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COLLISION OF MICRO-CONTINENTS WITH EASTERN SULAWESI: RECORDS FROM UPLIFTED REEF TERRACES AND PROVEN-POTENTIAL PETROLEUM PLAYS

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ABSTRACT

Sulawesi is an assemblage of collided terranes. Australoid terranes comprising Buton-Tukang Besi and Banggai-Sula micro-continents collided with Eastern Sulawesi in the Neogene. Buton-Tukang Besi micro-continent collided with the SE Arm of Sulawesi/Muna Block from early Miocene until late Miocene. The collision has overthrusted the Kapantoreh ophiolitic suture, shortened and uplifted Buton. Tukang Besi, contrary to previous interpretations, is interpreted here as one micro-continent with Buton; which never collided with Buton. It separated from Buton as a response to post-collisional tectonics. Banggai-Sula micro-continent collided with the East Arm of Sulawesi beginning in the middle Miocene until Pliocene. The collision has overthrusted the East Sulawesi Ophiolite Belt, shortened and uplifted the frontal part of Banggai-Sula micro-continent.

Before the collision, the oceanic front of both micro-continents subducted beneath Eastern Sulawesi. Subduction ceased with the advent of collision. The junction between subducted oceanic crust and frontal micro-continents broke off and these continental parts began to exhume by gravity tectonics, causing collisional uplifts. We have observed coastal areas and islands sitting on these exhumed micro-continents comprising Buton, Wakatobi (Tukang Besi), and Luwuk (Banggai) areas. The uplifting of Quaternary reef terraces in these areas are manifestations of the collisional exhumation of the micro-continents. The rates of uplift range from 0.53 to 1.84 mm/year.

Foreland basins formed by collision are prolific hydrocarbon basins worldwide. Buton and Banggai Basins are proven petroleum provinces in Sulawesi. Collisional tectonics has affected formation of the foreland basins with structural traps, maturation of source rocks, and petroleum charging history.

Several oil and gas fields are being produced in Banggai area. There is a significant asphalt mine in Buton and numerous oil and gas seeps have been recorded. The two basins are continually explored.

INTRODUCTION

Sulawesi Island is the best place in Indonesia to study collision tectonics. Structures related to collision as defined by Garzanti et al. (2007), are fulfilled ideally by Sulawesi (Satyana et al., 2007). The island assemblage is the result of tectonic collision of terranes/micro-continents coming from Sundaland and Australian areas. Formation of the island has occurred since Oligo-Miocene. Evidence of the last collision of Sulawesi with Buton-Tukang Besi and Banggai-Sula micro-continents (Figure 1) is ongoing as confirmed by the continued uplift of Quaternary reefal terraces at the eastern coastal lines of Sulawesi and islands to the east and southeast of Sulawesi.

Collision tectonics has important implications for petroleum systems. Of the giant oil fields identified in the world, 27.8 % are associated with collisional tectonic settings (Mann et al., 2003). In Sulawesi, foreland basins formed by collision of Buton-Tukang Besi and Banggai-Sula micro-continents are prolific and one of the basins (Banggai Basin) is oil producing. Gas will be produced from this basin in the future. Prospects with good hydrocarbon potential await drilling. In Buton Basin, asphalt deposits, related to biodegraded marine-sourced oils have been mined since the early 1900s, and the basin still has non-biodegraded petroleum remaining to be explored.

This paper presents the tectonic history of collision of the Buton-Tukang Besi and Banggai-Sula micro-continents with Eastern Sulawesi, evidenced by uplifted Quaternary reefal terraces in Eastern Sulawesi, and the implications of the collision to proven and potential petroleum plays.

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METHODS

Preparation of this paper progressed through three stages: (1) understanding the tectonic history of the collision of Buton-Tukang Besi and Banggai-Sula micro-continents with Eastern Sulawesi, (2) examination of evidence that the collision is ongoing as evidenced byuplifted Quaternary reefal terraces, and (3) consideration of implications of the collision on future petroleum exploration. At the onset, the authors collected published literature from various proceedings and journals and studied them for relevance tothe framework of this paper. Field excursions to Banggai, Buton, Wakatobi (Tukang Besi islands) were conducted separately. The last excursion to Wakatobi Islands was completed in December 2010. Maps produced by DEM (digital elevation model) were used to present the topography of the terraces. Seismic lines were thoroughly examined to identify proven and potential hydrocarbon play types. All examinations of published literature, field survey results, DEM maps, and seismic interpretations were integrated in this paper.

RESULTS & DISCUSSIONS

Muna/SE Sulawesi - Buton Collision

Davidson (1991) and Milsom et al. (1999) detailed the collision between Muna/SE Sulawesi and Buton micro-continent.

Little can be said about the geology of Muna, a monotonous limestone plateau (*Figure 2A*) gently sloping up toward the southeast, where the highest elevations are a little over 400 m. Steep, narrow ridges along much of the east coast may mark the site of a former barrier reef complex. The limestones generally are considered to be of Quaternary age and have been correlated with the Wapulaka Formation of Buton (Sikumbang et al., 1995). Older rocks are exposed only at Tanjung Batu (Rocky Point) in the western part of the island, where a small outcrop of schist was observed (Milsom et al., 1999). The schist seems similar to the widespread schists of SE Sulawesi.

Buton is considered to be a rifted fragment of the Australia-New Guinea continent based on stratigraphic similarities (Figures 2A, B). The stratigraphy of Buton follows from its history as part of Australia (pre-rifting sequence), its detachment from Australia (syn-rifting sequence), movement to its present location (syn-drifting sequence), and during and after the collision with SE Sulawesi (syn-orogen and post-orogen sequences). Pre-rift sediments occurred before the Middle Triassic when Buton was a part of the Australia-New Guinea continent. The Buton pre-rift Triassic stratigraphy comprises continental-derived clastic sediments deposited unconformably on Permian meta-sedimentary rocks. Final separation from Australia occurred in the Late Triassic or Early Jurassic, preceded by a transition from pre-rift to syn-rift sedimentation in the Middle–Late Triassic. Late Triassic rocks (Winto Formation) rest on pelitic phyllites and slates (Lakansai Formation) that are exposed about 40 km northeast of the island. Both the Winto and the overlying Early Jurassic Ogena Formation consist dominantly of limestone, but the Ogena appears to have been deposited in deeper water. Clastic sediments, principally shales, are common in the Winto of southern Buton. Both formations contain abundant organic material, generally considered to be the hydrocarbon source.

A fully open marine environment with passive margin sedimentation commenced in the Middle to Late Jurassic with pelagic carbonates as dominant lithologies. The uppermost Mesozoic on Buton is poorly exposed. It begins with the deep-marine siliceous and calcareous mudstones of the Upper Jurassic Rumu Formation and continues with the Tobelo Formation, which comprises pelagic limestone with nodules and stringers of red chert. The Tobelo was originally classified as entirely Upper Cretaceous, but has now been shown to extend from the end of Rumu deposition up into the upper Eocene or lower Oligocene (Smith and Silver, 1991). Both the Rumu and the Tobelo were evidently laid down very slowly, and their lithologies are consistent with deposition during the drift of an isolated continental fragment. This event is also marked by the overall decrease in clastic sedimentation derived from the continental area.

In the Early Miocene, collision between Buton Island and Muna/SE Sulawesi took place (Figure 3). A hiatus at the top of the Tobelo Formation can be attributed to this collision. The collision led to shortening of about 60% and to the development of thin-skinned thrusts and folds in southern Buton. Northern Buton was not affected until the middle Miocene when maximum regional compression led to uplift and the establishment of an unconformity representing a hiatus. In the Late Miocene, the subduction zone became choked. This event was followed by accretion of Buton to Muna/SE Sulawesi. The oceanic crust between Muna and Buton was obducted and sheared, forming a range of ophiolitic mountains called Kapantoreh. The Kapantoreh ophiolites based on gravity data (Milsom et al., 1999) are rootless, detached forming thin thrust slices removed from their areas of origin. A terrane suture is most probable along the line of the Buton Straits, which can be interpreted as a successor basin produced by slight relaxation of compression following collision. The gravity data suggest that the suture swings west just north of the narrowest part of the strait and cuts across southern Muna. Exposed ophiolites in Buton are allochthonous detached klippen that were transported away from their root zone by thrusting (Milsom, 1991).

After the collision, syn-orogenic clastics were deposited as molassic sediments. The sediments immediately above the unconformity, forming the coarse clastic upper Miocene–Pliocene Tondo Formation, composed mainly of carbonate detritus, but ultramafic and mafic fragments become dominant later, indicating uplift of the ophiolites above sea level. Tondo Formation deposition was brought to an end by subsidence of Buton to bathyal depths at approximately 5 Ma and deposition of the Sampolakosa chalks and marls. Subsequent uplift was accompanied by the development of reefal carbonates of the Wapulaka Formation.

Buton-Tukang Besi Collision

The relationship between Buton and the largely submerged Tukang Besi platform to the east remains unclear. Hamilton (1979) regarded eastern Buton and Tukang Besi as a single micro-continental fragment distinct from western Buton and Muna. Fortuin et al. (1990), Davidson (1991) and recent work by Tanjung et al. (2007) argued that Buton and Tukang Besi platform are two separate micro-continents. Buton collided with Muna in early Miocene, Tukang Besi collided with Buton in late Pliocene (Figure 3). The initial effects of the Buton-Tukang Besi micro-continental collision are recorded in the late Pliocene strata where reefs developed on uplifted blocks while deep marine foraminiferal packstones and marls were deposited on the downthrown blocks. The second collision produced a more uplifted terrain in south Buton compared to the north, as evidenced by the distribution of Pleistocene reefs and development of drowned estuaries and subsiding atoll in the north. However, Milsom et al. (1999), based on gravity data, suggested that in the east, the Buton terrane includes the almost entirely submerged Tukang Besi platform. They also suggested that Tukang Besi separated from Buton as a response to post-collision extension.

Milsom et al. (1999) suggested that the Tukang Besi platform lies immediately east of southern Buton. Its limits can be placed at the 2000 m bathymetric contour, which encloses a considerable area of relatively shallow sea floor and beyond which there are rapid increases to oceanic depths to the north, east, and south. Three sub-parallel, northwest-southeast–trending ridges rise to sea level from a plateau at 1200–1500 m depth, each some 150–200 km long and terminating some 10–20 km east of the eastern coast of Buton. These three ridges are called: Langkesi (north), Wangi Wangi (central) and Karang Kaledupa (south). The contrast between their orientations and the roughly north-south alignment of Buton supports the widely held assumption that the two blocks have been only recently juxtaposed. No rocks other than Quaternary reef limestones have been reported on the islands of the Tukang Besi platform. Dredging on the steep northeastern margin of the platform (the Hamilton fault) recovered diabase dated at about 9 Ma and a variety of sediments of late-middle Miocene and late Miocene age (Silver et al., 1985). Seismic lines from the Scripps Institution of Oceanography *Mariana 9* cruise, touched only on the fringes of the platform, and recorded a generally thin cover of young sediments and the presence in places of a strong angular unconformity beneath which Paleogene or older sediments were poorly resolved.

If the Tukang Besi platform collided with Buton in post-Miocene, abundant evidence of this event would be expected to the east of Buton in Kulisusu Bay (Kolowara-Watabo Bay) surrounds the supposed suture zone. However, based on the Scripps Institution of Oceanography Mariana 9 cruise at the Kulisusu Bay, Milsom et al. (1999) argued that the sediments appear to have been deposited in an extensional depression between the Buton and Tukang Besi blocks, which must have been already adjacent to each other when the oldest visible sediments were deposited. The long wavelengths and low amplitudes of the folds seem inconsistent with the suggestion (Fortuin et al., 1990; Davidson, 1991) of a late Pliocene collision between Buton and Tukang Besi leading to major uplift of Buton. There is no geophysical evidence for a compressional terrane boundary between Buton and the Tukang Besi platform, but there is geological evidence for some 60% compressional shortening of Buton itself (Davidson, 1991). Without the thickening, which would inevitably accompany such shortening, the crust beneath

Buton would be roughly the same thickness as the crust beneath the platform.

Milsom et al. (1999), based on gravity analysis and interpretation, argued that there was no collision between Tukang Besi and Buton. They were one micro-continent which separated in later time. Gravity data confirm that the crust is of continental thickness beneath Buton and of near continental thickness beneath the Tukang Besi platform (Figure 4). Neither the seismic reflection evidence immediately east of Buton nor the paleomagnetic evidence for systematic post-Miocene rotation of southern relative to northern Buton supports a late Neogene collision between Buton and the Tukang Besi platform. Steep gravity gradients east of Buton (Figure 5) define, even more clearly than do the bathymetric contours, the division of the region into a number of discrete blocks. The straight-line segments of these gradients seem improbable sites for thrusting, but may plausibly be interpreted as marking extensional or transcurrent faults. Continuing uplift of southern Buton and Muna during the Pleistocene, and perhaps also the central ridge of the Tukang Besi platform, may be consequences of the Banda arc–Australia collision triggering the detachment of some part of the lithosphere thickened by the middle Miocene collision, leading to isostatic rebound and perhaps further dispersal, rather than local compression. The overall impression is one of fragmentation (Figure 5) of a formerly more compact Buton–Tukang Besi block, rather than amalgamation.

We considered that Tukang Besi forms one micro-continent with Buton. This is based on the analogy with the Banggai-Sula micro-continent (Figure 6) discussed below. There are extensional and collapse structures between Banggai and Sula areas (Garrard et al., 1988). The collapse structures were isostatic response to collision of the frontal part of the micro-continent (Banggai portion). Seismic and gravity data discussed above (Milsom et al., 1999) support this analogy for Buton and Tukang Besi. Buton is the frontal/anterior/head part of the micro-continent, whereas Tukang Besi is the rear/posterior/tail part. When the head uplifted following collision with Muna Block, it compensated by relaxation forming collapse/extensional structures at the area between the head and the tail, in the junction area between Buton and Tukang Besi. If Tukang Besi collided with Buton, there would be uplifted suture; however, as revealed by seismic, there are only collapse structures. Detachment of Tukang Besi from Buton was an isostatic rebound due to lithosphere thickening during the middle Miocene collision of Buton and Muna. The conceptual fold and thrust belt in Tukang Besi micro-continent due to its collision with Buton as revealed on schematic geologic section of Davidson (1991) is unsupported and there is no geologic or geophysical data to prove or disprove the concept.

East Sulawesi-Banggai Sula Collision

The Banggai and Sula Islands, encompassing the main islands of Peleng, Banggai,Taliabu, Mangole and Sanana (Figure 6) located east of Sulawesi and immediately north of the North Banda Basin, are widely believed to have originated in the Australia-New Guinea region and to have been transported as a micro-continent to their present position impacting the East Arm of Sulawesi (Hamilton, 1979; Pigram and Panggabean, 1984; Simandjuntak, 1986; Garrard et al., 1988; Davies, 1990).

Garrard (1988) detailed the detachment and emplacement of the Banggai-Sula micro-continent, interpreted to be a fragment of the north Australia - New Guinea continent. This is supported by similarities in the age and type of basement, in the Mesozoic stratigraphy and in the age of a Mesozoic unconformity that marks the beginning of rifting from northern Australia and New Guinea (Pigram and Panggabean, 1984). During the Late Mesozoic the Banggai-Sula micro-continent broke away and drifted west towards the Asiatic Plate. This extensional period is represented by a transgressive phase of continental to shallow marine Jurassic clastics overlain by deeper water anoxic shales. Essentially passive margin sedimentation took place through the Cretaceous and into the Tertiary during the drift westwards. Bathyal conditions probably existed with little clastic sediment input on the micro-continent.

Based on field geology of Banggai-Sula Islands (Garrard et al., 1988), it is known that the micro-continent is dominated by an early Jurassic continental to shallow marine coarse clastic formation (Bobong) followed by deeper marine argillaceous facies (Buya) (Figure 12 B). Late Cretaceous to Paleocene deep water carbonates (Tanamu Formation) represent the top of the sequence. Deposition is believed to have taken place initially within a rift-graben setting, followed by restricted shallow marine conditions and finally by subsidence and open, deep water marine conditions. Formations (Salodik/Pancoran) of Tertiary age follow unconformably and are dominated by shallow water platform carbonates.

There then followed an Oligocene-Middle Miocene phase of carbonate deposition onto a stable shelf area covering all of Banggai-Sula. Localized reef growth occurred around the margins of the micro-continent, whilst deeper water, low-energy carbonate deposition occurred to the west of the reefal build-ups under what is now the eastern arm of Sulawesi.

The mechanism for the westward drift of the Banggai-Sula micro-continent has long been the subject of debate (Hamilton, 1979; Pigram and Panggabean, 1984). The most popular theory supports left lateral displacement along the North Sula and South Sorong fault systems, although this does not account for many of the structural features seen in the area. The recent paper by Ferdian et al. (2010) based on newly acquired seismic and multibeam data north of Banggai-Sula Islands re-examined the existence of the North Sula Fault. Ferdian et al. (2010) concluded that there is no evidence for a continuous E-W-trending North Sula-Sorong Fault; if it exists it terminates between Obi and Mangole, at the eastern end of the Sula Islands. A zone of broadly south- thrusting, previously termed the Sula Thrust, lies along the foot of the north-dipping continental slope. However, it is diffuse, variable in orientation and genesis, and no major through-going thrust zone exists. To the east, north of Mangole, thrusting is related to convergence between a complexly deformed wedge of sediments squeezed out of the Molucca Sea collision zone, and the continental slope. The Banggai-Sula micro-continental margin has been tilted northwards under this south-propagating wedge, causing large fragments of the slope to slide into the deep basin to the north.

Collision of Banggai-Sula with the Asiatic Plate took place from Middle Miocene to Pliocene (Garrard et al., 1988) and resulted in Asiatic oceanic crust, the Sulawesi ophiolites, being overthrusted to the east onto the Banggai-Sula micro-continent (*Figure 6*). Overthrusting of the ophiolites onto the western edge of Banggai-Sula micro-continent occurred in the latest Miocene (Davies, 1990) indicating that collision of the Sula platform with East Sulawesi must have occurred at 5 Ma (end of Miocene). This compressive episode was responsible for producing imbricate thrust structures developed mainly in foreland Banggai Basin, probably producing thrust structures on the Taliabu Shelf**.** Following overthrusting and uplift of eastern Sulawesi, eastward directed molasse deposition commenced in the early Pliocene (Figure 7). Pliocene and Pleistocene molasse sediments prograding eastward filled basin areas west of Peleng Island. Elsewhere, late Pliocene to Pleistocene normal faulting, caused partly by relaxation of earlier compressive stresses, resulted in subsidence of the Peleng Strait. The uplift of Peleng, Banggai and Taliabu Islands appears to have been a relatively recent event. Present-day erosion has left the Miocene exposed on West Peleng and Jurassic and Basement exposed on East Peleng and Banggai Island. The uplift and exposure of late Cretaceous and Paleocene sediments occurred only in northern Taliabu and Mangole (Garrard et al., 1988).

Satyana (2006 b) and Satyana et al. (2007) provided the reasoning for structural deformaton in this collision zone. The predominance of faulting, rather than folding, is a direct consequence of the mechanical competence of the stratigraphic column. Here a pressured thick basement section is overlain by a relatively thin Tertiary carbonate sequence. The direction of the thrust orientation varies from NNW-SSE to NE-SW. This change in thrust orientation is a consequence of the rotation of the east and southeast arms of Sulawesi towards each other. However, thrust emplacement may not have followed an orderly sequence as there is good evidence in the onshore area for reactivation of faults. Here, the ophiolite section repeatedly overlies, and is overlain by Pliocene clastic deposits, rich in ophiolite debris.

Origin of Uplift in Collisional Tectonics: Exhumation

Many authors consider that uplift always relates to compression (lateral geologic force). This was also considered by Fortuin et al. (1990) and Davidson (1991), explaining Quaternary uplift in southern Buton resulted from the collision of Buton and the Tukang Besi platform.

However, in many cases of collisional orogens in Indonesia (and other worldwide cases), discussed by Satyana et al. (2007), uplifts related to collision commonly resulted from 'exhumation' which has no relation to compression, but to vertical/gravity tectonics due to differential density of collided crustal masses (Satyana, 2010).

Collision of two tectonic plates will be preceded by subduction of the oceanic front of each plate. When subduction occurs, the distance between the two continents closes due to slab pull, like the movement on a conveyor belt. Eventually, the subduction will cease when the two continents collide. There are two processes involved when subduction ceases and collision begins: (1) a portion of the oceanic crust will split, detach and subduct into the mantle; a detached oceanic crust will be obducted overlying the frontal part of one continent, (2) the frontal part of the plate with overlying oceanic crust will be dragged for some distance and period of time into the mantle following its oceanic front.

The 'subducting' continental portion will eventually stop due to the buoyancy of the continent relative to the mantle. The more dense oceanic crust will keep subducting, whereas the less dense (buoyant) continental crust cannot be subducted in the same manner, it will break off from its oceanic front. After the break off, the buoyant continental fragment will resume its position at the surface, uplifting all overlying crustal masses and all of their covers. This process is called *exhumation*. Exhumation is gravity tectonics causing uplift and has nothing to do with compression.

Satyana and Armandita (2008) explained that gravity tectonics due to exhumation was responsible for uplift of the Meratus Mountains, SE Kalimantan. Meratus Mountains are an ophiolitic suture of collision between Schwaner (South Kalimantan) and Paternoster (South Makassar Strait). The Meratus Mountains are presently located on the stable area far from plate convergence. The uplift of the mountains was interpreted by many authors as a result of compression related to Muna-Buton-Tukang Besi collision. Absence of compressive structures in South Makassar Strait thwarts this interpretation. Due to the buoyancy relative to the upper mantle, the subducted Paternoster micro-continent broke off its oceanic front and began to exhume in Late Cretaceous time. The exhumation of the Paternoster continent has uplifted the Meratus ophiolites since then.

Quaternary Reefal Terraces of Buton

Geomorphology and distribution of Pleistocene reefs suggest that south Buton is currently being uplifted while North Buton is subsiding. Quaternary uplift in southern Buton is expressed by spectacular flights of coral terraces rising almost 500 m above sea level (Figure 8). Maximum differential uplift between adjacent fault blocks is approximately 700 meters. Regional Quaternary uplift in south Buton is estimated at 2,500 meters (De Smet et al., 1989). The northern part of the island, where uplift began earlier, is now subsiding (Davidson, 1991) and rapid sedimentation continues in Kulisusu Bay, a broad, and in places very deep, embayment in the east coast of Buton that is bordered to the north by swampy lowlands. Oblique compression and associated strike slip faulting have continued to the present day. Style and orientation of Recent structures suggest that the entire Buton micro-continent is currently within a transpressive zone (Davidson, 1991).

Late Pliocene to Pleistocene (N21-22/23) reefs developed on uplifted blocks while deep marine foraminifera1 packstones and mark were deposited in the lows. The reefs are poorly cemented, intensely
karstified, bioclastic limestones. Microfauna indicate a shallow water, inner neritic, reef or near reef depositional environment. Deposition was as platform carbonates on block faults, interpreted by Davidson (1991) as created during the Buton - Tukang Besi collision. Incremental uplift of the blocks produced spectacular raised terraces, forming ampitheaters (at Lianawonti, Nelandi, Pasarwajo bays), now exposed at surface in south Buton. At least 11 terraces can be recognized to compose the cliff of the bays (*Figure 8*). Two small islands to the south of Buton: Siumpu and Kadatuang Islands, are also comprised of reef terraces. Total formation thickness is dependant on degree of block uplift and ranges from 20 meters in north Buton to a maximum of 700 meters in south Buton.

A study of Quaternary processes and events in SE Asia by Thiramongkol et al. (1987) estimated that a rate of uplift for Buton Island is 0.6 mm/year. The results are calculated from the elevation of Holocene terraces and the ages related to the Quaternary sea-level changes curve.

Quaternary uplift in southern Buton was attributed by Fortuin et al. (1990) and Davidson (1991) to collision between Buton and the Tukang Besi platform. There are no data prove the collision of Tukang Besi platform with Buton and seismic, gravity and magnetic data (Milsom, 1999) supports that Tukang Besi was the detached part of the micro-continent Buton-Tukang Besi, which is also supported by analogue to Banggai-Sula micro-continent; the mechanism of uplift of South Buton has not been caused by collision of Tukang Besi to Buton, but may be because of exhumation of the once subducted frontal part of the Buton micro-continent when collision initially took place. Geologic sections from Davidson (1991) illustrated the frontal part of the Buton micro-continent which subducted following its oceanic front when subduction took place, but when collision took place, the detached oceanic fragment of Kapantoreh ophiolites was obducted onto the Buton micro-continent, the frontal part of the micro-continent broke off its junction to the oceanic front, and started to exhume, uplifting southern Buton, also resulting in reef terraces of Wapulaka Formation.

Quaternary Reefal Terraces of Tukang Besi (Wakatobi Islands)

Tukang Besi Islands are made up of four major islands of Wangi-Wangi (Figure 9), Kaledupa, Tomea, and Binongko (abbreviated as 'WaKaToBi'). The four islands have been formed by uplift of fossil coral terraces, evident in the step-like appearance of these islands from afar. Rising from the depths of the Banda Sea these islands boast all three of the major coral reef formations: atolls, fringing reefs, and a single barrier reef off the island of Wangi-Wangi. The Tukang Besi Islands are now reserved as Wakatobi Marine National Park. Divers and modern coral reef experts found Wakatobi reefs as 'jewel' of Indonesian diving (Muller, 1999) and an excellent place to study modern coral reefs (Crabbe et al., 2006).

The region has generally been avoided by research vessels because of the presence of uncharted reefs and shoals. The largest island, Wangi-Wangi on the central ridge, reaches a maximum height above sea level of about 270 m, and three other large islands also rise above 200 m. Quaternary uplift of the central ridge has thus been comparable with uplift in southern Buton, but extensive atoll development points to subsidence of the southern ridge. The northern ridge, which is capped by two small islands, seems to have been the most stable of the three.

Field survey and interpretation of the topographic map generated by DEM at Wangi-Wangi Island found at least five limestone terraces (Pleistocene-Holocene) forming concentric rings like atolls (Figure 9). Reef at the core of the rings is the oldest reef and is located at the highest point (270 m above sea level). Distributed outward from the rings, the reefal terraces get younger. Living reefs are growing in the surrounding sea. These concentric rings represent sequential uplifts undergone by Wangi-Wangi Island. Submerged island resulted in reef core development. As the island was uplifted, the reef ceased to grow, and it was uplifted sub-aerially. With the flanks of the uplift still submerged, younger atoll developed encircling the uplifted area. As the flank was uplifted, it resulted in an outer ring of terraces relative to the first uplifted reef core/terraces. The processes repeated several times until presently there are five terraces forming Wangi-Wangi Island. The terraces are limestone, most of them are coralline carbonates with sandy parts (Figure 10). Some of the terraces show karstification forming dolinas, uvalas, and open polje. Other islands (Kaledupa, Tomea, Binongko) also show the existence of the terraces, but not as many and or as clear as that of Wangi-Wangi.

Milsom et al. (1999) attributed that Banda arc–Australia collision triggering continuing uplift of the Tukang Besi platform. If Tukang Besi was another micro-continent which collided Buton. The uplift of reef terraces at Wangi-Wangi and other major islands can be attributed to exhumed continent at the collision zone. However, there is no data to support this collision. We consider that the uplift of the Wakatobi Quaternary reef terraces has been affected by the same mechanism which uplift southern Buton reef terraces, namely exhumed once subducted frontal part of the Buton micro-continent. Tukang Besi is the tail part of the micro-continent therefore the uplift there has been resulted from Buton collision to Muna. The rate of uplift of the reef terraces of Wangi-Wangi Island is not yet determined, but it can be derived from radiometric dating of each reef terrace relative to the elevation of the terraces and sea level fluctuations.

Quaternary Reefal Terraces of Luwuk (East Sulawesi)

Luwuk is a coastal town near the eastern tip of Sulawesi's East Arm. The terrace morphology of the Luwuk area was studied by Sumosusastro et al. (1989) to determine timing, rate and magnitude of Quaternary uplift known to be taking place in this region of suturing crustal elements. As discussed, the Banggai-Sula micro-continent collided with the East Arm of Sulawesi from middle Miocene to Pliocene (Garrard et al., 1988). The Luwuk area is situated in the central portion of the arcuate thrustbelt resulted from collision of Banggai to East Sulawesi where Quaternary reefs show maximal elevation. The elevation gradually decreases towards the east tip of the peninsula and towards the southwest (Batui area).

The coastal morphology of Luwuk is dominated by raised coral reef terraces, reaching elevations of over 400 m (Figure 11). A lower group of 6 to 10 terraces reach maximum heights varying between

30 and 100 m. A middle group, elevated up to 250 m, forms an 18 ° to 22 ° seaward sloping surface that is bordered by coast-parallel faults. The upper group of terraces is more than 400 m above sea level. Four reef terraces at 410, 62, 19 and 6.6 m above high tide have U/Th ages ranging from 350,000 to 67,000 years ago. Using the sea level curve, uplift rates for the Luwuk area can be calculated. The highest terrace has risen at an average rate of 1.84 mm/year. The three dated terraces of the lower group also indicate net uplift, but at a much lower rate, which is partially due to subsidence at 0.53 mm/year between 101,000 and 67,000 years ago. Intermittent subsidence could be due to isostatic compensation and/or drag by the downthrown parts during periods of crustal relaxation in the fault zone.

Detailed sampling and mapping of the Luwuk terraces presented by Sumosusasto et al. (1989) indicate that considerable differential uplift is taking place between a rapidly rising hinterland and a probably subsiding Peleng Strait. Quaternary uplift and subsidence undergone by reef terraces at Luwuk area represents gravity tectonics due to exhumation of the frontal part of Banggai-Sula micro-continent which subducted following its oceanic front but then broke off and started to exhume, uplifting all overlying crustal masses including their sedimentary covers and the uppermost cover of Quaternary reefs. The occurrence of the reef terraces expresses the sequential uplifts.

Petroleum Implications of Eastern Sulawesi-Australoid Micro-continents Collision

Collision tectonics is important for petroleum implications. Of the 877 giant fields (those with ultimately recoverable 500 million barrels of oil or 3 trillion cubic feet of gas) identified in the world between 1868 and 2002, 244 fields (27.8 %) have collisional tectonic setting (Mann et al., 2003).

Continent-continent collision margins produce deep but short-lived basins in interior areas, and broad, wedge-shaped foreland or foredeep basins in more external parts of the deformed belt where most giants are found. Giant fields of the Arabian Peninsula and Persian Gulf are concentrated in a large foreland basin formed during the late Cenozoic collision of the Arabian Peninsula with Eurasia and in undeformed passive margin areas southwest of the basin. Other examples of collisional foreland oil fields include Alberta, Wyoming, the Andes, Verkhoyansk, Taiwan, northern Carpathian, and the Apennines. Petroleum generation occurs from source rocks shortened and buried in the more interior parts of the deformed belt. Migration takes place both vertically and horizontally updip in sedimentary sections overridden and loaded by large thrust sheets.

Regional review of the relationship between collision tectonics and petroleum implications in Indonesia basins was discussed by Satyana et al. (2008).

The collisions of Buton-Tukang Besi and Banggai-Sula micro-continents with Eastern Sulawesi were responsible for the formation of: foreland basins of Buton and Banggai basins, their kitchen foredeeps, and their traps related to fold-thrust belts due to collision. The collisions also control direction of hydrocarbon charging from kitchen foredeep to updip areas of the micro-continents or collisional-thrusted anticlines.

Hydrocarbon prospectivity of Buton is considered favorable. Detailed discussion of each element and process of the petroleum system are provided by Davidson (1991). Abundant asphalt occurrences, coupled with numerous gas and "live" oil seeps, confirm that hydrocarbons have been generated. Triassic bituminous shales and limestones are primary source rocks (*Figure 12A*). Upper Cretaceous, Early to Middle Miocene, and Pliocene clastics and carbonates are potential reservoirs. Primary traps include Miocene thrust and/or Pliocene wrench-related anticlines. Faults are the principal conduits for hydrocarbon migration. For oil exploration, Buton is considered a medium to high risk area with good potential for hydrocarbon accumulations. Principal strengths include the widespread distribution of very prolific Triassic source rocks, live oil and gas seeps, and well-defined Miocene to Pleistocene structures. Primary weaknesses are reservoir quality and lateral continuity, reduced sealing potential due to recent tectonism, and the possibility for severe hydrocarbon biodegradation. Both south and north Buton are now being explored by oil companies, one exploration well is programmed for drilling this year in south Buton based on newly acquired seismic lines and lessons learned from failures of previous wells.

Detailed discussion on each element and process of the petroleum system of the Banggai foreland basin is provided by Davies (1990). The relationship between collision and petroleum in East Sulawesi -

Banggai-Sula has been discussed by Satyana (2006 a). Banggai-Sula micro-continent has two distinct structural styles, two contrasting sedimentary sequences, and two reservoir units. The structural styles were developed, firstly, as Banggai Sula moved westward towards its present position, and secondly, as it entered the collision zone with the East Sulawesi Ophiolite Belt. The pre-collision Miocene sequence is characterized by two carbonate units, and the post collisional Pliocene-Pleistocene sequence by a thick clastic section of claystones, conglomerates, sandstones, and limestones. The reservoir units occur within the Miocene carbonates (*Figure 12 B*). In the lower unit, composed of a sequence of platform limestones, Tiaka oil field has been discovered. The field is currently producing oil. In the upper carbonate unit, which is characterized by a mixed platform reefal assemblage, gas fields have been discovered: Minahaki, Matindok, Senoro, Donggi, Sukamaju and Maleo Raja fields. Source rocks for the hydrocarbons discovered have been identified in the Miocene section. Generation and migration of hydrocarbons took place in Pliocene/ Pleistocene times after the deposition of thick burial molassic sediments.

The play types recognized in the Banggai collision are (Figure 13): (1) Miocene carbonate reefal build ups, (2) Miocene carbonates on wrench-related structures, (3) Miocene carbonates on imbricated structures; the potential play types are: (4) ophiolite belt (basal sands or fractured reservoirs), (5) Mesozoic section on imbricated structures, and (6) Mesozoic section in graben structure. 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 to pre-collision tectonics where reefal build ups grew at the front of the Banggai-Sula micro-continent 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. The trap is related to collision and post-collision tectonics. Tiaka oil field proves this play type. The wrench fault anticline play type involves thrusted anticlines where traps have been formed as en echelon folds along strike-slip faults formed during Pliocene post-collision escape tectonics. Matindok discovery and southern Senoro field prove this play type. The play of thrusted anticlines related to basement faults is observed in the Taliabu shelf, Sula islands. Mesozoic sediments were deposited as syn-rift sequence in grabens of the Banggai-Sula micro-continent. When collision of the micro-continent took place in the Late Miocene, the rift grabens were overprinted by compressional tectonics resulting in thrusted anticlines. Some thermogenic gas and minor oils seeps occur in this area.

Collision and post-collision tectonics in the Buton-Tukang Besi and Banggai-Sula collisions to Eastern Sulawesi significantly affect : (1) foreland basin formation due to isostatic subsidence and underthrusting of the micro-continent, and post-collision extension, (2) sedimentation of post-collision/molassic deposits, playing a role as burial sediments, (3) subsidence of the basins due to deposition of molasses and/or thrust sheet of post-collision sequences, (4) generation of hydrocarbons in Miocene and Mesozoic sources due to: isostatic subsidence, subsidence by burial sediments, and subsidence by multiple thrust sheets, (5) trap formation related to collisional thrusting and post-collision wrench, and (6) charging/migration from subsided kitchen to updip area of the micro-continent where carbonate reefs developed or to thrusted anticlines formed by collisional deformation (Satyana et al., 2008).

CONCLUSIONS

Sulawesi Islands are the best place in Indonesia to study collisional tectonics. The islands were formed by collision of terranes/micro-continents coming from Sundaland and Australian areas. Buton-Tukang Besi and Banggai-Sula are the last micro-continents assembled islands.

Buton-Tukang Besi micro-continent collided with the SE Arm of Sulawesi/Muna Block in early Miocene until late Miocene. The collision has overthrusted Kapantoreh ophiolite; an oceanic crust was originally located between Muna and Buton. The collision has shortened Buton 60 % and uplifted the island. Differing with previous authors who interpreted that Tukang Besi as another micro-continent which collided Buton in Pliocene, the authors interpreted that Tukang Besi was part of Buton that later separated as a response to post-collisional tectonics. No collision suture of Buton and Tukang Besi micro-continents has been found, contrarily, collapses structures indicating separation of Tukang Besi from Buton are found.

Banggai-Sula micro-continent collided with the East Arm of Sulawesi beginning in middle Miocene until Pliocene. The collision has overthrusted East Sulawesi Ophiolite Belt, shortened and uplifted frontal part of Banggai-Sula micro-continent. Fold and thrust belts called Batui imbricated zone were formed mainly in Banggai foreland basin. Following overthrusting and uplift of eastern Sulawesi, eastward directed molasse deposition commenced in the early Pliocene. Following the collisional uplift, late Pliocene to Pleistocene normal faulting, caused partly by relaxation of the earlier compressive stresses, has resulted in subsidence in several areas.

Before the collision, the oceanic front of each micro-continent subducted beneath Eastern Sulawesi. This subduction brought frontal parts of each micro-continent. Subduction ceased when collision occurred. Subduction of continental crust into the mantle will stop due to the buoyancy of the continent. The continent will break off from its oceanic front and will resume its position at the surface, resulting in 'exhumation' - an uplift due to gravity tectonics. Quaternary reef terraces in coastal areas and islands sitting on these exhumed micro-continents comprising Buton, Wakatobi (Tukang Besi), and Luwuk (Banggai) areas are being uplifted, recording collisional exhumation of the micro-continents with the rates of uplifts from 0.53 to 1.84 mm/year.

Foreland basins formed by collision are prolific basins worldwide. Buton and Banggai Basins are proven petroleum provinces in Sulawesi. Mesozoic to Miocene sediments are proven sources (carbonates and shales) and reservoirs (sandstones and carbonates) are present. Several oil and gas fields have been discovered and produce in Banggai area. An asphalt mine in Buton is significant and there are numerous oil and gas seeps. The two basins are continually explored, pursuing active petroleum systems and various play types. Collisional tectonics provided significant essentials for petroleum geology and petroleum systems in the basins. It has affected formation of the foreland basins, structural traps, maturation of source rocks, and petroleum charging history.

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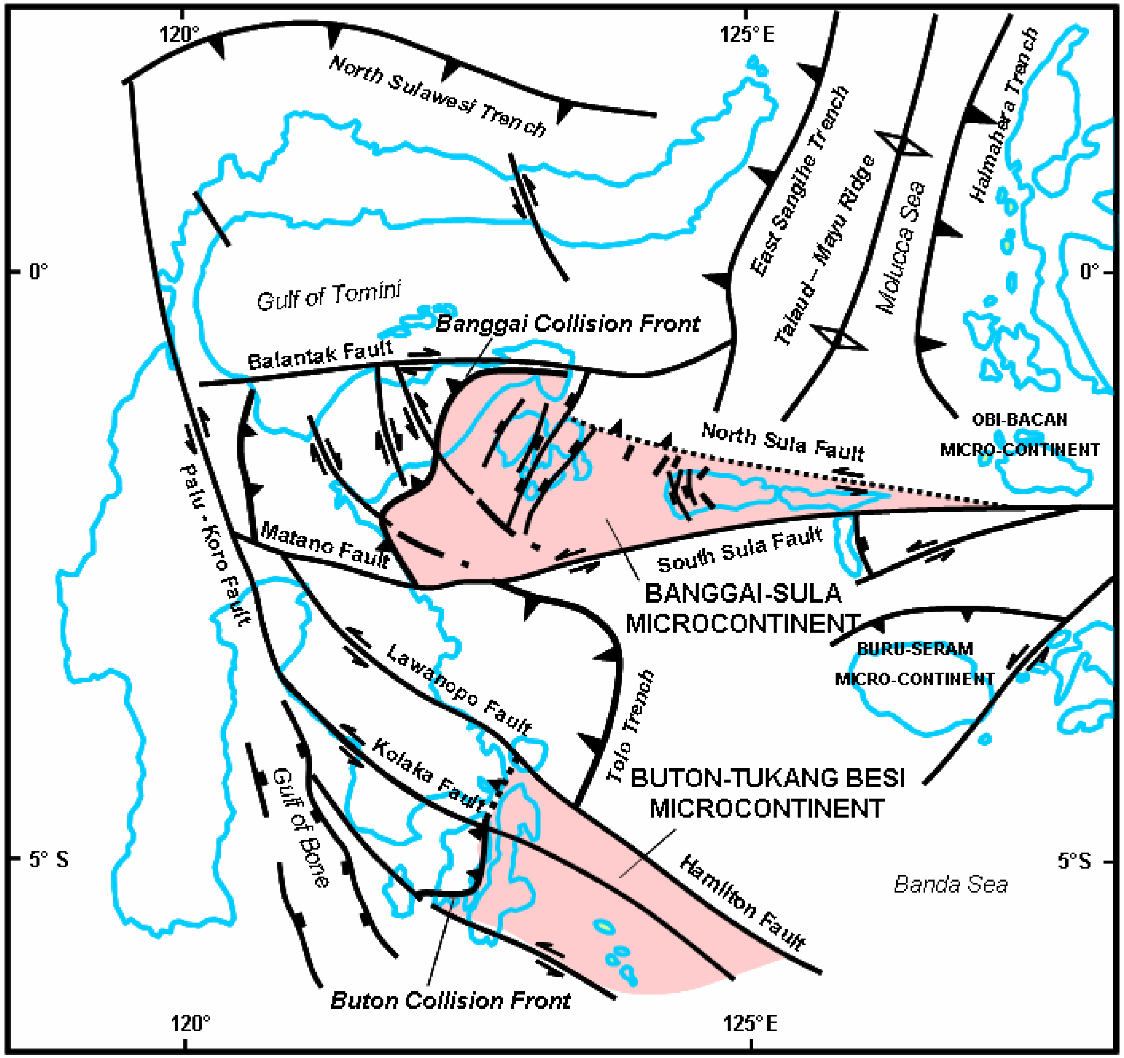

Figure 1

Figure 1 - Southeast Arm and East Arm of Sulawesi was collided by Buton-Tukang Besi and Banggai-Sula microcontinents, respectively. Collision fronts of Buton and Banggai are indicated, and they are characterized by imbricated fold and thrust belts. Major strike slip faults and extensional faults occurred as response to post-collisional relaxation, isostatically compensating collisional uplifts.

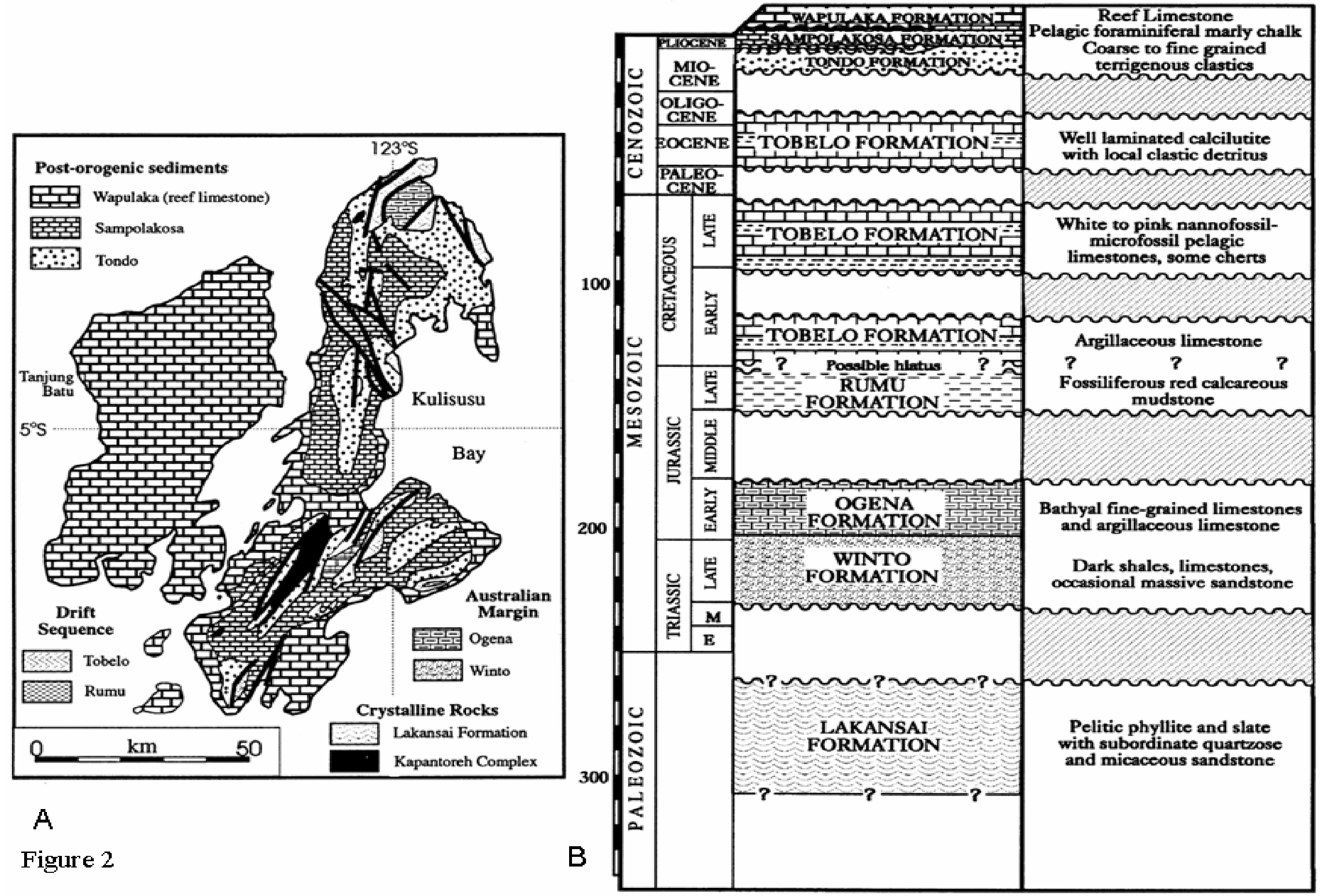

Figure 2 - A. Simplified geology of Buton (after Smith and Silver, 1991; Sikumbang et al., 1995; Milsom et al., 1999).
B. Stratigraphic column of Buton (Davidson, 1991; Milsom et al., 1999).

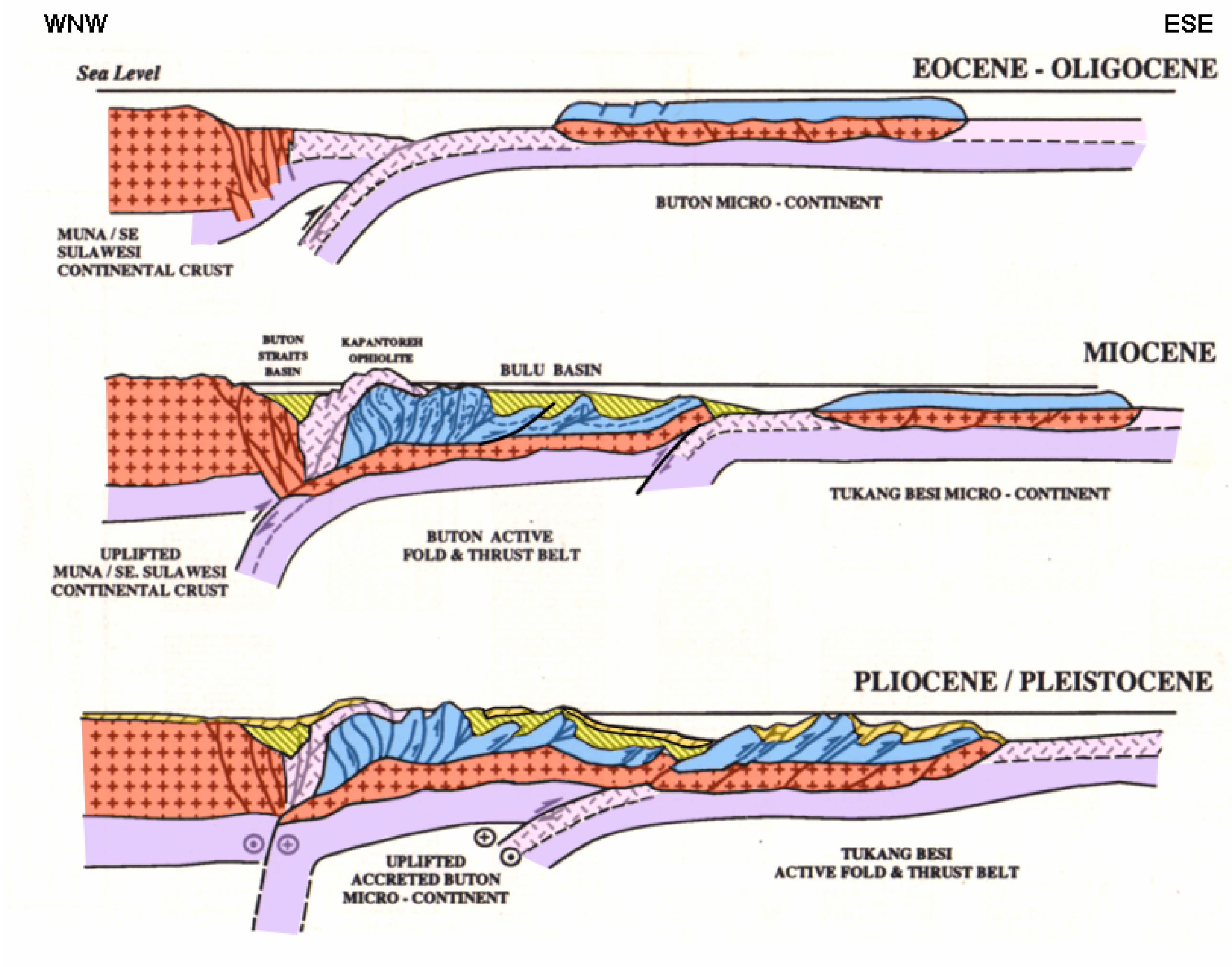

Figure 3

Figure 3 - A Plate tectonic model for the Tertiary deformational history of Buton Island, Tukang Besi, and Muna / S.E. Sulawesi (Nolan, et al., 1989; Davidson, 1991). The diagram shows double subduction of Muna-Buton and Buton-Tukang Besi. No data support the collision of Tukang Besi otherwisely, Tukang Besi is dispersed mass of Buton-Tukang Besi microcontinent due to relaxation after Buton uplift.

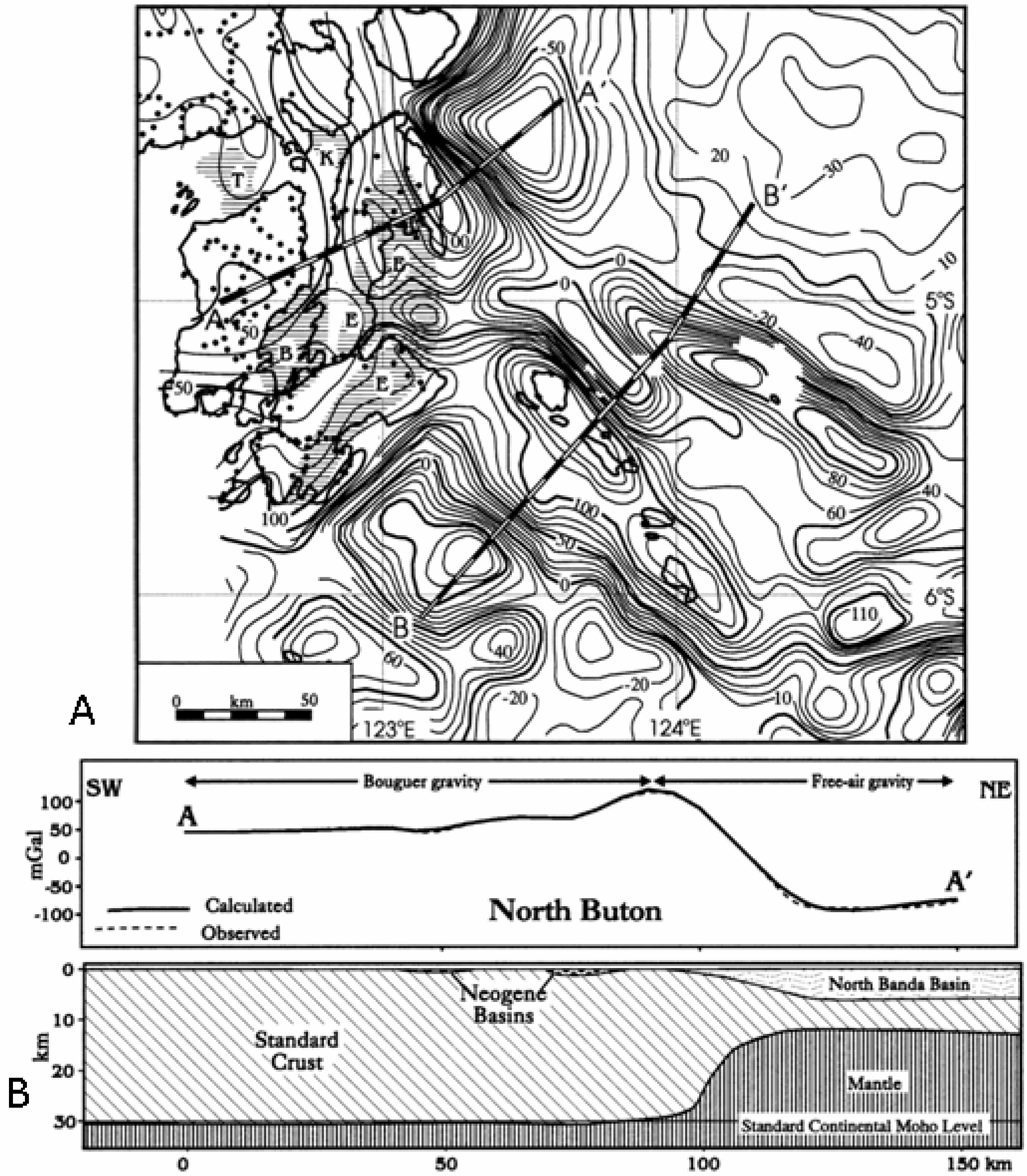

Figure 4 - **A.** Gravity map of the Buton region showing satellite-derived free-air gravity in the Banda Sea and Bouguer gravity elsewhere (Milsom et al., 1999). Contour interval is 10 mGal. Lines AA′ and BB′, segmented at 10 km intervals, show locations of profiles modeled. Horizontal hachure shows the “exploration fairways” defined by Davidson (1991) and identified by capital letters. T = Tiworo Basin, K = Kolono Basin.

B. Buton Straits Basin, and E = East Buton Basin. Black circles show the locations of onshore gravity stations. B. North Buton combined Bouguer and free-air gravity profile and gravity model.

C. Tukang Besi free-air gravity profile and gravity model. Location of “isostatic” Moho is based on a standard crustal thickness of 30 km and an assumed density contrast of 0.4 Mg/m3 across the Moho. The modeled Moho deviates considerably from its “isostatic” location, but the cross sectional areas (and hence mass excesses and deficits) above and below this ideal line are roughly equal except in the extreme southwest.

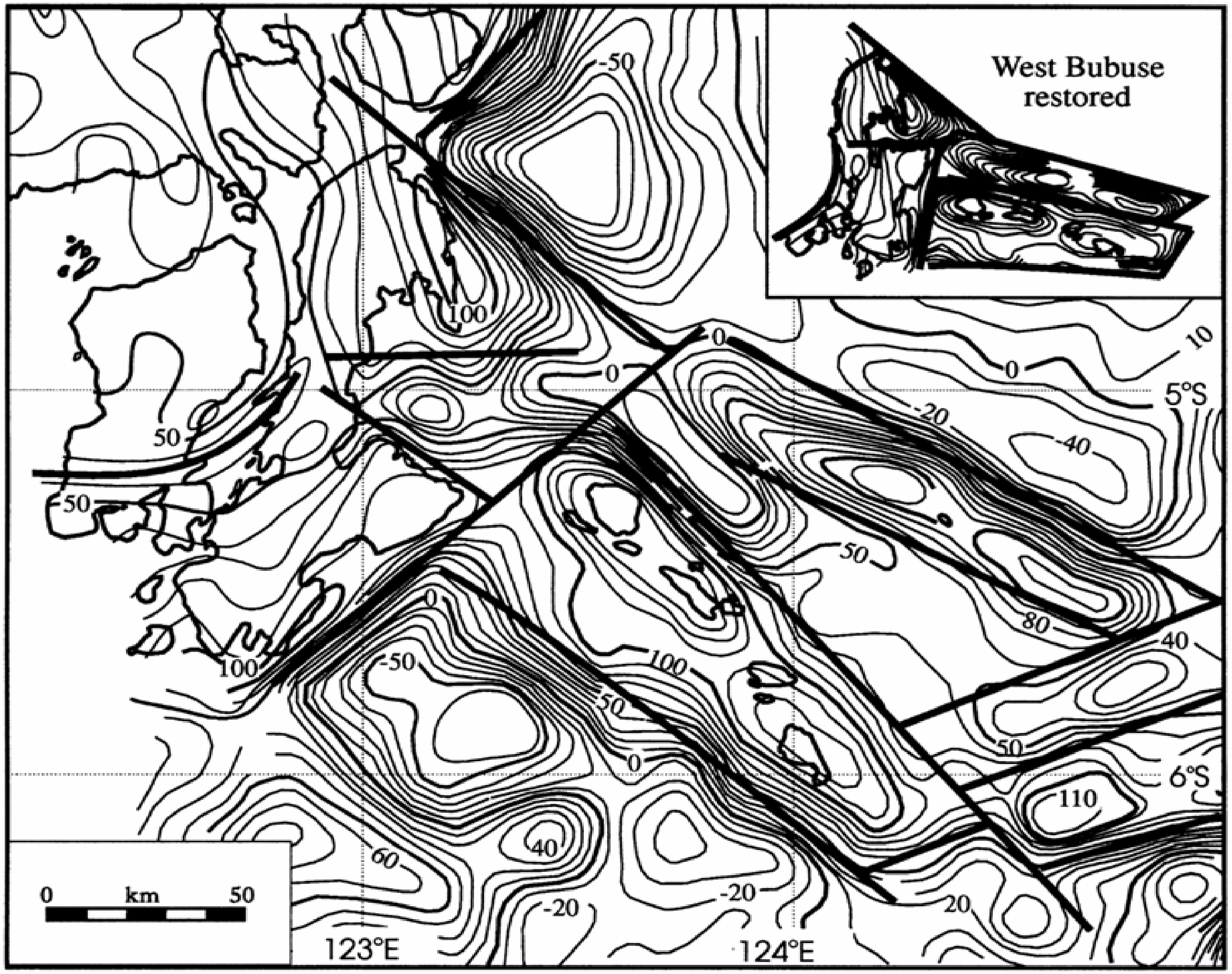

Figure 5 - Fragmentation in the Buton region. Thick black lines show approximate locations of interpreted rifted margins and of the Buton-Muna suture. Inset shows possible prerift configuration (Milsom et al., 1999).

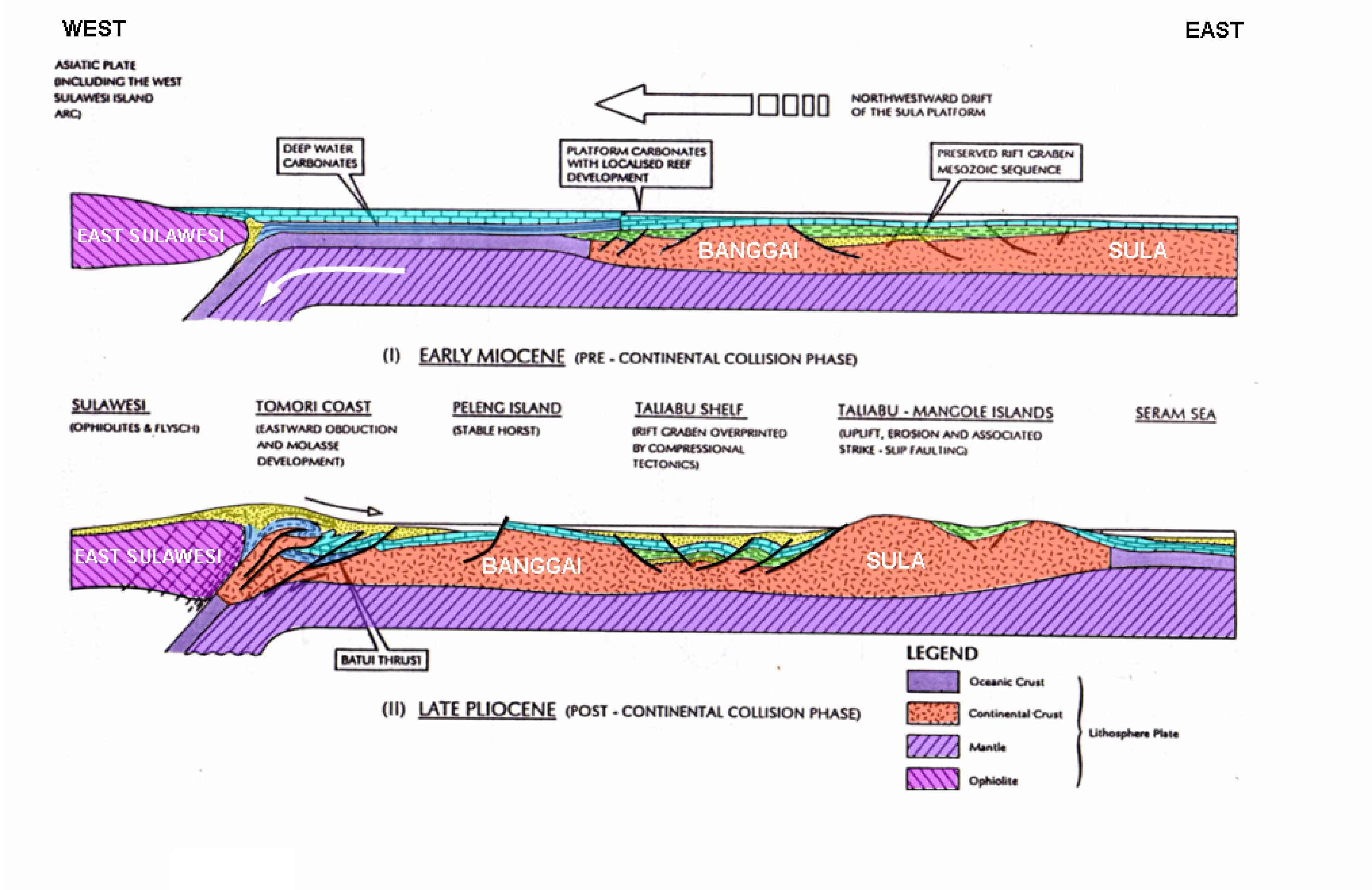

Figure 6 - Possible tectonic development of the Banggai-Sula microcontinent colliding East Arm of Sulawesi. Note the collapse/extensional structures between Banggai and Sula. The collisional foreland basin of Banggai was formed (Garrard et al., 1999)

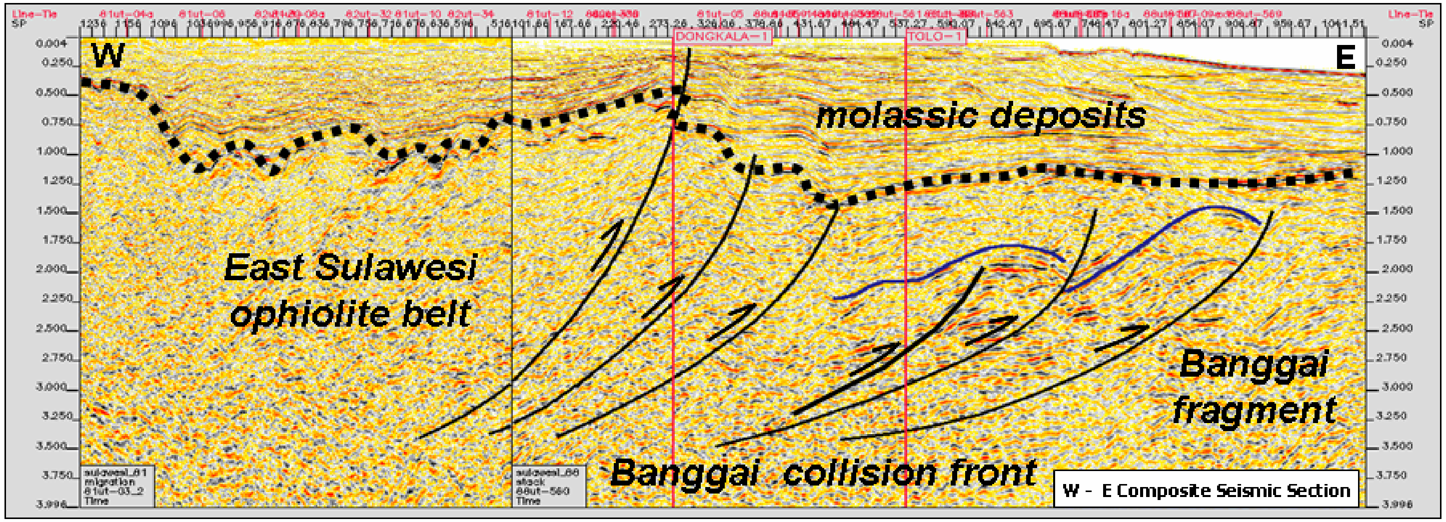

Figure 7 - Seismic section across collision front of East Sulawesi ophiolite and Banggai-Sula micro-continent. Collision front is represented by imbricated duplex structures of Batui Thrust. Mollasic deposits were deposited in foreland basin overlying the collision zone.

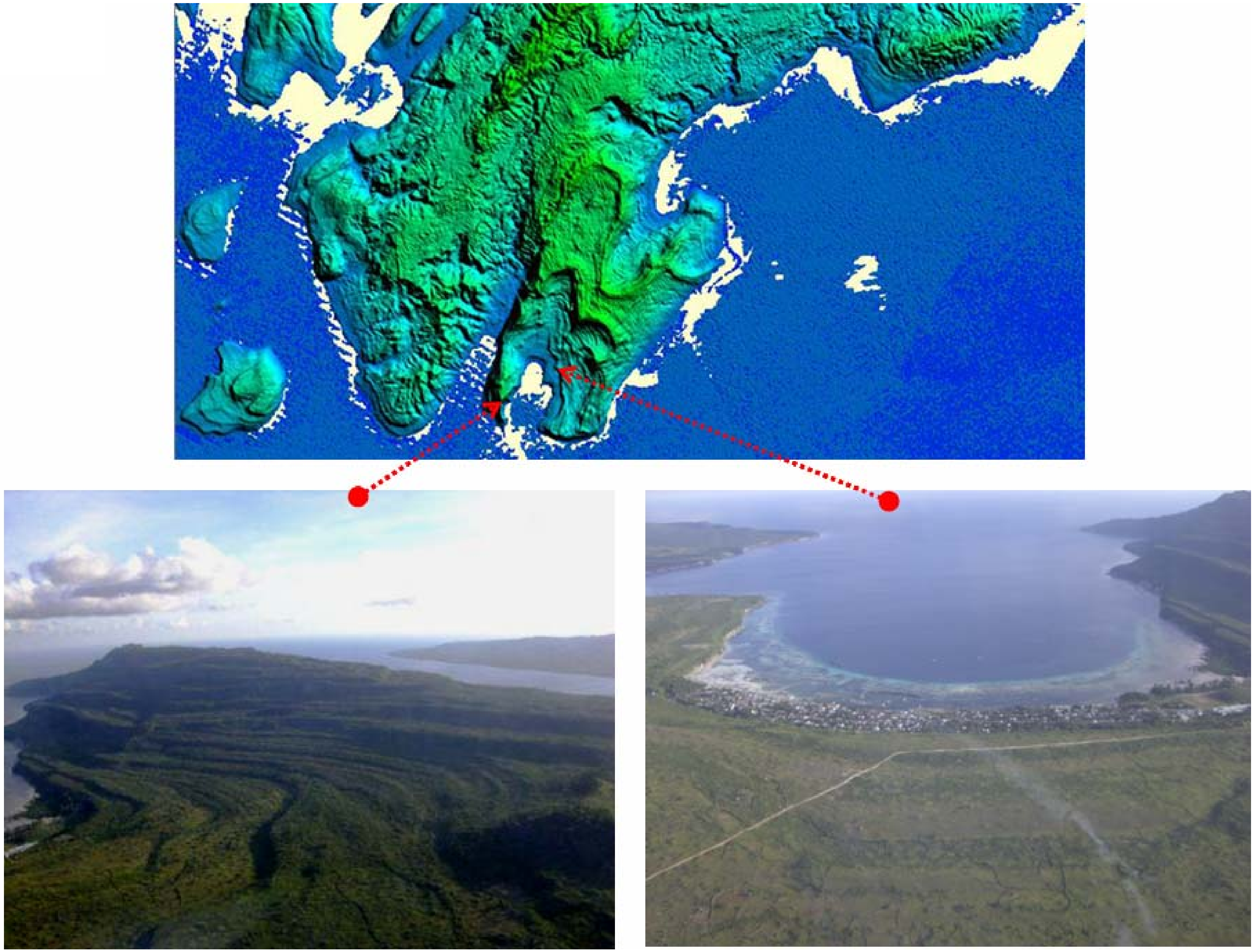

Figure 8 - Uplifted Quaternary reef terraces of south Buton Island. At least, 11 terraces can be recognized. The oldest reef is at the crest, the youngest and living reef belt is at the shallow sea forming a barrier to the bay of south Buton.

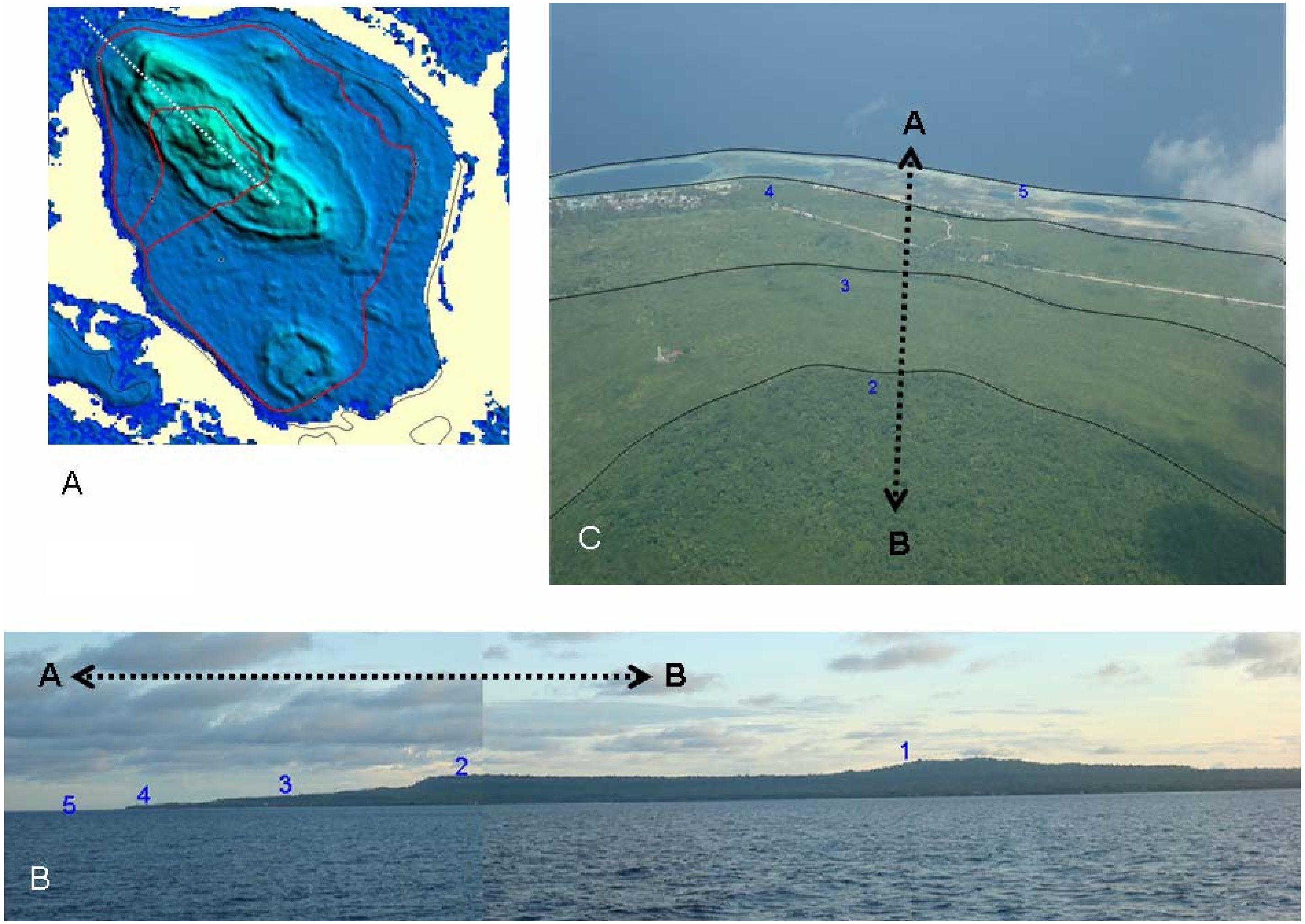

Figure 9 - DEM map shows presence of concentric reef terraces (like-atoll terraces) at Wangi-Wangi Island (A), Tukang Besi area. At least, five terraces (B) can be recognized. White dotted line at Wangi-Wangi Island is the section of reef terraces photographed (B). The oldest reef terrace is number 1, the youngest which is still living is the reef belt at offshore Wangi-Wangi Island (C).

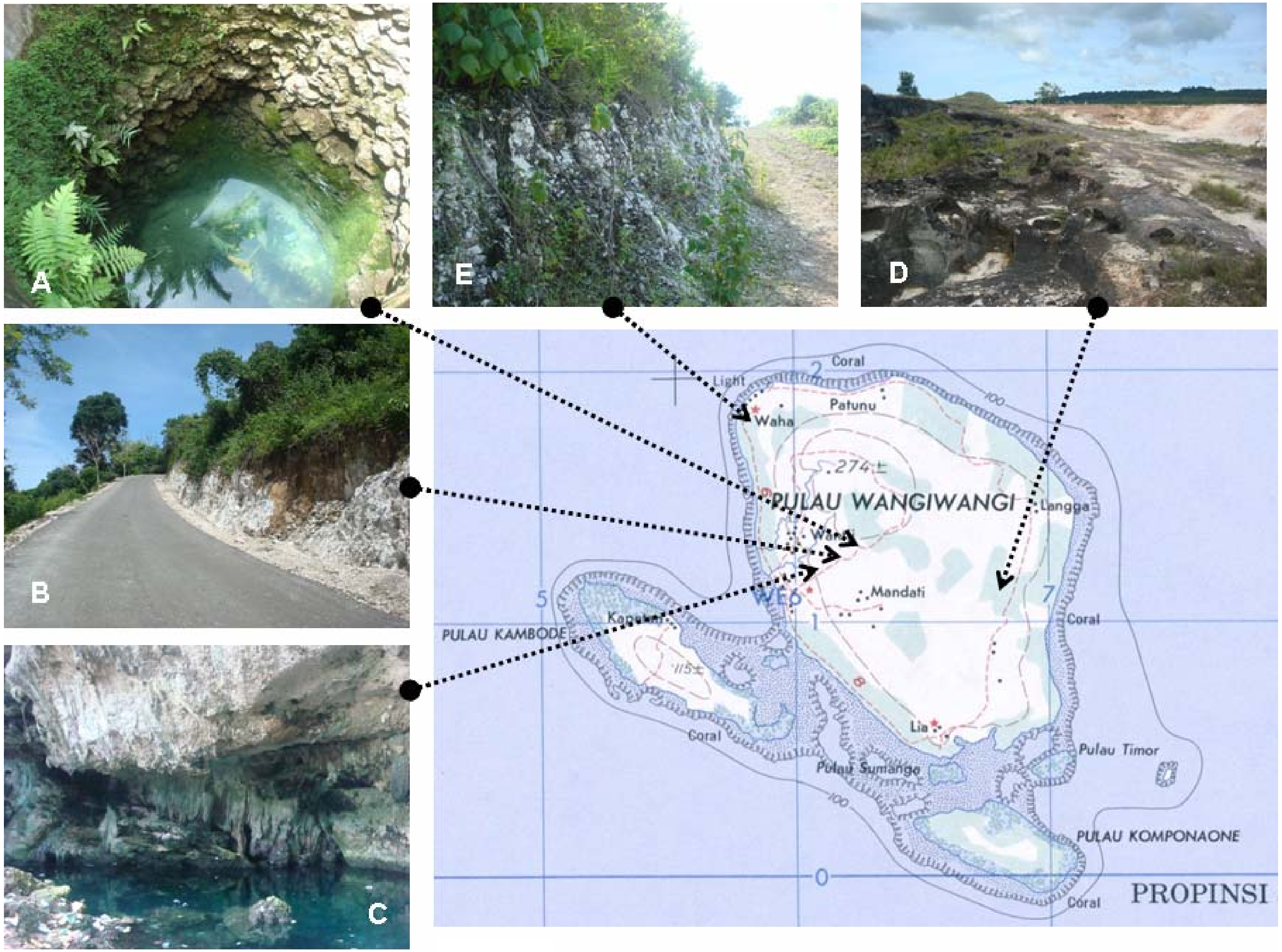

Figure 10 - Carbonates, in various composition (such as coralline limestone and sandy limestone) compose the reef terraces of Wangi-Wangi Island. Going outward from the middle of the island, the carbonates are getting younger. In this picture, the oldest carbonate is at the A terrace, the youngest is at the E terrace.

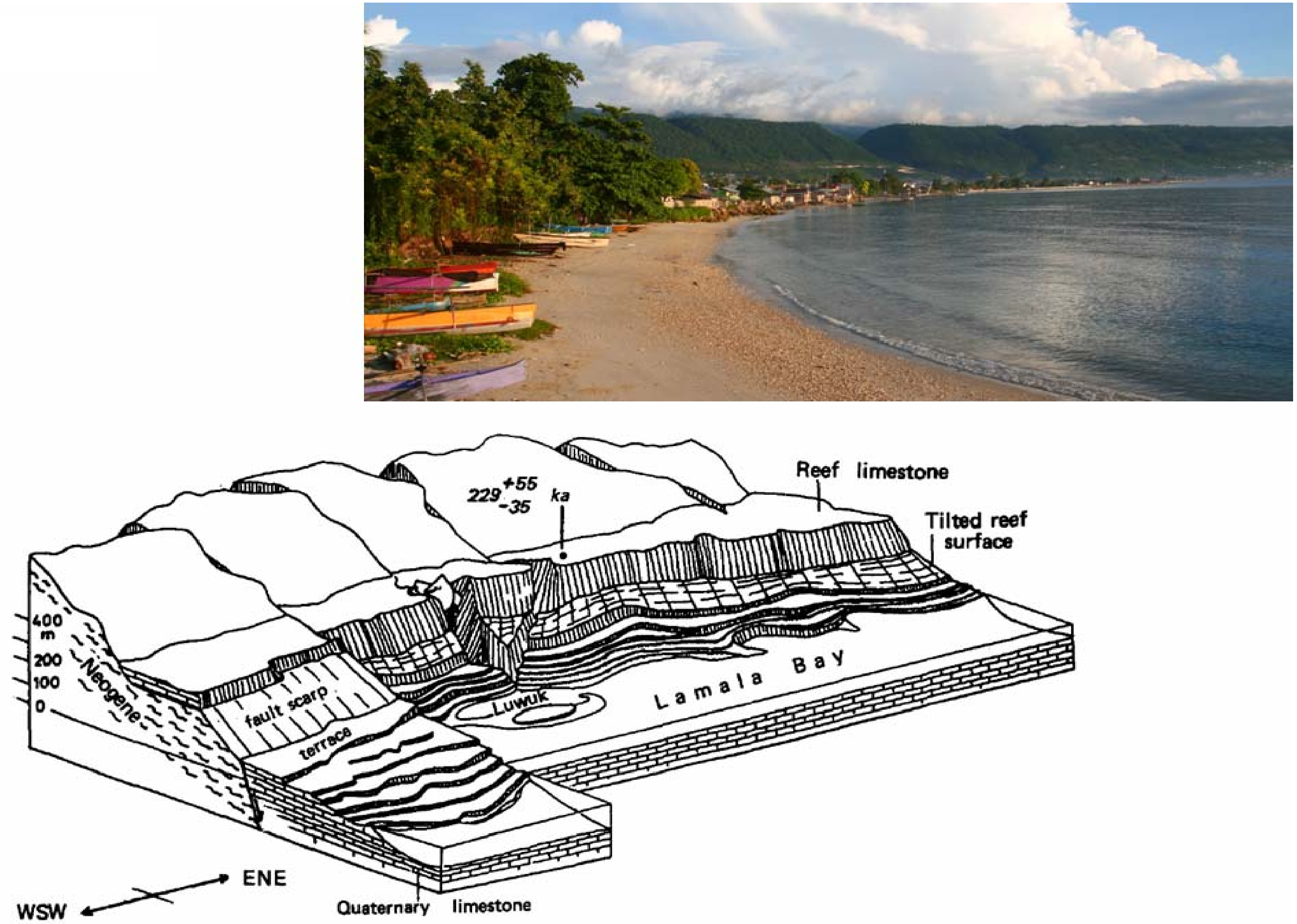

Figure 11 - Geomorphologic block diagram of the Luwuk area. Three groups of terraces comprise a middle series, that near Luwuk town consists of moderately seaward slanting surfaces and an upper group. The low terrace offshore Luwuk town is attached by a recurved spit to the mainland. Vertical exaggeration is approximately x2 (Sumosusastro et al., 1989). The photograph shows Luwuk coastal area with uplifted reef terraces forming coastal cliffs at the back.

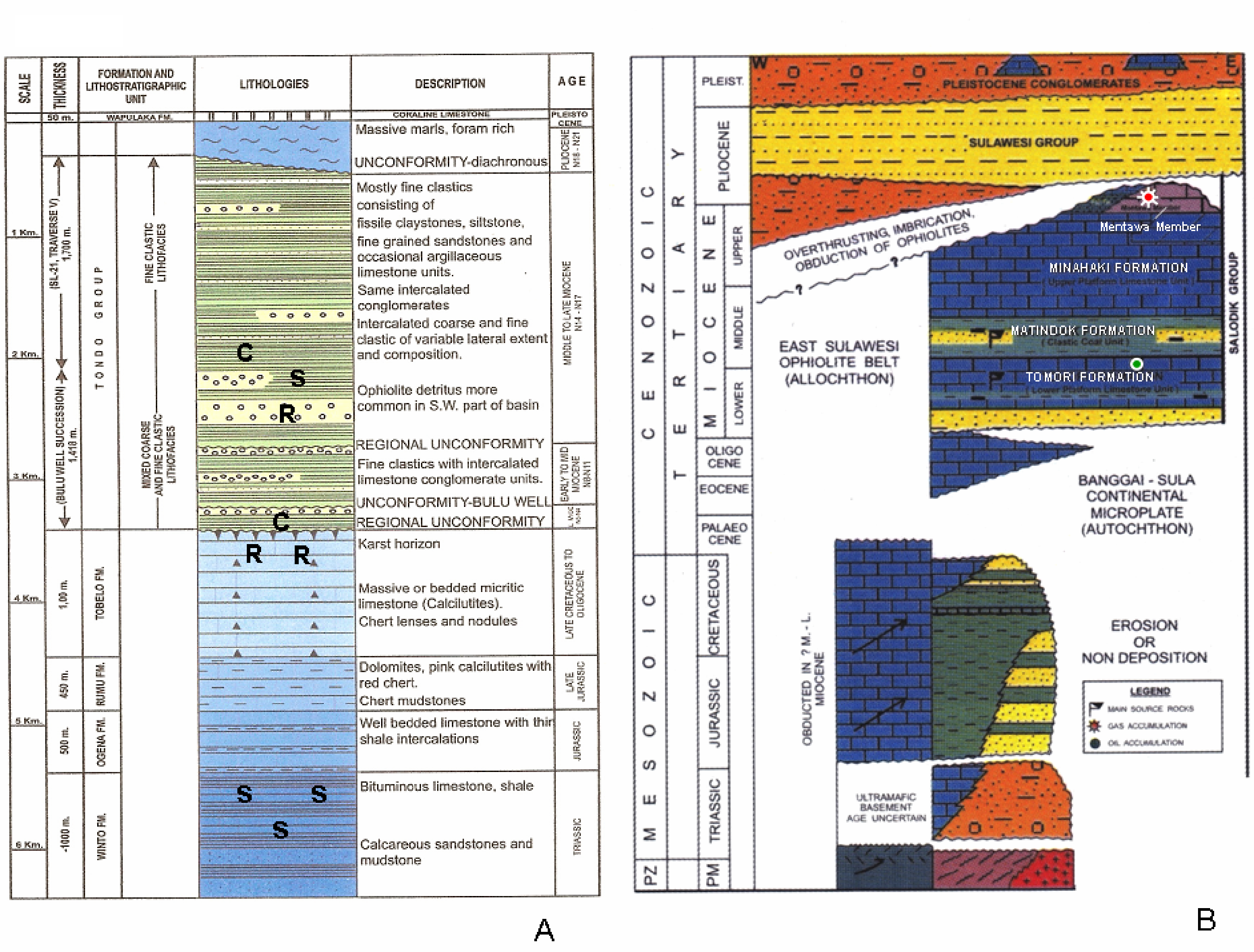

Figure 12 - A. Stratigraphic column and petroleum system elements of Buton area. Elements of petroleum system: S-source, R-reservoir, and C-caprock. The main source rock of Buton is the Triassic Winto marine shales (type II kerogen), the Tondo shales are potential source rocks (type III kerogen).
B. Stratigraphic column and petroleum system elements of Banggai area. Proven sources and reservoirs are of Miocene carbonates and shales. Potential sources and reservoirs are Mesozoic section (Ardana et al., 1996)

LEGEND	PLAY TYPES	DISCOVERY / ANALOG
A	MIOCENE REEFAL BUILD-UP	SENORO, DONGGI, MINAHAKI
B	MIOCENE CARBONATES ON WRENCH-RELATED STRUCTURE	MATINDOK-1
C	MIOCENE CARBONATES ON IMBRICATED STRUCTURES	TIAKA, KALOMBA
D	OPHIOLITE BELT (BASAL SAND OR FRACTURED RESERVOIR)	DONGKALA-1 (SHOWS)
E	MESOZOIC SECTION ON IMBRICATED STRUCTURE	OSEIL-1 OF SERAM (ANALOG)
F	MESOZOIC SECTION IN GRABEN STRUCTURE	LOKU-1 OF SULA (ANALOG)

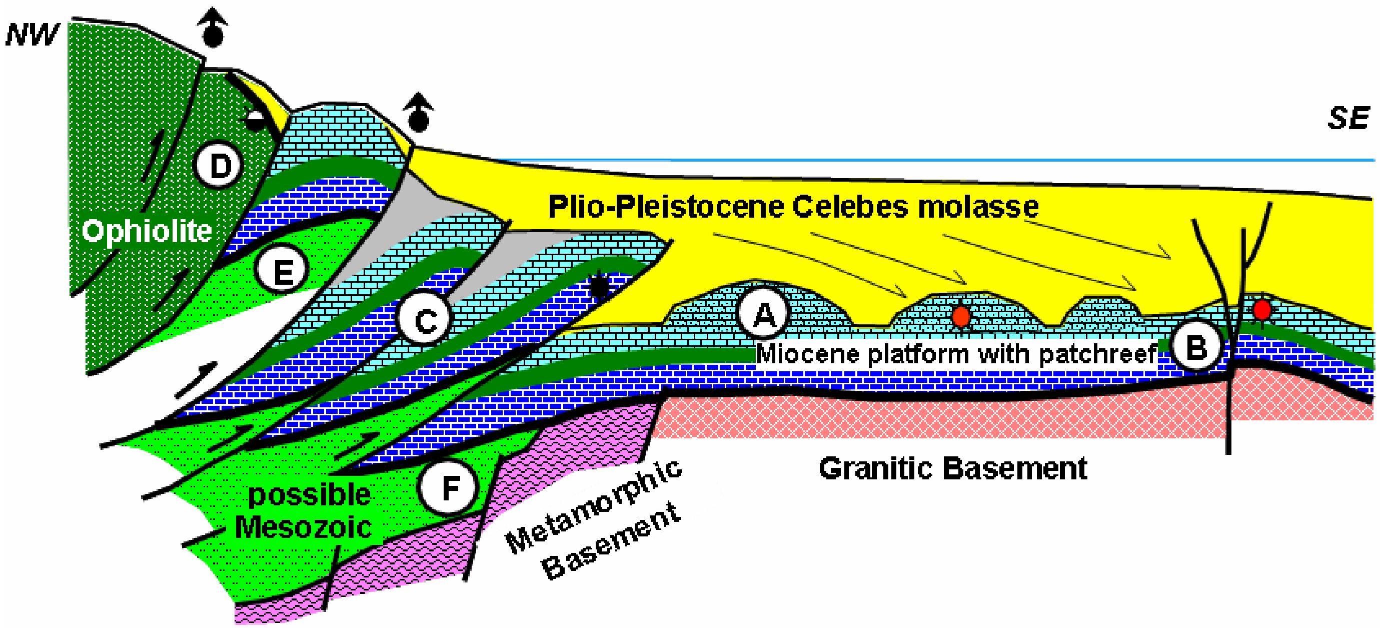

Figure 13 - Play types of Banggai Basin, proven and potential. Productive play types are types A, B, C. Proven sources are Miocene carbonates and shales. Mesozoic section in the graben (passive margin Australoid sediments) is potential sources.