Proceedings of the 5th International Conference of Geological Engineering Faculty, Vol. 1, Issue 2, 2020, pp.70-85

ISSN 2783-8652 online
DOI: https://doi.org/10.17501/27838652.2020.1206

FLEXURER SUBSIDENCE OF MAKASSAR STRAIT

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Abstract: There were two types of hypothesis concerning formation of Makassar Strait and surrounding areas during the Tertiary periods namely, compressive and extensional tectonics. The compression is characterized by formation of Samarinda Anticlinorium in East Kalimantan and West Sulawesi Thrust Fold Belt in Sulawesi whereas the extension was characterized by formation of aulacogen occupied by widening of Mouth of Mahakam River in Makasar Streat and also the presence of block faulting and atenuation on pre Tertiary basement.

This study on the basis of analysis new surface and subsurface data of those areas including DEM , Field data and also seismics profiles suggest that the sedimentation cycles and tectonic evolution in the area were simultaneously related to compressional tectonic rather than the extensional tectonics and form flexure subsidence activities. The flexure subsidence itself is related to loading due to tectonic and denudation processes occured in the Tertiarry to Quarternary and this is usually generated during and post collisional activities.

Keywords: Makassar Strait, compression, extension, aulacogen, collision, denudation, flexure subsidence

Introduction

The Makassar Strait is located in between Kalimantan and Sulawesi islands. Morphologically, this depression is is flanked by two structural mountain ridges exposed respectively in Meratus Mountain in East Kalimantan and Bantimala Mountain in West Sulawesi, those are related to compressive tectonic forming thrust fold belts in the regions. The distance of those thrust fold belt is abaut 400 km (Figure 1).

Another opinion, the formation of Makassar Strait was related to extentional tectonics that caused the base of ocean underwent rifting and caused the development of Mahakam Delta (Sukamto, 1975; Hamilton, 1979; Chambers & Moss, 1999; Moss & Chambers, 1999; Kadarusman, et. al., 2004; Figure 1). Setiana (2015) also suggest that tectonic evolution of the Makasar Streat was related to an extensional activity on the basis seismic and gravity profiles showing block faulting and attenuating of the pre-Tertiary basements.

On the basis of seismic interpretation, stratigraphically the Makasar Streat itself is composed of pre Tertiary sucession overlain unconformably by undeformed and deformed Paleogen, Neogen to Quarternary sediments and indicate theses still belong to continental crust. Structural Geology as

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product of pre-Tertiary and Neogen compressive tectonics can be clearly seen in the seismics profile (Figure 2).

The geological data used in this recent study are obtained from recent geological mapping, DEM analyses, laboratoriun analyses and seismic interpretation.

The main objective of the recent study is to confirm tectonic and geological condition of the Makasar Streat and surrounding areas wether these were related to extensional or compressional activities.

Methodology

This recent study uses primary and secondary data sources. The primary data are surface data taken from geological mapping including rock description, rock association, geological structure measurement, and sample analysis in laboratory and also DEM for better surface geological structures interpretation, mainly in East Kalimantan and West Sulawesi Regions. The Secondary data are the pubslihed result of interpretation subsurface geological of Makasar Streat.

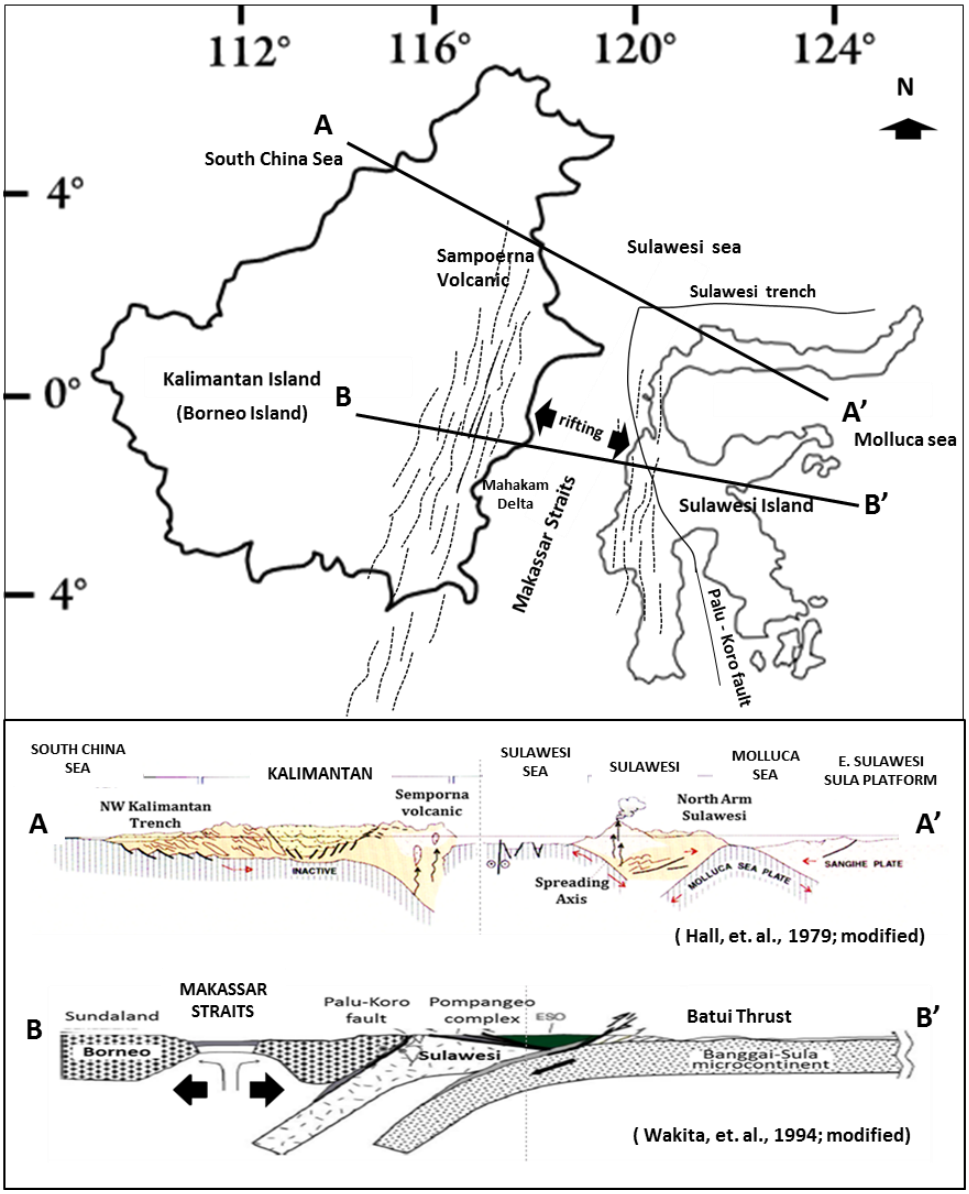

Figure 1. Two different tectonic models in Kalimantan-Sulawesi, both concluded rifting as the event causing the formation of Makassar Straits

(Modified from: Sukamto, 1975; Wakita, et. al., 1994; Hall, 1979).

Pre Tertiary Geology of Sundaland and West and South Sulawesi

Pre-Tertiary Geology of Sundaland

Kalimantan and Java Islands in southeastern part of Sundaland continental plate (Figure 2) is occupied by pre Tertiary rocks comprising Paleozoic and Mesozoic metamorphic, sedimentary and granitic rocks distributed almost in whole Kalimantan hinterland and also some places in Java Island.

In this study, observation and analysis geological condition is emphasized in the Cretaceous metamorphic, granitic, ophiolit, volcanic and sedimentary rocks that are exposed both in hinterland and thrust fold belt region and in plate boundary.

In Kalimantan, the Cretaceous granitic, ophiolite, metamorphic and sedimentary rocks are exposed in Meratus Mountain, Pulau Laut and Semenanjung Mangkalihat. The Cretaceous sedimentary rocks comprise deep marine sediments and Orbitulina limestone, exposed in west and eastern slope of Meratus Mountain and in Pulau Laut (Amiruddin 1999). The Cretaceous metamorphics belonging green schist facies and Cretaceous granites are exposed in the region. Ophiolite rocks including chert and pelagic sediments area widely distributed in Meratus Mt. Wakita *et al*. 1998 analyzed the age of radiolarian chert indicating Middle Jurassic- Late Cretaceous.

The similar rock association occupying Meratus Mt. are also present in Java Island namely in Bayat , Karangsambung (Lok Ulo) and Ciletuh regions.

On the basis of the similarity of those rocks association above suggest that the Cretaceous Orogenic belt (subduction – Collisonal zones) extend from Meratus Mountain to Java Island throuh Karang Sambung and Ciletuh Region as shown in Figure 2.

According to Witts et.al (2014) The Cretaceous Orogenic Belt of Meratus Mt. had been uflifted during Middle Miocene, which separated Barito Basin and Asam Asam Basin.

In the Barito Basin and Asam Asam Basin, the pre Teriary basements is overlain by Tertiary to Quarternary sediments.

Pre-Tertiary Geology of West and South Sulawesi

The similar Cretaceous rock association of Meratus Mts. is alo exposed In West and South Sulawesi comprising metamorphics, ophiolite and sedimentary rocks. Those rocks are exposed in Latimojong Mts, Burru, Bantimala and Marada Regions. The Cretaceous Metamorphic rocks consists low grade metamorphism consting metasediments, slate, phyllite and schist and retrograded metamorhic rocks. The Cretaceous Sedimentary rocks consist of deep water Balangbaru Fm, and Marada Fm. Those rocks have been thrusted into Neogen sediments forming a Thrust Fold Belt. Those rock associations indicate that the lithology association were usually formed in Subduction and Collisional Zones.

Pre Tertiary Geology of East Sulawesi – Banggai Sula and Southeast Sulawesi

The pre-Tertiary basements exposed in East Sulawesi consist of Paleozoic High grade and low-grade Metamorphic Rocks and Triassic – Jurassic silisiclastic rocks and Cretaceous limestone. Those rocks were originally derived from the southern edge of Australian continent based on . paleomagnetic data in Latitude 3.5° - 2° positions (Saiful Bachri & Sidarto, 2013; in Surono and Hartono, 2013). The other fragment of the continent also found in the eastern part, like in Banggai-Sula, Tukang Besi, Buton and south-eastern part of Sulawesi (Simandjuntak, 1986; Surono, 1996).

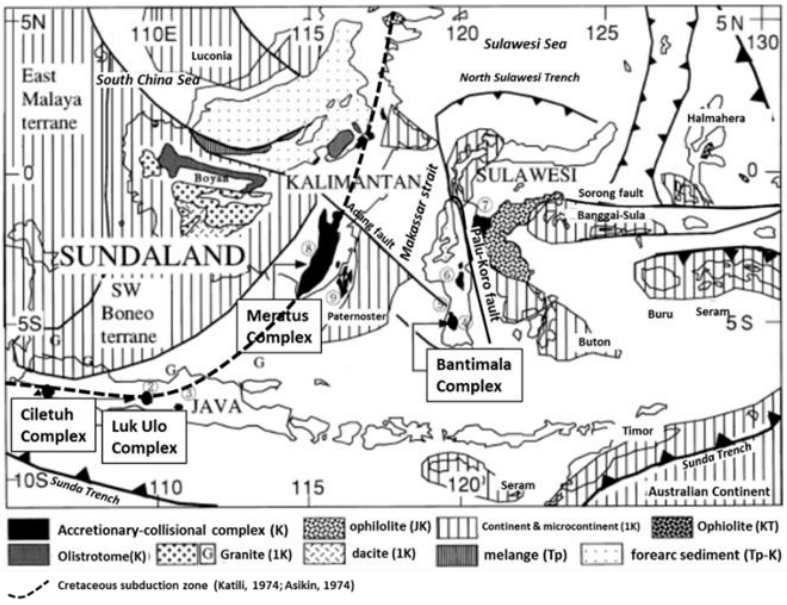

Figure 2. Tectonic framework of the West part of Indonesia

(Adapted from: Wakita, et.al., 1994; modified).

Pre-Tertiary Geology of Makasar Streat

The pre-Tertiary basement can be well recognized from seismic profil in Makasar Streat (Figure 4). The basement is highly deformed and is unconformably overlain by Cretaceous Sediments which is probably equivalent to the Cretaceous sedimentary rocks in Meratus Mts and West- South Sulawesi. These pre Tertiary rocks is unconformably overlain by Paleogene to Neogene sediments.

In 2009, Exxon Mobil did a drilling in the middle of Makassar Strait. The well named Rangkong-1, with the position in the middle Makassar Strait in 2255 meters, down to 4485 meters. Although this well did not reach the basement, but in the deepest part found volcanic rocks that petrochemically assosiated with continental crust (Bacheller, *et al*., 2011; Satyana *et al*., 2012

Tertiary Stratigraphy of East Kalimantan- Makassar Strait-West Sulawesi

In East Kalimantan to West Sulawesi, the oldest sedimentary rocks that lied unconformably on pre-Tertiary basement, is the terrestrial rocks that formed the terrestrial environment to deltaic in Eocene. Marine sedimentary rocks lie conformably on the top of it until Early Pliocene. Towards late Pliocene to Pleistocene, a portion of basin experienced tilting, causing sedimentation process in East Kalimantan and West Sulawesi occured in deltaic to terrestrial environments. Sedimentation occurred

in the Makassar Strait, since Eocene-Oligocene until recent and remain in the marine environmental conditions.

In the Barito Basin, Eocene rocks were represented by the Tanjung Formation. The rocks consist of conglomerates, quartz sandstones, carbonaceous shale, and coal. These formations indicate that most of East Kalimantan at that time was in the transition to terrestrial environments. This formation was successively covered conformably by other marine sedimentary rocks, among other Montalat Formation, Berai formation, Pamaluan Formation, Bebuluh Formation, Pulau Balang Formation, Warukin Formation, Balikpapan Formation, Kampung Baru Formation, and the late Pleistocene of Dahor Formation (Figure 3).

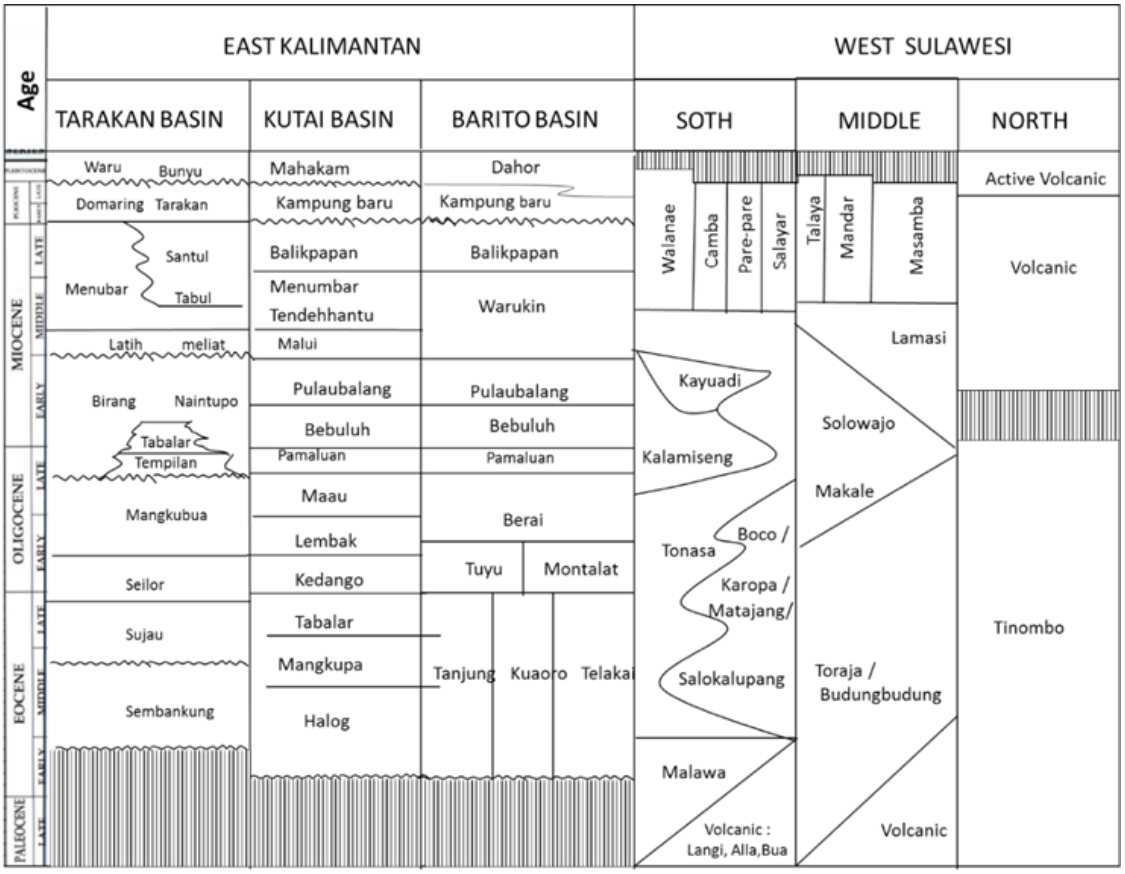

Figure 3. The Stratigraphy of East Kalimantan and West Sulawesi (adapted from: Regional Geology Map, GRDC 1993)

Sedimentary structures in sandstone of Pamaluan Formation outcrop in Muru river, Pasir District – East Kalimantan, among others are graded bedding, wavy, and slump structure, as well as the discovery of the trace fossil of zoovicos. These data shows that the sedimentation process as it is happened in the deep-sea environment with a favorable factor of the gravity flow mechanism. Towards Middle Miocene to late Tertiary, the basin was shallowing to deltaic environment, which is characterized by the development of carbonate rocks ranging from bounstone to wackstone, and clastic sedimentary rocks such as sandstones, conglomerate, mudstone with coal seam inserts. From Middle Miocene until now, deltaic sediment in East Kalimantan shifted from west to east. The Mahakam Delta sediments located in the Makassar Strait has thickness about 4000 m, has been active

since Late Miocene and continues until now. The last sedimentation process occurs in terrestrial environments, which is represented by Dahor Formation and alluvium.

In West Sulawesi, the oldest rocks that lied on top of the basement is volcanic sediment of Paleocene to Eocene age. In South and Central Sulawesi, part of that rock named as Malawa Formation, Budung-Budung and Tinombo. Furthermore, in Late Eocene to the Pliocene, on top of this formation, respectively lied conformably marine sedimentary rocks and volcano-clastic sediments. In the late Pliocene to Pleistocene, sedimentation processes occured in the terrestrial environment to form layers of conglomerate, sandstones with mudstone inserts. This sedimentary rock grouped into Budong-Budong Formation equivalent to Dahor Formation in East Kalimantan.

Through the seismic interpretation, the spreading of rock layers in the mainland of East Kalimantan and West Sulawesi, constantly spread into the basin of Makassar Strait (Nuraeni, *et al*., 2009 and Puspita *et al*., 2009; Figure 4). In the central part of the basin, the oldest sedimentary rocks that lied directly on the basement is equivalent with Tanjung Formation (Nuraeni, *et al*., 2009). Most of the hydrocarbon accumulation in the western part of the Makassar Strait can be correlated with Miocene delta (Lin *et al*., 2005, Satyana, 2012). From this data, the Makassar Strait basin have been formed during the Late Eocene, and at that time Kalimantan and West Sulawesi still join in one land. Both were separated by the Makassar Strait began towards Late Eocene, which is characterized by the accumulation of marine sediments until now. Since then, the Mahakam delta region and the Makassar Strait continued to subsidence, causes the development of thicker sediment in the delta and the enhanced bottom of the strait until reached a depth of about 4500 m.

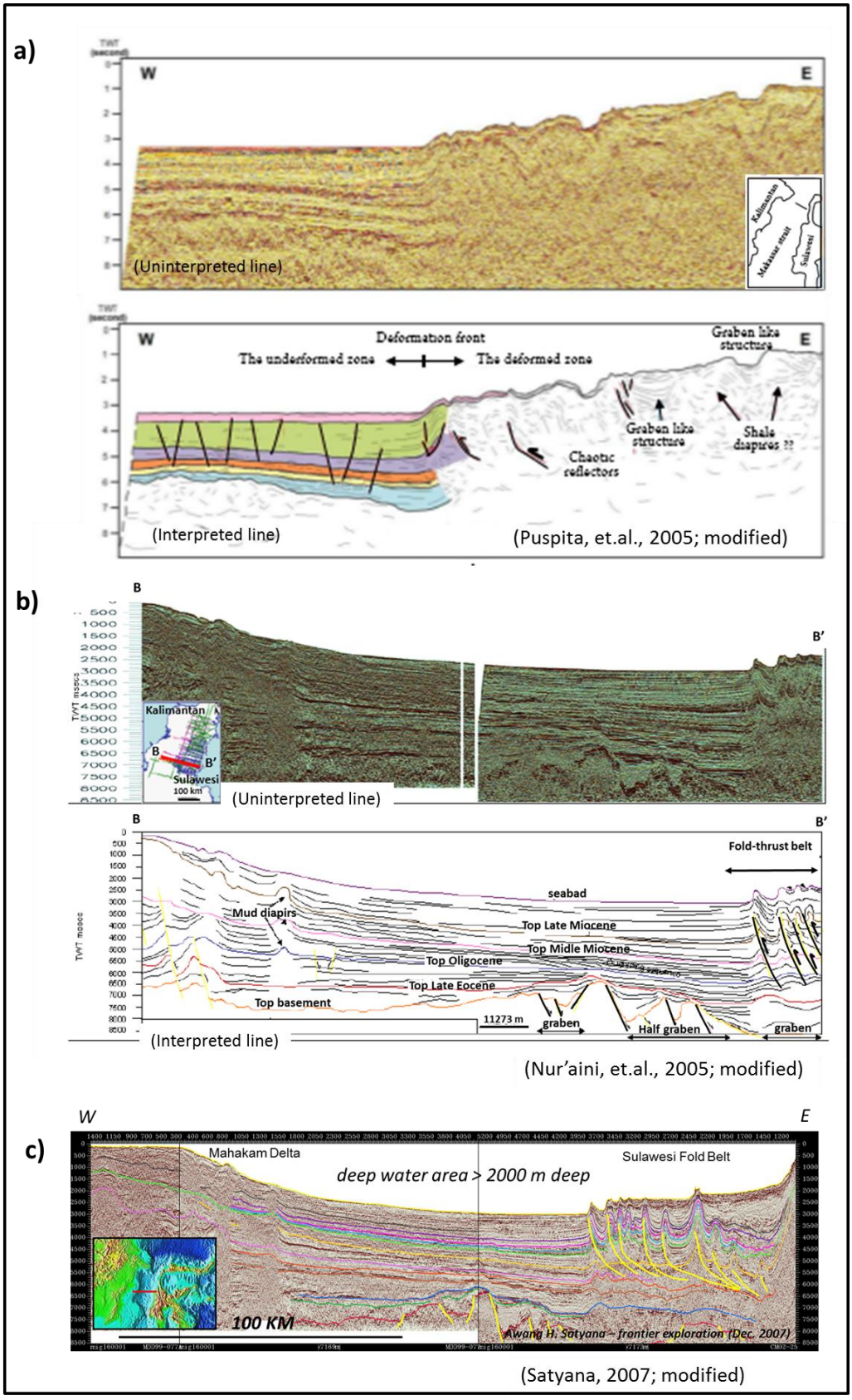

Figure 4. The Stratigraphy and the structure pattern in Makassar Strait. Thrust System developed in the east and west of the basin, while in the center is bending (adapted from : Puspita, Et al., 2005; Nur'aini et al., 2005; Satyana, 2007).

Geological Structure in East Kalimantan – Makassar Strait – West Sulawesi

There are some similarities in the patterns of the geological structure in the mainland of East Kalimantan and West Sulawesi, equally dominated by a reverse fault with a north-south direction (Figure 5). Through reverse fault and magmatism activity, the rock melange of the two islands exposed to the surface.

In East Kalimantan, most of the fold thrust belt caused by reactivation of old faults that have formed simultaneously when the Cretaceous subduction process underway, and others are formed by younger tectonic. Both formed a pattern of the same structure which is named as Samarinda Anticlinorium. In general, the fold thrust is leaning towards the west. This Anticlinorium stretches from South Kalimantan to the north approaching Mangkalihat mountain. The indications of Fold thrust belt in the field, including the discovery of mirror fault, breccia fault, drag folds, as well as vertical layer (Figure 6). Not all the contact boundaries between basement and sedimentary rocks on it in the form of fault lines. In some locations, such as those found in the Muru river, the contact boundaries between schist and Eocene conglomerate layer are unconformity.

Through seismic of Kutai Basin, described a structure pattern included into the thin skin tectonic, but in the southern part, which is on the boundary between the Barito Basin and Meratus Mountain, the pattern of structure is basement Involved or as a thick skin tectonic (Figure 7). The thin skin tectonic and the thick skin tectonic also seen on the seismic section in Kutai Basin - Mahakam Delta (Figure 7), which is the basement shows compressional fault block in the form of reverse fault that is constantly break sedimentary rocks above and normal faults that are growing only on the cover of sediments (Peters, KE, 2000).

Samarinda Anticlinorium, decollement or basement involved; all involve the Tertiary to Pleistocene sedimentary rocks. Meratus mountain involve Dahor Formation, whereas East Samarinda involving (involve) deltaic sediment layers that are younger than Kampung Baru Formations. This fact shows that compressional tectonics is still active until now. Associated with the development of the delta sediment shifted eastward, it can be concluded that the uplift began in the middle of Kalimantan and continued eastward. The uplift occurs through a mechanism of reverse fault that grows eastward (sequences of thrust eastward).

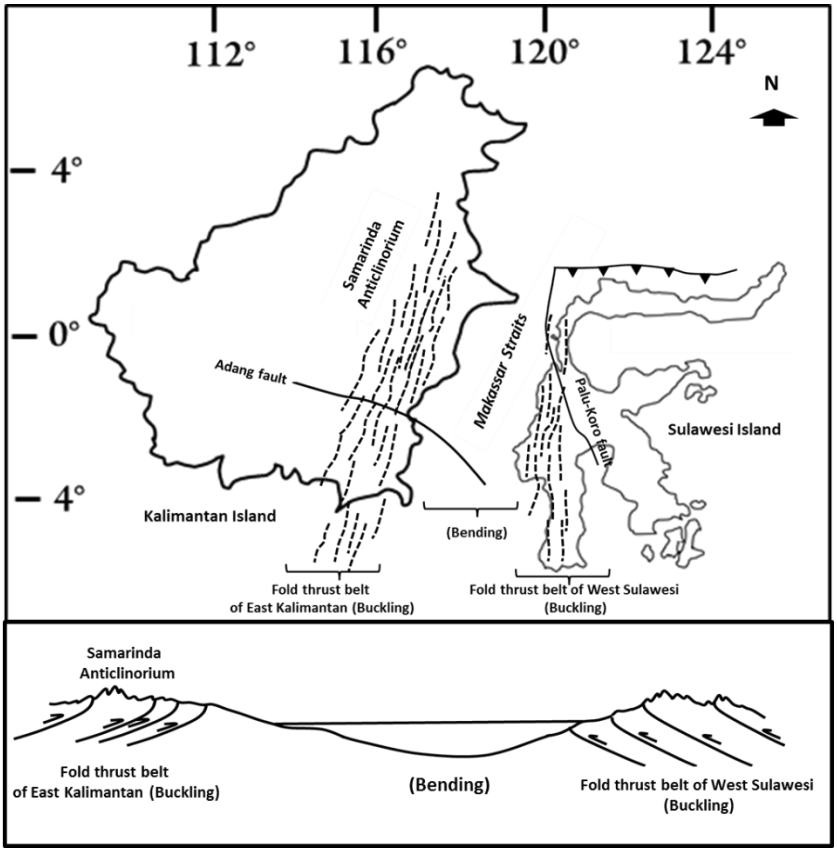

Figure 5. Fold thrust belt in East Kalimantan and West Sulawesi, both trending north – south, however contradictory each other. Sequence of thrust in Kalimantan is from west to east, otherwise in Sulawesi is from east to the west (adapted from various sources, modified).

Figure 6. Outcrop in several location: a. Small and solitary Granite hill within a wide plain landscape composed of Quaternary sediments of the Dahor Formation (Central Kalimantan); b. Limestone schist as part of Melange Meratus (East Kalimantan; c. Contact of schist with conglomerate layers and sandstone conglomerates equivalent to the Tanjung Formation on the Muru River (East Klimantan); d. The vertical layer of conglomerate insertion of sandstone conglomerates equivalent to the Tanjung Formation (Longikis-East Kalimantan); e. Dragfold of coal seams interspersed with claystone and sandstone layers (South Kalimantan); f. Drag-fold of claystone inserted by sandstones (Pasir-East Kalimantan); g. Upright layer of sandstone interspersed with claystone (Samarinda-East Kalimantan); h. The sedimentary rock layer of the Kampungbaru Formation aged Plio-Plistocene (Samarinda-East Kalimantan); i. Zoopicos in the sandstone layer characterizing the deep sea sediments.

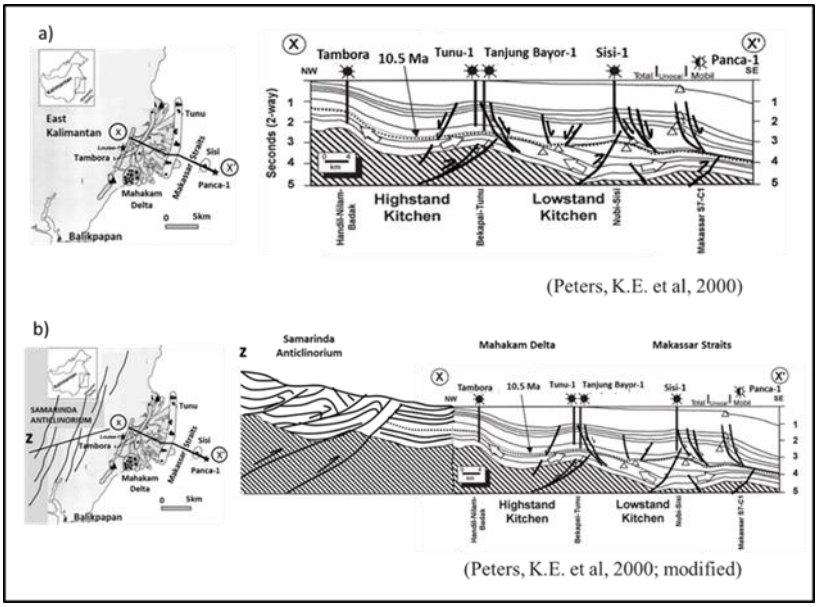

Figure 7. Thrusting in basement and fold thrust belt (Samarinda anticlinorium) indicates compressional and normal fault system in sediment cover of Mahakam delta indicates ekstensional system (source : Peters, K.E. et al, 2000; modified).

In West Sulawesi, The size of folds and reverse fault structures, are inconsistent as long as in East Kalimantan. This is possibly due to the effect of flattening the Palu-Koro fault that stretches from the Gulf of Bone to the South China Sea (Figure 5). As the case in East Kalimantan, the pattern of fold thrust belt in this area partly is thin skin tectonic and others are thick skin tectonic that cause the melange of Bantimala exposed to the surface. Generally, the pattern of folds structure in West Sulawesi leaned towards the west, this condition is the opposite to what happened in East Kalimantan that inclined towards the east (Figure 5). Indications of this fault in the field, among others, with the discovery of an upright layer with offset and fault mirrors in carbonaceous mudstone layers and from morphology aspects such as lineament of hills with steep fault scarp (Figure 8).

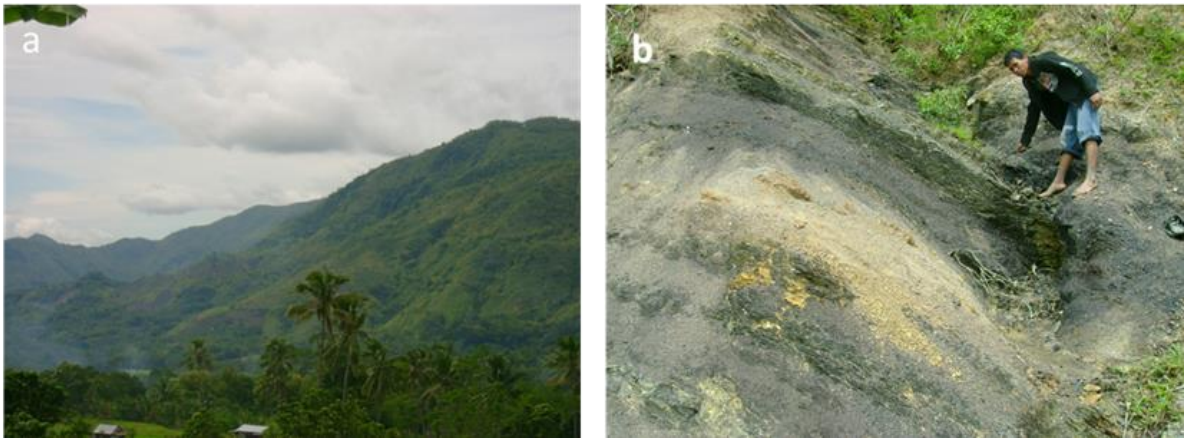

Figure 8. Indications of fault in the field: a. Hills linemanet of north-south trending, with steep fault scarp; b. Upright layer of the carbon mudstone - black shale, indicated compressional system. The location is in Mamuju, West Sulawesi. (Photo by Haryanto).

In the middle of the Makassar Strait, the structural pattern of the sedimentary layers is bending (non-deformation). This condition shows the tectonic that take place in extensional settings, in line with the process of subsidence that has been going on Late Eocene, when the sedimentation of marine sediments begins. Structure pattern in the west and east of the Makassar Strait is buckling characterized by the formation of a reverse fault and fold structures leaning towards the west, except in the Mahakam Delta (Figure 5).

Recent Tectonic analysis

Based on recent geological data found in East Kalimantan and West Sulawesi suggest that during Late Cretaceous and Early Tertiary there were two compressive tectonic activities including subduction and collision had been generated. The first, subductions between oceanic crust and Asia continent produced Meratus Thrust fold belt and magmatic arc in West Kalimantan and another subduction was occur between the oceanic crust of Makasar streat and Australian Continent which produced Bantimala Thrust Fold Belt in West Sulawesi. Those are respectivelly characterized by presence of Early Cretaceous melange and volcanic rocks (Figure 9A). After that, the collision had been generated on Early Tertiary where both thrust fold belts have been collided forming a collisional zone accompanied by formation a sedimentary basin in Makasar Streat known as a foreland basin due to flexure prosses as shown in Figure 9B and 10A. The wide of basin was probably at least 400 km, it is very wide. Furthermore, the basin was filled by very thick Paleogen-Neogen sediments and then at least during Neogen to present day compressive activities have been being generated again and cause the Meratus Mts and Balikpapan-Samarinda uplift forming new thrust fold belt in East Kalimantan and the other side in Sulawesi was also generated West Sulawesi Thrust Fold Belt, however, in the middle of Makasar Streat the strata of sediments are relatively undeformed and tend to be bending, indicating in the middle area have been generated a flexure bending due to tranversal loading whereas in both sides in East Kalimantan and west Sulawesi have been being generated buckling due to longitudinal stress (compressive activities) forming thrust fold belts as shown in Figure 10.

This tectonic event continues until now, evidenced by the development of coastal terraces, thick river alluvium and deformation of the recent carbonate layer with a slope of above 40 ° (Figure 11).

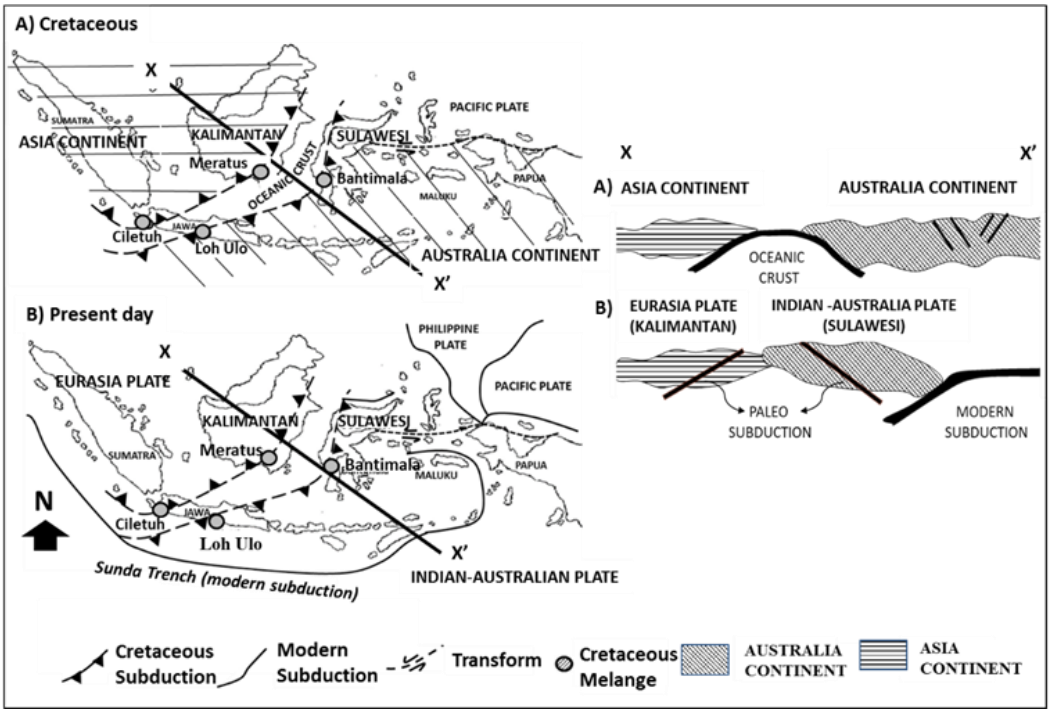

Figure 9. The evolution of plate collision A) Double subduction approaching Late Cretaceous and B). The collision in Early Tertiary.

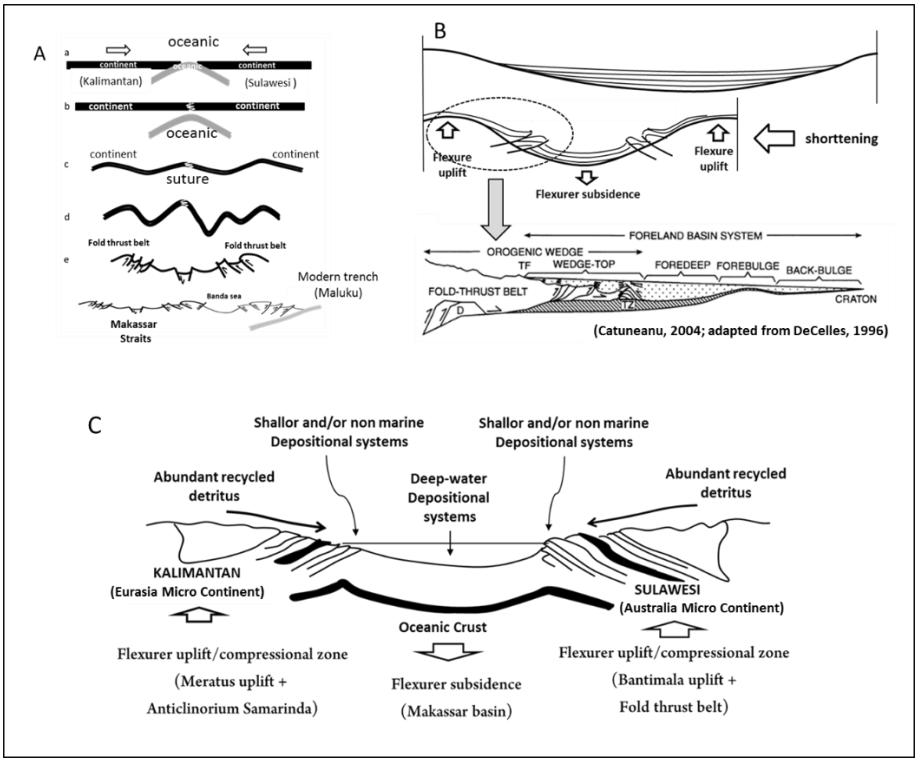

Figure 10. The mechanism of flexurer (+ and -), orogenesis and early sedimentation, until the deformation of sedimentary rocks in the basin due to the basement compression (shorttening).

Figure 11. Uplift tectonic in Eastern Indonesia continues until today, evidenced by, A. The layer inversion structure of quartz sandstone (Batimavulii Island, South Maluku); b. Deforming of the Recent carbonate (Loc. Tanimbarese-South Malucu); c. Thick alluvium (Loc. Sagihe island-North Sulawesi). (Photo by Haryanto).

Conclusion

- Makassar Strait Basin was firstly generated by double subduction tectonics during pre-Tertiary (Late Cretaceous) and produced respectively subduction zones and magmatic arc in East Kalimantan and West Sulawesi. Furthermore, during Early Tertiary those orogenic belts have been collided and form a collision zone and a flexure sedimentary basin.

- The basin then was filled by very thick Paleocene – Neogen sediments derived from the those thrust fold belts and the basin is possible represent a retroarc foreland basin because of the collision of two continent,

- The compressive activities generating during early Neogen – nowdays have been being uplifted at the west side of East Kalimantan and east side of West Sulawesi whereas in the middle of Makassar Strait the basement and sedimentary covers underwent bending and subsidence due to flexure subsidence.

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