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DOCKING AND POST-DOCKING TECTONIC ESCAPES OF EASTERN SULAWESI : COLLISIONAL CONVERGENCE AND THEIR IMPICATIONS TO PETROLEUM HABITAT

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SUMMARY

The escape (extrusion) concept, referring to the motion of a package of rocks towards a free edge within a compressional environment, has been much described as by-product of docking (collision). While the collisional zone is represented by thrust-fold belts, the tectonic escape of blocks is accommodated by large strike-slip faults and extensional structures.

Collisional/docking zone of Eastern Sulawesi is marked by (1) overthrusting of East Sulawesi ophiolite, (2) formation of foreland Batui-Balantak fold and thrust belt, and (3) emplacement of Kolokolo melange. The K-shaped Sulawesi Island is considered to be formed by post-docking escape tectonics. The tectonics has caused: (1) arc polarity reversal of Sulawesi arms from being convex eastward to being concave eastward, (2) opening of the Gulf of Bone, (3) formation of large strike-slip faults of Palu-Koro, Kolaka, Lawanopo, Hamilton, Matano, and Balantak Faults, and (4) extensional faults in East Arm and surrounding areas.

Petroleum has been discovered and produced in this area. Docking and post-docking of the microcontinents have controlled the petroleum habitat and system. They are responsible for formation of basins and traps, sedimentation of burial and sealing deposits, generation and migration of petroleum, and preservation of accumulation. Good understanding of the docking and post-docking escape tectonics will help evaluation of petroleum possibilities in any area of collisional convergence.

INTRODUCTION

The joining of two crustal masses - once separated (terranes), by collision is called *docking*. It is a process of amalgamation or accretion in plate's margin. Continent grows through docking of accreted crustal masses (Satyana, 2003). After the process of docking, there will be a process of tectonic readjustment called the *post-docking* compensation. In many ways, this process is attained by *tectonic escape* - a lateral motion toward a free edge or free face out of the compressional environment (Burke and Sengör, 1986). The lateral motion is dominantly attained by movement on strike-slip faults.

Sulawesi Islands in Central Indonesia provides a good place to examine docking and post-docking escape tectonics (see Figure 1). The islands were assembled by docking of terranes and have been modified by post-docking escape tectonics. Petroleum exploration in Sulawesi has been concentrated in the areas of collisional convergence. This paper will discuss the docking and post-docking tectonics of Eastern Sulawesi and how they affect the petroleum habitat.

DOCKING OF BUTON-TUKANG BESI AND BANGGAI-SULA MICROCONTINENTS

Different authors have different interpretations on the mode and timing of collision of Buton-Tukang Besi and Banggai-Sula microcontinents. Hall (1996) reconstructed the detachment of the microcontinents from the Bird's Head of Papua, their transfer to the west, and their dockings with eastern Sulawesi. At 20 Ma (Early Miocene), these microcontinents were dismembered from the Bird's Head by Sorong Fault splay. At 15 Ma, a strand of Sorong Fault propagated westward, at 11 Ma Buton-Tukang Besi collided with Sulawesi. Collision of Buton-Tukang Besi with Sulawesi locked the strand of the Sorong Fault and requiring a development of a new fault strand which caused the detachment of Banggai-Sula microcontinent. Banggai-Sula drifted northward and collided with Sulawesi ophiolite. Overthrusting of the ophiolite onto the western edge of Banggai-Sula microcontinent occurred in the

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latest Miocene (Davies, 1990) indicating that collision of the Sula platform with East Sulawesi must have occurred at 5 Ma (end of Miocene).

The collision of East Sulawesi ophiolite and Banggai-Sula microcontinent is marked by overtthrusting of the ophiolite, formation of the Batui-Balantak fold and thrust belt and emplacement of the Kolokolo melange. The development of duplex structure in Nambo and Balantak areas is related closely with the foreward migration of the Batui Thrust during and/or subsequent to the collision (Simandjuntak, 1987).

POST-DOCKING TECTONIC ESCAPES OF SULAWESI COLLISION

The K-shaped Sulawesi Island is considered as a response to post-docking rotation of the curvatures of four arms of Sulawesi from being convex eastward to being concave eastward. This rotation has been partly proved by paleomagnetism. Opening of the Gulf of Bone is due to rotation of Southeast Arm. Associated with the rotation, or following shortly after, was the development of major strike-slip faults crossing the island like Palu-Koro, Kolaka, Lawanopo, Hamilton, Matano, and Balantak Faults. More recent transtensional movement is responsible for opening pull-apart basins of Poso, Matano and Towuti Lakes, as well as the Palu depression.

Frontal to the collision of Banggai-Sula microcontinent is the development of strike-slip faults in East Arm: the Balantak, Toili, Ampana, and Wekuli Faults (Simandjuntak, 1987, 1993). The lateral motions detached East Arm of Sulawesi and escaped the rocks apart from the compressional collision eastward into the oceanic free edge/face in the East-Sangihe subduction zone. Extension structures which are almost parallel to the convergence direction are observed in the East Arm of Sulawesi until offshore Banggai-Sula area. Peleng Island is deformed intensively by normal faults. Normal faults of the grabens sometime reactivate the short limbs of the folds of the Batui-Balantak fold and thrust belt. It can be inferred that the eastern half of East Sulawesi collision zone is undergoing extension driven by slab-pull at the East Sangihe trench.

PETROLEUM IMPLICATIONS

Significant, large to giant gas fields have been discovered in Banggai Basin. Almost 25 year-exploration period from 1980 to 2004 have discovered Minahaki, Matindok, Senoro, Donggi, Sukamaju, and Maleo Raja gas fields. Oil was discovered in Tiaka field. The field has started its production in July 2005 with initial production of 1,200 BOPD. Early January 2006, production has reached 1,850 BOPD. In Buton area, oil seeps, gas seeps and asphalts are abundant. Asphalt deposits have been mined since 1920's from 19 fields (Davidson, 1991) and the island holds the Asia's largest deposits of natural asphalt.

The play types recognized in the Banggai collision are: (1) carbonate reefal build ups, (2) thrust-sheet anticlines, (3) wrench related anticlines, and (4) thrusted anticlines of basement related faults. (Garrard *et al*., 1988; Davies, 1990; Davidson, 1991; Hasanusi *et al*., 2004). The Miocene carbonate reefal build up play type is the largest stratigraphic play as proved by discoveries in Minahaki, Senoro, Donggi, Sukamaju, and Maleo Raja gas fields. The trap is related with pre-docking tectonics where reefal build ups grew at the front of the Banggai-Sula microcontinent during its drifting. The thrust-sheet anticline play type involves structural closures at the leading edges of a series of imbricated collisional thrust sheet of the Miocene platform carbonates (Hasanusi *et al*., 2004). The trap is related with syn-docking and post-docking tectonics. Tiaka oil field proves this play type. The wrench fault anticline play type involves trusted anticlines where traps have been formed as en echelon folds along strike-slip faults formed during Pliocene post-docking escape tectonics. Matindok discovery and southern Senoro field prove this play type. The play of thrusted anticlines related with basement faults is observed in the Taliabu shelf, Sula islands. Mesozoic sediments were deposited as syn-rift sequence in grabens of the Banggai-Sula microcontinent. When docking of the microcontinent took place in the Late Miocene, the rift grabens were overprinted by compressional tectonics resulting in thrusted anticlines. Numerous thermogenic gas seepages and minor oils were reported to occur in this area (Garrard, 1988). Three play types are recognized in the Buton-Tukang Besi collision (Davidson, 1991): (1) thrust-related anticlines, (2) wrench- related anticlines, and (3) carbonate reefal build ups. The onshore thrust-related anticlines are Late Miocene age and developed as a result of the docking of Buton and Muna/Southeast Sulawesi. Wrench-related anticlines were developed during the oblique collision of Buton with Tukang Besi in Plio-Pleistocene time.

Docking and post-docking tectonic escape in Buton-Tukang Besi and Banggai-Sula collision significantly affect: (1) basin formation due to isostatic subsidence and underthrusting of the microcontinents, and post-docking extension, (2) sedimentation of post-docking/molassic deposits, (3) subsidence of the basins due to deposition of molasses and/or thrust sheet of post-docking sequences, (4) generation of hydrocarbons in Miocene and Mesozoic sources due to basin subsidence, (5) trap formation related with collisional thrusting and post-docking wrench, and (6) preservation of oil accumulation (case of Buton asphalt).

CONCLUSIONS

1. Docking of the Buton-Tukang Besi and Banggai-Sula microcontinents to Eastern Sulawesi took place during the Miocene. Docking of the microcontinents resulted in obduction of the East Sulawesi ophiolites onto the microcontinental blocks, formation of foreland Batui-Balantak fold and thrust belt, and emplacement of Kolokolo melange. Post-docking tectonic escapes followed afterwards. They started with rotation of arms of Sulawesi, opening of the Gulf of Bone, formation of Sulawesi's major strike-slip faults, and occurrences of extension fractures.

2. Collision areas of eastern Sulawesi have been proven as petroleum provinces. Docking and post-docking tectonics affect the tectonic habitats of petroleum in Banggai-Sula and Buton-Tukang Besi areas. They are responsible for formation of basins and traps, sedimentation of burial and sealing deposits, generation and migration of petroleum, and preservation of accumulation.

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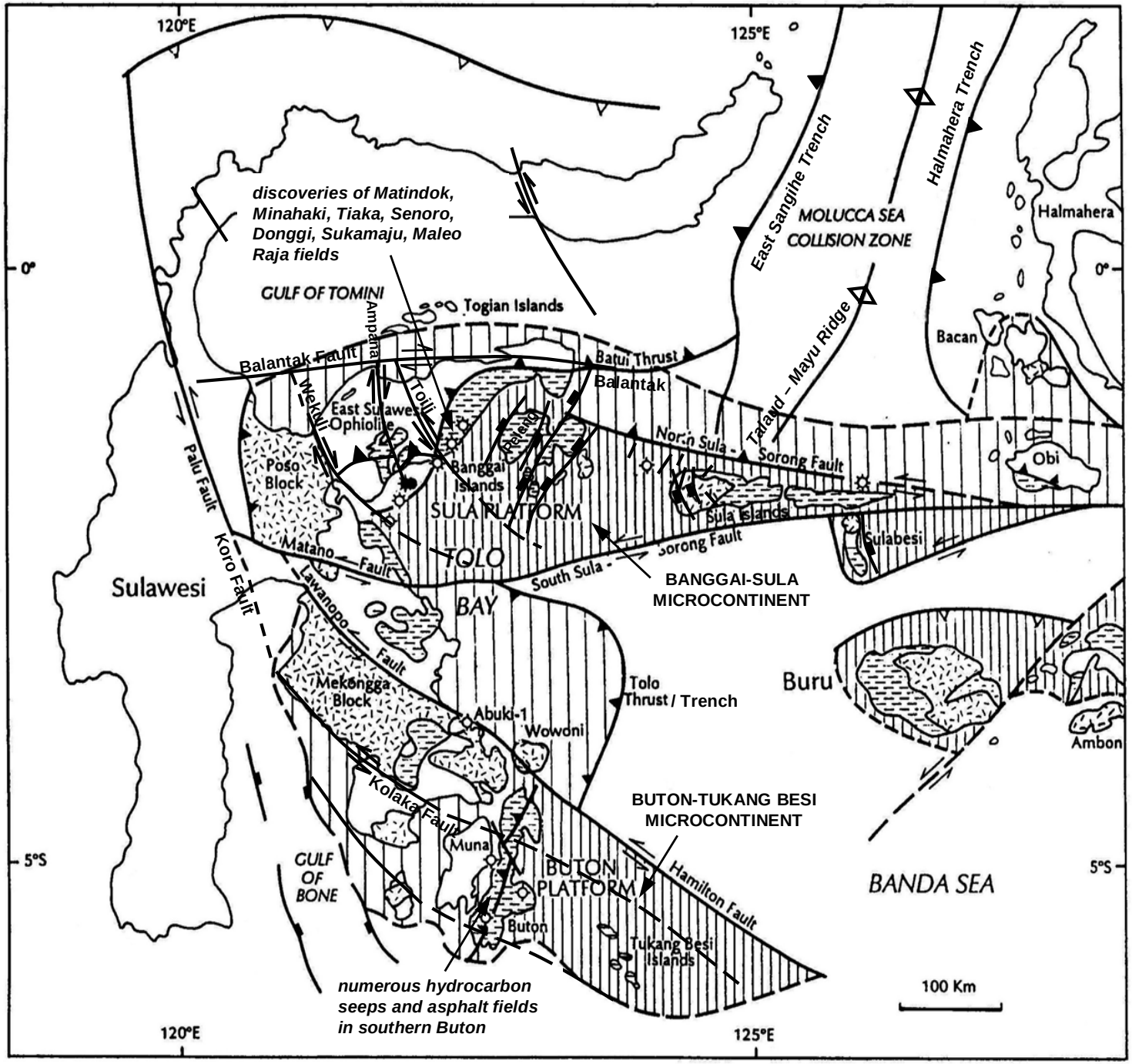

Figure 1. **Docking/ collision of Banggai-Sula and Buton-Tukang Besi microcontinents with Eastern Sulawesi. Collision zone is marked by overthrusting of East Sulawesi ophiolite and formation of foreland Batui-Balantak fold and thrust belt. Post-docking escape tectonics resulted in K-shaped Sulawesi Island due to arc polarity reversal of Sulawesi arms from being convex eastward to being concave eastward. Opening of the Gulf of Bone; formation of large strike-slip faults of Palu-Koro, Kolaka, Lawanopo, Hamilton, Matano, and Balantak Faults; and extensional faults in Banggai Islands are features of tectonic escapes. The package of rocks moved towards a free edge of East Sangihe Trench and Tolo Thrust/Trench where oceanic crust subducted. Gas and oil fields have been discovered in Banggai area. Numerous hydrocarbon seeps and asphalt deposits are numerous in Buton Island. Docking and post-docking tectonics affect the petroleum habitat. They control formation of basins and traps, sedimentation of burial and sealing deposits, generation and migration of petroleum, and preservation of accumulation.**