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Reef Development as An Indicator of Sea Level Fluctuation: A Preliminary Study on Pleistocene Reef in Bulukumba, South Sulawesi

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Abstract - Coral reef is one of the best archives of a climate change. The reefs record the condition of environment where they developed. Indonesia as a tropical country has abundant coral reefs from Tertiary to Recent. The ancient reefs are commonly found along the coast and they form terraces. This research is located at the Selayar limestone of Bulukumba Regency, South Sulawesi. The objective of this research is to define paleoclimate change based on the coral development and sea level fluctuation. Sample collection was done by applying five intersect lines perpendicular to the cliff. Petrographic analyses of fossils, and microfacies study as well as the sea level fluctuation were analyzed by studying organism, reef development, and morphology. This article is focused on the sea level fluctuation analysis. There are three stages of the reef development and sea level fluctuation. It was initiated within a protected shallow marine to a reef front slope unconformably overlying siliciclastic rock. The second period of the reef development is characterized by the growing of branching, delicate, robust, and massive corals associating giant *Tridacna* sp. The third period is the formation of bafflestone delicate branching coral and robust branching corals. Following the Pleistocene reef development three beach abrasions (notches) were identified indicating the sea level fluctuation. Beach abrasions occurred during the Pleistocene reef development as the first notch. The second notch occurred at the reef crest and back reef during the first sea level fall and finally the recent sea level as the third notch.

Keywords: sea level fluctuation, Pleistocene, reef development, Selayar limestone

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Introduction

Quaternary reefs are well exposed along coasts in the eastern part of Indonesia. One of the reefs is found at the southern tip of South Sulawesi and it is mapped as Selayar limestone. The Selayar limestone spread out from Selayar Island in the south through Bulukumba Regency in the north. The ages of the rocks range from Upper Miocene to Pleistocene (Van Bemmelen, 1949) including raised Quaternary reef. In studying the Selayar limestone in Bulukumba Regency, Imran and Koch (2006) explained that the limestone developed as narrow coral reefs. Furthermore, the rocks are differentiated by terraces in which the highest terrace consists of the oldest rock in the northern part and the lower terrace is composed of the youngest one in the southern part. Imran (2000) divided the rock into four rock units, namely early Late Miocene reef of knoll-reef unit, Late Miocene – Early Pliocene reef of upper terrace unit, Late Pliocene reef of middle terrace unit, and Early Pleistocene reef of lower terrace unit. The development of reef terraces was driven by the uplifting that intensively affected the region of the southern arm of Sulawesi since Neogene (Sukamto, 1975). The Pleistocene reef growth shows a small reef complex as a fringing reef found along the coast of Bira area of South Sulawesi. Kennedy and Woodroffe (2002) discuss that sea-level fluctuations are important in the development of fringing reef. Furthermore, they propose seven reef growth models which are: model A, the fringing reef is established at a depth and primarily accretes vertically towards the sea surface; model B initiates at sea level and due to the lack of vertical accommodation space grows laterally; model C has a similar morphology to model B; however, the reef progrades over a nonreefal sediment wedge; and model D where the reef occurs episodically lateral and vertical growth with a stepwise progradation of the fore reef. The remaining models are characterized by a seaward reef framework behind which unconsolidated sediments accumulate. In model E, reef-crest growth forms a barrier leading to the development of a backreef lagoon. Model F has a similar morphology to model E, except that the reef crest is formed by hurricane rubble accumulation rather than a framework accretion, and is periodically reworked.

Coral skeletons give an excellent record of climate archives of tropical and subtropical areas (Eakin and Grottoli, 2006). Changes of sea condition such as temperature, salinity, upwelling, and ocean circulation are well preserved within coral skeletons. Indonesia as a tropical country has a lot of coral reefs from ancient to recent and is susceptible to a climate change. In the period 1997 - 1998, Indonesia experienced high damage of coral reef due to the changing of El Nino characterized by global warming (EUSAI, 2001). In the last 300 years, there is a significant increase in CO_2 concentration from about 280 ppm in 1700 to 360 ppm in 2000 (Figure 1).

De Klerk (1982) has studied the development of coral reefs (based on 14_C dating) in Spermonde Platform, South Sulawesi. He found that 4500 years before present, seawater was as high as 5 m above the present sea level. Hantoro *et al*. (1994) describeed an evolution of geodynamic processes in Alor Island, Indonesia, is affected by an uplifting with reference to Quaternary reefs. The indication of the uplifting was also found on

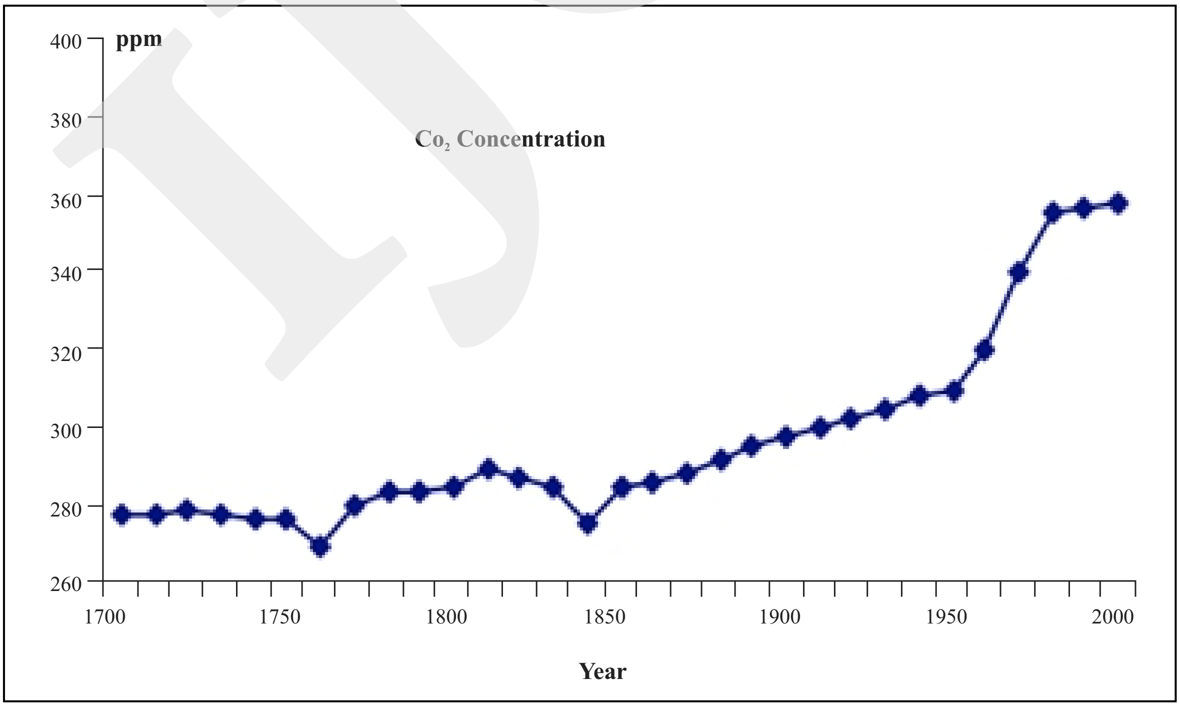

Figure 1. Historical data of rising CO_2 concentration during 300 years (1700 - 2000). Sources: Joosa *et al*. (1999).

the Quaternary coral reefs in Luwuk, east arm of Sulawesi (Sumosusastro *et al*., 1989) and in Bulukumba (Imran and Koch, 2006). Mann *et al*. (2016) have studied the Spermonde Island and suggest that there was a sea level fluctuation ca. 5600 cal. yr BP and reached the present sea level that was at around 4000 cal. yr BP.

The studied area is predominantly made up of Plio-Pleistocene reef, Pleistocene reef, and modern reef. They are the member of Selayar limestone, Walanae Formation (Sukamto and Supriatna, 1982). The Selayar limestone in Bulukumba area formed at least four terraces (Figure 2) indicating an active tectonism during and after the reef development. According to Imran (2000) and Farida (2002), the studied area experienced rapture, forming terraces of reefs as well as the presence of notches (cliff abrasion results). The purpose of this study is to determine the depositional environment and the sea level fluctuation based on the reef development. At the end of this

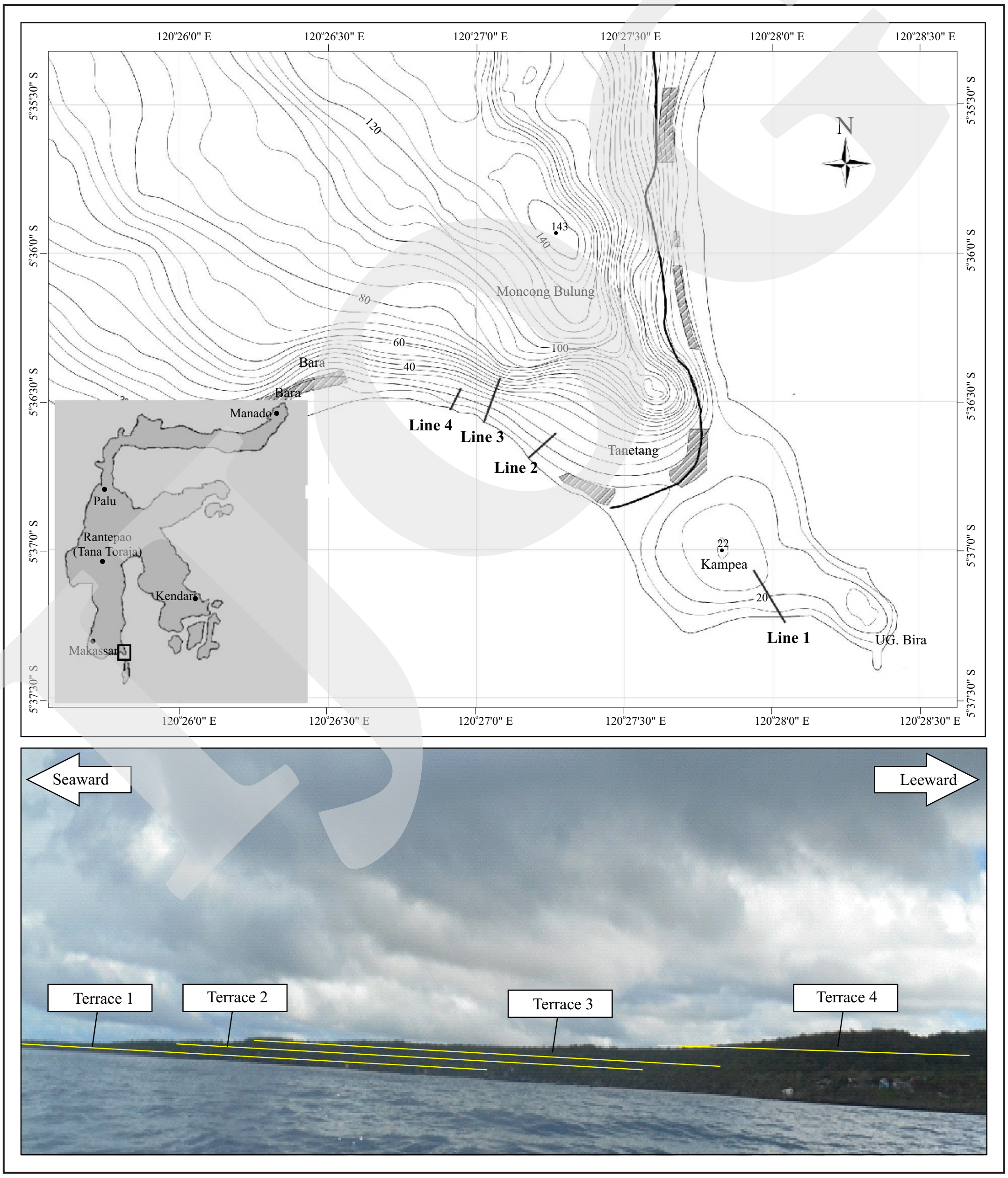

Figure 2. The studied area with four line transects (top), morfology of west side of Pleistocene reef showing terraces. The older terrace (terrace 4) lies on leeward corresponding to Pliocene reef (down).

study, a paleoclimate change as base data will be constructed to predict the future climate condition.

Methods

The study is focused on the Pleistocene reef cropping out in a lower terrace. Several methods were applied in this study, namely field survey, morphology and petrography analyses. The field survey was taken on four line transects which perpendicular and parallel to the shoreline (Figure 2). In order to get the geometry of the reef, a morphology view was done from the highest level surrounding the studied area. Petrography analyses on 21 thin sections were applied on matrixes for microscopic needs such as microbiofacies and fossil analysis. Thin sections from samples were done in Bandung. Furthermore, a petrography analysis was done in Petrography Laboratory of Geology Department, Hasanuddin University. The analysis was done under a polarized microscope to take the type and textural components of the rock. The lithology nomenclature used the classification of Dunham's (1962) as well as Embry and Klovan (1971). The paleontology analysis was done for identifying organism contents, especially foraminifera in Paleontology Laboratory, Geology Department, Hasanuddin University.

Results and Discussion

Geological Setting

Walanae Formation formed in the Walanae Depression trending north - south of South Sulawesi. It consists of volcanic rock, sandstone, and carbonate rock including Selayar Limestone (Sukamto and Supriatna, 1982). During the Middle Miocene, the growth of carbonate production in the western part of South Sulawesi was interrupted by volcaniclastic materials which buried the shallow water carbonate and allowed a new carbonate production in other sites (Wilson, 2000). Bromfield and Renema (2011) argued that the Selayar Limestone developed contemporaneously with volcanic activity in a protected area of distal environment during Late Miocene to very Early Pleistocene. The Plio-Pleistocene event was accompanied by a general uplift of the region as indicated by the subaerial nature of most Quaternary deposits. The local appearance of thin coal layers at the upper part of the Walanae Formation may indicate the beginning of this uplift. Raised Pleistocene coral reefs in the Walanae Depression and in North Bone probably lie unconformably upon the gently folded Neogene rock (Van Leeuwen, 1981).

Imran (2000) mentioned that the stratigraphy of the studied area is composed of foraminiferal Selayar Limestone overlain by Walanae Formation in some places. The Selayar Limestone has an age 5.8 - 1.4 million years or Late Miocene to Early Pleistocene and correlated with Taccipi Limestone Members of Walanae Formation (Bromfield, 2013). In the southern tip of Sulawesi, the limestone exposes several terraces, similar to limestone in the Selayar Island (Figure 3). The lower terrace has been described as a lower Pleistocene reef (Imran, 2000) and in Selayar Island is dated as very Early Pleistocene or 1.6 to 1.4 Ma (Bromfield, 2013). Through the observation of the reef terraces, it is determined that the higher terraces are located leeward and the lower terraces seaward. This geographic position is proportional to their age; the higher terrace is older. Similar characteristics were also studied in Alor Island, eastern part of Indonesia by Hantoro *et al*. (1994). His observations documented that the reefs were developed under the control of tectonics and sea level fluctuation and, therefore, the oldest terrace was developed in the highest part leeward.

Based on larger foraminiferal assemblage and lithologic characteristics supported by other organisms, the Selayar limestone is informally divided into four units (Imran, 2000; Imran and Koch, 2006). The units are: a. foraminiferal limestone unit; b. coral reef unit in the Bontotiro area and upper terraces on the Bira area of Bulukumba; c. coralgal reef unit on the middle terrace; and d. raised coral reef unit in the lower terrace. This study is focused on the raised coral reef and mapped as Quaternary raised coral reefs

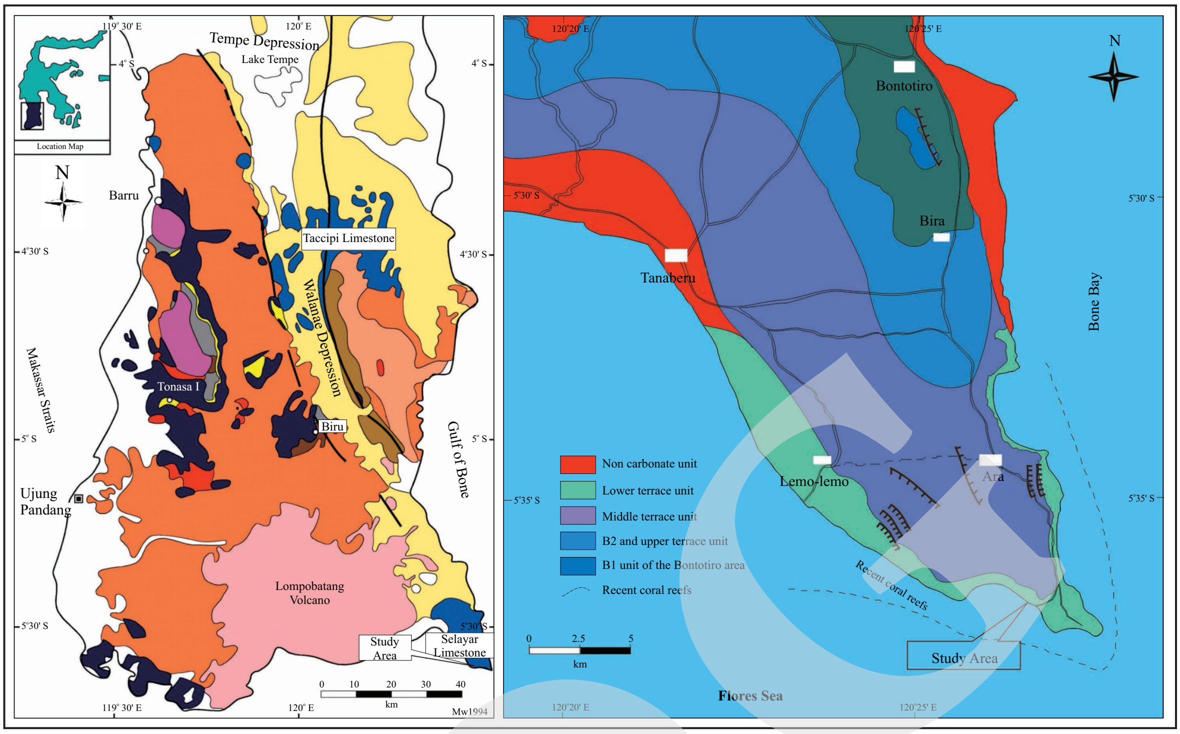

Figure 3. Geological map of South Sulawesi (left) and Selayar Limesone of Walanae Formation (right). (Modified from Sukamto and Supriatna,1982; Imran, 2000).

of Pleistocene age (Van Leeuwen, 1981; Van Bemellen, 1949).

The morphological survey shows that there are three subterraces consisting of Pleistocene reef in the west coast. The terraces indicating sea level fluctuations during and after the development of the reef can be interpreted as a result of a short term climate change and/or tectonic activities. Another indication of the sea level fluctuation is the presence of notches. There are three notches found in the Bira area, one notch at the Pliocene reef and two notches at Pleistocene reef. The Pleistocene reef is separated from the older Pliocene reef by a notch indicating sea level rise. The condition allowed the development of Pleistocene reef. The sea level fall occurred after the development of the reef marked by notches at the reef crest and back reef. The sea level fall continues to the present sea level and is marked by a cliff along the present coastline.

Pleistocene Reef Development

Three facies are described at the Pleistocene reef of Bulukumba Regency (Imran *et al*., 2015), those are: a. reef front facies, b. reef core facies, and c. back reef facies. The reef was initiated to develop within the protected shallow marine. It unconformably overlies siliciclastic rock of Walanae Formation. The second period of the reef development is characterized by the growing of branching, delicate, robust, and massive corals associating giant *Tridacna* sp. The third period is the formation of bafflestone dominated by branching coral. During its development, the reef has experienced at least three times of sea level fluctuation indicated by beach abrasion (notch). The notches occurred during the reef development which abraded the Pliocene reef, during the first sea level fall as the second notch at the reef crest and back reef and finally the recent sea level as the third notch.

Reef Colonization or Establishment (Model A)

Reef colonization of Pleistocene reef in Bulukumba is well exposed in the south coast of Bira area. It unconformably overlies the older rock of Walanae volcanics (Figure 4a). At the lower part, the reef is dominated by soft branching coral

(Figure 4b) which is mostly fragmented (Figure 4c). The other corals found at the base of the reef are massive. Burrowing structures commonly appear at the bottom of the reef (Figure 4d). They tend to increase in communities to the upper part (diversification zone). The reef forms a fringing reef establishing at a certain depth and accreting vertically towards the sea surface.

Under a microscope, matrix of the reef is characterized by bioclastic-packstone - grainstone. The bioclasts of the reef matrixes are commonly composed of coral fragment, red algae, gastropods, and foraminifera (Figures 5a and b). On the other hand, a thin section of tuff shows rich planktonic foraminifera (Figures 5c and d). Imran *et al*. (2015) suggested that the reef developed in the front reef zone as a reef front facies. The facies corresponds to the fore slope microfacies zone of Flügel (2010) and Wilson (1975). The presence of burrowing structures and branching corals indicates a low energy regime and is interpreted as a shallow subtidal and intertidal environment. It agrees to the theory of Garrett's (1977). The growth of the reef at the upper part from siliciclastic rock of Walanae Formation at the lower part separated by an angular unconformable relationship indicates a sea level rise environment. Such coral reef growth is the initiation to grow isolated coral colonies (Kennedy and Woodroffe, 2002). This first stage of reef development grew vertically to approach the sea level rise. This stage of Pleistocene reef in Bulukumba continues to form reef diversification.

Reef Diversification or Reef Model D

The reef diversification or model D developed not only vertically but also laterally. The reef model has a thick zone and diversifies coral organisms. The diversification of coral is characterized by the presence of massive coral with a

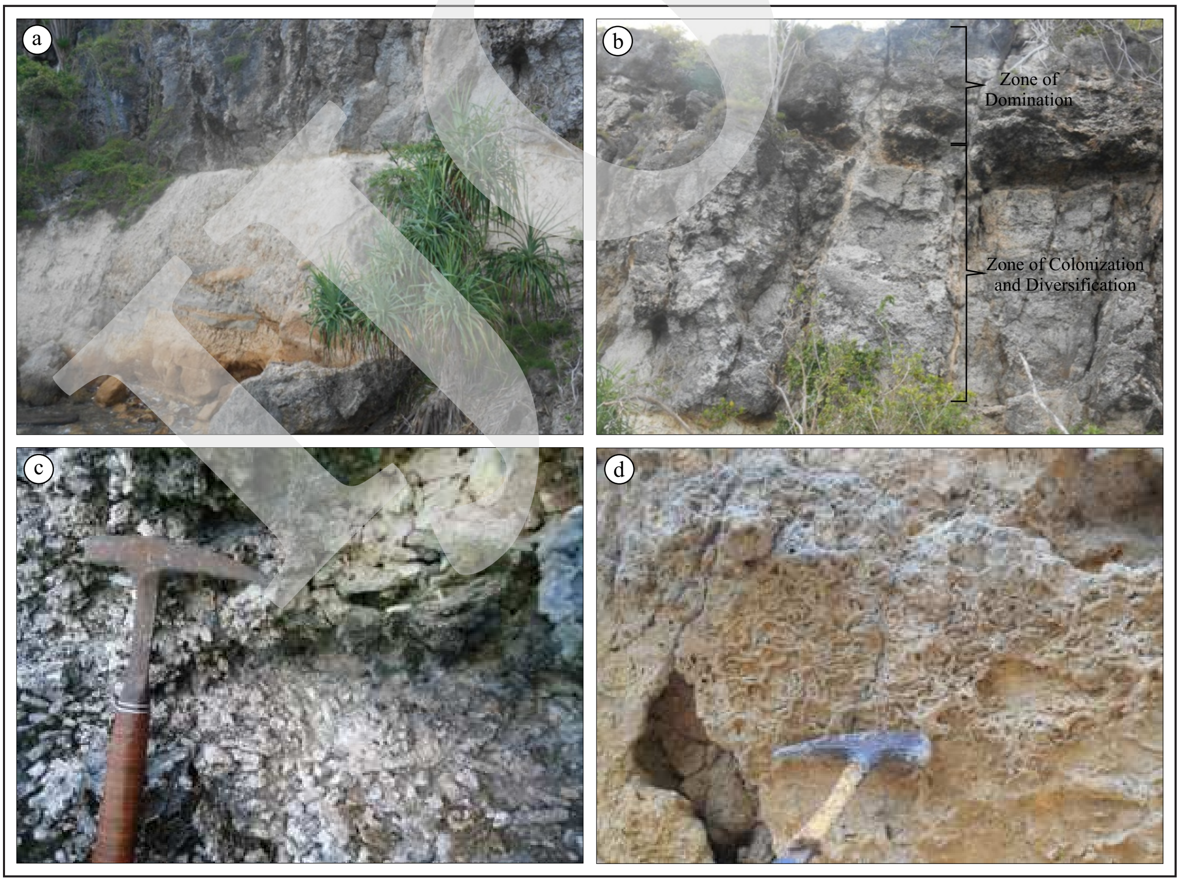

Figure 4. Field view of unconformable contact between Walanae volcanics at the lower part and Pleistocene reef at the upper part (a), reef development from reef colonization to reef domination (b), abundant burowing structures at the lower part of the Pleistocene reef (c), and well preserved of bioclast dominated by gregment of branching coral (d).

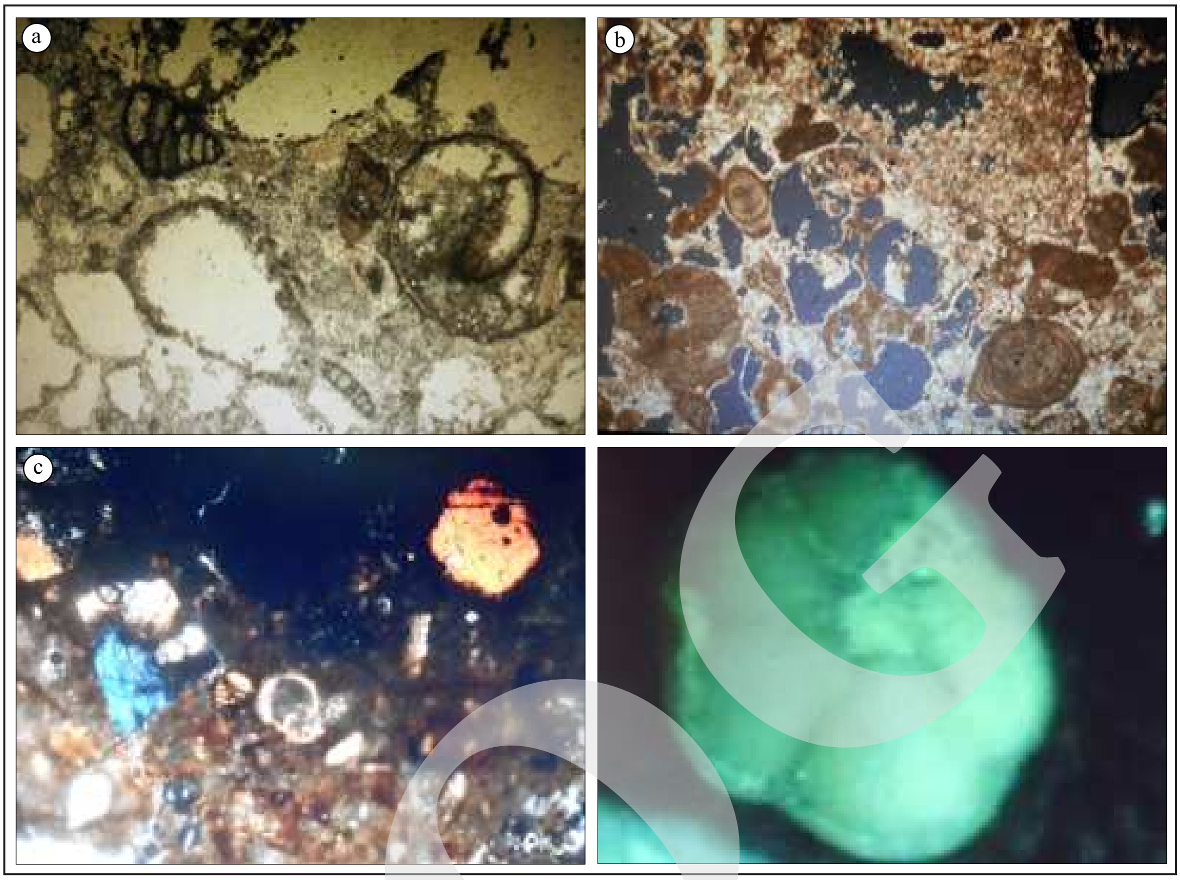

Figure 5. Photomicrograph of matrix within the reef colonization zone shows fragments of coral (a), red algae (b). planktonik froaminifera in thin section (c), and in a grain of *Globorotalia* sp. (d) found at the top of siliciclastic rock (tuff) (magnification 50x).

growth position standing as high as 1.5 m (Figure 6a) as a dominant organism to the leeward (Pliocene reef). The other common corals found in this zone are branching coral, head coral (Figure 6b), platy coral (Figure 6c), and delicate branching coral. Molluscs (*Tridacna* sp.) with a diameter of 10 - 45 cm (Figure 6d), small pelecypods, and gastropods as well as algae are commonly found as a reef builder within this reef model.

Laterally, the reef developed from reef slope the leeward, and formed back reef lagoon. Rhodolith channel-like deposits composing rhodolithic rudstone (Figure 7a and 7b) developed within this reef model. It has graded bedding structure with fining upward and contains foraminifera of *Amphistegina* sp. (Figure 7c), *Calcarina* sp. (Figure 7d), and *Heterostegina* sp.

The association of organisms and rock texture suggests a shallow marine environment with high energy. This type of environment appropriates to a reef front zone as suggested by James (1983) and Veron (2002). The presence of rhodolith channel-like is probably influenced by an upwelling current from Makassar Strait. Fragments of red algae (rhodolith) and rock fragments contained in this facies interprete that they experienced transport and accumulated in the channels at the diversification zone. The presence of *Tridacna* sp. in modern environments found up to 10 m of water depth (Rosewater, 1965) designates a shallow marine environment. In general, this reef zone, based on faunal compositions, developed in depth of about 10 - 20 m.

Reef Domination or Model E

The reef is the uppermost part of the reef complex consisting of reef-crest and backreef lagoon. This reef model is dominated by branching coral of Acroporidae (Figure 8a) extending from fore reef to back reef facies (Figures 8b - d).

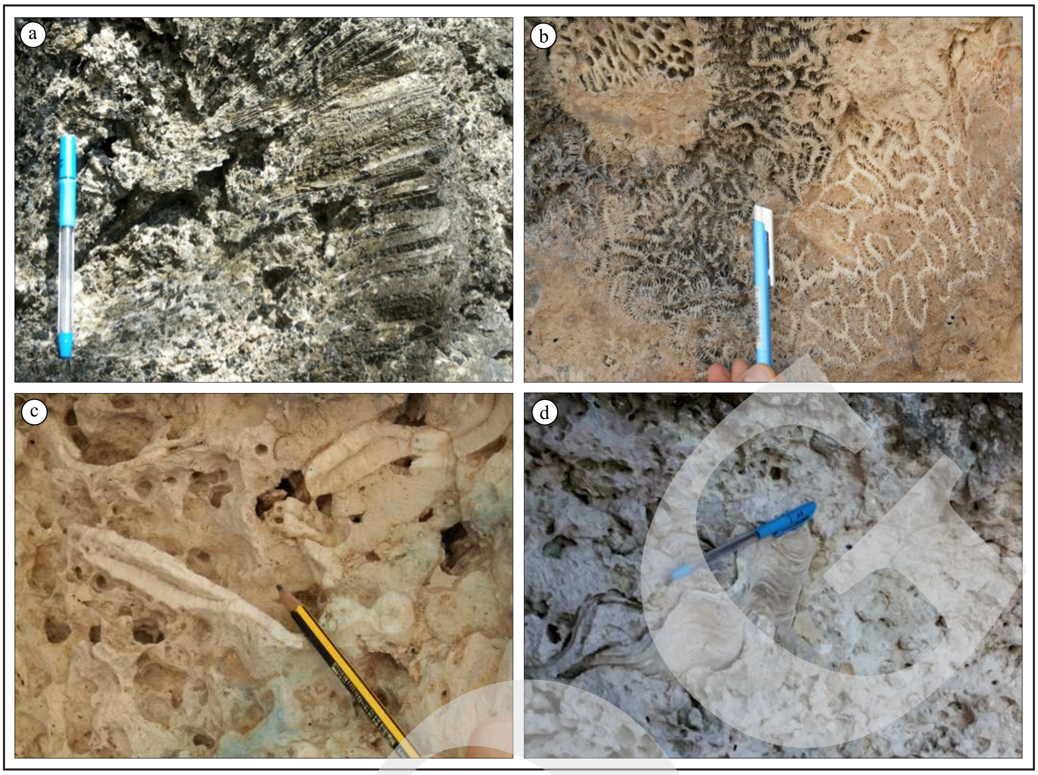

Figure 6. Outcrop coral variety within the reef diversification zone or reef model D showing massive coral of porites (a), head coral (b), platy coral (c), and bottom of the a pseudo bedding plane with *Tridacna* sp. (d).

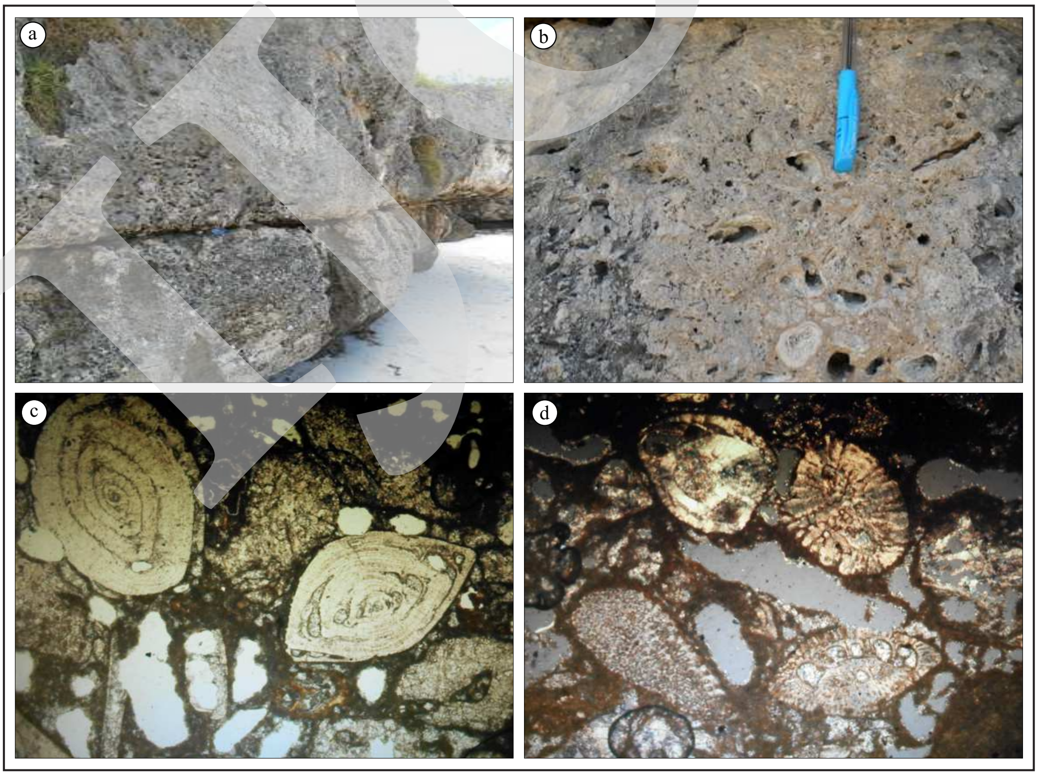

Figure 7. The outcrop of reef diversification zone or reef model D shows a pseudobedding plane separating rhodolite channel-like deposits at the lower bed to coral reef layerat the upper part (a), a fining upward grading of rhodolith-rich layer (b). Photomicrograph of *Amphistegina* sp. (c) and *Calcarina* sp. (d) are accumulated within the rhodolith layer. enlarged (magnification 50x).

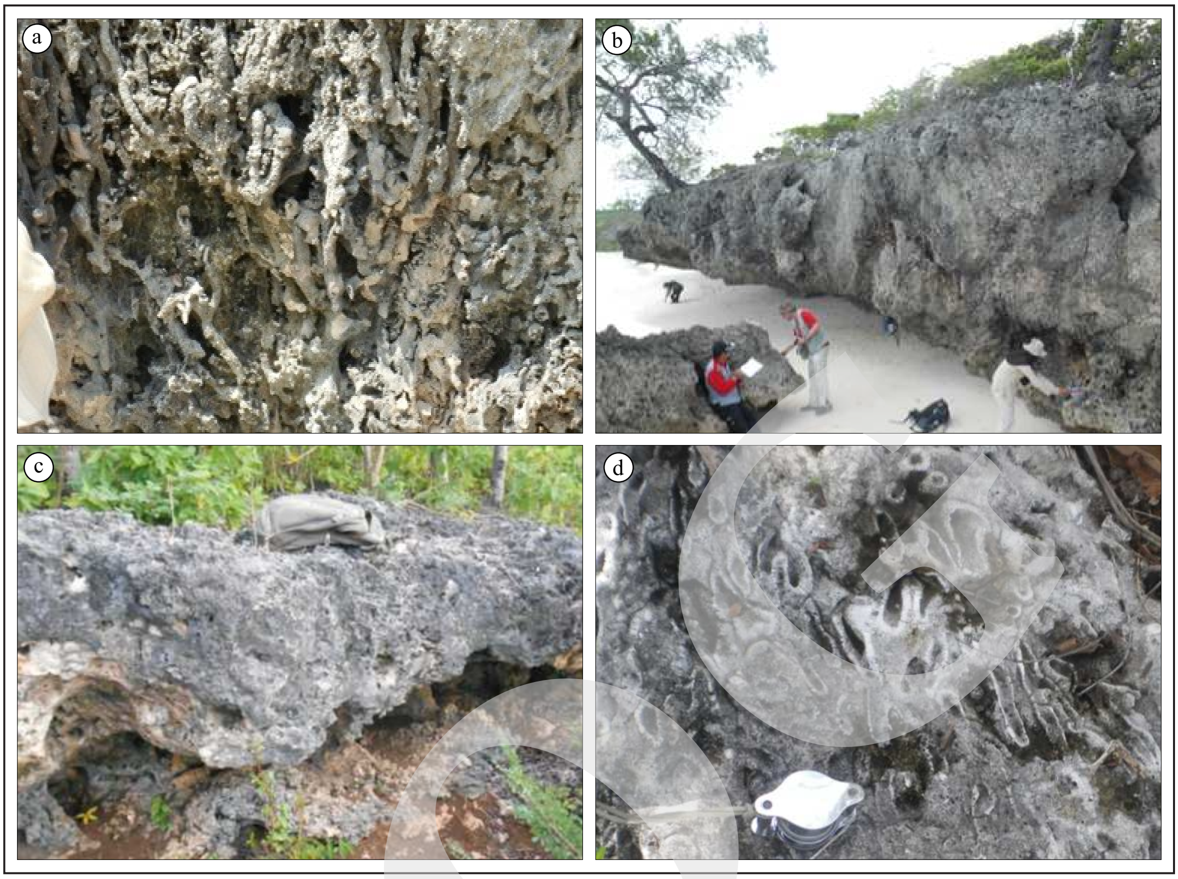

Figure 8. Outcrop of reef domination or E zone dominated by branching coral (a) and cropping out along the west coast (b) in the back reef facies. The reef is also found at the reef crest facies (c) which also common branching coral. The reef crest were abraded marked by notch. Branching corals are also common at the reef front (d).

To the north, branching corals are more common and form beach cliff as high as 5 - 7 m (Figure 8b)

Most of the corals are highly dissolved (Figure 9a) due to a diagenetic process since the rock exposes. They are also found as fragmented sediments and form bioclastic grain-rudstone texture at the reef slope towards lagoon or closed to the reef crest (Figure 9b). The other organisms found in this reef are red algae (Figure 9c) and foraminifera such as *Calcarina* sp. (Figure 9d), as well as green algae (Figure 9e). These organisms are commonly found within the matrix.

The presence of corals of genus Acropora as a fragile organism suggests a low energy environment with high sedimentation rate. Such environmental deposition corresponds to back reef or at reef slope in reef front. The reef is interpreted to develop as back reef and reef crest in the shallow marine. This reef zone (back reef and reef crest) experienced seawater abrasion marked as a notch. The environment of Acropora agrees with the Quaternary counterpart in southeast Sulawesi studied by (Crabbe *et al.*, 2006). Furthermore, they find that the reef crest and reef flat deposits are dominated by branching Acropora and developed in very shallow waters.

Sea Level Fluctuation During the Pleistocene Reef Development

The development of Pleistocene reef characterized by burrowing structures at the base of reef indicates a protected shallow marine environment overlying siliciclastic rock of Walanae Formation. This agrees with Suyono and Kusnama (2010) who found that sandstone of Beru Member (Walanae Formation) in the northern part of South Sulawesi was deposited within a transition zone during the Pleistocene time. The reef development is as an initiation of Pleistocene reef within

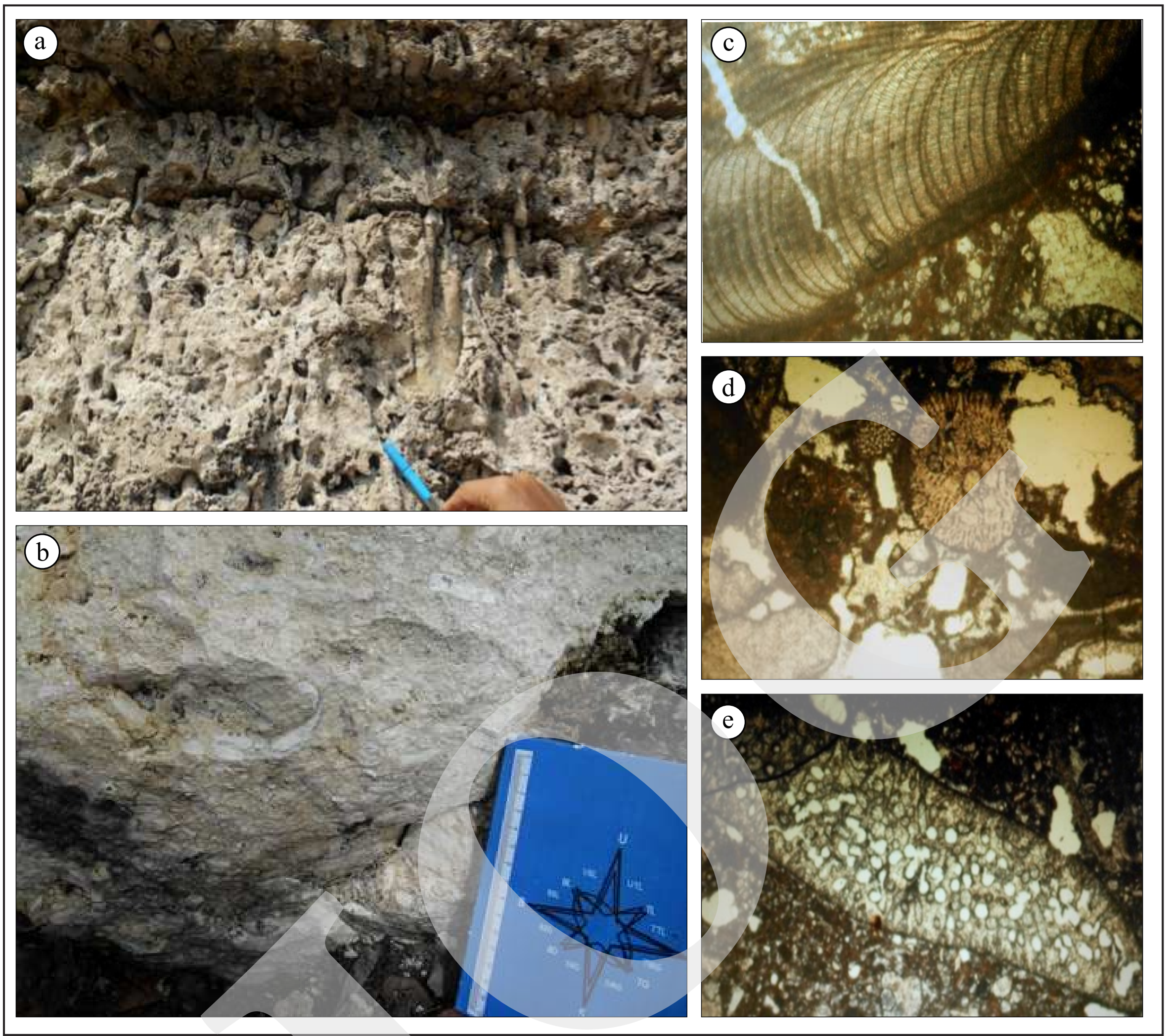

Figure 9. Outcrop coral variety within the reef diversification zone or reef model D showing massive coral of porites (a), head coral (b), platy coral (c) and bottom of the a pseudo bedding plane with Tridacna sp. (d) (magnification at figures c, d, e 50x).

the protected shallow marine. The occurrence of transgression allowed coral reef to diversify spreading from reef slope to back reef. During the transgression, it allowed soft branching coral to develop as high as up to 20 m. The sea level rise continuously occurred where branching coral development dominated this zone.

The sea level fluctuation on Pleistocene reef in Bulukumba can be traced by the presence of notches and reef development. The development of the reef from colonization through reef domination suggests a sea level rise or transgression (Figure 10). The development started from colonization on the Walanae Formation within slopes. It is marked by abundant burrowing structures. The sea level rise occurred to allow the reef community to grow and diversify in the diversification zone. This zone is designated by several types of coral such massive, branching platy, and head corals. This transgression continued to develop the domination zone of branching coral. These coral types are found from front reef to back reef. The environment development can be inferred from modern counterpart in Indo-Pacific region which has a 6 -15 m depth (Cabioch *et al*., 1999). Chappell *et al*. (1996) suggested that the Late Quaternary sea levels in Huon Peninsula represent a global pattern. They measured the sea level fluctuation in the reef terraces and to be in an agreement throughout the last glacial cycle.

Bromfield and Renema (2011) described environmental deposition of the Selayar Limestone

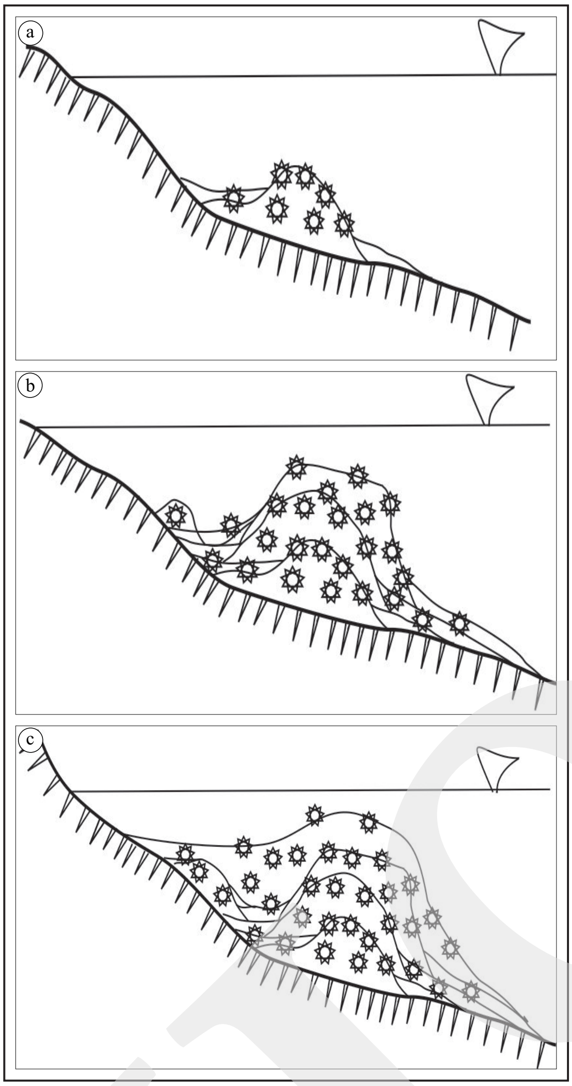

Figure 10. The illustration of the reef development in three stages: reef colonization (a), reef diversification (b), and reef domination (c).

with reference to Selayar Island ranging from 10 - 20 m depth in the reef slope. Furthermore, they argue that the presence of reef slope channel with reverse graded bedding in the upper Pleistocene reef represents a reef slope channel a higher energy environment. In the diversification reef, such channel deposits dominated by rhodolite imply a high energy regime.

A superimposed marine notch is identified on the older Pleistocene reef and Pleistocene reef. The notch spread out parallel to the recent coastline at the latitude of around 15 m which abraded the Pliocene reef (Imran, 2000; Imran *et al*., 2015), 7 m at reef crest and back reef (Figure 11) above the present sea level. The notch at the Pliocene reef indicates an abrasion process during the development of Pleistocene reef (or sea level rise). On the other hand, the notches at the back reef and reef crest indicate a sea level fall after the reef development (Figure 12). The sea level fall continues to the present sea level and abrades the lower part of the Pleistocene reef.

The study of sea level fluctuation related to the presence of notches has also been done by Hantoro *et al*. (1994) on Quaternary reef in Alor Island, eastern Indonesia. They found two superimposed marine notches at about 5.0 m and 8.6 m respectively above the present MLWST level. They interpreted to be corresponding to a glacial interstadial and to the Holocene sea-level peak. Chappell *et al*. (1996) calculate that the sea level

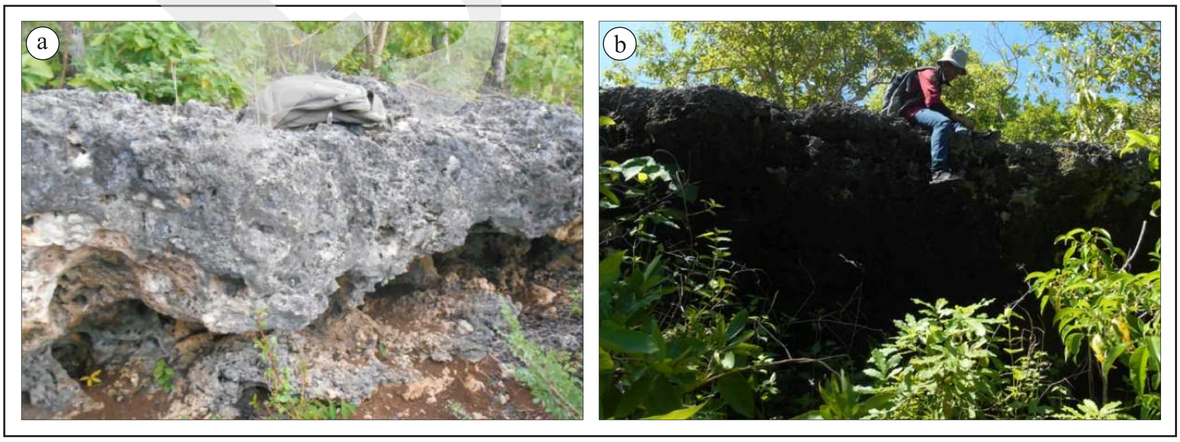

Figure 11. Field photographs of notches exposing in reef crest (a) and in back reef (b) in the elevation of around 7 m above the present sea level.

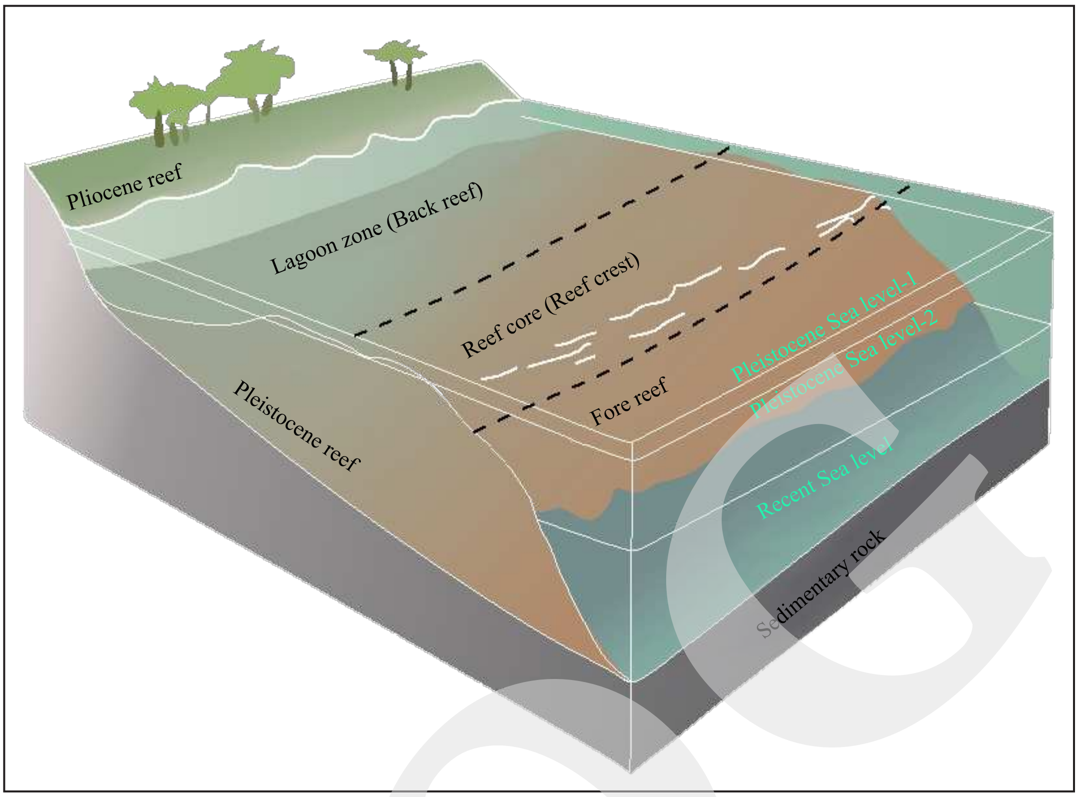

Figure 12. Idealized facies development at the Pleistocene Reef Complex in Bira area (modified from wikipedia.org, 2005 with condition in reef of Bira area, Bulukumba).

was about 6 m above the present sea level between 129 and 122 ka at Huan Peninsula and this matched to the interglacial sea level rise. Supposing the age of the Pleistocene reef of Selayar limestone at Toto section from 1.6 to 1.4 Ma or very early Pleistocene (Bromfield and Renema, 2011), as a reference to the Pleistocene Selayar reef in Bulukumba, the reef development does not match the interglacial sea level. Nevertheless, it has two superimpose marine notches (as in Quaternary reef in Alor).

Conclusion

Based on the facies distribution and textural dominant, the studied area is a small fringing reef complex. It developed in three stages, namely coral colonization or reef model A, coral diversification or reef model D, and coral domination or reef model E. The reef started to develop from a protected shallow marine to a reef front slope seaward. Laterally, the top the reef developed from the reef front seaward to the back reef with narrow lagoon with depth of <20m.

Sea level fluctuation played an important role in reef terraces. Three terraces and two notches are identified in the Pleistocene reef. The reef has experienced at least three times of sea level fluctuation. Sea level rise allowed reef development from colonization to domination. This sea level is identified by a line of notch within Pliocene reef. After the reef development, sea level fall occurred, indicated by marine abrasion at reef crest and back reef. This continued to the present sea level.

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