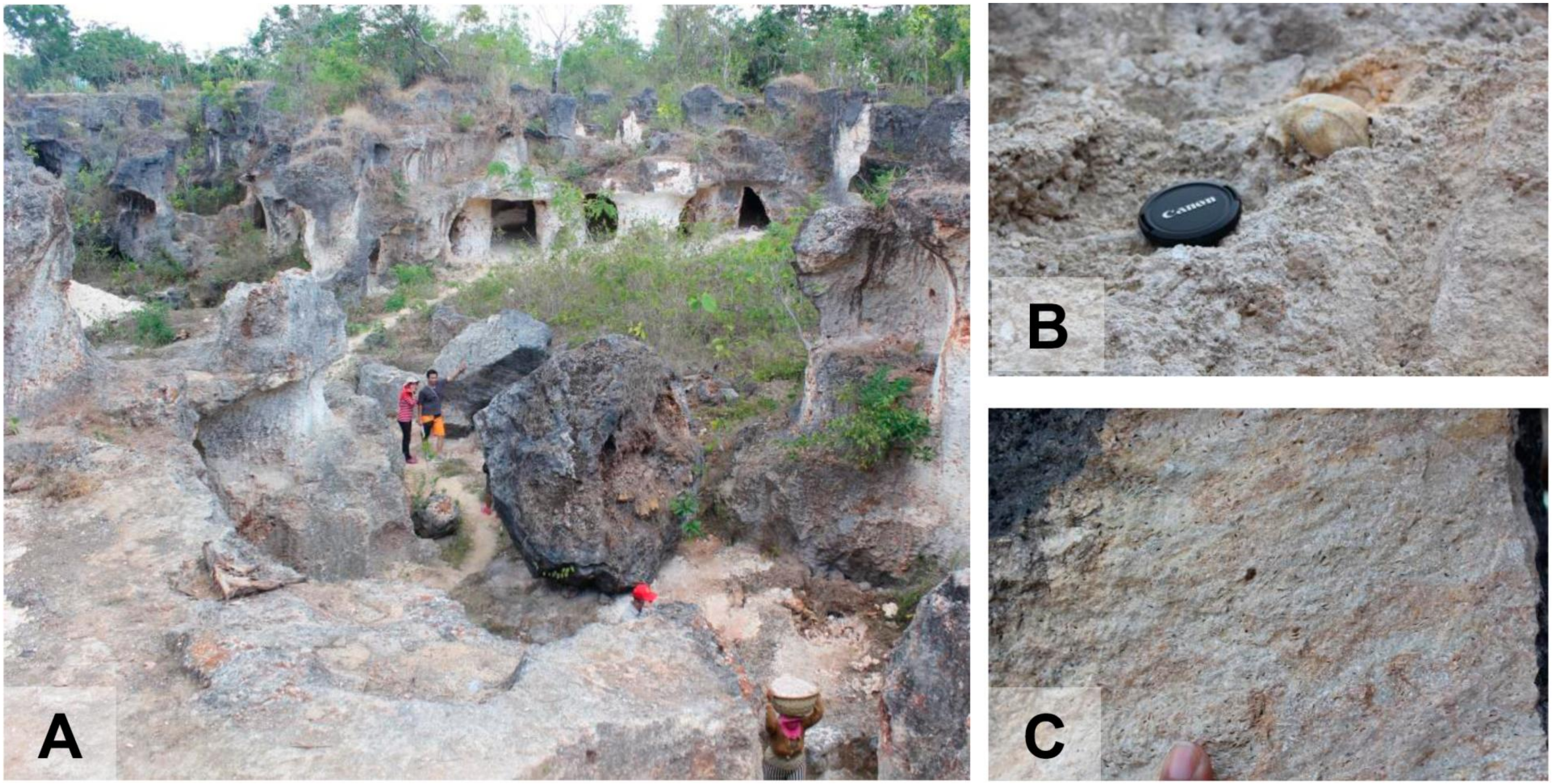

Figure 6. Outcrop of foraminifer grainstone – rudstone as deeper marine facies (reefal limestone – fore reef facies?).

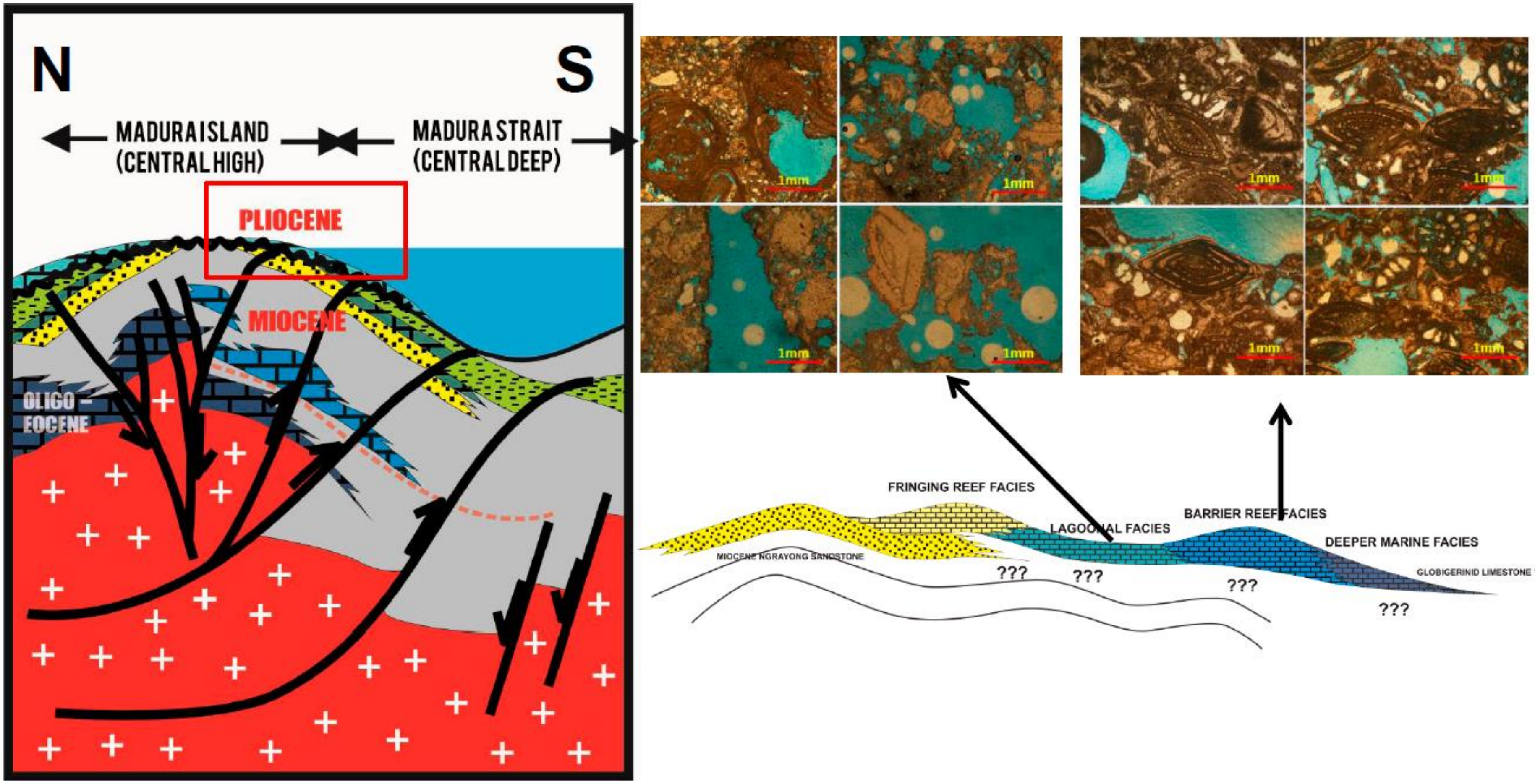

Figure 7.Geologial and facies changing model of Pliocene carbonate in Madura to Puteran Island (Modified from Sharaf et al., 2005).